Kodak's Ergonomic Design for People at Work

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Second Edition

The Eastman Kodak Company

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Preface

The application of human factors/ergonomics principles to the workplace has been of interest to Eastman Kodak Company for many years. *Ergonomic Design for People at Work,* Volumes I and II (published in 1983 and 1986, respectively) summarized data, experience, and thoughts assembled from the published literature, internal research, and observations by the members of the Human Factors Section/Ergonomics Group at Eastman Kodak Company.

Almost twenty years later, the field has evolved, much work and research has taken place both inside and outside Eastman Kodak Company, and there are many more publications in the field of industrial human factors/ergonomics. However, we still think there is a continued need for a practical discussion of issues such as design (workplace, equipment, job, and environment), analysis (of jobs, equipment, and workplaces), and the link to people's abilities. To reflect the spread and growth of information, Kodak and the editors have drawn on expertise outside the company to update and revise the material in the original books.

In response to a number of comments and requests from users of the Kodak books, this edition has been condensed to one volume. However, the focus of this work has not changed: to distill a lot of information and give fairly simple and straightforward guidelines and how-tos that can be used by people who are not professionally trained ergonomists. A basic understanding and knowledge of science, mathematics, and terminology on the part of the reader is assumed. One of the criteria for inclusion of material is that it has been tried in the plants, and it works! In many instances, this book provides alternative ways of addressing ergonomics problems in the workplace compared to the traditional biomechanical and modeling approaches that are given in other books.

The goal of this book is to provide information of a practical nature that can be used to solve problems in the workplace. The intended audience is practitioners, rather than researchers, and so the book is not a compendium of state-of-the art human factors and ergonomics information. The selection of material has been guided by the types of problems the authors have been asked to address in industrial settings. The guidelines and examples of approaches to design problems are most often drawn from case studies. The principles have been successfully applied in the workplace to reduce the potential for occupational injury, increase the number of people who can perform a job, and improve performance on the job, thereby increasing productivity and quality.

It is our hope that the experience gained from problem solving in an industrial setting by a group that includes many disciplines, will be of value to others with fewer resources available to them, and that the material will be useful in the solution of human factors and ergonomics problems in industries in many countries.

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Somadeepti N. Chengalur

1 Ergonomics Design Philosophy

ERGONOMICS AND HUMAN FACTORS

The Scope and Purpose of This Book

Since the first edition of this book, health and safety professionals and the public have become much more familiar with the term *ergonomics*. In spite of, or perhaps because of, the increasing availability of information on ergonomics and its impact, there is still a demand for guidelines that recognize the capabilities of people in manufacturing systems across the world. In this revised edition of *Kodak's Ergonomic Design for People at Work*, we have recognized the increased sophistication of the book's users. There is not as much basic science, and there is more emphasis on the practical guidelines that are useful to the ergonomist practicing in industry. We have also answered the needs of students by condensing the two volumes of the previous edition into one.

This book is intended for use by practitioners of ergonomics in the design of jobs, workplaces, equipment, and the physical environment in the industrial setting. The guidelines in this volume are not specifically relevant to product design but may be applicable in many instances. Although physiological and psychological data have been used to develop the guidelines, results are expressed in terms that engineering, safety, or medical personnel can easily transfer to the plant. Terms such as *reach, height,* and *comfort level* are used throughout the book wherever possible.

The art of applying ergonomics principles to the workplace depends on understanding the limitations of the data available. The information in this book is suitable for the design of new workplaces, equipment, and processes and for the modification of existing equipment, workplaces, and processes. The guidelines must be interpreted before being used to evaluate injury risk in existing conditions.

The first section in this chapter discusses the scope and focus of applied industrial ergonomics with regard to the fields of human factors engineering and ergonomics, and briefly reviews ergonomics at Eastman Kodak Company. Ergonomics programs in general and two specific examples of programs in other companies are presented in the second section. A problem-solving approach to ergonomics follows next. The fourth section of this chapter addresses the questions of whom we design for and how to apply human capacity data to the design of workplaces, environments, equipment, and jobs. Tables of capacity data are included that are based on studies in many countries, where available. Examples of how the data can be used to determine working height, push force, and acceptable workload are also given. We wrap up with a brief discussion of standards relating to ergonomics and human factors that were in place as of June 2002.

The rest of the book provides guidelines for design and methods for analyzing jobs and identifying the level of risk for injury or illness (where available data can be applied). Some case study problems are included to illustrate how the information on capabilities can be applied in the occupational setting to solve problems on the shop floor or in the office.

Definitions

Ergonomics is a multidisciplinary activity striving to assemble information on people's capacities and capabilities and to use that information in designing jobs, products, workplaces, and equipment. In the United States, the military and aerospace industries were among the first to accept human factors principles; however, over the past couple of decades other industries have seen the benefits of doing so and have begun to incorporate them into their activities.

The terms *ergonomics* and *human factors* are sometimes used synonymously. Both describe the interaction between the operator and the demands of the task being performed, and both are concerned with trying to reduce unnecessary stress in these interactions. Ergonomics, however, has traditionally focused on how *work* affects people. This focus includes studies of, among other things, physiological responses to physically demanding work; environmental stressors such as heat, noise, and illumination; complex psychomotor assembly tasks; and visual-monitoring tasks. The emphasis has been on methods to *reduce fatigue* by designing tasks so that they fall within people's work capacities. In contrast, the field of human factors, as practiced in the United States, has traditionally been more interested in the human-machine interface, or human engineering. It has focused on people's behavior as they interact with equipment and their environment, as well as on human size and strength capabilities relative to product and equipment design. The emphasis of human factors is often on designs that *reduce* the potential for *human error.*

The Benefits of Ergonomics and Human Factors

The benefits of well-designed jobs, equipment, and workplaces are improved productivity, safety, and health, and increased satisfaction for the employees. This is achieved by removing unnecessary physical effort from jobs or by reducing mental demands (e.g., by improving the way in which information is transferred between people, or between product and people, as in inspection). This allows for greater productivity and, ultimately, higher profitability.

As concerns about productivity, employee job satisfaction, and health and safety in the workplace have increased, interest in ergonomics has increased as well. Many schools include courses in human factors, often within industrial engineering or psychology departments, and industrial hygienists are expected to know some ergonomics principles for certification. Medical professionals are also recognizing the value of ergonomic analyses of jobs to assist them in the rehabilitation of people returning to work after illness.

Ergonomics at Eastman Kodak Company

Although people have been applying human factors and ergonomics principles in the workplace for many years, it has only been over the last couple of decades that many industries have formally recognized the field by establishing internal groups to study and address such issues. At Eastman Kodak Company, there has been a group investigating and applying the principles of ergonomics and human factors for almost half a century.

In early 1957, Dr. Charles I. Miller and Harry L. Davis met with Dr. Lucien Brouha, who was then the head of Haskell Laboratory at E.I. duPont de Nemours & Co. The Haskell laboratory had conducted a number of studies related to heat stress problems and the capacities of people doing hard physical work. Having learned from him, they began work physiology data collection on jobs at Kodak and formulated ideas and plans for a broad-spectrum human factors function within the company. By 1960, a small laboratory had been developed and a human factors group function formed. It was a joint effort of the Medical Department and the Industrial Engineering Division of the Kodak Park Division in Rochester, New York. The group specialized in workplace and job analysis, and design within a very large industrial complex that manufactures a diversity of photographic products, papers, chemicals, and hardware products.

Expansion of the group into a variety of disciplines resulted in a corresponding increase in its activity and a broadening of its scope beyond Rochester to a worldwide arena (in 1972). The area of product design was also developed, and the group eventually split into two sectors, one that applies ergonomics and human factors principles to product design (Human Factors) and another that applies the same principles to evaluating work situations (Ergonomics).

The ergonomists at Eastman Kodak Company serve the entire corporation and interact closely with manufacturing personnel as well as with the Medical, Safety, Industrial Hygiene, Epidemiology, Industrial Relations, Design Engineering, Industrial Design, and Industrial Engineering staff groups to identify and resolve potential problems.

In 1992, Eastman Kodak formalized its commitment to applying ergonomic principles in the workplace by establishing a corporate performance standard that requires all company facilities and processes (worldwide) to be "designed, constructed, operated and maintained to accommodate human capabilities and limitations in order to enhance employee safety, health, and performance." Around the same time, formal expectations were established about the programs and processes that would be used to focus on proactively improving the workplace environment and concomitantly reducing the risk of musculoskeletal disorders.

Each facility and organization is expected to evaluate its performance against the performance standard. Conformance is also formally evaluated through periodic corporate audits. Every few years, the associated programs and processes are revisited and modified based on the company's experience with them. Currently, the programs and processes used to meet the company's performance standard encompass the following basic tenets:

- Employees should receive training on basic ergonomics principles. The aspects covered in the training depend on the work environment they have.
- Employees whose activities impact the work environment (e.g., engineers, supervisors, maintenance groups, and health and safety professionals) should receive in-depth training commensurate with their activities.
- Newly designed or modified workplaces, processes, and equipment should meet established ergonomics or human factors guidelines.
- A continuous improvement process should be used to reduce fatigue and human error, as well as the risk of injury associated with existing workplaces, processes, or equipment.
- Affected employees should be involved in the planning and implementation of changes to workplaces, equipment, or processes.
- Reports of work-related injuries or illnesses should be followed up with root cause analyses, and the workplace, process, or equipment should be modified accordingly.

Eastman Kodak Company encompasses a wide spectrum of businesses, manufacturing environments, and service organizations. As a result, the manner in which the above tenets are implemented vary from organization to organization, according to their needs and their organizational structure and systems. The information provided here is the basis for much of the training and for the principles used when designing or evaluating workplaces, equipment, or processes.

ERGONOMICS PROGRAM CHARACTERISTICS IN OTHER COMPANIES

Influences on Ergonomics Programs

The evolution of ergonomics efforts, programs, and analysis techniques in industry has been affected by a number of factors:

- Application of increased knowledge and awareness gained from research and experience in both academia and business
- Integration of business initiatives such as productivity, quality, and statistically driven process efforts in order to meet the challenge of competitiveness and changes in resource allocation
- Changes in management/leadership that may result in changed emphasis or direction of the ergonomics program
- Technology advances incorporating new or evolved ergonomic solutions, as well as analyses methods within the ergonomics program
- Social and population changes and diversification (Schwerha and McMullin 2000)
- Globalization of companies and businesses, requiring them to address varied cultural differences as well as communication, training, and standardization issues (Joseph 2000)
- Local, national, and international regulatory efforts in ergonomics

There are additional considerations that are not listed. Some may be specific to the business or company, what they produce, and other factors.

Regulatory Influences

Regulatory efforts in ergonomics have contributed a great deal to ergonomics programming and efforts being initiated in the United States. Many companies would not have started an ergonomics effort, let alone go to the extent some programs have, without the motivation of a regulation. In the United States, the Occupational Safety and Health Administration (OSHA) implemented guidelines and regulatory efforts starting in the late 1970s that have affected ergonomics programming.

Most of these regulations and guidelines were written to be broadly applicable across general industry, regardless of the size, nature, or complexity of operations (though at times particular industries have been excluded). The most specific one is the “Ergonomics Program Management Guidelines for Meatpacking Plants (the Guidelines),” published in 1990. Multiyear agreements signed between OSHA and various companies, as well as numerous company-specific citations, have used the meatpacking guidelines. These guidelines and regulatory efforts advocate that an ergonomics program should have the following core elements:

- Management leadership and employee participation
- Hazard awareness and identification
- Training and education
- Medical management
- Job hazard analysis
- Hazard prevention and controls
- Program evaluation

For more information on regulations and standards in other parts of the world, refer to "United States and International Standards Related to Ergonomics," later in this chapter.

Level of Responsiveness

The continuous development and maturation of an ergonomics process is depicted in Figure 1.1, which considers the level of responsiveness and focus of the ergonomics program and the level of ergonomics assessment tools applied.

The level of desired ergonomics responsiveness—reactive, proactive, or strategic—will aid in determining the structure and level of programming required. Typically, the initial level of responsiveness toward ergonomics efforts is reactive in nature. Reactive ergonomics applies intervention efforts after an issue is recognized—for example, to address musculoskeletal disorders (MSDs) or other problems (see Figure 1.2). This application of ergonomics to the individual or group of workers and their work, workstation, or work area is also known as microergonomics (Hendrick 1987). The reactive perspective can be usefully integrated with proactive and strategic levels of ergonomics responsiveness, with microergonomics serving to determine design and possible system issues from a historical perspective.

The next level of responsiveness in ergonomics is proactive—designed to preempt any MSD event or problem (see Figure 1.3). This is accomplished by having the appropriate person or system apply ergonomics principles in designing products, workstations, work areas, plants, programs, and systems for manufacturability and to enhance work (Rodgers 1984). Proactive ergonomics should be established as much as possible at the product and process development systems level (Westgaard and Winkel 1997, 2000; Joseph 2000; Hagg 2000). Specific systematic processes should be implemented so that designers, engineers, and support personnel can better work together and communicate both organizationally and geographically (Joseph 2000). Gener-

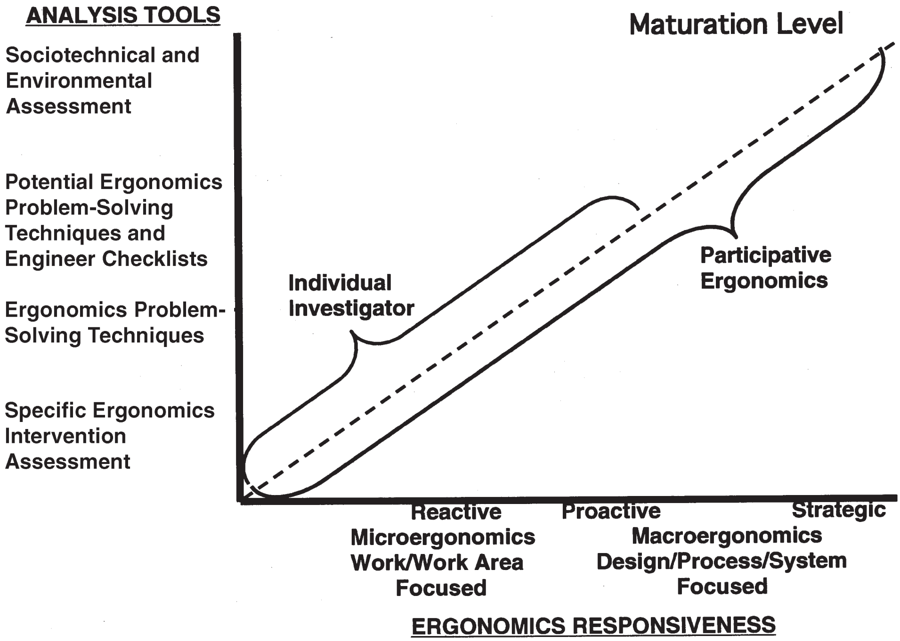

FIGURE 1.1. The Continuous Evolvement and Maturation of an Ergonomics Process

ally, proactive ergonomics efforts are undertaken by designers, design engineers, engineers, planners, and schedulers. However, ergonomics problem-solving teams are allowed to participate as much as possible in this effort as well (Day 1998).

Proactive ergonomics may be seen as separate from reactive ergonomics, but the two should be integrated with past reactive ergonomic studies and efforts in order to gain a historical perspective. Proactive ergonomics should directly interface with participatory ergonomics problem-solving teams as well (see Figure 1.4).

The next level of responsiveness in ergonomics programming, strategic efforts, incorporates analysis of management, sociotechnical, and environmental systems of work. This effort is known as the study of organizational design and management (ODAM) or macroergonomics (Hendrick 1987). Companies sometimes move in this direction; however, they may not ever achieve true macroergonomics, which begins with an analysis of the relationship of sociotechnical systems to the design of work systems, including a systematic analysis of technology, personnel, and external environmental systems (Hendrick 2001). Macroergonomics studies have shown that if microergonomics, or fixing just the work or work area, is the only approach used within an organization, the sociotechnical or environmental systems that contributed to or were the root causes for the risk may not be fixed, and therefore the problem may well arise again or not be fixed in the first place (Gilmore and Millard

Characteristics of a Reactive Ergonomics Program

Program Structure

- Intervention studies aimed at a specific problem, usually at a particular workstation or work area. This effort may be seen as short-lived in that it identifies the problem, solves it, and moves on.
- Associated programs will be aimed at specific work issues or work areas being studied.
  ⇒ Back schools, awareness training, behavioral safety, work hardening
  ⇒ Productivity enhancements as well as quality management efforts
- Utilization of participatory ergonomics efforts will be the preferred structure.

Analysis Models

- Individual investigators, outside experts or from within the company, may be used in analysis of specific work or work areas in the initial phases of an ergonomics effort.
- Individual investigators may still be used even in participatory efforts; however, they must work very closely with the ergonomics coordinator, ergonomics team, engineer, and steering committee.
- Structured ergonomics problem-solving techniques are used to arrive at technically and economically feasible solutions.
- Specific investigative ergonomics analysis tools are integrated with the problem-solving technique.
- Participatory ergonomics efforts are incorporated using the operating employee members.

FIGURE 1.2. Characteristics of a Reactive Ergonomics Program

1998; Kleiner 1999; Kleiner and Drury 1999; Zink 2000; Hendrick 2001). Hendrick (2001) concludes that if effective macroergonomics is applied, then microergonomics would automatically be included in the system's overall structure.

A critical factor to be considered is that an ergonomics expert, whether outside or inside the organization, must possess a high degree of organizational design background and experience as well as the traditional ergonomics background and experience. On the other hand, an outside or inside organizational design and management expert needs to have a high level of ergonomics background and experience. Also, the organization must be prepared to make the additional effort to begin and implement macroergonomics.

Mature Ergonomics Efforts: Programs to Processes

Many companies are labeling their ergonomics program as an "ergonomics process." This change in name supports the change in program direction and

Characteristics of a Proactive Ergonomics Program

Program Structure

- Intervention studies using internal or external experts may still be used; however, they work very closely with the ergonomics coordinator, ergonomics team, steering committee, and engineers/designers.
- Associated programs are usually integrated with the ergonomics program and are aimed at specific work issues or work areas, but they look at the process and begin to look at work systems, aligning efforts with scheduled changes and potential concerns.
  - ⇒ Back schools, awareness training, behavioral safety, work hardening
  - ⇒ Productivity enhancements as well as quality management efforts specifically used and integrated with ergonomics, including Six Sigma, flow technology, action workouts, cell technology, and others
- Safety or human resources personnel can initiate these efforts, but many times production, engineering and leadership will initiate the need for a study of concerns that are being anticipated.
- Emphasis is given to the training and assimilation of ergonomics design principles for designers, engineers, and planners.
- Knowledge is extended through training or awareness, and criteria are set for suppliers, vendors, and outside contractors.
- Utilization of participatory ergonomics efforts will be the preferred structure.

Analysis Model

- Participatory ergonomics efforts are incorporated with design team members at specific points in design processes.
- A structured, systematic ergonomics analysis process is available to and used by designers and engineers for proactive identification and "potential" problem-solving using specific ergonomics analysis tools and checklists.
- Specific investigative ergonomic analysis tools will be used for specific needs.
- Additional tools, e.g., Six Sigma and continuous improvement processes, will integrate ergonomics principles and analysis and be used to look at processes and work systems.

FIGURE 1.3. Characteristics of a Proactive Ergonomics Program

scope to that of a process that addresses a series of systematically planned actions that produce change or development directed toward ergonomic design or redesign of work and work systems (Day and Rodgers 1992; Joseph 2000). As ergonomics processes mature, they adopt *participatory ergonomics processes* and use *ergonomics problem-solving techniques*. They will inherently consider work system design issues at the reactive and proactive levels, though not to the degree to which macroergonomics would review the additional

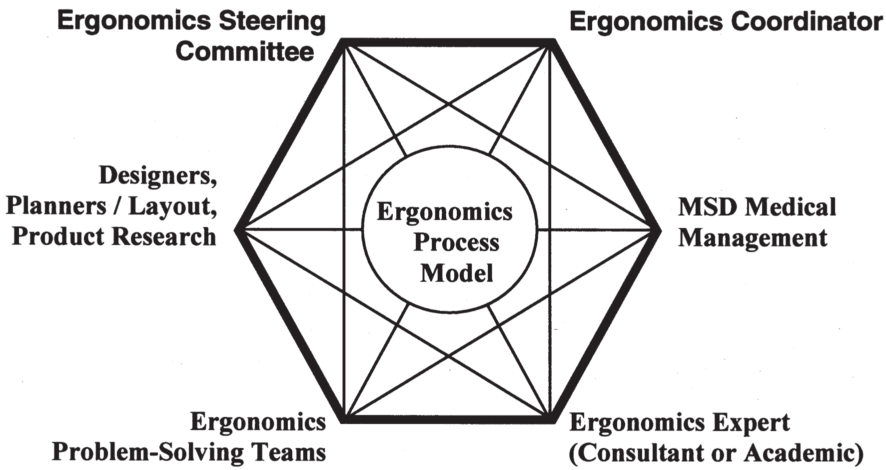

FIGURE 1.4. Participatory Ergonomics Process Model

sociotechnical and environmental systems (Rodgers 1992; Day and Rodgers 1992; Moore and Garg 1996; Haims and Carayon 1998; Robertson 2000).

Participatory Ergonomics

A company or business will typically start with an individual investigator who does ergonomics assessments. The individual investigator will generally be used for specific issues or studies in the reactive or proactive levels. In contrast, macroergonomics generally employs multilevel and multifunctional teams to assess and address systems. The individual investigator is still used in a mature ergonomics process, but to a much smaller degree, and he or she is usually required to work with the ergonomics problem-solving teams or design teams. Participatory ergonomics efforts, on the other hand, can be used across all levels of ergonomics responsiveness and can be directly involved with all levels of ergonomics assessment tools (Rodgers 1992; Day and Rodgers 1992; Day 1998; Hendrick 2000).

Benefits from using general participatory programs have been well established (Sherwood 1988; Allen 1991; Proctor 1986; Auguston 1989; Pasmore 1990). There is evidence that shows participatory ergonomics programs result in some of those same benefits (Rodgers 1984; Hendrick 1987, 2001; Imada and Nagamachi 1995; Wilson 1995; Moore and Garg 1996; Rosecrance and Cook 2000). Participatory ergonomics, a hybrid of other organizational design and management efforts, is more than just "doing ergonomics" or "involving the employee in ergonomics." Rather, employees from all levels and from all functions and organizations work and communicate collectively, in functional or natural groups or teams, using ergonomics as a forum. Through the participatory ergonomics process, a commitment is made to agree upon and attain desirable outcomes for microergonomics as well as macroergonomics problems (Day 1998).

Participatory ergonomics can be used effectively across reactive, proactive, and strategic (macroergonomics) levels of ergonomics responsiveness. It is recognized as a very important aspect of macroergonomics (Hendrick 2001; St. Vincent, Laberge, and Lortie 2000). The initial phases of participatory ergonomics are led by an outside expert who trains and guides the ergonomics team through initial analyses and well into the learning curve. There is a process of transferring the guidance and control from the outside expert to the internal participatory structure. Another variation of participatory ergonomics is the participatory action research model, which requires the investigators to work collaboratively with the study population (Moore and Garg 1996; Haims and Carayon 1998; Rosecrance and Cook 2000).

An external expert must have some plan to eventually transfer the guidance and control of the participatory process to the participants and not override the participants' growth (Haims and Carayon 1998). Care must be taken to monitor the effectiveness of the participatory structure as it begins to take control and to ensure that the ergonomics problem-solving teams will be effective in the analysis process and not become extensions of the outside expert (St. Vincent, Laberge, and Lortie 2000).

One model for the structure of the participatory ergonomics process is shown in Figure 1.4.

The structure should be flexible, allowing for continuous improvement of the ergonomics process over the long term. If there is no structure, these initiatives will not be long-lasting (Day 1998). The structure of the ergonomics process should include all specialized functional groups in the organization and ensure that they are linked either geographically or by regular communications. Both of these concerns will be critical for designers, planners, and product designers (Joseph 2000).

Specific Ergonomics Process Issues

Globalization

Many companies that have facilities in other countries have found that the transfer and standardization of knowledge and processes, outcomes, and communication become critical areas for introducing ergonomics outside of the home country. Joseph (2000) details the following tasks to implement an ergonomics effort in a new region:

- Secure and establish a local ergonomics steering committee that develops, manages, and owns the ergonomics process. Adjust the process to meet local requirements.
- Train using the established company ergonomics training course.

- Establish and implement a single system to document the ergonomics process, ergonomics analysis process, and results to be used for best practices and lessons learned for all sites worldwide. The goal is eventually to have an automated system for recording and storing this information.
- Establish a continuous improvement process that integrates the ergonomics process and can be centrally located and globally implemented.
- Establish a global rollout partnership to assist smaller sites that have fewer resources.
- Roll out a country-based ergonomics process with site representatives selected to implement the rollout specific to their site and country.
- Develop a specific audit process to measure the success of the ergonomics process.
- Global and local regulatory issues may differ and need to be specifically addressed. Finally, cultural and social issues must be considered and integrated into the plants' local ergonomics process (Joseph 2000).

Integrating Productivity Enhancements

Many ergonomic analysis models have begun to integrate quality-driven analysis process such as continuous improvement models (Joseph 2000; Axelsson 2000; Rosecrance and Cook 2000; Moore and Garg 1996), as well as statistically driven processes such as Six Sigma (Harry 1994). Often, quality analyses processes are selected that are comparable to the company's internal quality analysis model, because consistency is critical to success. The model in Figure 1.5, based on ergonomics problem-solving techniques (Rodgers 1988, 1992), is one road map for the ergonomics problem-solving team.

<u>Step 1:</u>	DEFINE	Identify concern, key players/stakeholder
<u>Step 2:</u>	MEASURE	Review data systems and survey work*
<u>Step 3:</u>	ANALYZE:	Apply specific ergonomics analysis tools, if appropriate: manual handling, repetitive work, others Apply the ergonomic problem-solving technique* Validate solutions and ensure that they agree with employees' perceptions* Review proposed solutions for effectiveness and added concerns
<u>Step 4:</u>	IMPROVE	Perform justification, select the best alternative, report out
<u>Step 5:</u>	CONTROL	Develop implementation plan and implement
<u>Step 6:</u>	EVALUATE	Reevaluate, interview employees,* complete documentation
<u>Step 7:</u>	VALIDATE	Interview employees after implementation,* monitor, follow up

*Employee involvement and input

FIGURE 1.5. General Ergonomics Problem-Solving Flow Process (adapted from Rodgers 1987, 1988, 1992; Day 1998)

Other business initiatives such as flow technology, action workouts, and other productivity enhancement tools should be integrated with ergonomics. Typically, these enhancement tools are focused on the product or process or system (Rodgers 1989; Day and Rodgers 1992). Many times the worker is not considered from an ergonomics viewpoint. Therefore, any enhancements program should have an ergonomics principles training module as part of the program's rollout. Ergonomics problem-solving techniques and specific ergonomics tools should be available and used by the enhancement team to assess the risk associated with the present situation and with the desired situation after the enhancement tool is applied. The integration of these enhancements and ergonomics will make the efficiency effort more ergonomically sound.

Program Examples

OSHA Ergonomics and Record-Keeping Agreement in a Manufacturing Facility (~600 employees) with Injection Molding and Assembly Operations (Day 1998)

Although ergonomics activities began in 1992, the OSHA Ergonomics and Record-Keeping Agreement was formally implemented in 1993 and was to end in 1997. This OSHA citation included 2,710 documented OSHA-recommended abatements for 189 citations. Each citation corresponded with a particular workstation. The number of operations per citation varied as well. Chronological efforts for the ergonomics program included the following:

- An Ergonomics Council (EC), whose members included leadership, operations, industrial relations, medical, safety, union, and engineering representatives, was established to respond to complaints and make recommendations to be carried out by the engineering/operations group.
- The EC identified an engineer whose role was to coordinate ergonomics recommendations and efforts.
- An outside ergonomics expert was hired in late 1992. Subsequently, a total review of the OSHA ergonomics agreement was made and a specific formalized structure was implemented that would both satisfy the terms of the OSHA agreement and be compatible with the company's leadership style, union representation, and culture. A specific ergonomics problem-solving analysis process that would include repetitive task analysis was designed and implemented as well (Rodgers 1988, 1992). See "An Ergonomics Problem-Solving Technique" later in this chapter.
- The EC role was changed to that of an overseeing effort. An ergonomics coordinator/engineer was appointed and three additional engineer/technicians were hired and assigned to specific assembly lines to perform the ergonomics problem-solving analysis process and implement solutions.

Although the engineers were to perform the analysis, the operators performing the tasks participated in several aspects and steps of the ergonomics problem-solving analysis process.

- The medical services direction was changed from an emergency physician to an on-site occupational health service approach to meet known ergonomics medical management needs. Initially, these personnel were working on the backlog of open cases and establishing set protocols for treatment and for tracking injury and illness mechanisms.
- The launch of new products began to incorporate ergonomics. Typically, an ergonomics engineer/technician would attend product development meetings and look for potential design/assembly issues. Designers were trained in ergonomics principles and incorporated them both into assembly applications and into design for the product's end user.

The company showed an 87 percent reduction in the cumulative trauma disorder (CTD) case incident rate (40 ± 2 pre-1992 to 5 in 1997). Incident rates are generally calculated as number of incidents per 100 full time employees. A 47 percent reduction in the lost work days–injury/illness (LWDII) case rate was seen from 1994 to 1996 (14.5 to 7.7, respectively). A 73 percent reduction in the LWD illness-only case rate was also seen from 1994 to 1996 (5.5 to 1.5). Other important indicators of program effectiveness to reduce upper-body musculoskeletal problems were seen in the results of a survey that was administered periodically to the employees from 1993 to 1996. The results showed consistent year-to-year reductions in discomfort or symptoms during this time frame: an overall 30 percent reduction in twelve-month-period prevalence rates, a 59 percent reduction in seven-day-period prevalence rates, and a 34 percent reduction in missed workdays in the previous twelve months.

The company spent $2.66 million from 1992 to 1997 for the overall process efforts. This included a prior cost in 1992 of $255,000 for training, administrative, and medical costs, and a minimal project investment; $36,000 for training; $700,000 for administration; and $142,000 for medical management. Of the $1.5 million spent for project investment, $800,000 was spent to implement ergonomic controls in project investment dollars ($700,000 was not directly related to ergonomics). Of this $800,000 in project investment costs, approximately 5 percent was for training, another 5 percent was for layout efforts, about 50 percent was for automation, and approximately 40 percent was for engineering changes, including new tools, fixtures, tables, and so on.

The reduction in CTD incident rates from 1992 to 1997 was very dramatic considering that only a fraction (10–27 percent) of the estimated cost ($5.75 million to $8 million) for OSHA-recommended abatements was spent. Over the five-year life of the agreement, an increasing amount was spent, up to 71 percent, on solutions that were generated from business needs as opposed to just ergonomics. This reflected a change in the company culture to seeing ergonomics as a benefit, not just an OSHA-generated necessity.

The company ergonomics process was very effective and was an ongoing maturation process, evolving from an authoritarian-reactive process to a participatory-proactive process that considered work systems. There may have been isolated ergonomics efforts prior to this time, but a true ergonomics program was not initiated until the OSHA citation process was begun. The results would have been much different, and possibly the timeline never would have been met, if the company hadn't had an effective ergonomic problem-solving analysis process and developed a structured process to support the ergonomics effort. The ergonomics and analysis processes generated a great deal of support from leadership, union representatives, and employees, and was a showcase locally, regionally, and nationally.

A Mature Ergonomics Process in a Moderate to Heavy Manufacturing Facility (~6,000 Employees) Including Fabrication, Assembly and Finishing Operations Within a Large Corporation (Rodgers 1989; Day 1999; McAchren 1999)

Initial introduction of ergonomics to this facility was as a pilot site within the corporate ergonomics process in 1989. A specific ergonomics problem-solving analysis process was designated as the corporate ergonomics analysis process (Rodgers 1988, 1992). See "An Ergonomics Problem-Solving Technique" later in this chapter. A corporation-wide ergonomics training effort was implemented from 1991 to 1994.

- The Environmental, Health, and Safety (EHS) department was directly involved with this effort. Several employees were trained as safety monitors within their respective departments.
- Initially, general employees and safety monitors in a few specific departments were trained. In 1992, a more formal ergonomics training and effort to establish ergonomics teams was initiated by training employees and designated department or building ergonomics teams. A couple of departments established a coordinator who worked directly with the business leader, ergonomics teams, and employees within the department. This proved to be a successful structure.
- In 1995, after several years of no formalized structure, the plant and union leadership created a Safety Committee. They held formal elections for each business unit to have a Safety Coordinator to work directly with the respective business leaders, ergonomics teams, and employees within the department on safety and ergonomics issues. The coordinator position was for a two-year term. Seed monies were established to implement the ergonomics solutions that the teams arrived at using the ergonomics problem-solving analysis process. Completion of the ergonomics problem-solving analysis process was required before any seed monies were allocated.

- Safety-specific employee-based teams were developed to mirror the ergonomics team success. About 60 percent of the employees in this facility participate in some aspect of the EHS efforts.
- The ergonomics problem-solving analysis process was further formalized (see Figure 1.5).
- At one point the safety coordinators requested a shortened ergonomics analysis tool, which was subsequently developed and implemented. However, later it was found that this shortened analysis did not adequately arrive at alternative solutions that were economically and technologically feasible. Investigation showed that this happened because there was no link between the identified risk and a root cause that could serve to lead the teams toward usable solutions. Therefore, the formalized ergonomics problem-solving analysis process was reinstated as a requirement to keep the ergonomics teams focused and assure a high-quality analysis.
- Continuous improvement was incorporated from the very beginning and kept the ergonomics process and all of the other EHS efforts and the participants focused on reaching enhanced reactive and proactive solutions. These included the following:
  - Engineers and planners were included in the ergonomics training sessions.
  - Specific ergonomics training was provided for designers and drafters and Center of Excellence (COE) business operations.
  - Specific efforts were made to incorporate the ergonomics process into the Six Sigma/quality efforts of this facility.

As a result of all these activities, the highest status (Star) was achieved in OSHA's Voluntary Protection Program (VPP) in 1999. In addition, the safety coordinator efforts worked so well that additional coordinator positions were implemented. Currently, this facility is leading an effort to develop an electronic version of the analysis process for the entire corporation.

The company's ergonomics process has been very effective in reducing the injury and illness rate from 20 in 1992 to 4 in 2000. The overall plant population did not vary to a large degree over the twelve-year period. At its peak, output of units increased by 460 percent. This was accomplished by many business and quality initiatives, and ergonomics certainly added to this outcome. Even though this ergonomics process could be labeled a mature ergonomics effort, it continues to evolve toward a participatory-proactive process that incorporates the work systems of the company.

Some Program/Process Traps to Avoid

- Assuming that training or empowering employees will make them effective

- Relying upon a few individuals or a single department to address ergonomics issues
- Not giving support, with a formalized structure as well as resources, to the ergonomics team
- Assuming that, if the problem is obvious, applying a typical ergonomics fix to the problem or concern will be effective
- Ignoring the effect on the ergonomics process when a company or organization reorganizes

Summary

To gain support and commitment from both the leadership and employees, the structure and analysis process must be carefully explored and selected (Day 1998). A great deal of variability in the analysis processes is present in different companies and organizations, and the effectiveness of the results also varies (St. Vincent, Laberge, and Lortie 2000). Characteristics of a mature ergonomics process include the following:

- Careful planning and involvement of all stakeholders across all functions is done prior to actually beginning to implement an ergonomics program (Day 1998).
- While the basic core elements of an ergonomics program are present, most efforts are moving toward a structure based on ergonomics process (Day and Rodgers 1992; Day 1999; Rodgers 1999).
- Participatory ergonomics principles are typically practiced (Day and Rodgers 1992; Moore and Garg 1996; Haims and Carayon1998; Hendrick 2000; Rosecrance and Cook 2000).
- Ergonomics efforts are integrated with other business initiatives (Kleiner 1999; Kleiner and Drury 1999; Hendrick 2000; Rodgers 2000).
- Ergonomics problem-solving techniques are more widely accepted and used (Rodgers 1992 and 2000; Moore and Garg, 1996; Day 1998; Joseph 2000; Rosecrance and Cook 2000).
- Proactive ergonomics efforts are more common (Rodgers 1984; Joseph 2000).
- Software technology, either developed internally within the organization or from an outside source, provides more accurate and timely data tracking. This is also true for specialized computerized ergonomics analysis tools.
- Flexibility and responsiveness are built into the process structure and analysis process to allow for changing business and organizational cultural needs.
- Auditing of the ergonomics program occurs at least yearly, but monitoring occurs more frequently.

- Programs are revisited or retooled every two to three years to remove any barriers and address additional or changed influences. This is needed to keep the ergonomics process fresh and state-of-the-art.

While all of these characteristics are present to varying degrees in a mature ergonomics process, they may vary in importance at different times.

AN ERGONOMICS PROBLEM-SOLVING TECHNIQUE

Background

A sampling of many job analysis methods is presented in Chapter 2. Most of these methods identify risk for injury or illness or for musculoskeletal fatigue and quantify the level of risk by using data on human capabilities. The quantification helps to set priorities for which ergonomics issues should be addressed first in a plant. Knowing how serious a problem is can be useful, but the generation of solutions that will significantly reduce the risk for injury is necessary if effective improvements are to be made. A technique to generate solutions via participative root cause analysis problem solving is described in this section. This technique has been used in ergonomics team training in manufacturing, service, and public sector jobs and has been successful in finding simpler and less expensive solutions to job problems by defining the job characteristics that must be improved.

Sources Contributing to This Problem-Solving Technique

The technique described below is loosely based on Socratic principles, wherein a trainer or leader facilitates the students/attendees in the discovery of new ideas and solutions through the use of questions and logic (Wilson, Dell, and Anderson 1993). Two problem-solving and decision-making techniques were adapted to assist the Socratic approach with more structure.

The problem analysis and decision-making methods of Kepner and Tregoe (1965) have an action sequence that starts with problem recognition, that is, what is really happening compared to what should be happening. If the problem is serious, an interim action should be implemented. This is often chosen after a problem analysis or decision-making analysis is made. The third step of the Kepner-Tregoe process is to find the root cause of the problem, usually through problem analysis. The fourth step is to determine the best corrective action by using decision analysis, and the last step is to implement the solution after checking to be sure that it has no adverse consequences or only minor ones.

The second problem analysis method borrowed from is the Functional Analysis Systems Technique (FAST), which has been used to analyze social systems and manufacturing processes (Bytheway 1971; Caplan, Rodgers, and

Rosenfeld 1991). One starts with a problem statement or a goal and starts by asking why the problem or goal exists. This process is repeated until the true goal or basic function is identified. There are often multiple answers at each level, so the analysis resembles a fishbone diagram when done thoroughly. There may be a need to weight the importance of each identified function in order to find the best analysis pathway. When reviewing the diagram generated this way, one reads it backward to check if each function along a chain accounts for the one before it. When the diagram is completed, one determines who will perform each function and develops job descriptions for the people working in the system.

The ergonomics problem-solving technique leads the user through the identification of ergonomic risk factors by body part first. Next, each risk factor is evaluated by asking why it is present, generating multiple reasons. This is repeated until common root causes for the presence of the risk factors are found. Strategies to reduce the risk are generated, and specific short-term and long-term solutions are developed. The preferred solution will usually be the one that improves the ergonomics of the job and reduces the risk for injury substantially at a relatively low price.

The Problem-Solving Process

Step 1: Identifying Jobs with Ergonomics Opportunities (Rodgers 1992, 1999)

Most problem jobs are known in a working unit because they are the tasks that people try to avoid or that have injuries associated with them. Some tasks are not physically demanding but leave very little latitude for the worker to vary the task or get adequate time for physiological or mental recovery between repetitions. Quality problems may signal ergonomics issues that need to be addressed on some jobs. Other tasks may be suitable only for people with hand sizes, functional reaches, or muscle strengths that are in the upper percentiles for those measures in the working population. Consequently, one of the best ways to identify ergonomic opportunities in a work unit is to ask people to list the three worst jobs and to indicate why they are problematic. A list of potential ergonomics problems should be included on the feedback form in order to help focus on ergonomics, not industrial hygiene or basic safety issues. An example of a list is shown in Table 1.1.

Step 2: Defining the Job Demands

The people in the work unit will usually be able to identify specific tasks that are associated with the "problem" job. A more formal task analysis may be done if there are many jobs to study, or if the problem tasks are not as easy to identify (OSHA 2000).

When the three jobs or tasks are identified in a work unit, additional infor-

TABLE 1.1
Indicators of Possible Ergonomics Issues and Risk Factors That Make Jobs Difficult (Rodgers 1999)

Ergonomics Issues Indicators	
Accident and incident history on the job	Frequent rework of product
Medical restrictions needed often	High turnover on job
Quality problems on the job	Above-average absenteeism
Second person needed to assist frequently	Few women or older workers
Long training times	Production bottlenecks
Lack of flexibility to meet production needs	Frequent overtime worked
Risk Factors That Make Jobs Difficult	
Sustained awkward working postures	Heavy manual handling
Low operator control over job pattern	High forces required
Very repetitive hand/foot work with force	High external pacing
Environmental stressors (heat, glare, noise)	Complex tasks; multiple tasks done simultaneously

mation about body discomfort can be obtained from the workers using a psychophysical scale and/or a body diagram (see Chapter 2). A ten-point scale for intensity of discomfort and a four-point scale for the frequency of discomfort have proved useful in studies of office and factory workers (Williams and Rodgers 1997). This additional information about the workers' level of discomfort can help set priorities for which tasks to address first.

The importance of learning as much as possible about the job before trying to solve the ergonomics problem cannot be underestimated. Much of this information will not be found on a job description or by talking to support staff. The best way to learn about the job is to observe the people who perform it and to learn from them by asking them good questions, respectfully. How the question is asked is just as important as what is asked. A list of some of the types of questions that can be asked to establish the job productivity, quality, safety, and variety requirements is given in Figure 1.6. Also included are questions to elicit information about workers' comfort and ability to perform the tasks as well as how they might improve their work to reduce the stress. It is important to gather this information in a way that does not suggest that everything they tell you will be implemented right away. Because this is done at the beginning of the problem-solving process, each specific suggestion should be rephrased into a more generic one so the strategy rather than the equipment is clearly defined. For example, a worker might indicate that he or she needs a pallet levelator to reduce the need to lift items off the floor. One can respond that frequent handling of boxes below the knees should be addressed by raising the load to a height of 15 to 20 inches above the floor.

Establishing the Production Requirements or Expectations

∗Would you describe a typical day on your job? What tasks are done? What percent of each shift is spent on each task?
∗How variable is your job from day to day? Are there seasonal tasks?
∗How long does it take to learn your job? Which tasks are the hardest to learn?
∗Do you do tasks that include heavy lifting or force exertion? What weights are handled or forces exerted, and how often do these take place in a typical day? How long are they usually done continuously (task duration)?
∗If your work includes repetitive tasks, what are the typical cycle times for each task (seconds, minutes)? How long before the cycle is repeated? Does this pattern vary during a shift?
∗Do you feel that there is enough time to do your job to the desired quality levels?
∗Do the work plans and schedules change frequently? How do you accommodate the changes?
∗How many changeovers occur on the production equipment (product changes, specification changes, etc.) in a shift? How long does it take to set up a new run (changeover time such as die changes, size changes)?
∗Are the parts, supplies, and tools made available in a timely manner to your workplace or location or do you have delays because of the unavailability of them?

Worker Comfort and Ability to Perform the Job

∗When you first started on this job, were there any muscle groups that were sore for the first week or more? How long was it before you adjusted to the work?
∗Are the work heights and reaches comfortable for you?
∗Can you see what you need to be able to see without having to take an awkward posture?
∗Are there environmental conditions (heat, cold, noise, vibration) that affect your comfort or make it harder to work on your job?
∗Do you have control over your pace and pattern of work? Can you vary it if a problem arises or when you need to recover from a difficult task?
∗Are there tasks you do that require high-precision actions or that are difficult to control?
∗What kinds of cues do you get if there is a quality problem with the parts or product? What options do you have to respond to that problem?
∗If you are working with some degree of automation, does the equipment/machine assist you, or does it control your work?

Ways of Improving the Job, Workplace, Equipment, and Organizational Factors on the Job

∗What can be done to make the job easier?
∗Are there places where extra effort is required that could be reduced by better tooling, workplace setup, flow of materials, or job design?
∗How could the movement of materials be improved to make your job easier?
∗How does work scheduling affect the way you can do your job?
∗For complex jobs, what can be done to make them easier to learn initially? And what can be done to make it less likely that errors or mix-ups can occur?
∗What things do you like most about your job?

FIGURE 1.6. Examples of Questions to Establish Information About the Job Demands (Rodgers 1992)

This might be achieved using a powered levelator, but it could also be accomplished, in some instances, by putting the pallet on a fixed-height platform (if the palletized load is not very tall) or by using empty pallets under the product pallet to move it to a higher position.

Questions about the consequences if the worker drops a part, does not complete the work on the part within the allotted time, does not have the proper tool, or does not have good parts to work with are also important to ask in order to estimate the amount of accountability that is present in the job being studied. This information also helps to build the case for why this particular job should be improved when a cost/benefit analysis is done.

Where possible, the observer of the job should get as much quantitative information as possible from existing data sources and from videotape analysis of the job with the assistance of people from the area. In a production line environment, the data collected could be:

- The numbers of items produced per shift
- The numbers of items rejected or reworked per shift
- The accident and incident history on the job over the past two to three years
- The number of people doing the job per year, both the ones trained to do it and the people who fill in on the job
- The number of people who have been medically restricted from the job over a two-to-three-year period

Step 3: Identify Risk Factors by Body Part for Each Task of Concern

The third step of the problem-solving process is to identify the risk factors associated with each body part involved in the task. Lists of risk factors from the job analysis methods presented in Chapter 2 can be used here. After completing the analysis, the risk factors can be entered into the Ergonomic Problem-solving process at Step 4. A summary of some common risk factors by body part is given in Table 1.2 to illustrate the problem-solving approach.

Step 4: For Each Risk Factor, Ask Why It Is Present Until a Dead End is Reached

When all of the risk factors have been identified by body part, it is important to determine why they are present in the job or task before looking for solutions to the problem. One finds that some body parts are affected by the same risk factor(s). The workers will have identified discomfort in particular body parts when they are describing the job and answering the questions about it, so this provides a way to begin to narrow down the analysis of risk factors. It is important to keep asking why in this part of the ergonomic problem-solving

TABLE 1.2
Risk Factors by Body Part for Ergonomic Problem Solving

Body Part(s)	Risk Factors for Discomfort
Eyes	Glare or reflections on a display Low contrast on screen or hard copy Repetitive eye movements between screen, document, keyboard, etc. Visual distance too great or too close Everything at same focal distance Competing visual targets or contrasts Brightness contrast between visual work and background is too great
Head, neck, and upper back	Craning neck—head forward Head turned or tilted to one side Neck extended backward Upper trunk bent forward with shoulders rolled forward
Shoulders	Tension in shoulders; raised One arm raised to a higher surface Static load on shoulders from armrests Extended forward reaches Reaching behind trunk Extended reaches to the side Work above shoulder height Unsupported arms while working at elbow height for extended periods
Upper arm and elbow	Extended reaches Elbow rotated outward from body High forces exerted while rotating forearm Elbow behind centerline of the trunk (reaching back) Hands below elbows during repetitive work Pressure on elbow Unsupported arms Wide grips
Forearm, wrist, hand, and fingers	Shoulder tension Pressure on wrist Strong wrist angles Wide or narrow grips Pinch grips High forces High repetition rates Wrist rotation

TABLE 1.2
(Continued)

Body Part(s)	Risk Factors for Discomfort
Lower back, trunk, and chest	Bending forward Leaning to one side Trunk twisted to one side Uneven load on buttocks/hips Slouched in chair Knees above hips when seated Weight handled on one side of body only Feet unsupported while seated Legs turned to one side or crossed when seated Static loading to resist chair backrest tension
Hip, leg, and knee	Pressure on back of thighs when seated Inadequate leg/thigh clearance when seated Extended reaches forward One leg higher than the other when seated Pivoting on leg (twist) Walking more than 3.5 miles per shift Constant standing or sitting while bending or leaning forward Working overhead
Ankle, foot, and toes	Extended reaches—on tiptoes Repetitive foot pedal use Forceful pedal activation Slippery surfaces Standing or walking on uneven or loose surfaces

process so that root causes are found. In addition, by having the proper mix of people participating in this exercise, much more is learned about the job and about the ways it can be effectively changed to reduce the risk of injury or the barriers to productivity and quality performance. An illustration of this approach is given in Table 1.3. The job is to do tolerance measurements on a part being machined in a turret lathe. The worker has been experiencing back, shoulder, and leg discomfort.

Through this analysis, we have learned that the gauging task discussed in Table 1.3 requires extended reaches and twisting and that the gauge is held out from the body, where it increases the stress on the back, shoulders, and legs. In an attempt to find out why the reaches are so long, we have learned that the lathe has a large base plate because of a need to handle many different-sized parts on it (for versatility). The reach is longer than the diameter of the base plate because there is a protective shield around the

TABLE 1.3
Root Cause Analysis—Why? Why? Why?

Risk Factor	Why?	Why?	Why?
Leaning forward	Reach > 30 in.	Shield restricts leg room and access in front of machine	Cutting fluid splashes off cutters and creates slip hazard on floor
		Base plate size	Multiple parts are worked on the lathe—all sizes
		Gauge design—long tool held in front of the body	Turret lathe moves, so it is hard to leave the gauges in place over the part
		Difficulty in reading small dials	Number size is determined by dial size (< 2.5 cm, 1 in.)
Twisting	Stabilizing the gauge on the part	No support for the gauge—muscle effort stabilizes it	Tool weight is the limiting factor
	Reading the dials	Arm can block the view of the dials	Location and orientation of dials on gauge

turret lathe to catch the cutting fluid that splashes from the cutters during lathe use. Another reason why the reach for gauging the part is extended and results in a twist of the trunk is because one hand has to be extended out toward the center of the base plate to support the weight of the gauge. The ability to add a support structure to the gauge is limited by the weight of the gauge and the need to put it in several places while gathering the needed measurements. We have also learned that some of the need to lean forward and to twist is related to the difficulty of seeing and reading the gauge dials at each measurement point. One of the implications of the difficulty of seeing the readings on the dials is that the process takes longer and so static fatigue of the back, trunk, shoulder, and leg muscles will be more likely to occur. There is also an increased opportunity for misreading the dials in this task because of the dial size and its distance from the gauger's best visual point. As the root cause analysis proceeds, some strategies for improving the task emerge that are then documented in the next stage of the problem-solving approach.

Step 5: Develop Strategies for How to Address the Root Causes and Generate at Least Three Solutions for Each Task of Concern

In step 4, some common causes for the back, leg, and shoulder discomfort have emerged relating to the gauging of the part in the turret lathe. These

TABLE 1.4
Generating Strategies and Solutions

Root Causes	Strategies	Solutions
Design of turret lathe	Reduce reach distances	Gate in shield to reduce reach 8 in.
Base size, shield		Gauge supports on lathe to rest tool
Dials on gauge—size and orientation	Make the dials easier to read	Electronic gauging and read-out Go/no-go indicators—larger
Gauge design	Support the tool	Support the gauge from overhead on a tool balancer Rest the tool on movable supports on the turret lathe
Task time—4 min	Make it easier to place the gauge accurately and to take the measurements	Movable supports on turret lathe Electronic gauge reading

are the extended reaches to get the gauge on the part and to hold it in place to take a reading and the visual need to get close enough to the dials to read them. The time it takes to do the task is influenced by the postures and difficulty of reading the dials. Strategies to address the gauging problem are first stated generically; subsequently, specific solutions are developed. Table 1.4 shows an example of this part of the ergonomic problem-solving process.

Other approaches will emerge depending on the background and experience of the people participating in the problem solving. By starting with strategies first, one can open up many different ways to improve the task.

Step 6: Choose the Solution(s) That Will Substantially Reduce the Ergonomic Problems and Be Within Affordable Cost Guidelines for the Plant

The best solution for the problems identified is to support the gauge and use electronic gauging. This reduces the time of the task, the need to twist while reaching and bending forward, and the torque on the back and shoulders from supporting the gauge away from the body. If the cost of electronic gauging is considered too high for the employer, some of the other solutions could be tried. With the participation of the workers, supervisors, technical and safety support personnel, and mechanics who will implement the changes, the process is successful because it focuses on the ergonomics risk factors and how much they need to be reduced. The simpler and more effective interventions can be found by finding the root causes for these observed risk factors instead of looking for a piece of equipment to address each risk factor. It is agreed in the earliest stages of the problem-solving process that there is a problem to resolve; the only questions are what it will take to reduce the risk and how it can be done to get the most benefit overall for the least cost.

FOR WHOM DO WE DESIGN?

In order to make work acceptable for most people in the workforce, it is important to design tasks, spaces, environments, equipment, and jobs so most people can perform them comfortably. As work demands increase because of increased competition in the global marketplace, there are fewer people available to assist on the heavier jobs, and long work hours are common. Thus it is even more important to design jobs within people's capacities to reduce the risk of overexertion injuries and illnesses and to minimize the opportunities for errors. In this section, some guidelines for the use of size and capacity data in design are discussed, as well as information on guidelines for people with some disability or for those who are returning to work after an extended absence. Data on capabilities of males and females are also included, and examples are presented to show how the design decisions can be made.

Accommodate the Functional Capacities and Capabilities of a Large Majority of the Potential Workforce

When determining the best height for a work surface, the best distance at which to place parts on an assembly workbench, the weight of parts or supplies trays, or the force needed to push a handcart, one has to consider the capabilities of the *potential* workforce, not just the people who are currently on those jobs. The *existing* workforce has developed as it is for several reasons. Examples of such reasons include:

- In an older business, they may be long-term employees who have been in the jobs since they were first hired.
- They may be the "survivors" from a much larger group, many of whom were injured or decided to look for other work that was less demanding.
- There may be trade or professional reasons why certain people are in certain jobs (e.g., apprentice programs were open only to men for many years before affirmative-action regulations were set).
- Social pressures may have classified the jobs informally, such as "men's work," "women's work," "young men's work," "tall person's work," etc.
- The facility may have been designed by a tall engineer who used him- or herself as a model for "what felt right."

By designing for the *existing* population whenever a new machine is added or a new line of work is initiated, one just perpetuates the problems. Considering the potential workforce (everyone of working age) and compromising toward the existing population only when design choices are required will open up the work to more people and allow the current workers to stay on the job longer.

For example, if most of the people working in a billing office are women and more than half of them are of Asian descent, who tend to be somewhat shorter than average, whom should the fixed height work surface height be designed for?

- If only one work surface height can be used, it would be natural to decide to design it for smaller women and set it at about 66 cm (26 in.) above the floor.
- If work surface thickness is 8 to 10 cm (3 to 4 in.) because there is a drawer under the surface, a work surface that is 66 cm (26 in.) high would be too low for tall people and larger people who could not get their thighs under the drawer comfortably. Tall people would also have neck and back discomfort from bending over their keyboard.
- If the work surface is raised to 74 cm (29 in.), most people can work comfortably if the smaller ones are provided with foot support. Individual accommodations can be made for people with very short legs. One might even consider providing some workplaces with lower work surfaces if the workplaces are shared.
- Adjustable-height keyboards can improve working comfort for most workers and generally are more effective than adjustable-height work surfaces in giving people the ability to make adjustments for personal comfort.

Why Design for the Large Majority?

There are many advantages to designing jobs, workplaces, equipment, and environments for most people: reduced risk of injury and illness, staffing flexibility, ability to stay on the job longer, enhancement of teamwork, and ability to conform to regulations and guidelines.

Less Opportunity for Overexertion Injuries and Illnesses

Many occupational musculoskeletal injuries and illnesses are associated with overexertion because of an excessive force or sustained heavy effort that fatigues the muscles and reduces their capacity to perform over the course of the shift. If tasks are designed within the strength and endurance capabilities of most workers, they should not become limiting during the shift, and so less opportunity for injuries should be present.

Flexibility in Staffing When People Are on Vacation

Tasks requiring efforts that exceed the capacities and capabilities of a large part of the workforce can still be done safely by some people. That is how many of the more difficult jobs have been staffed over the years. But when the people who usually do those jobs take vacations, go on training assignments, or are out with a cold or the flu, it is often very difficult to find a replacement with the same capabilities. Nonergonomic jobs limit the flexibility of the department to respond to increased production demands, too, because people are working too close to their limits to be able to give more without putting themselves at risk of fatigue and overexertion injuries.

Ability to Stay on the Job Longer

When jobs are designed with older as well as younger workers in mind, it will be possible for the older workers to stay on the job longer. In addition, it should not be necessary to provide restricted work if they develop some chronic illnesses or have a reduced work capacity.

Enhancement of Cellular or Modular Teamwork

In positions where teamwork is needed and everyone has to be able to do each job in the module or cell, ergonomic design makes it possible to rotate between tasks equally.

Ability to Meet EEO and ADA Regulations and Guidelines

Because some of the heavier or more difficult tasks are harder to staff, workers in those jobs may be paid more. Or they may be entry-level jobs that lead to higher-paying jobs in a department. If the demands of the job make it difficult for women, older workers, or workers with disabilities, there may be a clustering of these protected groups in the lower-paying jobs. By removing physical barriers and designing for more people, one can satisfy the affirmative-action and management goals of the business while making the work improved for everyone. Time lost from work because of injuries and illnesses (both occupational and nonoccupational) is usually shortened significantly, and workers' compensation costs are reduced.

In short, there is every reason to design jobs and tasks for most people. It is good for business, for the workers, and for society at large. It is perhaps fair to say that more people are disabled by nonergonomic design than by occupational injuries. This book provides guidelines for ergonomic design that will make the jobs, workplaces, equipment, and environment compatible with the large majority of potential workers.

Determining Whom to Design for So Most People Can Work Comfortably

There are many human capabilities used in jobs: reach; strength; perceptual capabilities such as hearing, seeing, and feeling; coordination; cognitive thinking, logic and memory; and aerobic, or endurance, capacities. In most instances, we can assume that these capabilities are distributed in the population according to the laws of normal distribution, seen in Figure 1.7. The horizontal axis is the measurement of a capability, capacity, or length, for example, while the vertical axis is the number of times that capability occurs in a given population of workers. The frequencies are usually distributed in a bell-shaped curve, and the percentage of cases that occur at 1, 2, or 3 standard deviations from the average, or mean, value can be determined from standard tables (Figure 1.8).

The goal in ergonomic design is to accommodate the largest percentage of the men's and women's distributions for the capability or measurement of concern. This is easier for some measurements than for others. For example, clearances should be designed for large people. If they fit, so will smaller people. However, one has to use the anthropometric (body size) data carefully when

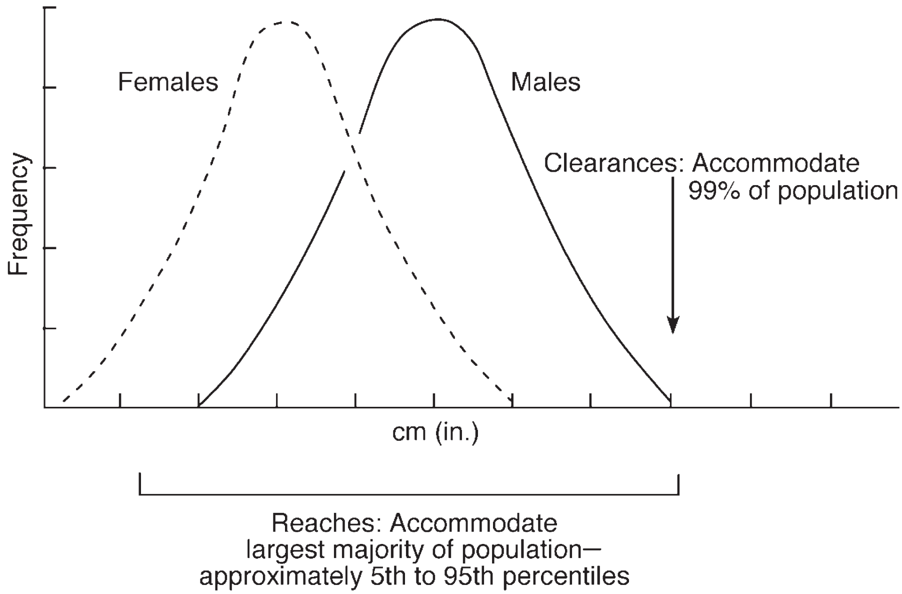

FIGURE 1.7. Examples of Frequency Distributions for Capability Measurements for Men and Women—Reaches and Clearances (Eastman Kodak Company 1983)

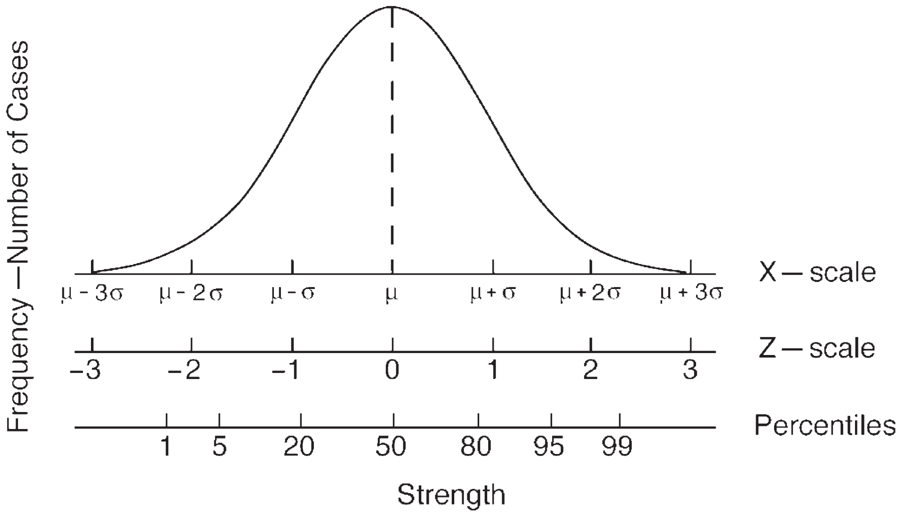

FIGURE 1.8. Statistical Characteristics of a Normal Distribution (after Freund 1967)

determining who the larger people are. This principle of accommodating the largest portion of the population is further explained through the following examples.

Designing Airplane and Auditorium Seating: Distribution of a Body Size Characteristic—Buttocks-to-Popliteal Length (Upper Leg Length)

One of the concerns in the design of row seating is to have enough length between the back of one seat and the one in front of it so that the knees do not poke the forward seat's occupant in the back. In addition, one must still have enough support under the thigh to prevent sliding forward, but the support shouldn't be so long that a short-legged person couldn't sit back and still have his or her feet on the floor. The need to sustain the seated posture for several hours at a time makes it important that these clearances and supports be adequate for most people.

First, one has to assume that the seat height is no higher than 41 cm (16 in.) above the floor (5th percentile popliteal height plus 1 inch for shoes). For thigh support and being able to get the feet on the floor, one should look at both the 5th percentile buttocks-to-popliteal length of 43 cm (17 in.) and the 99th percentile male buttocks-to-popliteal length of 56 cm (22 in.) and add an additional knee depth of 13 cm (5 in.), for a total upper leg length of 69 cm (27 in.). This would suggest that the seats should be 43 cm (17 in.) long from the backrest to the front edge, and the aisle width in front of the seat with the forward seat reclined should be at least 69 – 43 = 26 cm (27 – 17 = 10 in.). Support for the longer thigh should be adequate because it is resting on the seat for three-quarters of its length.

Determining the Maximum Heights for Valves or Controls: Distribution of Overhead Reach (Standing)

The ergonomics goal in the design of a control panel or in the placement of valves or other manual controls on equipment or in facilities is to have them where most operators can operate them without excessive reaches or needing a ladder or step stool. Overhead functional reach (standing) is the measurement of interest for many controls where force is not of concern. Where force may be an issue, as in breaking open long-shut valves in a chemical mixing operation, the measurements of interest are forces exerted below shoulder height.

Functional overhead reach is measured to the center of the hand as it is raised above the head. The 5th percentile overhead reach is about 188 cm (74 in.), so toggle switches and dials should not be placed higher than that on a panel display. For short and infrequent control operation, it is possible to go up another 8 cm (3 in.) by standing on tiptoe, but this should not be required unless there is a design problem with limited space.

To be able to use the stronger arm muscles to open a valve that may be stuck or to do any other control manipulations that require more than light effort, the control should be located below the 5th percentile shoulder height, or 125 cm (49 in.). They should also be no lower than the 95th percentile knuckle height, or 81 cm (32 in.), so that the taller person does not have to squat to operate them.

These guidelines assume that the person can stand very close to the control. If there is an intervening shelf or obstruction and the reach has to be both up and out, the design criterion can be obtained by looking at the 5th percentile two-handed standing forward functional reach data in Figure 3.5 (Chapter 3).

Determining Force Requirements for Performing a Repetitive Task (Manual Crimping): Distribution of Grip Strength

The frequency distributions for muscle strengths for men and women exhibit some differences compared to the anthropometric data. The male data are usually distributed over a much wider range than the female data are, as can be seen in the graphs in Figure 1.9 (Kamon and Goldfuss 1978). The overlap of the male and female strength distributions varies by muscle group, being greatest for push and pull forces and least for shoulder flexor strengths (Eastman Kodak Company 1986).

Although the distributions are not as bell-shaped as the anthropometric ones, we assume that they would be if there were more cases in the study populations, and we treat them statistically as normal distributions. This reduces the accuracy of the estimates of what percentage of the population is accommodated by a given design. In many instances, the strength capacity of interest is not just one muscle group but several. The Liberty Mutual psychophysical

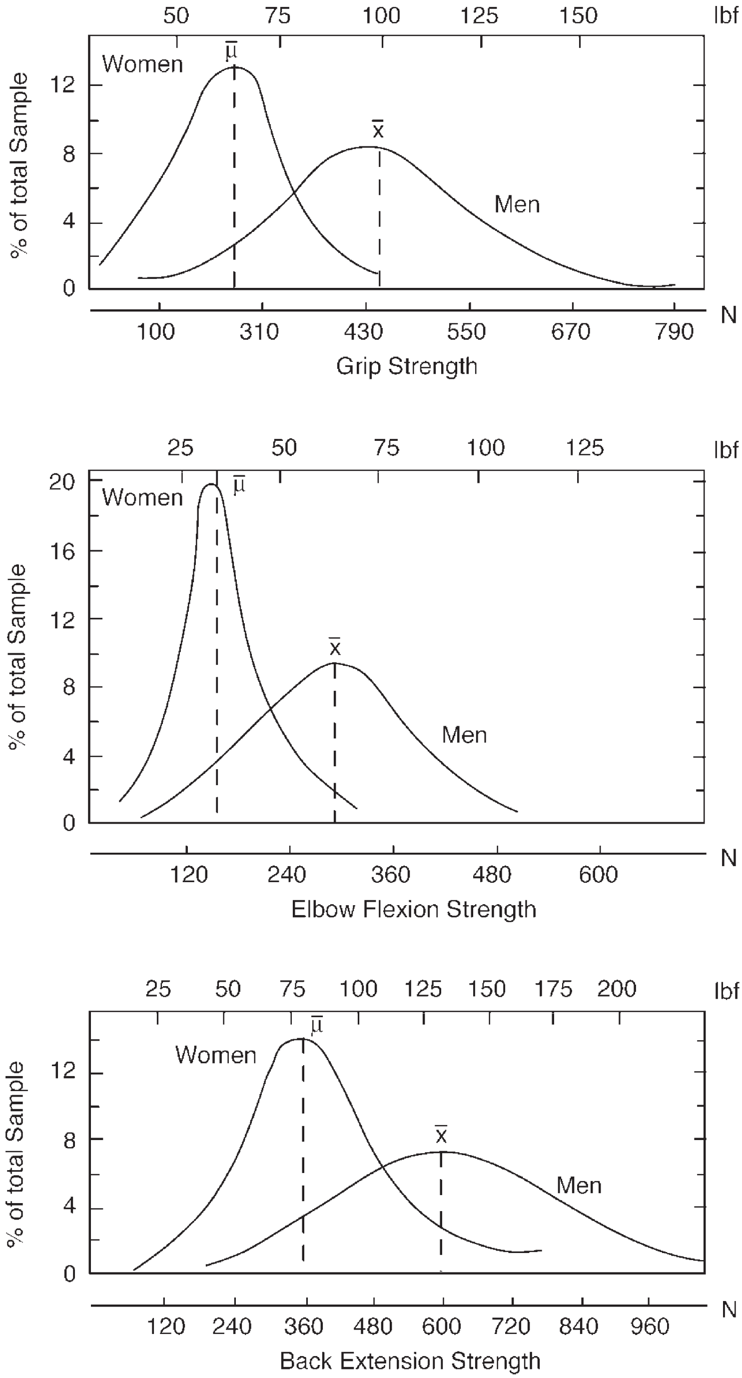

FIGURE 1.9. Muscle Strengths of an Industrial Population (Kamon and Goldfuss 1978; reprinted by permission of American Industrial Hygiene Association Journal)

studies of acceptable lifts and force exertions are a valuable resource for determining the acceptability of common manual handling tasks. Their frequency distributions of acceptable weights and forces for males and females have been used as one of the bases of the NIOSH Guidelines for Manual Lifting (see Chapter 2 and Chapter 7). They are also used in determining the percentage of the population accommodated in the guidelines developed from the NIOSH data in the graph in Figure 7.5.

For hand grip strength, a study by Kamon and Goldfuss (1978) of applicants in a paper company (see Figure 1.9) shows that the average male grip strength at the optimum span was 46 kgf (101 lbf, or about 450 newtons). The average female grip strength at the optimum span was 27 kgf (60 lbf, or 268 newtons). It is the weaker female who should be considered for the design of a repetitive force exertion task, and a figure of 18 kgf (40 lbf, or 176 newtons) has been used to accommodate at least 75 percent of the female population for very short, infrequent force exertions. If the grip span, wrist angles, grip duration, or frequency of gripping increases from the optimum range, the acceptable forces become lower.

Smaller spans and pinch grips also reduce the acceptable forces (see "The Design of Repetitive Work" in Chapter 6 for further discussion of the impact of force, frequency, duration, and body postures on acceptable workloads for the upper extremities).

Consider for example, the task of crimping wires with a manual crimper. The span of the tool handles is about 10 cm (4 in.) when the force is applied, and each exertion is 3 seconds long and repeated six times a minute. The wrist and hand are relatively straight when the tool is used. Using the information later in this section, it can be seen that the 10-cm (4-in.) span reduces maximum grip strength by about 40 percent, dropping the 18 kgf (40 lbf or 176 N) capacity to 10.8 kgf (23.8 lbf, or 106 N). At a frequency of six times a minute for a majority of the shift, only about 8 percent of grip capacity can be used safely (Jorgensen et al. 1988; Westgaard 1988). Thus, 0.9 kgf (1.9 lbf, or 8.5 N) would be the upper limit for force that should be used in the crimping operation to have the task be acceptable to about 90 percent of the mixed male and female workers. Whereas most hand crimpers require more force than that, it would be justified to use an automatic crimper for the task.

Designing Tasks That Require Lifting Items Above Shoulder Height

In warehousing, storage areas, fiber and fabric manufacturing, and many other businesses, items may be placed on shelves or supply roll pegs that are above shoulder height for most workers. The muscle group that is most limiting in lifting items to high locations from locations that are often below waist height is the shoulder flexors. Unless the item can be regrasped and boosted to the higher location, the shoulder flexors will be the primary group of muscles that have to transfer the load to the high location. They are among the weakest muscles for the female population, especially. On the average, women have about 40 to 50 percent of the shoulder flexor strength of men (Table 1.15). The average young female was found to have about 4.5 kgf (10 lbf, or 44 N) of strength at 135 degrees above shoulder height (Yates et al. 1980), and a 25th-percentile woman would have about 3.2 kgf (7 lbf, or 31N) at the same location. This would be the flexor strength at about 178 cm (70 in.) above the floor. Although the muscles are a little stronger below shoulder height, they are still limiting throughout the process of lifting items with the arms extended in front of the body.

Assume that the task being designed involves lifting 2-kg (4.4-lb.) spools of fiber to pegs on a creel so it can be pulled through to form a beam for weaving. One can see that spool pegs above shoulder height and up to 178 cm (70 in.) above the floor will probably be acceptable as long as the spool pegs are relatively horizontal. The earlier analysis of overhead reach height suggested that a 188-cm (74-in.) reach was acceptable for most females. The small spool is within the acceptable handling weight at that height for at least 50 percent of the females, although the pattern of loading the creel should be designed so the high spools are done intermittently, not continuously.

In many such fiber and fabric mills, attempts are made to improve efficiency by increasing the length of the fiber on the spool—that is, making larger spools. If the spool weight increases to 7 kg (15 lbs.), less than 25 percent of the women and about 80 percent of the men will be accommodated, making it difficult to include creel loading in a cell team's list of tasks to share. Designing the creel so it can be loaded and assembled in sections and so that all items are handled between 51 cm (20 in.) and 114 cm (45 in.) above the floor eliminates the need to use the shoulder flexors in the high lifts.

Determining Acceptable Workloads for Eight-Hour Shifts: Distribution of Aerobic Work Capacity

The interaction of work demands with hours of work determines what the total physical demands of the job will be, and the pattern of work determines whether a worker will develop significant fatigue during the shift. This is discussed in more detail in Chapter 6. Unless the worker is unable to control his or her work pattern because it is being controlled by a machine or is associated with a monetary benefit (some incentive systems), most people will arrange their tasks to avoid fatigue and the potential for injuries and accidents. Much of the data used to determine acceptable workloads come from studies of people at work, and the acceptable levels for given times follow the percentage of maximum aerobic capacity curves developed in early work physiology studies (see "Dynamic Work" in Chapter 6).

A customary job at the end of a production line is to take product off the conveyor and place it on floor pallets. Most of the lifting is done below waist level, so the upper body is lifted as well as the product. The job often needs to be done throughout the shift. The products weigh from 6 to 13 kg (13 to 29 lb.) and the handling rate is about nine per minute. Typical measurements of such a workload show that it takes about 14.5 ml O_2 per kg of body weight per minute to do the job. For an eight-hour shift, the average workload should be about 27 percent of aerobic capacity for whole-body work when the primary task is low lifting (Legg and Pateman 1984). If 14.5 is 27 percent of aerobic capacity, it follows that people who can do the job without significant fatigue will have aerobic capacities of 53 ml O_2 per kg of body weight per minute (less than 5 percent of the population, mostly men).

To make the task more efficient and less fatiguing, it should be reduced to a workload of 8 ml O_2 per kg of bodyweight per minute. This would make the eight-hour shift workload acceptable for at least half of the women (average female aerobic capacity for whole-body work is approximately 30 ml O_2 per kg of body weight per minute; see Table 1.20). The workload could be reduced by raising the pallets so that less bending over is required. If the workload could be decreased to 7 ml O_2 per kg of body weight per minute, people with aerobic capacities of 27 ml O_2 per kg of body weight per minute should find the job acceptable—roughly 75 percent of the potential workforce, male and female (see Figure 1.21).

If the task can't be changed and there is no easy way to reduce the workload, the job can be made better by limiting the length of time the worker has to do it before moving to lighter work. If the task is done only for two hours a shift, 35 percent of aerobic capacity can be used, so people with whole-body aerobic capacities of 36 ml O_2 per kg of body weight per minute would find the task acceptable. Based on studies of industrial workers, the two-hour task would be acceptable to about 45 percent of them (see Figure 1.21), although many more men than women.

Designing Tasks That Use Perceptual, Sensory, Cognitive, and Memory Capabilities

For such tasks, it is the older worker who needs to be accommodated in many instances.

A discussion of the effects of aging on perceptual and cognitive capabilities is included in the next section of this chapter. The following capabilities may be lower in the older worker, and job demands should be designed to accommodate these losses:

- Hearing acuity and high-frequency detection
- Signal-in-noise detection (discrimination of tones)
- Visual acuity
- Contrast sensitivity
- Dark adaptation
- Color sensitivity
- Mental processing speed

- Memory recall and retention
- Multichannel processing of information
- Ability to concentrate for prolonged periods
- Learning to operate very complex systems
- Performing under time pressure

Some general guidelines for accommodating the older worker are:

- Keep systems simple.
- Provide visual and auditory information to operators of machines when emergency situations occur.
- Provide the operator with as much control as possible over the way the work is done.
- Provide high-quality lighting at the workplace. Make supplemental lighting available where needed.
- Use special-purpose lighting techniques to make low-contrast targets (e.g., defects) more visible.
- Use color coding and shape coding to reduce the complexity of control panels or equipment.
- Provide illustrated instructions to help workers learn new processes, and use visual aids at the workplace to remind them of critical performance needs.
- Minimize the use of small print in instructions, in orders, or on equipment.

Designing to Accommodate the Needs of Employees with Disabilities or Reduced Work Capacities

General Design to Include People With Disabilities: Access

Legislation to accommodate people with disabilities in the workplace culminated in the Americans with Disabilities Act (ADA 1990). Because each person's disability is unique, the tendency has been to treat each job placement and accommodation individually. But many of the accommodations are similar to ergonomic design principles that are discussed throughout this book, and so by designing to accommodate most workers, many of the people who have reduced work capacities because of illness, injury, or developmental problems will be able to perform the tasks.

The areas where generic accommodations may apply most broadly have been in building access and workplace design for wheelchair users as well as in the provision of redundancies in alarms and displays for people with limited vision or hearing. A summary of some of the most relevant guidelines is given here. (More detail can be found in ADAAG for Buildings and Facilities 1998, ADA Standards 1994, ANSI A117.1 1998, Kristensen and Bradtmiller 1997; and Bradtmiller and Annis 1997.

- Door width should be a minimum of 81.5 cm (32 in.) when the door is open at 90 degrees; a preferred width is 112 cm (44 in.). Thresholds should be beveled and not more than 1.9 cm (0.75 in.) high.
- The preferred passage width for a wheelchair is 92 cm (36 in.). Two wheelchairs need a minimum of 152 cm (60 in.) to pass in an aisle or corridor.
- A clear space of 76 by 122 cm (30 by 48 in.) is needed to accommodate a person in a stationary wheelchair in front of or to the side of an object, such as a drinking fountain.
- To make a 180-degree turn in a wheelchair, a clear space of 152 cm (60 in.) diameter or a T-shaped space is needed.
- The forward reach range in a wheelchair is from 38 to 122 cm (15 to 48 in.) above the floor. The side reach height range is from 23 to 137 cm (9 to 54 in.) above the floor.
- A slope of 1:12 is the maximum value recommended for ramps in new buildings. For older buildings, a slope of 1:10 is acceptable when the maximum rise is 15 cm (6 in.); if the maximum rise is 7.6 cm (3 in.), a 1:8 slope can be used.
- On a flight of stairs, the riser depth and tread width should be uniform with the stair tread width not less than 28 cm (11 in.) measured from riser to riser. This should accommodate people with reduced visual capacity when ascending and descending the stairs.
- Handrails should be placed on both sides of a stairway, be continuous, and extend at least 30 cm (12 in.) plus the width of one tread beyond the top and bottom risers.
- There should be a clearance between the handrail and the wall of at least 4 cm (1.5 in.). The handrail top should be mounted from 86 to 96 cm (34 to 38 in.) above the stair nosings.
- Elevator displays should be at least 183 cm (72 in.) above the floor. Visual elements (e.g., floor indicators) should be at least 6.5 cm (2.5 in.) high for detection by people with limited vision.
- The safety switch to detect a person in the elevator doorway should cover a range of heights of 12 to 74 cm (5 to 29 in.) above the floor.
- Emergency controls in elevators should be placed no lower than 89 cm (35 in.) above the floor. Floor buttons should be mounted no higher than 122 cm (48 in.) above the floor.
- A sliding force of 22 newtons (5 lbf) should not be exceeded for opening interior hinged doors or a folding partition.

- Water fountains should have a spout height no greater than 92 cm (36 in.) above the floor and a water flow height of at least 10 cm (4 in.) above the spout. The spout should be within 7.6 cm (3 in.) of the front edge of the fountain to be accessible for wheelchair users approaching it from the front.
- There should be a clear floor space under the water fountain of at least 76 by 122 cm (30 by 48 in.) so that wheelchair users can make a parallel approach to them.
- Toilet seats should be 43 to 48.5 cm (17 to 19 in.) above the floor. Flush controls should be no more than 112 cm (44 in.) high and be located on the wide side of the toilet area.
- For toilet stalls less than 152 cm (60 in.) deep, there should be at least 23 cm (9 in.) of toe clearance in the front and one side partition.
- Shower stalls should be 92 by 92 cm (36 by 36 in.) in size and have a seat mounted at 43 to 48.5 cm (17 to 19 in.) above the floor that extends to the end of the stall.
- Sinks should be no more than 87 cm (34 in.) above the floor with knee clearance that is at least 68.5 cm (27 in.) high, 76 cm (30 in.) wide, and 48.5 (19 in.) deep.
- Handrails and grab bars should have gripping surfaces 3 to 4 cm (1.25 to 1.5 in.) in diameter.
- Storage racks, shelves, or closets should have clear space in front of them of at least 76 by 122 cm (30 by 48 in.).

Specific Accommodations for People with Disabilities: Workplaces

The following guidelines are recommended for workplace designs to accommodate people in wheelchairs, people with visual or auditory losses, or people with limited reach capabilities:

- Desk or work surfaces should be placed from 71 to 86.5 cm (28 to 34 in.) above the floor.
- Knee clearances at seated workplaces should be at least 68.5 cm (27 in.) high, 76 cm (30 in.) wide, and 48.5 cm (19 in.) deep.
- Reaches more than 10 inches in front of the body will require a seated person to lean forward or stretch upward or down. Reach heights of 117 cm (46 in.) above the floor are the upper limit for forward or side reaches of up to 61 cm (24 in) without having to move out of the seat. The guidelines for comfortable seated reach in Chapter 3 should be used as design criteria for all workers because they are for comfortable, not extended, reaches.
- Extended reaches should be avoided because they can contribute to a loss of balance in older workers especially (Rogers, Fernandez, and

Bohiken 2001). If reaches are kept within the guidelines given in Chapter 3 for standing forward functional reach, a loss of balance should not be a problem for most workers.

- When precision control tools are used, the designer should consider the older worker's need for a higher coefficient of friction between the operator's fingers and the tool surface. By reducing the smoothness or slipperiness of the tool handle, tool use can be made easier for people who may have reduced tactile sensitivity in their hands (Lowe 2001).
- Alarms should be both auditory and visual to accommodate the needs of workers with some reduced vision or hearing. The size of the letters on warning labels and signs should take account of the need for making the information easy to read even with vision impairments. Use of color to highlight a message or to signal a safety problem is also recommended. See Chapter 5 for more information about design guidelines for information transfer.

The Job Accommodation Network has a large supply of information about ways to accommodate people with disabilities in the workplace. The Employers Forum on Disability is a British source of information on accommodations and how to get funding for them. URLs for these sources can be found in the references section of this chapter.

The Effect of Aging on Perceptual and Cognitive Abilities

Both perceptual and cognitive abilities decline with age. The source of perceptual (also referred to as sensory) deteriorations may be linked to physiological changes of the body that occur with age. However, the cause of age-related decline in cognitive abilities is a little more complex and may even be linked to perceptual deterioration (Tsang 1992). Schneider and Pichora-Fuller (2000, p. 156) offer four potential causal factors to explain and clarify this age-related decline in abilities:

> The first possibility is that perceptual decline causes cognitive decline (the sensory deprivation hypothesis). The second possibility is that both perceptual and cognitive declines reflect either widespread degeneration in the central nervous system or changes in specific functions or circuitry that have systemwide consequences (the common-cause hypothesis). Third, cognitive declines could contribute age-related difference in sensory measures (the cognitive load on perception hypothesis). A fourth possibility is that there is a decline in cognitive performance because unclear and distorted perceptual information is delivered to the cognitive systems, thereby compromising cognitive performance (the information-degradation hypothesis).

PERCEPTUAL ABILITIES Age-related perceptual deterioration is most commonly associated with the loss of auditory and visual acuity. This section will discuss these topics as well as other age-related perceptual deteriorations.

Aging and Vision Declines in visual functioning become most apparent to an individual around age 50 (Fozard 1990). Presbyopia, or the loss of the ability to focus the eye sharply on nearby objects, tends to occur with old age. Decrease in the eye's accommodative ability occurs gradually until around age 45, at which time it begins a more rapid decline (Goldstein 2002). As one gets older, the near point (the closest an object can be and still be in focus) moves farther away from the observer. For a 20-year-old, the near point is around 10 cm or 4 in., and by 30 years of age it increases to approximately 14 cm or 5.5 in. At 40 years of age the near point is about 22 cm or 8.5 in, and by 100 years of age it is about 60 cm or 24 in.(Goldstein 2002). This decline in the ability to accommodate occurs as a result of the lens hardening and the ciliary muscles, which are responsible for controlling accommodation, becoming weaker. As a result, it is more difficult for the lens to change shape for close range vision (Goldstein 2002). Corrective lenses are the only solution for presbyopia; they provide the focusing power needed to allow light to focus on the retina (Goldstein 2002).

Light Sensitivity. The lens allows the eye to filter light and form images. The ability of the lens to transmit light diminishes with age, especially in respect to shorter wavelengths. However, the rate of adaptation is not affected by age. This information is of practical use in respect to older adults driving at night, because greater illumination is required in order for the older adult to clearly see the target, such as a road sign. However, this also raises the issue of glare, a result of high levels of illumination. Older adults require a longer time to recover from the effects of glare, which could be a debilitating factor when driving at night (Fozard 1990). This is probably associated with some clumping of the ocular media that results in greater scattering of the light (Williams 2002).

Color Vision. A ten-year study of color vision and aging in 577 males ages 20 to 95 years concluded that no change in color vision occurs as a result of age, with above 90 percent accuracy levels of men over 80. Later studies of women produce coinciding results (Fozard 1990). Further studies indicate that decrements in color vision in aging occur only at lower levels of illumination (Fozard 1990). Hence, the actual decrement is that of light sensitivity. Blue sensitivity may decline a little with age and make it harder to see defects in the blue range (Williams 2002).

Acuity. Visual acuity is poorer in elderly adults than in younger adults; distance acuity starts to decline around age 45 (Fozard 1990). Aberrations tend to get bigger with aging, too (Williams 2002).

Contrast Sensitivity. Contrast sensitivity, specifically with intermediate and high frequencies, declines with age (Fozard 1990). Difficulties in facial recognition under low-contrast conditions increase with age.

Visual Perception. All of the above—light sensitivity, color vision, and contrast sensitivity—affect higher-order visual functions, including field of view, motion, and binocular processes, specifically depth perception. These functions are highly essential in the location, detection, recognition, and identification of objects. "For example, a reduction of the effective visual field, combined with a loss of peripheral sensitivity, would seriously disrupt visual search" (Schneider and Pichora-Fuller 2000, p. 173).

Older adults have a slower rate of scanning and a more limited field of view than younger adults, most likely caused by reduced visibility in the periphery (Fozard 1990). Visual search tasks require the observer to acknowledge objects in the periphery. Elderly adults have difficulties in detecting, locating, and identifying objects in their periphery. The age-related decline of the "useful" visual field can be an even greater disadvantage to older adults if the visual field is cluttered or contains distracters, which could include a second task (Schneider and Pichora-Fuller 2000). This could have serious implications to real-world environments, such as driving.

Motion perception, in terms of being sensitive to moving objects, also declines with age. In addition, older observers have difficulties tracking moving objects when the object has high velocity. This also applies when the relative motion between the object and the older observer is high (Schneider and Pichora-Fuller 2000).

Depth perception also degenerates with age, most likely caused by the increase in time of retinal or binocular disparity. Hence, it may be assumed that stereopsis, which is dependent on retinal disparity, also declines with age. However, concurrent research is inconclusive (Schneider and Pichora-Fuller 2000; Fozard 1990). Research is also limited pertaining to aging and monocular depth cues, such as linear perspective, size constancy, and so on (Fozard 1990). Deterioration of depth perception may have human factors implications related to stereoscopic or 3D displays.

Auditory Perception. "Hearing is the third most prevalent chronic disability among older adults, exceeded only by arthritis and hypertension" (Schneider and Pichora-Fuller 2000, p. 157). The anatomy, biomechanics, and the physiology of the subcortical auditory system change with age. The changes can affect a person's perception of sounds. Elderly adults have decreased ability to tune out background noises, meaning they have difficulties hearing in noisy environments (Fozard 1990). Older adults also have greater difficulties in detecting simple, low-intensity sounds and discriminating small changes in intensity or frequency. Because of inhibited biaural processing, the ability to locate the source of a sound may also decrease with age (Schneider and Pichora-Fuller 2000). The degradation in these auditory processing abilities limit and hinder the interactions and activities of everyday life.

COGNITIVE SKILLS Cognitive skills also decline with age, and as the working population ages, it is important to consider these factors when designing jobs, equipment, or systems.

Learning and Problem-Solving Abilities. Older adults do not learn new material or skills as easily as younger adults. This may have important implications for older adults when introducing a new system or making changes to an existing one, in that the new or changed features may be difficult for them to adapt to. However, it has also been concluded that both young and old adults can improve equally with practice (Strayer and Kramer 1994). One plausible explanation as to the differences in older and younger learning abilities is that older adults exhibit more-conservative response strategies than younger adults (Strayer and Kramer 1994). In other words, older adults cognitively operate on a "speed-accuracy function," meaning that they respond and/or learn at a slower pace in order ensure accuracy in their performance (Strayer and Kramer 1994; Tsang 1992). Hence their reaction times are slower (Tsang 1992).

Attention. Studies demonstrate that elderly adults have difficulty attending to two tasks or activities at the same time. Attentional capacity may also be related to working memory capacity (Hardy and Parasuraman 1997). Attention defects may also be linked to age-related limitations of visual search.

Memory. Between 4 percent and 24 percent of variance in performing memory tasks is age-related (Tsang 1992). Although the common belief is that memory performance declines with age, different aspects of memory may be affected more than others. The short-term or working memory, which is associated with such cognitive tasks as reasoning and comprehension, is minimally affected by age: working memory span is unaffected by age, while the effectiveness of the process is affected (Tsang 1992). With respect to long-term memory, the ability to retrieve information from long-term memory as well as transfer information from long-term to short-term memory deteriorates with age (Tsang 1992).

In conclusion, cognitive slowing and perceptual decrements are major debilitating and limiting factors associated with aging. These age-related deficits can impair and hinder all aspects of living, ranging from coping with different environments encountered daily to carrying out activities at home and performing on the job. Human factors implications include identifying, accepting, and accommodating the needs and limitations of the older population in system design configurations. Special specifications may be needed to accommodate the older population in design of visual and auditory displays. Computers, cars, phones, ATMs, and signs, specifically road signs, are a few areas of interest in designing for the older adults (Rogers and Fisk 2000). Throughout the discussion several human factors design implications have been identified pertaining to specific cognitive or perceptual deteriorations. The human factors discipline should take into consideration the capabilities and limitations of the older population in the system designs in order to enhance "the life, work, and leisure of individuals as they grow older" (Rogers and Fisk 2000, p. 559).

Design of Lifting Tasks for People with Low Back Disorders

Ohio State University (Marras et al. 2001), with support from the Ohio Bureau of Workers' Compensation, is developing the following guidelines for lifting when returning to work (RTW) after an absence related to a low back disorder (LBD). The graphics provide lifting limit guidelines for people with low back disorders (LBDs). These data are based upon laboratory studies of 110 subjects wearing the lumbar motion monitor (LMM). The guideline is based on low-frequency lifts of about 1 per minute.

Note that the maximum weight recommended under the best circumstances for those with a LBD is 11.5 kg (25 lb.), and that has a medium risk of reinjury.

To use the guide:

- Determine the angle of asymmetry (the trunk twisting angle associated with the lifting task—it doesn't matter if the twist is to the left or to the right). Use the chart that corresponds to the appropriate asymmetry category:
  - Less than 30°: Figure 1.10
  - Between 30° and 60°: Figure 1.11
  - Between 60° and 90°: Figure 1.12
- Determine the region of the maximum horizontal reach distance from the spine and the vertical lift origin from the floor for each lift. A horizontal reach distance of 30 cm (12 in.) is made with the arms partially extended. A distance of 61 cm (24 in.) from the spine is made with the arms fully extended.
- The shade in each zone indicates the degree of risk for a LBD:
  - Low risk indicates spinal disc compressive loading of less than 3,400 N (765 lbf).
  - Medium risk indicates compressive loading between 3,400 N and 6,400 N (765 and 1,438 lbf).
  - High risk indicates compressive loading of greater than 6,400 N (1,438 lbf) or shear loading greater than 1,000 N (204 lbf).

These charts can be used as follows:

- Employers can use these guidelines to evaluate lifting tasks and make changes to the design or to the weight of the object being lifted to minimize the risk of reinjury during manual material handling tasks.
- The medical community, in communication with the employer, can use these guidelines to assess a LBD patient's readiness to return to work, thus minimizing the risk of injury.

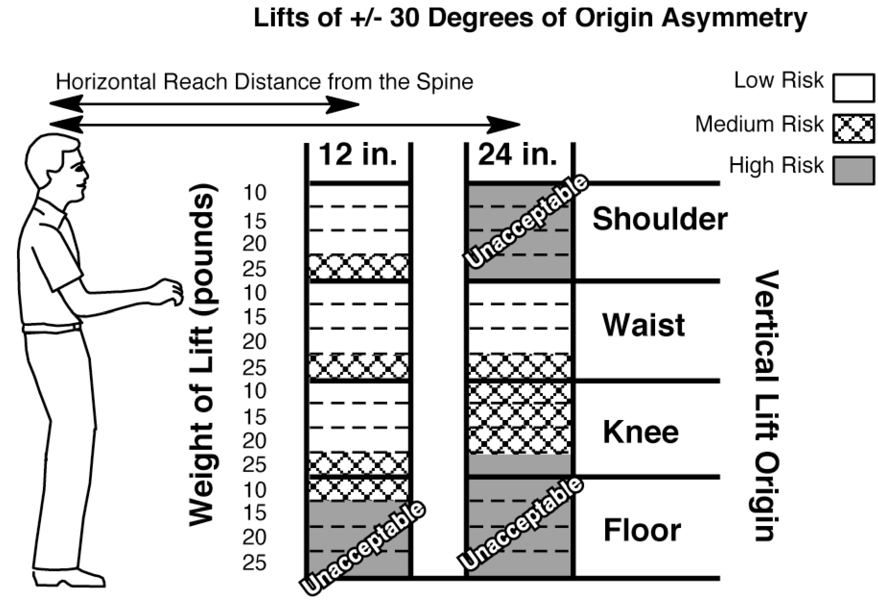

FIGURE 1.10. Return-to-Work Guidelines for Lifts of ± 30 Degrees of Origin Asymmetry (from work funded in part and requested by the Ohio Bureau of Workers' Compensation, 2002)

- **The shade in each zone indicates the degree of risk for low back disorders (LBD).**
- **Determine region (zone) of the maximum horizontal reach distance from spine and vertical lift origin from the floor for each lift.**
- **Select weights corresponding to the low-risk zone to minimize risk of recurrent LBD.**

Note: Derived from: W.S. Marras, K.G. Davis, S.A. Ferguson, B.R. Lucas, and P. Gupta (2001), "Spine Loading Characteristics of Patients with Low Back Pain Compared with Asymptomatic Individuals," Spine 26(23): 2566–2574.

Capacity and Capability Data

When determining whom to design for, one has to find measurements on populations that reflect the workforce of interest. Ample anthropometric data have been collected on military populations around the world, but data on industrial workers has been hard to find. Strength data are often from physical education students in colleges, and aerobic capacity data come from young athletes as well. Recently, more strength testing has been done in rehabilitation programs, and anthropometric studies have been initiated on civilians as part of an SAE International initiative (SAE 2002). Because of a current lack of civilian data, the data in this book are based on the best data we have found in the literature and on some of our own past studies with small numbers of participants. It is expected that better civilian data will be available within the next decade to improve our design decisions for industry across the industrialized countries.

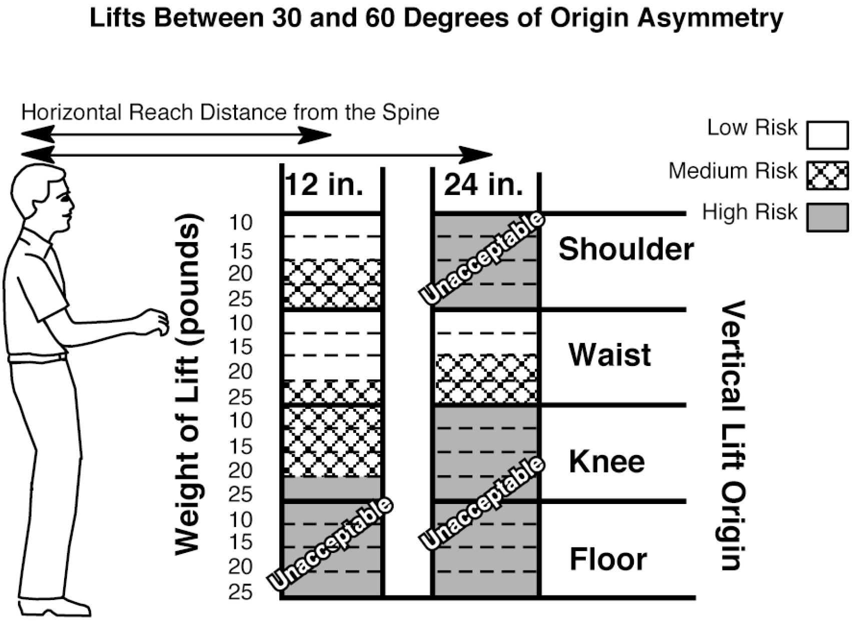

FIGURE 1.11. Return-to-Work Guidelines for Lifts Between 30 and 60 Degrees of Origin Asymmetry (from work funded in part and requested by the Ohio Bureau of Workers' Compensation, 2002)

- **The shade in each zone indicates the degree of risk for low back disorders (LBD).**
- **Determine region (zone) of the maximum horizontal reach distance from spine and vertical lift origin from the floor for each lift.**
- **Select weights corresponding to the low-risk zone to minimize risk of recurrent LBD.**

Note: Derived from: W.S. Marras, K.G. Davis, S.A. Ferguson, B.R. Lucas, and P. Gupta (2001), "Spine Loading Characteristics of Patients with Low Back Pain Compared with Asymptomatic Individuals," Spine 26(23): 2566–2574.

Anthropometric Data

A number of new compilations of anthropometric data have been completed since the mid-1980s, when the first edition of this book was published. In the United States, a major survey of the army was completed in 1989 (Gordon et al. 1989) that looked at several measurements on men and women, almost all of whom were under the age of 40. A NASA compilation of data and set of guidelines for the design of space systems (NASA 1995) chose measurements from a 5th-percentile Japanese woman and a 95th-percentile American man as their inclusion criteria. Private studies commissioned by companies for use in product design decisions have not been available to the general public but can be purchased from consulting groups (for example, Anthropology Research Associates). Publications may summarize the data from these studies and suggest guidelines for their use in the design of workplaces, equipment, and products (Dreyfuss 1971; Pheasant 1986; Roebuck 1995).

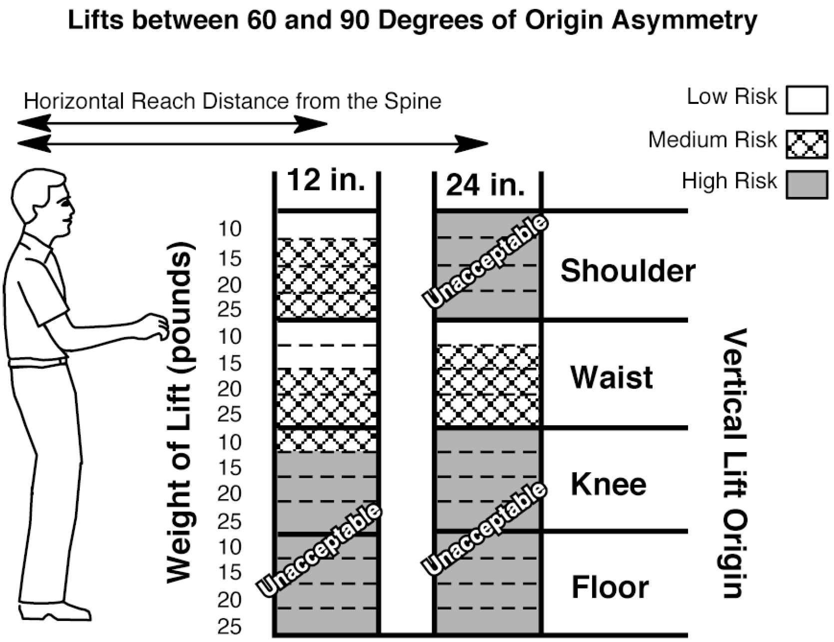

FIGURE 1.12. Return-to-Work Guidelines for Lifts Between 60 and 90 Degrees of Origin Asymmetry (from work funded in part and requested by the Ohio Bureau of Workers' Compensation, 2002)

- **The shade in each zone indicates the degree of risk for low back disorders (LBD).**
- **Determine region (zone) of the maximum horizontal reach distance from spine and vertical lift origin from the floor for each lift.**
- **Select weights corresponding to the low-risk zone to minimize risk of recurrent LBD.**

Note: Derived from: W.S. Marras, K.G. Davis, S.A. Ferguson, B.R. Lucas, and P. Gupta (2001), "Spine Loading Characteristics of Patients with Low Back Pain Compared with Asymptomatic Individuals," Spine 26(23): 2566–2574.

The Data: United States

In reviewing the more recent studies and comparing them to the data selected for use in the first edition, it was apparent that the values for the basic U.S. dimensions of interest were not substantially changed from those in the 1978 NASA compilation (NASA 1978). The 5th-percentile values were somewhat lower in the Natick study (Gordon et al. 1989), which may reflect a larger percentage of Asian-Americans in the new sample. It was decided to retain the 1979 data in this section, and that is presented in Tables 1.5 (in centimeters) and 1.6 (in inches). Some of the Kodak data on workers are included in parentheses in the same tables for comparison. Figures 1.13 and 1.14 provide illustrations of the measurements given in these tables.

TABLE 1.5
U.S. Anthropometric Data, Centimeters (Champney 1979; Muller-Borer 1981; NASA 1978)*

The data are taken primarily from military studies, where several thousand people were studied. The numbers in parenthesis are from industrial studies where 50–100 women and 100–150 men were studied. The data in the footnote are from a study on 50 men and 100 women in industry. Figures 1.13 and 1.14 illustrate the measurements.

The data from men and women are statistically combined to derive the 5th, 50th, and 95th percentile values for a 50/50 mix of these populations.

	Males		Females		Population Percentiles, 50/50 Males/Females		
Measurement	50th percentile	± 1 S.D	50th percentile	± 1 S.D	5th	50th	95th
STANDING							
1. Forward functional reach							
a. Includes body depth at shoulder	82.6 (79.3)	4.8 (5.6)	74.1 (71.3)	3.9 (4.4)	69.1 (65.5)	77.9 (74.8)	88.8 (86.5)
b. Acromial process to functional pinch	63.8	4.3	62.5	3.4	57.5	65.0	74.5
c. Abdominal extension to functional pinch**	(62.1)	(8.9)	(60.4)	(6.7)	(48.5)	(61.1)	(74.5)
2. Abdominal extension depth	23.1	2.0	20.9	2.1	18.1	22.0	25.8
3. Waist height	106.3 (104.8)	5.4 (6.3)	101.7 (98.5)	5.0 (5.5)	94.9 (91.0)	103.9 (101.4)	113.5 (113.0)
4. Tibial height	45.6	2.8	42.0	2.4	38.8	43.6	49.2
5. Knuckle height	75.5	4.1	71.0	4.0	65.7	73.2	80.9
6. Elbow height	110.5 (114.6)	4.5 (6.3)	102.6 (107.1)	4.8 (6.8)	96.4 (98.8)	106.7 (110.7)	116.3 (123.5)
7. Shoulder height	143.7 (146.4)	6.2 (7.8)	132.9 (135.3)	5.5 (6.6)	124.8 (126.6)	137.4 (140.4)	151.7 (156.4)
8. Eye height	164.4	6.1	151.4	5.6	144.2	157.7	172.3
9. Stature	174.5 (177.5)	6.6 (6.7)	162.1 (164.5)	6.0 (7.2)	154.4 (155.1)	168.0 (170.4)	183.0 (188.7)
10. Functional overhead reach	209.6	8.5	199.2	8.6	188.0	204.5	220.8
SEATED							
11. Thigh clearance height	14.7	1.4	12.4	1.2	10.8	13.5	16.5
12. Elbow rest height	24.1	3.2	23.1	3.0	18.4	23.6	28.9
13. Midshoulder height	62.4	3.2	58.0	2.7	54.5	60.0	66.5
14. Eye height	78.7	3.6	73.7	3.1	69.7	76.0	83.3
15. Sitting height normal	86.6	3.8	81.8	4.0	76.6	84.2	91.6
16. Functional overhead reach	128.4	8.5	119.8	6.6	110.6	123.6	139.3
17. Knee height	54.0	2.7	51.0	2.6	47.5	52.5	57.7
18. Popliteal height	44.6	2.5	41.0	1.9	38.6	42.6	47.8
19. Leg length	105.1	4.8	100.7	4.3	94.7	102.8	111.4
20. Upper-leg length	59.4	2.8	57.4	2.6	53.7	58.4	63.3
21. Buttocks-to-popliteal length	49.8	2.5	48.0	3.2	43.8	49.0	53.6

TABLE 1.5
(Continued)

Measurement	Males 50th percentile	Males ± 1 S.D	Females 50th percentile	Females ± 1 S.D	Population Percentiles, 50/50 Males/Females 5th	50th	95th
22. Elbow-to-fist length	38.5 (37.1)	2.1 (3.0)	34.8 (32.9)	2.3 (3.1)	31.9 (28.9)	36.7 (35.0)	41.1 (41.0)
23. Upper-arm length	36.9 (37.0)	1.9 (2.5)	34.1 (33.8)	2.5 (2.1)	31.0 (28.9)	35.7 (35.0)	39.4 (41.0)
24. Shoulder breadth	45.4	1.9	39.0	2.1	36.3	42.3	47.8
25. Hip breadth	35.6	2.3	38.0	2.6	32.4	36.8	41.5
FOOT							
26. Foot length	26.8	1.3	24.1	1.1	22.6	25.3	28.4
27. Foot breadth	10.0	0.6	8.9	0.5	8.2	9.4	10.8
HAND							
28. Hand thickness, metacarpal III	3.3	0.2	2.8	0.2	2.7	3.0	3.6
29. Hand length	19.0	1.0	18.4	1.0	17.0	18.7	20.4
30. Digit two length	7.5	0.7	6.9	0.8	5.8	7.2	8.5
31. Hand breadth	8.7	0.5	7.7	0.5	7.0	8.2	9.3
32. Digit one length	12.7	1.1	11.0	1.0	9.7	11.8	14.2
33. Breadth of digit one interphalangeal joint	2.3	0.1	1.9	0.1	1.8	2.1	2.5
34. Breadth of digit three interphalangeal joint	1.8	0.1	1.5	0.1	1.4	1.7	2.0
35. Grip breadth, inside diameter	4.9	0.6	4.3	0.3	3.8	4.5	5.7
36. Hand spread, digit one to digit two, first phalangeal joint	12.4	2.4	9.9	1.7	7.5	10.9	15.5
37. Hand spread, digit one to digit two, second phalangeal joint	10.5	1.7	8.1	1.7	5.9	9.3	12.7
HEAD							
38. Head breadth	15.3	0.6	14.5	0.6	13.8	14.9	16.0
39. Interpupillary breadth	6.1	0.4	5.8	0.4	5.2	6.0	6.7
40. Biocular breadth	9.2	0.5	9.0	0.5	8.3	9.1	10.0
OTHER MEASUREMENTS							
41. Flexion-extension, range of motion of wrist, in radians	2.33	0.33	2.46	0.26	1.92	2.4	2.8
42. Ulnar-radial range of motion of wrist, in radians	1.05	0.23	1.17	0.24	0.81	1.15	1.49
43. Weight, in kilograms	83.2	15.1	66.4	13.9	47.7	74.4	102.9

* These values should be adjusted for clothing and posture
** Add the following for bending forward from the hips or waist. Male: waist, 25 ± 7; hips 42 ± 8. Female: waist 20 ± 5; hips 36 ± 9

TABLE 1.6
U.S. Anthropometric Data, Inches (Champney 1979; Muller-Borer 1981; NASA 1978)*

The data here are the same as in Table 1.5, but they are expressed in inches.

Measurement	Males 50th percentile	Males ± 1 S.D	Females 50th percentile	Females ± 1 S.D	Population Percentiles, 50/50 Males/Females 5th	50th	95th
STANDING							
1. Forward functional reach							
a. Includes body depth at shoulder	32.5 (31.2)	1.9 (2.2)	29.2 (28.1)	1.5 (1.7)	27.2 (25.7)	30.7 (29.5)	35.0 (34.1)
b. Acromial process to functional pinch	26.9	1.7	24.6	1.3	22.6	25.6	29.3
c. Abdominal extension to functional pinch**	(24.4)	(3.5)	(23.8)	(2.6)	(19.1)	(24.1)	(29.3)
2. Abdominal extension depth	9.1	0.8	8.2	0.8	7.1	8.7	10.2
3. Waist height	41.9 (41.3)	2.1 (2.1)	40.0 (38.8)	2.0 (2.2)	37.4 (35.8)	40.9 (39.9)	44.7 (44.5)
4. Tibial height	17.9	1.1	16.5	0.9	15.3	17.2	19.4
5. Knuckle height	29.7	1.6	28.0	1.6	25.9	28.8	31.9
6. Elbow height	43.5 (45.1)	1.8 (2.5)	40.4 (42.2)	1.4 (2.7)	38.0 (38.5)	42.0 (43.6)	45.8 (48.6)
7. Shoulder height	56.6 (57.6)	2.4 (3.1)	51.9 (56.3)	2.7 (2.6)	48.4 (49.8)	54.4 (55.3)	59.7 (61.6)
8. Eye height	64.7	2.4	59.6	2.2	56.8	62.1	67.8
9. Stature	68.7 (69.9)	2.6 (2.6)	63.8 (64.8)	2.4 (2.8)	60.8 (61.1)	66.2 (67.1)	72.0 (74.3)
10. Functional overhead reach	82.5	3.3	78.4	3.4	74.0	80.5	86.9
SEATED							
11. Thigh clearance height	5.8	0.6	4.9	0.5	4.3	5.3	6.5
12. Elbow rest height	9.5	1.3	9.1	1.2	7.3	9.3	11.4
13. Midshoulder height	24.5	1.2	22.8	1.0	21.4	23.6	26.1
14. Eye height	31.0	1.4	29.0	1.2	27.4	29.9	32.8
15. Sitting height normal	34.1	1.5	32.2	1.6	32.0	34.6	37.4
16. Functional overhead reach	50.6	3.3	47.2	2.6	43.6	48.7	54.8
17. Knee height	21.3	1.1	20.1	1.0	18.7	20.7	22.7
18. Popliteal height	17.2	1.0	16.2	0.7	15.1	16.6	18.4
19. Leg length	41.4	1.9	39.6	1.7	37.3	40.5	43.9
20. Upper-leg length	23.4	1.1	22.6	1.0	21.1	23.0	24.9
21. Buttocks-to-popiteal length	19.2	1.0	18.9	1.2	17.2	19.1	20.9
22. Elbow-to-fist length	14.2 (14.6)	0.9 (1.2)	12.7 (13.0)	1.1 (1.2)	12.6 (11.4)	14.5 (13.8)	16.2 (16.2)
23. Upper-arm length	14.5 (14.6)	0.7 (1.0)	13.4 (13.3)	0.4 (0.8)	12.9 (12.1)	13.8 (13.8)	15.5 (16.0)
24. Shoulder breadth	17.9	0.8	15.4	0.8	14.3	16.7	18.8
25. Hip breadth	14.0	0.9	15.0	1.0	12.8	14.5	16.3

TABLE 1.6
(Continued)

Measurement	Males 50th percentile	Males ± 1 S.D	Females 50th percentile	Females ± 1 S.D	Population Percentiles, 50/50 Males/Females 5th	50th	95th
FOOT							
26. Foot length	10.5	0.5	9.5	0.4	8.9	10.0	11.2
27. Foot breadth	3.9	0.2	3.5	0.2	3.2	3.7	4.2
HAND							
28. Hand thickness, metacarpal III	1.3	0.1	1.1	0.1	1.0	1.2	1.4
29. Hand length	7.5	0.4	7.2	0.4	6.7	7.4	8.0
30. Digit two length	3.0	0.3	2.7	0.3	2.3	2.8	3.3
31. Hand breath	3.4	0.2	3.0	0.2	2.8	3.2	3.6
32. Digit one length	5.0	0.4	4.4	0.4	3.8	4.7	5.6
33. Breadth of digit one interphalangeal joint	0.9	0.05	0.8	0.05	0.7	0.8	1.0
34. Breadth of digit three interphalangeal joint	0.7	0.05	0.6	0.04	0.6	0.7	0.8
35. Grip breadth, inside diameter	1.9	0.2	1.7	0.1	1.5	1.8	2.2
36. Hand spread, digit one to digit two, first phalangeal joint	4.9	0.9	3.9	0.7	3.0	4.3	6.1
37. Hand spread, digit one to digit two, second phalangeal joint	4.1	0.7	3.2	0.7	2.3	3.6	5.0
HEAD							
38. Head breadth	6.0	0.2	5.7	0.2	5.4	5.9	6.3
39. Interpupillary breadth	2.4	0.2	2.3	0.2	2.1	2.4	2.6
40. Biocular breadth	3.6	0.2	3.6	0.2	3.3	3.6	3.9
OTHER MEASUREMENTS							
41. Flexion-extension, range of motion of wrist, in degrees	134	19	141	15	108	138	166
42. Ulnar-radial range of motion of wrist, in degrees	60	13	67	14	41	63	87
43. Weight, in kilograms	183.4	33.2	146.3	30.7	105.3	164.1	226.8

* These values should be adjusted for clothing and posture.
** Add the following for bending forward from the hips or waist. Male: waist 10 ± 3; hips 16 ± 3. Female: waist 8 ± 2; hips 14 ± 4

Other Ethnic or Regional Data

Compilations of anthropometric data including U.S. and other world populations give a clear indication of the differences in size of several ethnic and racial groups (Chapanis 1975; Jurgens, Aune, and Pieper 1990; Pheasant 1986; Roebuck 1995).

The U.S. military data include many of these populations, so designing to accommodate most U.S. men and women will, for many measurements, be

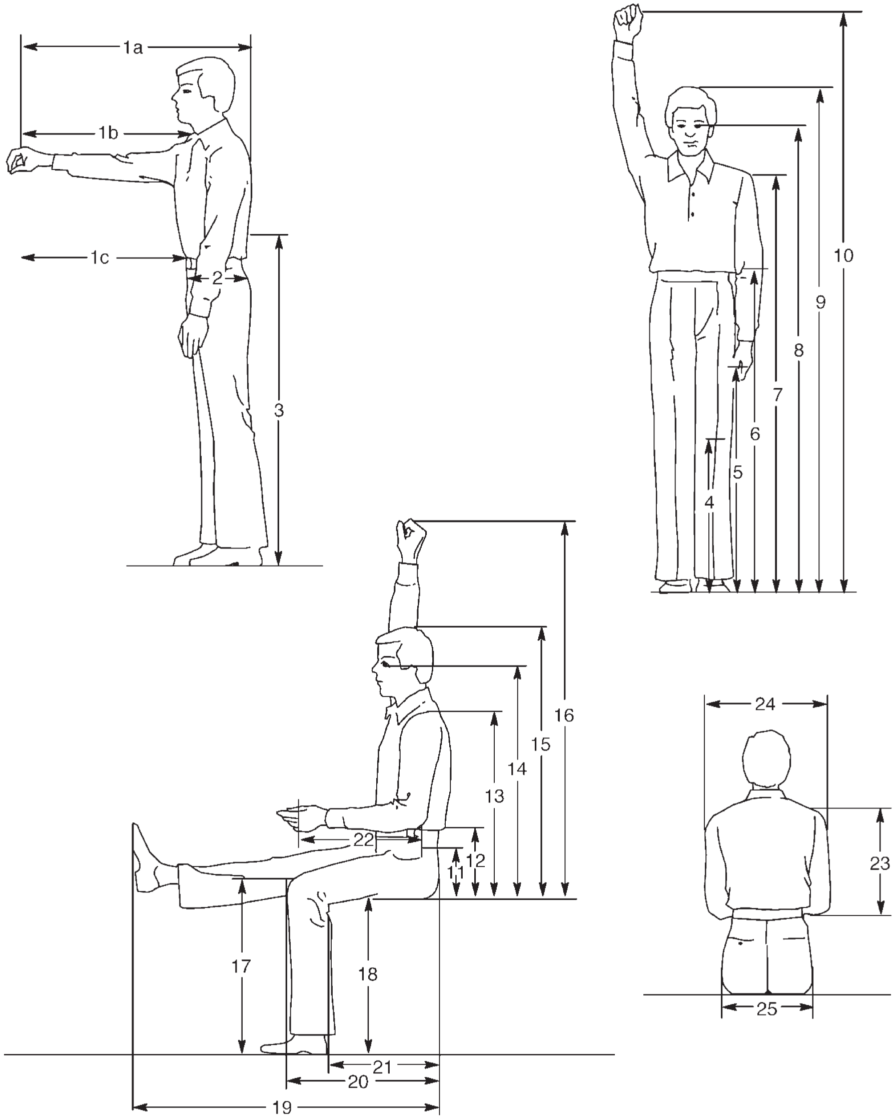

FIGURE 1.13. Anthropometric Dimensions, Standing and Sitting (Champney 1975, 1979: Muller-Borer 1981 NASA 1979)

within good design guidelines for most Europeans, many Africans, most other North Americans, and many South Americans as well. Asian populations, which are generally smaller in size, will need to be accommodated through appropriate adjustments.

In this section, Tables 1.7 (in centimeters) and 1.8 (in inches) show some anthropometric characteristics of other world populations, indicated by including the range of values for the 5th, 50th, and 95th percentiles of several measurements for men and women from Europe, Sri Lanka, China, Japan, India,

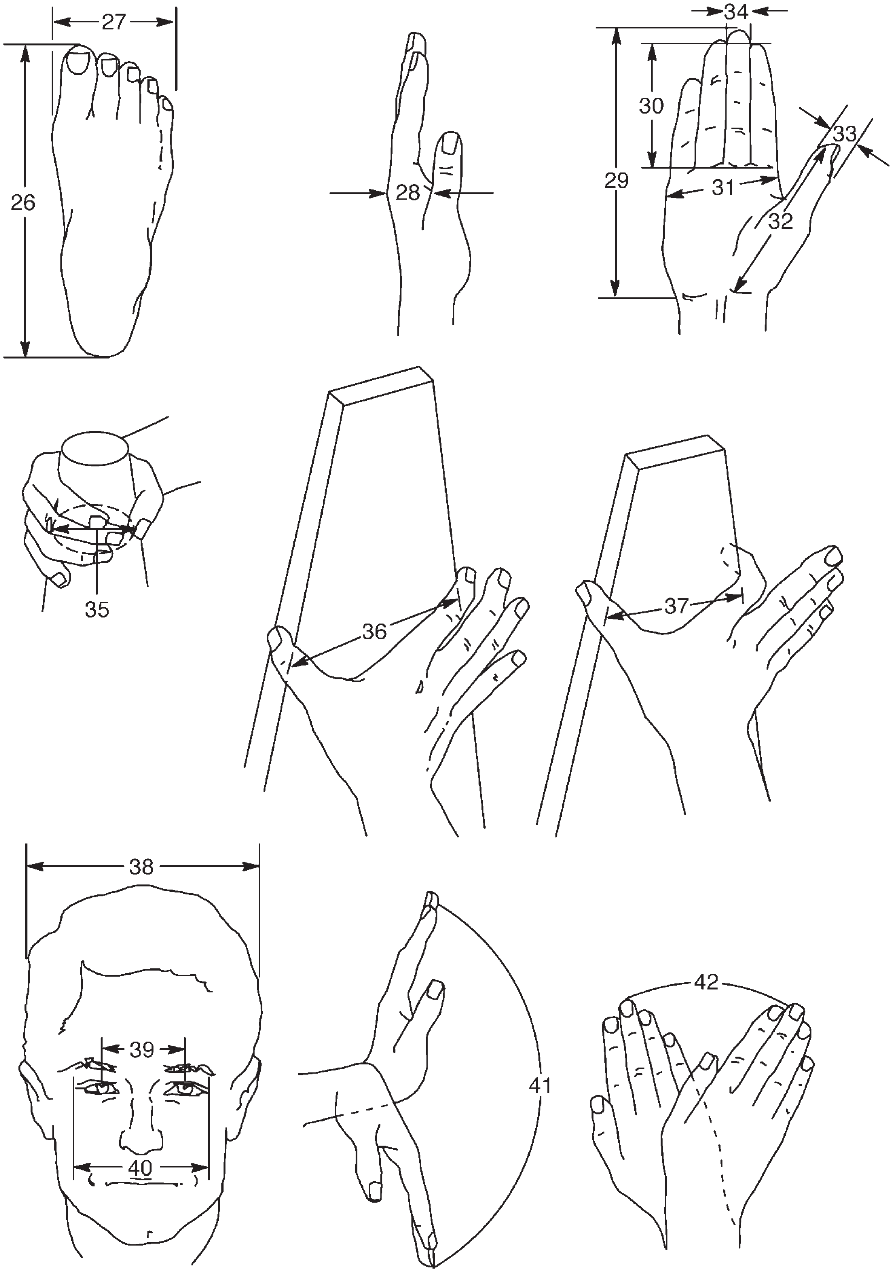

FIGURE 1.14. Anthropometric Dimensions, Hands, Face, and Foot (Champney 1975, 1977, 1979; Muller-Borer 1981 NASA 1979)

TABLE 1.7
Anthropometric Data (in Centimeters) Across Ethnic and Racial Groups (after Jurgens et al. 1990; Ministry of Defence 1997; Pheasant 1986)

Measurement (cm)	Percentile	Males 5th	Males 50th	Males 95th	Females 5th	Females 50th	Females 95th
Stature	All	162	174	186	150	161	171
	(Range)	(152–171)	(162–181)	(171–191)	(139–158)	(152–169)	(156–179)
Eye height, standing	All	152	163	174	140	150	161
	(Range)	(142–158)	(150–167)	(164–176)	(132–144)	(142–154)	(150–164)
Shoulder height, standing	All	132	142	154	122	131	140
	(Range)	(125–140)	(134–150)	(142–159)	(108–126)	(114–136)	(122–146)
Elbow height, standing	All	100	109	118	93	100	108
	(Range)	(93–102)	(102–115)	(108–122)	(87–98)	(94–107)	(100–114)
Hip height, standing	All	84	92	100	74	81	88
	(Range)	(76–88)	(83–97)	(90–106)	(70–84)	(76–92)	(81–98)
Knuckle height, standing	All	69	76	82	66	72	78
	(Range)	(54–74)	(60–80)	(64–84)	(54–70)	(57–78)	(60–84)
Sitting height, above seat height	All	85	91	96	80	85	91
	(Range)	(78–90)	(84–95)	(88–100)	(72–84)	(78–90)	(83–95)
Sitting shoulder height, above seat height	All	54	60	64	50	56	61
	(Range)	(52–57)	(56–62)	(59–67)	(48–54)	(52–58)	(58–62)
Sitting elbow height, above seat height	All	20	24	30	18	24	28
	(Range)	(16–22)	(20–26)	(24–30)	(15–22)	(18–25)	(22–30)
Thigh thickness	All	14	16	18	12	16	18
	(Range)	(10–15)	(12–18)	(14–21)	(7–14)	(8–16)	(10–20)
Buttock-to-knee length	All	54	60	64	52	57	62
	(Range)	(50–58)	(53–63)	(58–67)	(45–55)	(48–60)	(51–64)
Buttock-to-popliteal length	All	44	50	55	44	48	53
	(Range)	(40–47)	(45–52)	(50–57)	(36–44)	(44–50)	(48–55)
Knee height, sitting	All	49	54	60	46	50	54
	(Range)	(41–52)	(46–56)	(50–61)	(38–47)	(42–52)	(46–56)
Popliteal height, sitting	All	40	44	49	36	40	44
	(Range)	(32–42)	(37–46)	(41–50)	(29–39)	(34–41)	(38–45)

and Brazil. The tables show the degree of overlap of the population distributions and give the user the option of designing to the part of the range that best represents his or her workforce. Table 1.9 takes the information in the previous two tables and suggests a design range for each measurement for a global workplace or for product or equipment design. It should be remembered that the design is dependent on the function being performed, so a thorough knowledge of the job requirements is needed before the anthropometric data are chosen.

TABLE 1.8
Anthropometric Data (in Inches) Across Ethnic and Racial Groups (after Jurgens et al. 1990; Ministry of Defence 1997; Pheasant 1986)

Measurement (in.)	Percentiles	Males 5th	Males 50th	Males 95th	Females 5th	Females 50th	Females 95th
Stature	All (Range)	64.0 (59.8–67.3)	68.5 (63.8–71.3)	73.0 (67.3–75.2)	59.3 (54.7–62.2)	63.4 (59.8–66.5)	67.3 (61.4–70.5)
Eye height, standing	All (Range)	59.6 (56.1–62.0)	64.2 (59.3–65.7)	68.7 (64.4–69.5)	55.3 (52.2–56.5)	59.3 (55.9–60.4)	63.4 (59.1–64.4)
Shoulder height, standing	All (Range)	51.8 (49.2–55.1)	56.1 (52.8–58.9)	60.4 (56.1–62.6)	47.8 (42.3–49.8)	51.6 (45.1–53.7)	55.3 (47.8–57.7)
Elbow height, standing	All (Range)	39.6 (36.6–40.2)	42.9 (40.0–45.1)	46.5 (42.5–47.8)	36.6 (34.3–38.6)	39.6 (36.8–42.2)	42.7 (39.4–45.1)
Hip height, standing	All (Range)	33.1 (30.1–34.8)	36.2 (32.7–38.2)	39.4 (35.2–41.7)	29.1 (27.6–33.1)	31.9 (29.7–??)	34.8 (31.9–38.8)
Knuckle height, standing	All (Range)	27.2 (21.5–29.3)	29.7 (23.4–31.3)	32.5 (25.2–33.3)	26.0 (21.1–27.8)	28.3 (22.4–30.5)	30.7 (23.8–33.3)
Sitting height, above seat height	All (Range)	33.5 (30.7–35.4)	35.8 (32.9–37.4)	38.0 (34.6–39.4)	31.3 (28.5–33.1)	33.5 (30.5–35.4)	35.8 (32.7–37.4)
Sitting shoulder height, above seat height	All (Range)	21.3 (20.5–22.4)	23.4 (21.9–24.4)	25.4 (23.2–26.4)	19.9 (18.7–21.1)	21.9 (20.7–23.0)	24.0 (22.6–24.6)
Sitting elbow height, above seat height	All (Range)	7.7 (6.3–8.7)	9.6 (7.9–10.2)	11.6 (9.3–11.8)	7.3 (5.9–8.5)	9.3 (7.3–9.8)	11.0 (8.7–11.6)
Thigh thickness	All (Range)	5.3 (3.9–5.9)	6.3 (4.7–7.1)	7.3 (5.5–8.3)	4.9 (2.8–5.3)	6.1 (3.3–6.5)	7.1 (3.9–7.7)
Buttock-to-knee length	All (Range)	21.3 (19.7–22.8)	23.4 (20.9–28.4)	25.4 (22.8–26.4)	20.5 (17.7–21.7)	22.4 (19.1–23.6)	24.4 (20.1–25.4)
Buttock-to-popliteal length	All (Range)	17.3 (15.9–18.5)	19.5 (17.7–20.5)	21.7 (19.5–22.4)	17.1 (14.2–17.3)	18.9 (17.1–19.5)	20.9 (19.1–21.7)
Knee height, sitting	All (Range)	19.3 (16.1–20.5)	21.5 (17.9–22.2)	23.4 (19.7–24.0)	17.9 (14.8–18.7)	19.7 (16.5–20.3)	21.3 (18.3–22.0)
Popliteal height, sitting	All (Range)	15.6 (12.8–16.3)	17.3 (14.6–17.9)	19.3 (16.1–19.9)	14.0 (11.4–15.4)	15.7 (13.2–16.1)	17.5 (15.0–17.7)

Range of Motion and Joint Centers of Motion

Biomechanical analyses of the torque on muscles and joints during work make assumptions about the range of motion of joints and the moment arms from the proximal joints to the centers of gravity of body segments. Figure 1.15 presents the location of body segment centers of gravity as percentages of segment length. For example, the upper arm's center of gravity is 44 percent of

TABLE 1.9
Who We Design for in Global Manufacturing: Suggested Values of Anthropometric Data for Specific Design Needs

Measurement	Design Usage	Suggested Range, cm (in.)
Stature	Clearance for standing access	203 (80); add 13 cm (5 in.) for motion and clothing to the 99th-percentile male value
Eye height, standing	Visibility of signs, displays	140 to 164 (58 to 64)
Shoulder height, standing	Upper limit for lifting or working	114 to 126 (45 to 50)
Elbow height, standing	Height of hands in assembly tasks	95 to 100 (37 to 40)
	Height of hands in packing tasks	90 to 95 (35 to 37)
Hip height, standing	Height over which a person can bend for short durations	73 to 78 (29 to 31)
Knuckle height, standing	Lowest height for work close to the body	54 to 70 (22 to 28)
Sitting height, above seat height	Clearance for seated work—overhead	100 (39)
Sitting shoulder height, above seat height	Upper limit for lifting or working	48 to 52 (19 to 21)
Sitting elbow height, above seat height	Height of hands in assembly or typing task, armrest height	17 to 20 (8 to 9)
Thigh thickness, seated	Minimum clearance under table or workbench	21 (8)
Buttocks-to-knee length	Forward minimum leg clearance, seated	67 (26)
Buttocks-to-popliteal length	Maximum length of seat to accommodate short thighs	44 (17)
	Minimum length of seat for people with long legs so 70% of thigh is supported	38 (15)
Knee height, seated	Lowest height for a seated work surface, from bottom	61 (24)
Popliteal height, seated	Lowest height of seat adjustability for small people	36 (14)
	Lowest height of seat adjustability for tall people	52 (20)

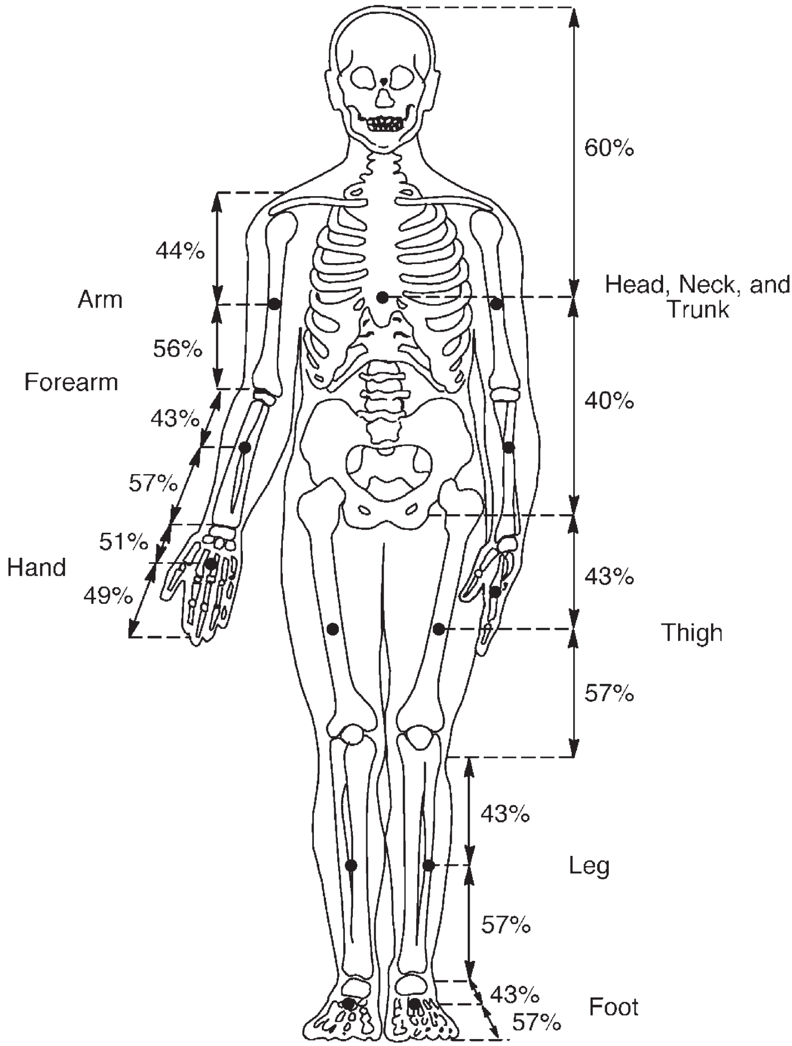

FIGURE 1.15. Estimated Body Segment Centers of Gravity Expressed as a Percentage of Segment Length (after Dempster 1955; Williams and Lissner 1962)

the distance from the shoulder to the elbow. This can be used to estimate the torque in upper-body handling tasks, for instance.

The ranges of motion of joints are shown in Table 1.10 and Figures 1.16–1.20. These are average values and can vary with gender, age, previous injury, or body size.

The most efficient work is done within the first third of the range of motion for the movement. The closer one gets to the extreme of the range, in general, the more stress there is on the joint and its supporting muscles. This is shown later in this section for wrist angles, for instance, where grip strength is lost as one gets closer to the extremes of wrist flexion.

TABLE 1.10
Normal Ranges of Joint Motion (adapted from the American Academy of Orthopaedic Surgeons 1965)

Joint	Motion	Range of Motion in Degrees	Range of Motion in Radians
Elbow	Flexion to extension	150	2.62
	Hyperextension	10	0.17
Forearm	Pronation	80	1.48
	Supination	80	1.48
Wrist	Flexion	80	1.40
	Extension	70	1.22
	Radial Deviation	25	0.44
	Ulnar Deviation	40	0.70
Shoulder	Abduction	180	3.14
	Adduction	75	1.31
	Forward flexion	180	3.14
	Backward extension	60	1.05
	Horizontal flexion	130	2.27
	Horizontal extension	50	0.87
Cervical spine	Flexion	45	0.78
	Extension	45	0.78
	Lateral bending	45	0.78
	Rotation	60	1.05
Lumbar spine	Flexion	80	1.40
	Extension	20–30	0.35–0.52
	Lateral bending	35	0.61
	Rotation	45	0.78
Knee	Flexion	135	2.36
	Hyperextension	10	0.17
Ankle	Flexion (plantar flexion)	50	0.87
	Extension (dorsiflexion)	20	0.35

Cautions on the Use of Anthropometric Data in Design

MILITARY VERSUS INDUSTRIAL POPULATION DATA Most of the U.S. data have been taken from studies done on military populations. The characteristics of a military population differ significantly from those of an industrial population when it comes to girths, especially. The extremes of the population tend to be screened out partly because the distribution of ages in the military population is skewed heavily toward those under age 40 (Gordon et al. 1998). They

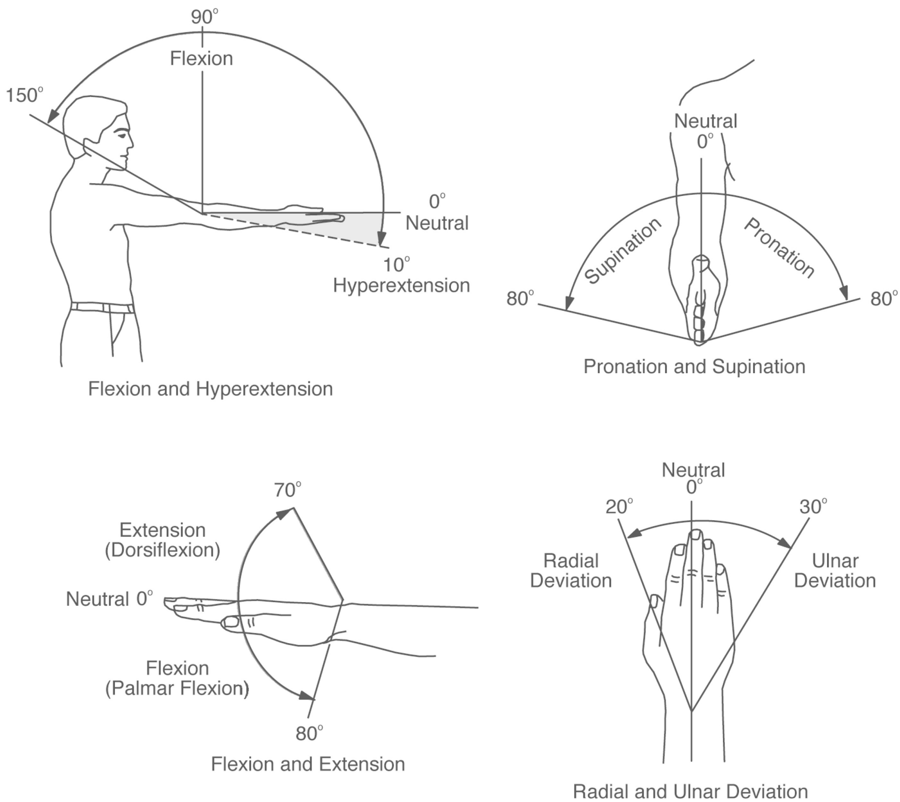

FIGURE 1.16. Ranges of Motion of the Forearm and Wrist (adapted from American Academy of Orthopaedic Surgeons 1965)

also tend to be more fit than the industrial population, which can be seen in the data on abdominal extension depth and limb girths (see Tables 1.5 and 1.6). Because of this population sampling difference between industrial and military data, the clearance guidelines included in this book are usually the 99th-percentile male values with an additional amount included for functional needs, if appropriate. For example, the access hatch width recommendation of 61 cm (24 in.) in Chapter 3 is based on a 99th-percentile male shoulder breadth of 51 cm (20 in.) plus 10 cm (4 in.) for movement through the hatch. This should accommodate most large industrial workers. If special equipment or clothing is worn (e.g., auxiliary breathing equipment), its clearance needs must also be considered.

USING ANTHROPOMETRIC DATA FOR DESIGN WHEN MORE THAN ONE MEASUREMENT IS INVOLVED Although we tend to think of people as being small or large, few small people are in the 5th percentile for all measurements and few large people are in the 95th percentile for most of their measurements.

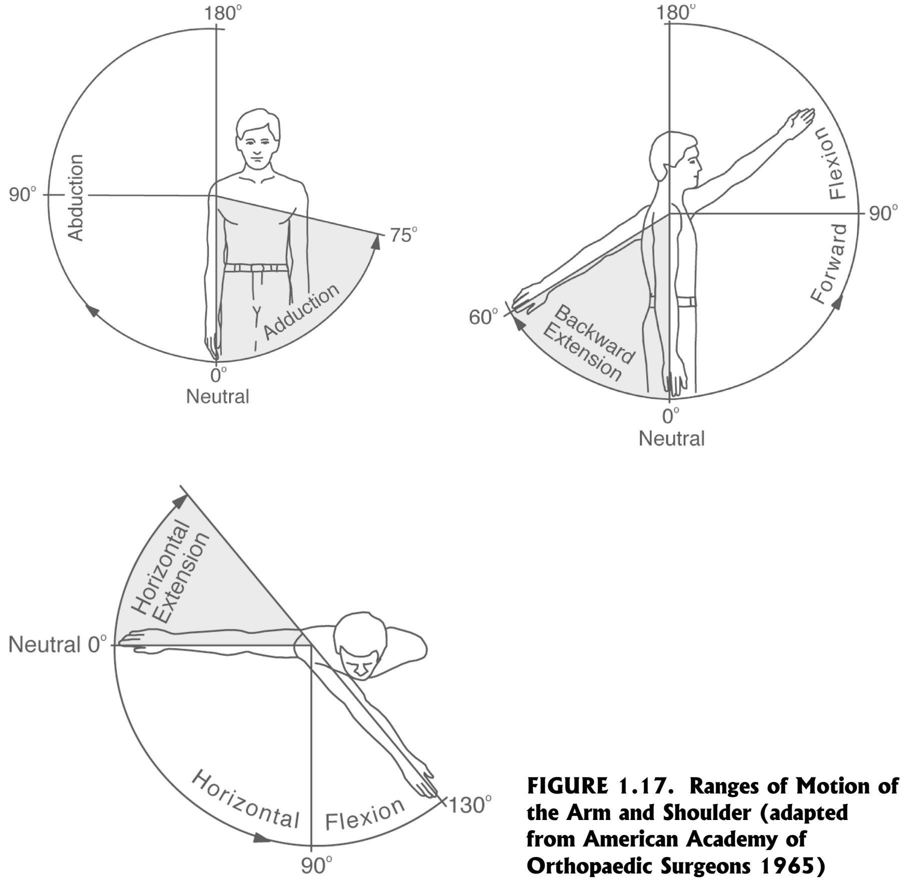

FIGURE 1.17. Ranges of Motion of the Arm and Shoulder (adapted from American Academy of Orthopaedic Surgeons 1965)

There is variability in the percentiles for different measurements, the correlation between them being less than 0.9 in most instances (Clauser et al. 1972; Roebuck 1995). A good example is shown in Table 1.11 for hand size measurements on fourteen people.

It is important to determine the relevant hand measures when designing items such as hand tools or consumer products that are grasped when used (e.g., cameras). The best design will accommodate the most hands across dimensions. As more measures are added, the number of people accommodated will be reduced because of the variability in hand size between dimensions (Garrett 1971). The challenge of designing hand tools and gloves to accommodate the hands of a large and diverse population was addressed in a research project where the hands of 1,081 U.S. and Mexican industrial workers were measured (Johnson and Rapp 1997). The sample was 4 percent African-American (86 percent male), 70 percent Hispanic (67 percent male), 13 percent Asian (46 percent male), and 13 percent Caucasian (40 percent male). The study found that the proportionality of digit and interdigit crotch

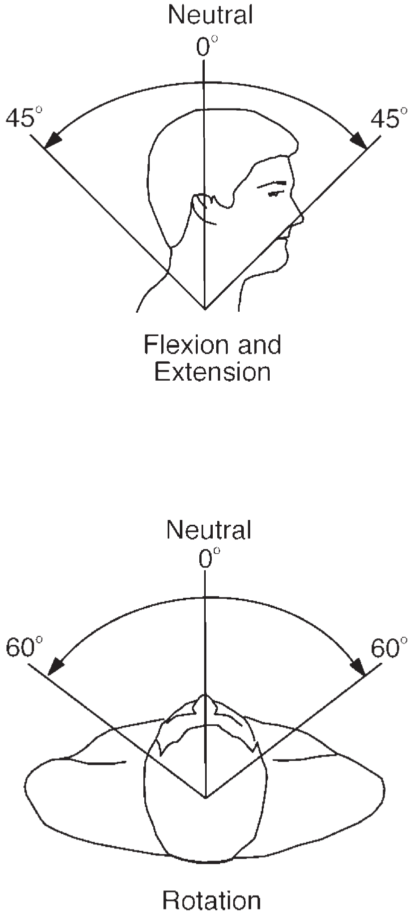

FIGURE 1.18. Ranges of Motion of the Cervical Spine and Spine Rotation (adapted from American Academy of Orthopaedic Surgeons 1965)

lengths relative to middle digit length was consistent across ethnicity and gender groups. Table 1.12 shows the proportionalities, using the middle digit as 100 percent.

Using these proportionality constants, it should be possible to project the glove sizes and hand tool characteristics needed to accommodate the population of interest when the range of middle-digit lengths is known.

The art of designing to maximize the fit between the person and the equipment includes the consideration of how well the person can use the equipment functionally and dynamically as well as how well the physical dimensions match the person's anthropometry. This matching is termed *affordance* and relates to how well the design affords the person the ability to perform well within its constraints (Dainoff, Mark, and Gardner 1999). As this concept is developed, it will require more than a simple choice of a measurement and matching the values to a particular segment of the workforce. More dynamic simulation of motion patterns and the interactions of relevant measurements can be included in the design

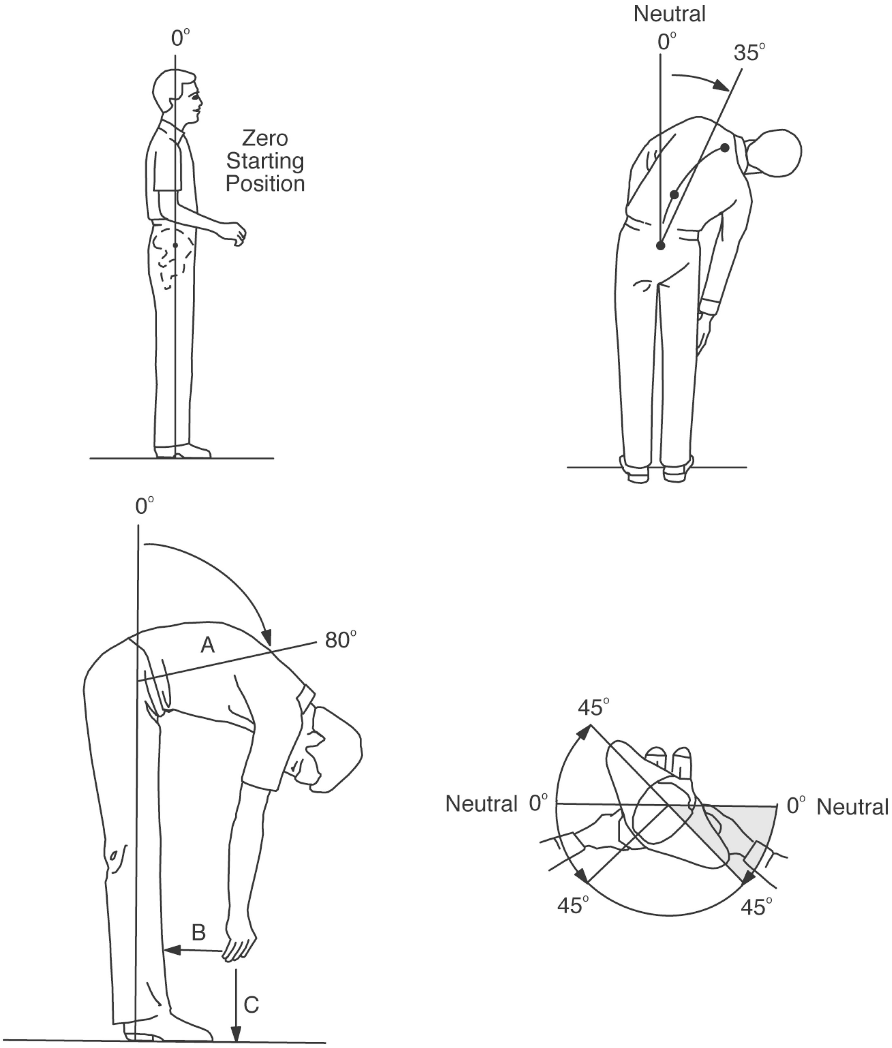

FIGURE 1.19. Ranges of Motion of the Spine (adapted from American Academy of Orthopaedic Surgeons 1965)

by computer modeling, for example. However, although the physical anthropometry described in this section is useful as a way to accommodate more people in designs, the ultimate design tools will be more complex in the future.

Muscle Strength Data

Obtaining data on the muscle strengths of industrial workers has been difficult because most of the studies are done in universities or rehabilitation clinics.

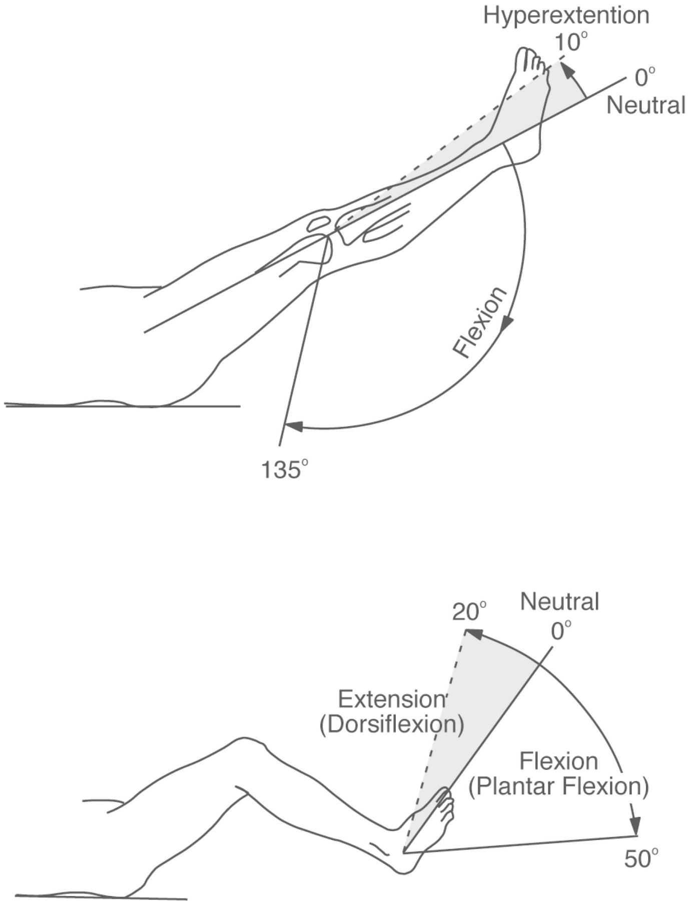

FIGURE 1.20. Ranges of Motion of the Knee and Ankle (adapted from American Academy of Orthopaedic Surgeons 1965)

The data included in this section are selected from literature studies and from some small sample studies done in the past in the ergonomics laboratory at Kodak. The data are presented by muscle groups and include grip strength, upper-extremity strengths, and whole-body pulling strength.

GRIP STRENGTH Table 1.13 summarizes the results of several studies of maximum power grip strength in men and women, industrial workers and civilians, ranging in age from 18 to 64. These studies did not all use the same methodologies, so there will be some variation in the values reported. Some had the strength measured at the preferred hand span of the subject, while others used a fixed span of 5 cm (2 in.). Nonetheless, there is fair agreement between the studies. They have been combined, weighted by the number of subjects, to determine an average ±1 standard deviation power grip strength

TABLE 1.11
Percentile Values for Several Hand Dimensions (Champney 1977)

Subject	Hand Length	Digit 2 Length	Hand Breadth	Hand Thickness	Grip Breadth	Hand Spread Wedge
1	1st	2nd	1st	52nd	3rd	2nd
2	2nd	15th	3rd	77th	32nd	17th
3	5th	15th	19th	63rd	32nd	2nd
4	7th	48th	26th	42nd	32nd	17th
5	8th	18th	1st	8th	6th	2nd
6	8th	48th	26th	52nd	17th	38th
7	9th	56th	54th	94th	17th	17th
8	41st	48th	3rd	3rd	50th	2nd
9	47th	56th	66th	60th	32nd	84th
10	51st	66th	59th	60th	50th	84th
11	66th	44th	84th	65th	32nd	95th
12	75th	69th	81st	98th	17th	17th
13	81st	56th	3rd	1st	50th	38th
14	87th	48th	96th	60th	84th	6th

for men of 490 ± 101 newtons (110 ± 14 lbf) and for women of 275 ± 62 newtons (62 ± 14 lbf).

The values shown in Table 1.13 assume that the maximum power grip was performed with an optimal grip span (5 ± 2 cm, or 2 ± 0.8 in.), neutral wrist posture, and bare-handed. It also assumes that the fingers can curl around the object being grasped and that the surface is not slippery. Table 1.14 provides information on the loss of grip strength as span, wrist angles, and glove use are varied.

Pinch grip is from 15 to 25 percent of power grip, depending on the type of pinch and the degree of precision needed to control it (Jacobsen and Sperling 1976; Jones 1974; Lowe 2001). This is about 40 N (9 lbf) for the average woman and 75 N (17 lbf) for the average man. Values of 22 N (5 lbf) are seen for precision grip maxima of the 5th percentile of the older mixed (M/F) population (Lowe 2001). With repetitive pinching, much lower forces are recommended (see the section on repetitive tasks in Chapter 6).

UPPER-EXTREMITY STRENGTHS Data on the maximum strengths and torques of upper-extremity muscles are presented in Tables 1.15 and 1.16 for men and women. These can be used to estimate the stress on muscles of the forearm, upper arm, and shoulder in tasks that require force generation or torque at the wrist, elbow, or shoulder. Because these are maximum values, the design guidelines will always be less than the values for the weaker segment of the workforce. The more repetitious the task, the lower the acceptable value for force will be, too. The guidelines are found in Chapters 2, 6, and 7.

TABLE 1.12
Digit Length Proportions for Four Ethnic Groups (Johnson and Rapp 1997)

Measurements	Proportion of Middle Digit Length
Middle digit length	100%
Thumb length	73%
Index digit length	96%
Ring digit length	94%
Little digit length	81%
Thumb-index crotch length	43%
Index-middle crotch length	58%
Middle-ring crotch length	57%
Ring-little crotch length	52%

WHOLE-BODY PULLING STRENGTH For most studies of lifting and force exertion tasks, several muscle groups are involved in performing the task because the load changes locations as it is handled. Isometric muscle strengths along the path of a lift or pull give some idea of the capabilities available for these tasks, but dynamic lifts require balance as well as strength. Consequently, the lifting and force exertion guidelines found in this book are lower than the isometric strengths that can be measured on the industrial population. Table 1.17 shows the average isometric pull forces measured on women and men when holding on to a tray. Three horizontal distances in front of the ankles and four heights above the floor were chosen to identify the effect of position on available pull strength. The highest pull strength was generated close to the body and at 33 cm (13 in.) above the floor. Using this as the 100 percent point for strength, the rest of the positions were evaluated for what percentage of that strength was available as the tray was moved farther from the spine and higher. Table 1.18 shows the relative strengths, which are related to which muscle groups are available or limiting and to the biomechanics of lifting as the horizontal distance increases. For further information on force exertion and lifting guidelines, see "Biomechanics" in Chapter 2, and also Chapter 7.

Because the average woman has from 33 to 60 percent of the isometric pull strength of the average man, it is important to design strength-requiring tasks for the less strong females wherever possible. Items that have to be lifted above shoulder height are less of a problem if they can be boosted instead of pulled up.

Aerobic Work Capacities of the Workforce and Aerobic Demands of Tasks

Total workload, or the metabolic demands of a job, should be designed so that most people can work within their capacities for different effort intensities and

TABLE 1.13
Maximum Power Grip Strengths of Men and Women

# of people	Population	Gender	Age Range	Newtons	Pounds of Force	Reference
463	Industrial applicants	M	Adults	449 ± 105	101 ± 24	Kamon and Goldfuss 1978
74	Industrial workers	M	Adults	535 ± 97	120 ± 22	Champney 1979 (Kodak)
310	Healthy civilians	M	18–25	530	119	Mathiowetz et al. 1985
			45–55	500	112	
104	Finnish men	M	20–54	530	119	Hanten et al. 1999
			55–64	480	108	
—	Office workers	M	18–45	451	101	Josty et al. 1997
	Car mechanics	M		515	116	
	Farm workers	M		527	118	
18	University and office workers	M	18–25	470	106	Haward and Griffin 2002
18		M	45–55	470	106	
1,047	***Weighted Average***	***M***	***18–64***	***490***	***110***	
# of people	**Population**	**Gender**	**Age Range**	**Newtons**	**Pounds of Force**	**Reference**
139	Industrial applicants	F	18–55	268 ± 64	60 ± 14	Kamon and Goldfuss 1978
18	Industrial workers	F	20–60	310 ± 59	70 ± 13	Champney 1979 (Kodak)
328	Healthy civilians	F	18–25	290	65	Mathiowetz et al. 1985
			45–55	260	58	
100	Finnish women	F	20–54	290	65	Hanten et al. 1999
			55–64	290	65	
18	University and office workers	F	18–25	270	61	Haward and Griffin 2002
18			45–55	280	63	
621	***Weighted Average***	***F***	***18–64***	***275***	***62***	

durations of tasks. The guidelines relating effort level and hours of work are discussed in Chapter 6, and methods to determine recovery time needs for sustained dynamic and static efforts can be found in Chapter 2.

There is not very much data on the aerobic capacities of industrial workers, so the guidelines for designing jobs within most people's capacities are

TABLE 1.14
Maximum Grip Strength Changes with Non-Neutral Wrist Postures and Glove Use (Champney 1979; Kamon and Goldfuss 1978; SUNYAB-IE 1982/83; Harkonen et al. 1993)

Condition	% of Max grip strength, bare-handed, 5-cm (2-in.) span, neutral wrist angles
45 degrees of wrist flexion	60
65 degrees of wrist flexion	45
45 degrees of wrist extension	75
25 degrees of radial deviation of wrist	80
40 degrees of ulnar deviation of wrist	75
Grip span of 2.5 cm (1 in.)	40
Grip span of 11 cm (4.5 in.)	45
Wearing rubber household gloves	81
Wearing gardening gloves	74
Wearing heavy heat-treated gloves	62
Wearing pressurized (3.5 psig) flight gloves	64

derived from data collected in industry (Eastman Kodak Company 1986) and general data on aerobic capacities of different age groups. NIOSH used similar data in its determination of acceptable workloads for frequent lifting tasks (NIOSH 1981, 1994; Rodgers and Yates 1991). See Chapter 2 for further information.

In this section some data on aerobic capacities of men and women are given. In addition, a listing of the aerobic demands of some tasks is included to help in defining the level of effort relative to the aerobic capacities.

AEROBIC WORK CAPACITIES **Whole Body.** Aerobic capacities are measured by performing standard tasks on equipment where the workload can be sequentially increased until physiological limits are met, such as reaching a maximum heart rate. Most studies of aerobic fitness in industry are run at submaximal levels and the maximum capacities are estimated from a predicted maximum heart rate. See the first edition of this book for more details about aerobic capacity testing and estimating capacity from submaximal tests. The data presented in Table 1.20 and Figure 1.21 later in this section are from treadmill testing of industrial workers at Eastman Kodak Company. There is ample data available on the aerobic fitness of healthy, young students, but industrial populations have not been studied very frequently. As the industrial workforce ages, and as extended work hours become more prevalent in manufacturing and service jobs, data on the older worker are especially needed to identify reasonable overall job demands. A recent study on the fitness of Finnish home care workers provides comparison data for women workers. The aerobic capacities were measured on a bicycle ergometer and taken until

TABLE 1.15
The Strength of Upper-Extremity Muscle Groups

Muscles	Gender	n	Newtons ± 1 SD	Pounds ±-1 SD	Torque Nm	Source
Isometric forearm flexion	M	436	276 ± 88	62 ± 20	70	Kamon and Goldfuss 1978
	M	74	336 ± 78	76 ± 18	85	Champney 1983
	F	136	160 ± 51	36 ± 12	38	Kamon and Goldfuss 1978
	F	18	174 ± 56	39 ± 13	41	Champney 1983
Isometric forearm extension	M	92	159 ± 29	36 ± 6	40	Tornvall 1963
	F	14	106	24	25	Kroll 1971
Dynamic forearm flexion—two hands	M	48	324 ± 46	73 ± 10	73	Kamon, Kiser and Landa-Pytel 1982
	F	—	168	38	40	
Isometric shoulder flexion—45 and 135°	M-45	62	124 ± 40	28 ± 9	62	Champney 1979
	M-135	9	95 ± 21	21 ± 5	48	Yates et al. 1980
	F-45	18	53 ± 22	12 ± 5	25	Champney 1979
	F-135	9	44 ± 14	10 ± 3	21	Yates et al. 1980

exhaustion or until the supervising medical personnel stopped the test. The measured values of aerobic capacity by age groups are shown in Table 1.19 were as follows (Pohjonen 2001):

The differences in the capacity tests and in the populations may explain the higher values for Finnish health care workers than for the industrial women in Table 1.20.

Another study using a maximal treadmill test showed women's aerobic capacities to range from 25.7 ± 3.0 ml O_2 per kg of body weight per minute in 33 women from 50 to 59 years to 26.9 ± 4.0 for 47 women from 40 to 49 years and to 29.1 ± 3.5 for 39 women from 29 to 39 years (Profant et al. 1972). These values are similar to the ones based on the submaximal treadmill studies presented in Table 1.20.

The predicted maximum aerobic capacities for the population of industrial workers shown above can be illustrated on a cumulative frequency distribution. From this one can estimate what percentage of the mixed male and female workforce would have the capacity needed to perform tasks of different effort levels for varying times during a work shift. The distribution is shown in Figure 1.21 with lines drawn to show where the 5th, 20th, 50th, 80th, and 95th percentiles for whole-body aerobic capacity would fall. The use of this data has been discussed earlier in this chapter; additional discussion of this use of whole-body capacity data can be found in Chapter 6 and in the first edition of this book, Volume 2.

TABLE 1.16
Maximum Torque Values for the Forearm and Wrist in Men and Women (Asmussen and Heebol-Nielsen 1961)

To get the torque values for Table 1.16, it was assumed that the forearm lengths for men and women were 0.254 m and 0.238 m, respectively. Moment arms assumed for the torque estimates were 0.5 m for men and 0.48 for women (Kamon et al. 1982).

Joint Motion	Sex	n	Nm ± 1 SD
Isometric wrist flexion	M	96	8.0 ± 1.8
	F	81	5.5 ± 0.9
Isometric wrist extension	M	96	10.1 ± 2.2
	F	81	6.9 ± 1.2
Isometric forearm pronation			
Handle	M	96	14.1 ± 3.1
	F	81	8.6 ± 1.6
Key	M	96	4.1 ± 0.6
	F	81	3.2 ± 0.5
Isometric forearm supination			
Handle	M	96	15.0 ± 2.7
	F	81	8.6 ± 1.5
Key	M	96	4.2 ± 0.7
	F	81	3.3 ± 0.5

TABLE 1.17
Maximum Isometric Pull Strengths (Newtons ± 1 SD) on a Tray (Champney 1979; Yates et al. 1980)

The bold figures show data points where 18 women and 37 men were included. The other values are based on 9 women and 9 men in a university setting. The additional people studied were industrial workers.

Height Above Floor in cm (in.)	Horizontal Distance 18 (7)	Horizontal Distance 36 (14)	Horizontal Distance 51 (20)
188 (74) M	177 ± 59	169 ± 44	122 ± 26
134 (53) M	293 ± 77	**253 ± 93**	**182 ± 69**
81 (32) M	**607 ± 158**	**323 ± 96**	251 ± 30
33 (13) M	**744 ± 221**	540 ± 144	302 ± 91
170 (70) F	66 ± 34	54 ± 23	41 ± 17
134 (53) F	104 ± 58	**115 ± 39**	**92 ± 41**
81 (32) F	**338 ± 146**	**184 ± 80**	118 ± 45
33 (13) F	**430 ± 190**	248 ± 50	131 ± 36

TABLE 1.18
Relative Isometric Pull Strength as a Function of Location of the Tray (Champney 1979; Yates et al. 1980)

Gender	Height Above Floor in cm (in.)	Percent of Maximum Isometric Pull Strength: Horizontal Distance 18 (7)	Horizontal Distance 36 (14)	Horizontal Distance 51 (20)
M	188 (74)	25	25	20
M	134 (53)	35	40	25
M	81 (32)	85	45	35
M	33 (13)	100	80	45
F	170 (70)	15	15	10
F	134 (53)	25	25	20
F	81 (32)	75	45	30
F	33 (13)	100	70	35

Upper-Body Aerobic Capacities. When activities are done that use primarily the upper extremities and some trunk muscles, there is less muscle mass involved in the work, and aerobic capacity is effectively reduced. Studies of arm cranking have been done to determine upper-body capacities, and they generally agree that it is about 70 percent of whole-body aerobic capacity (Astrand et al. 1965). Studies of 10 industrial women and 11 industrial men doing a lifting task that was between waist and shoulder heights showed a ratio of 64 percent for the women and 75 percent for the men when comparing upper-body lifting aerobic capacity to submaximal treadmill whole-body aerobic capacity (Rodgers 1973). The gender difference was probably related to the differences in shoulder musculature. For the purposes of designing jobs for most people, we have used 70 percent of whole-body aerobic capacity to define the upper-body aerobic capacity for tasks done primarily with the upper extremities.

AEROBIC DEMANDS OF SOME OCCUPATIONAL TASKS The energy costs of some occupational tasks are categorized in five effort levels. The aerobic demands are shown as ranges and given in ml O_2 per kg of body weight per minute, to match the units of aerobic capacity data given above. In addition, the values have been roughly translated into kilocalories per minute. The tasks have been categorized as upper-body or whole-body work based on the jobs observed and measured. The third column in Table 1.21 gives an estimate of the usual amount of time a task is sustained before a change to another task occurs. The entry in this column applies to both the upper-body and whole-body tasks in the adjacent columns. The effort category is dependent on the usual duration of the task, so tasks that exceed these continuous time periods will probably move into the next highest effort level. For more extensive information on job demands, see Volume 2 of the first edition of this book (Eastman Kodak Company 1986).

TABLE 1.19
Measured Values of Aerobic Capacity by Age Groups (Pojohnen 2001)

Age Range	n	Aerobic Capacity ($ml\ O_2$ per kg BW per min)
21–35	40–42	36.3 ± 6.2
36–44	28–34	34.0 ± 4.7
45–59	46–56	29.6 ± 5.4

TABLE 1.20
Whole-Body Aerobic Capacities of Industrial Men and Women (Rodgers 1975)

Gender	n	Age, in years Mean ± 1 SD	Weight, Mean ± 1 SD in kg (lb.)	Maximum Aerobic Capacity in ($ml\ O_2$ per kg BW per min)
Men	84	37 ± 12	78 ± 11 (178 ± 24)	38 ± 7
Women	37	33 ± 12	62 ± 9 (136 ± 20)	31 ± 6
50/50 mix	121	35 ± 12	70 ± 12 (154 ± 26)	34 ± 8
Men	27	24 ± 2	78 ± 11 (172 ± 24)	39 ± 8
	21	32 ± 2	77 ± 10 (169 ± 22)	39 ± 6
	20	46 ± 3	82 ± 12 (180 ± 26)	35 ± 7
	13	52 ± 2	78 ± 13 (172 ± 29)	37 ± 6
Women	20	24 ± 3	59 ± 6 (130 ± 13)	34 ± 5
	8	34 ± 3	61 ± 8 (134 ± 18)	30 ± −5
	4	44 ± 4	72 ± 16 (158 ± 35)	26 ± 4
	5	55 ± 3	66 ± 6 (145 ± 13)	25 ± 3

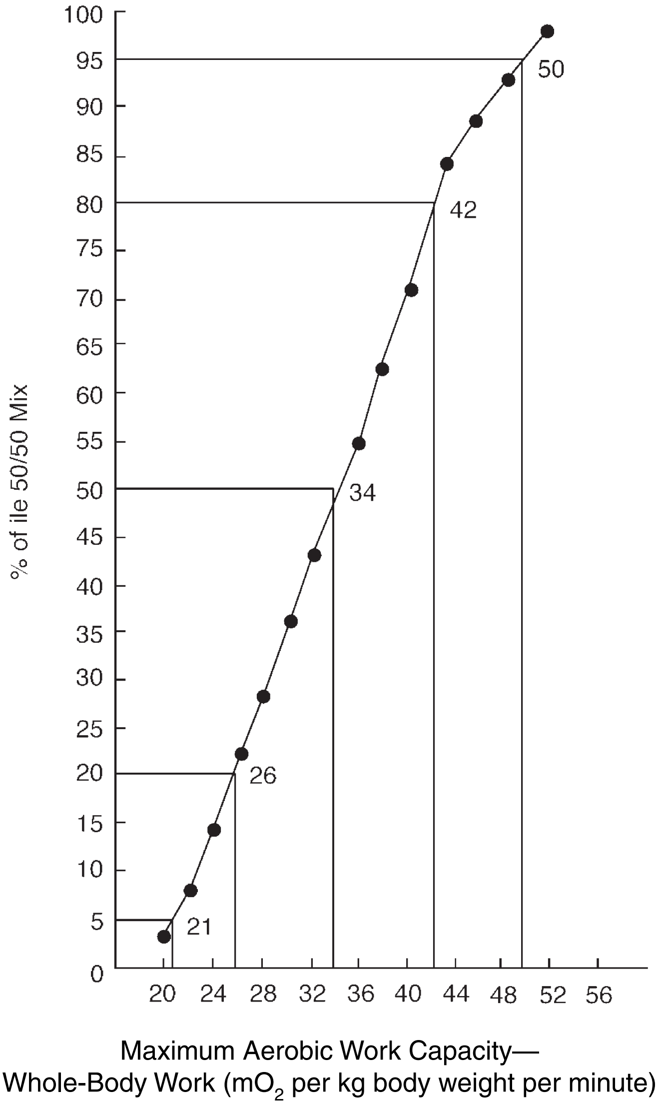

FIGURE 1.21. A Cumulative Frequency Distribution of Whole-Body Aerobic Capacities (Rodgers 1975)

Each situation encountered in a job has its own set of variables that the ergonomist has to discover by careful and respectful questioning and data collection. By keeping ergonomic principles in mind during the design process and tapping into the wealth of knowledge resident in the people who do the jobs, businesses can reap many benefits. These include a reduced risk of occupational injuries, improved employee comfort so that quality can be the focus of the people making the products or providing the service, and a higher quality of work life with increased flexibility to respond to changing production or output demands.

TABLE 1.21
Effort Levels of Some Occupational Tasks (after Eastman Kodak Company 1986)

Effort Level—Aerobic Demand, ml O_2 per kg BW per min (kcal/min)	Tasks—Whole Body	Usual Time	Tasks—Upper Body
Light— 3.0–7.0 (1–2.5) WB ≤ 5 (≤ 1.8) UB	Lecturing, public speaking	1–2 h	Paperwork—records
	Sitting, using hands and feet	> 2 h	Light assembly work
	Sitting in car or truck	> 2 h	Inspection work, monitoring
	Standing, light manual work	> 2 h	Data processing, computer work
Moderate— > 7.0–10.7 (2.5–3.8) WB > 5–7.5 (> 1.8–2.6) UB	Operating a press	> 2 h	Electrical assembly work
	Driving a truck	> 2 h	Bookkeeping/payroll
	Machine tending	> 2 h	Camera assembly
	Machining parts	> 2 h	Sewing on sewing machine
	Plastic molding work	> 2 h	Punch press operation
	Expediting/walking	> 2 h	Electronics packaging
	Lifting items at waist level up to 10 kg (22 lb.), 6/min	> 2 h	Building brick wall (waist level)
		> 2 h	Using light hand tools
Heavy— > 10.7–17.1 (> 3.8–6) WB > 7.5–12 (> 2.6–4.2) UB	Shoveling ash	1–2 h	Hand press operation
	Carpentry	> 2 h	Assembly work, heavier items
	Cleaning	1–2 h	Clerical work, filing
	Mail delivery (walking)	> 2 h	Food preparation
	Tool room work	> 2 h	Boot/shoe repair/fabrication
	Truck/vehicle repair	> 2 h	House painting
	Welding	< 1 h	Grinding, filing metal
	Polishing metal parts	> 2 h	Lathe operation
	Pushing/pulling carts	< 15 min	Unloading rolls from slitter
	Stoking furnace	< 15 min	Tapping and drilling
	Mixing cement	< 15 min	Turning handwheel with force
	Loading trailers with boxes	> 2 h	Printing press operation
	Digging trenches	< 1 h	Standing Punch press operation
	Loading chemicals into vat	< 15 min	Lifting heavy cases > 6/min
	Power truck driving	> 2 h	Laundry operations
	Stacking lumber	< 1 h	Wrap/pack large products
	Making beds	< 15 min	Use power tools overhead
Very Heavy— > 17.1–28.6 (> 6.0–10) WB > 12–20 (> 4.2–7.0) UB	Jackhammer use	1–2 h	Using power tools overhead
	Bottle/can handling (heavy)	> 2 h	Medium press operation
	Chopping wood	< 1 h	Lifting above shoulders 6/min
	Cutting sheet steel	> 2 h	Breaking out die-cut cardboard
	Filling and stacking bags	> 2 h	Bookbinding, standing
	Push tubs/carts/wheelbarrows	< 15 min	Unloading commercial laundry
	Stone masonry	> 2 h	Operating square cutter
	Tree felling	1–2 h	Heavy overhead cleaning
	Furnace cleaning (heavy)	1–2 h	Spray painting in woodworking
	Sledge hammer use	< 15 min	
	Climbing ladder/stairs	< 15 min	

TABLE 1.21
(Continued)

Effort Level—Aerobic Demand, ml O_2 per kg BW per min (kcal/min)	Tasks—Whole Body	Usual Time	Tasks—Upper Body
Extremely Heavy— > 28.6 (> 10.0) WB > 20 (> 7.0) UB	Firefighting	1–2 h	Lifting light cases 15/min—waist
	Trimming trees	1–2 h	Lifting moderate loads 10/min
	Slag removal, iron/steel	1–2 h	Using power saw overhead
	Shoveling in foundry	< 15 min	Turning crank with 2 hands
	Heavy lifting 10/min	< 15 min	Turning handwheel with high R

In some countries and industries (e.g., the semiconductor industry) these principles have been codified into standards, guidelines, or regulations. These are briefly discussed in the following section.

UNITED STATES AND INTERNATIONAL STANDARDS RELATED TO ERGONOMICS

There are many standards that relate to ergonomics because there are multiple domains and specialty areas. For example, in the United States there are specific standardization documents related to the military, such as "Human Engineering Design Criteria for Military Systems, Equipment and Facilities," MIL-STD-1472F, and several documents pertaining to transportation, such as "Human Interface Design Methodology for Integrated Display Symbology," ANSI/SAE ARP4155. Although a standard may be developed by an interested group from a specific domain, it can often become widely adopted by users in other areas for whom it may not have been originally intended. For information about possible standards in specific domains or on narrow topics, consider making inquiries through related societies or associations. Access to military standards may be difficult without a contract with the government.

Of the numerous existing ergonomics standards, there are only a few that are legislated as mandatory within a country or group of countries. Other standards within countries are nonmandatory and are developed by standard-setting bodies based on professional consensus or experts in the topic area. On occasion, a nonmandatory standard may be legislatively cited and enforced.

This section will introduce some of the more widely known ergonomics standards and guidelines in the area of safety and health and provide reference to the main standard developing bodies as resources. Some international standards are adopted by several countries, as are European standards that are enfolded into most European Union (EU) members' laws. There is a rising need for standardization as business becomes more global, and consequently standards are always being developed or updated, so the following should be checked periodically to ensure that they are current.

Internet Locations for European and International Standards

The Web page www.osha-slc.gov/us-eu is a joint product of the U.S. Occupational Safety and Health Administration (OSHA) and the EU. Both European and U.S. legislation can be accessed through this site. In addition, there are links to sites maintained by each member country and by Switzerland, Iceland, Norway, Canada, and Australia. Nonlegislated standards are developed by different groups and can be obtained through the European Committee for Standardization (below), which provides links to European groups, or through links on the OSHA-EU page.

The European Committee for Standardization (CEN) has nineteen members (fifteen from the European Union, three more from the European Free Trade Association, and the Czech Republic). Its Web page is located at www.cenorm.be. The members of CEN develop and vote for the ratification of European standards. The agreement with member countries is to implement such standards as national standards, withdrawing all conflicting national standards on the same subject. All European standards developed by CEN are issued in three languages: English, French, and German. Through the CEN Web page there are links to each member country's standard-setting group. Note that these groups are not the legislative groups of the countries. Most standard-setting groups require subscriptions or charge for a standard.

Perinorm (www.perinorm.com) provides a subscriber-based service that offers a database of international, European, and national standards. Standards of eighteen countries are available; in addition to European countries, these include the United States, Japan, Australia, Turkey, and South Africa.

International Standards

International Organization for Standardization (ISO)

There are 97 categories of voluntary ISO international standards; see the ISO's Web site at www.iso.org. Apart from specific ergonomics-related ones, some of the categories may be pertinent to particular industries, such as electronics, or to particular types of equipment, such as material-handling equipment. The industry-based or equipment-based standards pertain to manufacturing issues, for example, equipment dimensions or stability tests.

In 1996, there was an initiative by the International Labor Organization (ILO) to propose ISO 18000, on occupational health and safety management systems. At the time, during a large international workshop on the topic, the majority rejected the idea of such a standard. There are some current efforts to revive ISO 18000.

The Ergonomics Technical Committee (TC 159) of ISO continues to develop new standards. Information about Technical Committee activity can be found through the ISO Web page. Most of the ergonomics standards that are already issued are under Category 13, "Environment, Health Protection, Safety." Section 13.180 is "Ergonomics." However, other sections of possible broad interest are:

13.100: Occupational Safety. Industrial Hygiene (cross-references to Workplace Lighting, 91.160.10).

13.110: Safety of Machinery.

13.140: Noise with Respect to Human Beings (cross-references to Acoustic Measures, 17.140, and Hearing Protectors, 13.340.20).

13.160: Vibration and Shock with Respect to Human Beings. This section has forty standards, many of which provide guidance on measuring vibration for specific handheld tools. The frequently cited standard of measuring hand-transmitted vibration has been updated to a 2001 version:

ISO 5349-1:2001 Mechanical Vibration: Measurement and Evaluation of Human Exposure to Hand-Transmitted Vibration—Part 1: General Requirements.

ISO 5349-2:2001 Mechanical Vibration: Measurement and Evaluation of Human Exposure to Hand-Transmitted Vibration—Part 2: Practical Guidance for Measurement at the Workplace.

13.340: Protective Clothing and Equipment.

13.180: Ergonomics. This section has a number of standards dated from 1977 to 2001. Several of these standards are part of a series or of similar topics and are grouped as shown in Table 1.22.

Other International Standards Groups

International Telecommunication Union (ITU): www.itu.org

International Civil Aviation Organization (ICAO): www.icao.org

World Wide Web Consortium (W3C): www.w3.org

European Standards

European Union (EU) Mandatory Directives

The European Union, created by the Maastricht treaty of 1993, has fifteen member nations: Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden, and

TABLE 1.22
ISO Documents That Relate to Ergonomics

Topic	ISO Document Number
General ergonomics (e.g., anthropometry, human-centered design)	ISO 1503:1977; ISO 6385:1981; ISO 7250:1996; ISO 13407:1999; ISO/TR 18529:2000
Signals and controls and displays	ISO 7731:1986; ISO 9355-1:1999; ISO 9355-2:1999; ISO 11428:1996; ISO 11429:1996
Speech communication	ISO 9921-2:1996
Ergonomic principles related to mental workload (2 parts)	ISO 10075:1991; ISO 10075-2:1996 (Part 3 is a working draft of TC 159)
Thermal environments	ISO 7243:1989; ISO 7726:1998; ISO 7730:1994; ISO 7933:1989; ISO 8996:1990; ISO 9886:1992; ISO 9920:1995; ISO 10551:1995; ISO/TR 11079:1993; ISO 11399:1995; ISO 12894:2001; ISO/TS 13732–2:2001
Ergonomic design for the safety of machinery (2 parts)	ISO 15534–1:2000; ISO 15534–2:2000; ISO 15534–3:2000
Ergonomic design of control centers (3 parts available, total of 8 parts planned; parts 4–8 will cover workstation layout, displays and controls, environment, evaluation of control rooms, and specific applications)	General principles and principles of arrangement and layout. ISO 11064–1:2000; ISO 11064–2:2000; ISO 11064–3:2000
Evaluation of static working postures	ISO 11226:2000
Principles of visual ergonomics—indoor lighting	ISO 8995:1989
Ergonomic requirements for office work with visual display terminals (17 parts—8 software and 9 hardware)	ISO 9241 Note—there are recent (2000) amendments to some parts. Parts date from 1992–2000. Parts 1–9 general overview requirements of task, posture and layout. Hardware requirements of visual display, colors, keyboard and input devices. Parts 10–17 software requirements—usability, dialogue principles, dialogues of menu, command, form filling and direct manipulation.
Ergonomic requirements for work with visual displays based on flat panels (part 1)	ISO 13406-1:1999 ISO/DIS 13406-2 (Draft)
Ergonomics manual handling Part 1: Lifting and carrying (1.2) Part 2: Pushing pulling and holding Part 3: Handling of low loads at high frequency	ISO/DIS 11228-1.2 (Draft) Parts 2 and 3 yet to be developed
Ergonomic procedures for the improvement of local muscular workloads	ISO/AWI 20646 (Approved work item by TC)

the United Kingdom. The EU develops directives that are legislation, mostly in the form of objectives, that member countries achieve through national legislation within a specified schedule. See www.europa.eu.int. Directives usually have enough flexibility to allow member states to interpret and achieve the objectives as they deem best. Regulations are another form of EU legislation that is immediately applicable in each member country without further legislation. At present there are no regulations related to ergonomics. The European Committee for Standardization oversees the development of EU directives and regulations (see above). There are frequent amendments to directives and consolidation of the legislation that may change the number of the directive or standard.

DIRECTIVE 89/391/EEC: HEALTH AND SAFETY AT WORK This is a general directive on health and safety at work that has nine sections. The documents outline employer and worker responsibilities, supplemented by individual directives for specific groups of workers, workplaces, or substances. Overall, the documents are general and, in summary, state that employers are to ensure a healthy and safe workplace through prevention, to evaluate risks, to track and report accidents, to consult workers in all safety and health issues, and to ensure adequate safety and health training. The workers are obliged to make correct use of machinery, give warnings of problems, and cooperate with changes imposed for protection. A few of the subdirectives of the nine sections are highlighted below.

Section 1.2.02: Use of Work Equipment (Directive 89/655/EEC). This delineates an employer's responsibility, including minimizing hazards; providing job information, instructions, and training; and regularly inspecting equipment. In addition, employers are "to take fully into account the work station and position of workers while using work equipment, as well as the ergonomic principles, when applying the minimum safety requirements."

Section 1.2.04: Work with Display Screen Equipment (Directive 90/270/EEC). The employer is obliged to analyze the workstations; meet minimum requirements for equipment, environment, and operator/computer interface; and ensure that workers have breaks from the screen. Workers are entitled to eye checks, and employers are to provide corrective lenses, if needed, at no cost.

Section 1.2.05: Manual Handling (Directive 90/269/EEC). Employers' obligations are to avoid the need for manual handling of loads; where this cannot be avoided, they are to take measures to reduce the risk. Workers are to receive adequate information about the weight of the load and its center of gravity and to receive training on handling the load.

Section 1.6: Physical Agents. This section refers to a proposal for a directive to protect against noise, mechanical vibration, optical radiation, and magnetic fields and waves. It may also include temperature and atmospheric pressure at a later stage.

NOISE DIRECTIVE 86/188/EEC Risks from exposure to noise must be reduced to as low a level as practicable. Noise levels should be assessed.

- Above an average level of 85 db (A), workers must be informed of the potential risk and personal protection must provided. Regular hearing checks must be conducted.
- If the level exceeds 90 db (A), the reasons must be identified and measures determined to reduce the exposure. Protection must be provided. Areas of excess must be delimited and identified by signs.

MACHINERY DIRECTIVE 98/37/EC As with most of the European directives, this one is intended to prevent safety and health matters being a barrier to trade. The directive requires designers to take ergonomics principles into account when considering how a machine will be used. The ergonomics emphasis is on controls and displays. European standard EN-894 helps implement the directive and is reflected in ISO 9355-1:1999 and ISO 9355-2:1999.

SAFETY OF MACHINERY: HUMAN PHYSICAL PERFORMANCE DRAFT EN-1005 There are four parts to this draft standard: Part 1, Terms and Definitions; Part 2, Manual Handling of Machinery and Component Parts of Machinery; Part 3, Recommended Force Limits for Machinery Operation; and Part 4, Evaluation of Working Postures in Relation to Machinery. The standard is being developed by the CEN Ergonomics Technical Committee to support the Machinery Directive.

European Nonmandatory Standards

Refer to CEN or to each country's standard-setting groups. See above for how to search for international and European standards.

Additional standard-setting organizations:

European Committee for Electrotechnical Standardization (CENELEC): www.cenelec.org

European Telecommunications Standards Organization (ETSI): www.etsi.org

United Kingdom (UK)

Mandatory Regulations

The UK laws, available at www.hse.gov.uk, originate with the proposals from the European Commission. There is a statutory Health and Safety at Work Act under which there are regulations that are law. These regulations are general but are interpreted in Approved Codes of Practice documents developed by the Health and Safety Executive (HSE). Approved Codes of Practice have special legal status and can be used in prosecutions. Guidance documents interpret the law and provide further detail for compliance that can be especially useful although they are not legally binding. There are several useful regulations known as the "Six Pack" that were issued in 1992. These regulations apply across all industries.

- Manual Handling Operations
- Display Screen Equipment
- Workplace (Health, Safety and Welfare)
- Provision and Use of Work Equipment
- Personal Protective Equipment at Work
- Management of Health and Safety at Work

Very practical guidance documents and Approved Codes of Practice correspond to the regulations and could be useful outside the UK. Additional HSE materials include employers' guides and manual handling solutions. There is a nominal charge for the HSE documents.

Nonmandatory Standards

As in most countries, there are many standards that are nonmandatory. The British Standards Institute is the primary standard-setting body in the UK (www.bsi-global.com). There is a charge for the standards.

United States of America (USA)

Occupational Safety and Health Act: Mandatory

The primary mandatory standard is the Occupational Safety and Health Act of 1970 (see www.osha.gov). The section pertinent to ergonomics is the general-duty clause, Section 5(a)(1), which states: "Each employer shall furnish to each of his employees, employment and a place of employment which is free from recognized hazards that are causing or are likely to cause death or serious harm to his employees."

Citations for ergonomics have been under the general-duty clause.

Americans with Disabilities Act (ADA): Public Law 101-336

The mandatory act, effective as of 1990, has some bearing on ergonomics. One part of the act addresses accessibility for the disabled and a second part pertains to employment (see www.access.gpo.gov). Two main points of the act under the employment section are:

- The ADA prohibits disability-based discrimination in hiring practices and working conditions.
- Employers are obligated to make reasonable accommodations to qualified disabled applicants and workers, unless doing so would impose undue hardship on the employer. The accommodations should allow the employee to perform the essential functions of the job.

Often modifications to a job to accommodate someone disabled can benefit all workers. Defining essential functions of a job may involve those responsible for ergonomics.

California Ergonomics Standard

This is a mandatory state law that became effective in 1997 and addresses formally diagnosed work-related repetitive motion injuries that have occurred to more than one employee. The employer has to implement a program to minimize the repetitive motion injuries through work site evaluation, control of the exposures and training. See www.dir.ca.gov/title8/5110/html.

Washington State Ergonomics Standard

A mandatory ergonomics rule was adopted by Washington State in 2000 with compliance expected within two to four years, depending on company size. The rule states that employers have to look at their jobs to determine if there are specific risk factors that make a job a "caution zone job" as defined by the standard. All caution zone jobs must be analyzed; employees of those jobs are to participate and be educated, and the identified hazards reduced. For more information, consult www.lni.wa.gov/wisha.

Repealed Ergonomics Program Standard

The federal government issued an ergonomics program rule in November 2000 that was repealed in March 2001 by the new administration (see www.osha.gov). The standard was issued in the Federal Register November 14, 2000, Vol. 65, No. 220.

The main elements of the standard were:

- Provide training in basic ergonomics awareness
- Provide medical management of work-related musculoskeletal disorders
- Implement a quick fix or go to a full program
- Implement a full ergonomic program when indicated:
  - Management leadership
  - Employee participation
  - Job hazard analysis
  - Hazard reduction and control
  - Training
  - Program evaluation

The Department of Labor has been charged to come up with an alternative plan to address ergonomics-related issues in the workplace. The with-drawn standard was similar to long-standing voluntary guidelines issued by OSHA, such as Ergonomics Program Management Guidelines for Meatpacking Plants (OSHA 3123) of 1990, which have been used successfully for many years by industries other than meatpacking.

ANSI Standards

There are many American National Standards Institute (ANSI) standards, and all of them are voluntary. However, legislative bodies have used consensus standards to define mandatory regulations. The following are just a few of the standards that exist or are being developed. Information about ANSI documents may be obtained through ANSI (www.ansi.org), but often they are purchased directly from the group responsible for developing the standard in coordination with ANSI.

ANSI/HFS 100-1988, AMERICAN NATIONAL STANDARD FOR HUMAN FACTORS ENGINEERING OF VISUAL DISPLAY TERMINALS This standard (available at www.hfes.org) addresses ergonomics principles related to visual display terminals. A revision in draft form was issued in March of 2002.

ASC Z-365, MANAGEMENT OF WORK-RELATED MUSCULOSKELETAL DISORDERS The Accredited Standards Committee Z-365 was formed in 1991. The most recent working draft of this standard was issued in October 2000 from the secretariat, National Safety Council (NSC) (www.nsc.org). The draft is currently under review by the committee.

The draft contains elements similar to those of the repealed federal standard and the OSHA meatpacking guideline. The document is programmatic rather than specific in that it does not provide details on how to conduct analyses or on interventions.

Elements include:

- Management responsibility
- Employee involvement
- Training
- Surveillance
- Evaluation and management of work-related MSD cases
- Job analysis and design
- Follow-up

ASC Z-10, OCCUPATIONAL HEALTH SAFETY SYSTEMS Established in 2001, this committee is still in the process of forming under the ANSI secretariat of the American Industrial Hygiene Association (AIHA), whose Web site is www.aiha.org. The objective is to develop a standard of management principles and systems to allow organizations to design and implement approaches to improve occupational safety and health.

OSHA was addressing safety and health programs, but the most recent rule agenda (May 2001) provided no date for further action on the issue.

HFES 200, SOFTWARE USER INTERFACE STANDARD This is a five-part standard being developed by the Human Factors and Ergonomics Society (HFES) under the auspices of ANSI; see www.institute.hfes.org. It will closely mirror the ISO 9241 standard on visual display terminals, except for original parts that will be on color, accessibility, and voice input/output.

ACGIH TLVs

The American Conference of Governmental Industrial Hygienists (ACGIH) has developed threshold limit values (TLVs) for chemical substances and physical agents. There are TLVs for hand-arm vibration and whole-body vibration as well as for thermal stress. Two new TLVs are for hand activity level, which is intended for monotasks (jobs performed for four hours or more), and for lifting, which provides weight limits based on frequency and duration of lift. See www.acgih.org.

NIST

The National Institute of Standards and Technology helps to develop measurement standards and technology. Their standards address measurement accuracy, documentation methods, conformity assessment and accreditation, and information technology standards. A current initiative is developing industry usability reporting guidelines that directly affect software ergonomics. The NIST Web site (www.nist.gov) can also be a source to link to military standards.

Miscellaneous Standard-Setting Groups

There are many other sources of standards that may be important to certain domains or specialties. A few others are:

American Society of Mechanical Engineers (ASME): www.asme.org
American Society for Testing and Materials (ASTM): www.astm.org
Institute of Electrical and Electronics Engineers (IEEE): www.ieee.org
Society of Automotive Engineers (SAE): www.sae.org

Canada

British Columbia (BC)

In the fall of 1994, a draft ergonomics regulation was issued by the Secretariat for Regulation Review, Board of Governors, Workers' Compensation Board of British Columbia. The regulation failed to be adopted by the BC legislature in 1995. However, since 1994, there is a two-page section on ergonomics in Part 4, General Conditions of the Occupational Health and Safety Regulations of the Workers' Compensation Board of BC. Sections 4.46-4.53, Ergonomics (MSI) Requirements, require employers to identify factors that might expose workers to the risk of a musculoskeletal injury (MSI), to assess the identified risks, and to eliminate or minimize the risks. Employees are to receive education and training and be consulted by the employers. Evaluation of effectiveness is required. See www.worksafebc.com.

Ontario (ON)

Draft legislation of Physical Ergonomics Allowable Limits were prepared for the Ministry of Labour, Government of Ontario (www.gov.on.ca). The report was rescinded and shelved in 1995–96.

The Occupational Health and Safety Act of 1979 was changed in 1990 with some significant additions. All employers have to have a health and safety policy and program, and the officers of corporations have direct responsibility. In workplaces of twenty or more workers there has to be a joint labor-management Health and Safety Committee that is responsible for health and safety in the workplace. The committee is to meet regularly to discuss health and safety concerns, review progress, and make recommendations. Workplaces with fewer than 20 workers have to have a health and safety representative. By 1995, employers had to certify that the members of their joint Health and Safety Committees were properly trained.

Canadian Standards Association (CSA)

The Canadian Standards Association (www.csa.ca).has produced voluntary standards pertaining to many areas. One standard that is widely used is Office Ergonomics, CAN/CSA-Z412-M89.

Australia

There are six states and two mainland territories that have each their own laws, as well as the commonwealth government, which has federal jurisdiction. The approach overall is similar to the European model in that it relies on a general duty of care by employers and employees. The focus is risk management based on risk assessment and control. Most of the states and territories have their own general health and safety act but vary on how developed their regulations and codes of practice are.

National Occupational Health and Safety Commission (NOHSC)

NOHSC (www.nohsc.gov.au) is the federal body of the Commonwealth of Australia. It is the primary source of national standards, regulations, and codes of practice, although the role of developing new standards has diminished. The commonwealth standards are very general, and individual states and territories either adopt them or go above and beyond these standards. The NOHSC Web page links to the sites of all other state and territories.

Specific to ergonomics is one standard and two codes of practice that are widely used. They stem from a National Occupational Health and Safety Commission Act of 1985.

- Manual Handling: National Standard NOHSC:1001 (1990). This standard delineates in very general terms the requirement to conduct a risk assessment and control any issues. The approach acknowledges a multifactorial risk and does not recommend weight control alone. The code of practice that is referenced provides greater guidance.
- Manual Handling, National Code of Practice NOHSC:2005 (1990). The code of practice provides considerable detail of risk assessment, criteria of risk, and examples of potential control methods. There are many illustrations and checklists.
- National Code of Practice for the Prevention of Occupational Overuse Syndrome NOHSC:2013 (1994). The approach is one of risk identification, assessment, and control. Specific risk factors are discussed but not quantified and include work organization and design issues. A checklist approach is used, and controls are presented in the form of principles. The document includes screen-based workstations (office environments).

Comcare

This is an informational branch of the commonwealth government that publishes some useful booklets and reports on pilot programs to assist with compliance with the law (www.comcare.gov.au). One example is a booklet entitled "A Guide to Health and Safety in the Office."

New South Wales (NSW) WorkCover Authority

New South Wales has recently (2000 and 2001) revised its Occupational Health and Safety Act and regulations, which are quite comprehensive in their legal coverage. See www.workcover.nsw.gov.au.

- Occupational Health and Safety Act 2000 (No 40)The act is general and delineates the duties of employers and employees. It refers to related regulations and more specific codes of practice. Inspections and legalities related to noncompliance are also provided for in the act.
- Occupational Health and Safety (OHS) Regulation 2001. Consistent with the national approach, the regulation delineates the steps required for risk management, namely, identification, assessment, and control of hazards. Employers are to identify potential manual handling and occupational overuse hazards and assess lighting and workstation design, among many other listed safety and health issues. Specifics are given on workplace consultation, which may apply to OHS committees, employee representatives, or consultants who contribute to risk management. Training of those involved is also specified.

Victoria WorkCover Authority

More information is available at www.workcover.vic.gov.au.

- Occupational Health and Safety Act 1985 (includes amendments up to 2001)
- Occupational Health and Safety (Manual Handling) Regulations 1999 (more expansive than the commonwealth manual handling standard, although it takes a similar approach to risk management)

South Australian WorkCover Authority

For additional information, see www.workcover.com.

- Occupational Health, Safety and Welfare Act 1986
- Occupational Health, Safety and Welfare Regulations 1995 (updated 1999; nonspecific, but employers are obliged to follow approved codes of practice that are listed in the regulation, one of which is for manual handling)

WorkSafe Western Australia

The Web site of this program is www.safetyline.wa.gov.au.

- Occupational Safety and Health Act 1984
- Occupational Safety and Health Regulations 1996 (based on a risk management approach, and less specific than regulations of other states such as NSW)
- Code of Practice Manual Handling 2000 (a simpler and updated version of the national code of practice)

Queensland Division of Workplace Health and Safety

See www.whs.qld.gov.au.

- Workplace Health and Safety Act 1995 (includes amendments to 2000)
- Workplace Health and Safety Regulations 1997
- Advisory Standards
  - Manual Handling (Building Industry) 1999
  - Manual Tasks 2000
  - Manual Tasks Involving People 2000

The Manual Tasks advisory standard 2000 provides specific guidance in risk identification, assessment, and control. Checklists and discomfort surveys are provided and a task analysis is described with example task analysis forms. The risk control section includes an implementation plan and evaluation step.

Workplace Standards Tasmania

See www.wsa.tas.gov.au.

- Workplace Health and Safety Act 1995
- Workplace Health and Safety Regulations 1998 (very general)

Australian Capital Territory (ACT)

ACT bases the material handling regulation and code of practice on the national (commonwealth) ones. Similar checklists and illustrations are used. ACT also supports use of the National Code of Practice for the Prevention of Occupational Overuse Syndrome. Additional information is available at www.workcover.act.gov.au.

- ACT Occupational Health and Safety Act 1989
- ACT Occupational Health and Safety Regulations 1991
- ACT Occupational Health and Safety (Manual Handling) Regulations 1997
- ACT Manual Handling Code of Practice 1999

Northern Territory Work Health Authority

There are no laws in the ergonomics area for the Northern Territory beyond the scope of the national ones. Their Web site is www.nt.gov.au.

Standards Australia

Standards Australia (www.standards.com.au) is a commercial group that are recognized as a main source for developing nonmandatory technical and business standards and the dissemination of Australian and international standards. Their principle is to adopt or closely align their standards with international standards whenever possible. Two standards related to ergonomics are:

- Occupational Health and Safety Management Systems—Specification with Guidance for Use (AS/NZS 4801:2001)
- Occupational Health and Safety Management Systems—General Guidelines on Principles, Systems, and Supporting Techniques (AS/NZS 4804:2001)

Japan

Japan has a general Labour Standards Law (revised in 1998) that states that measures should be taken to ensure reasonable working conditions and to improve working conditions. Additional laws supplement the general Labour Standards Law, including the Industrial Safety and Health Law. There is a national system that ensures the law is followed through guidance as well as inspection.

Ministry of Health, Labour, and Welfare

This national ministry (www.mhlw.go.jp) oversees the Industrial Safety and Health Law, passed in 1972. To support the law, there is an enforcement order and many ordinances that describe the minimum required to comply with the law. Of particular note are:

- Ordinance on Industrial Safety and Health
- Ordinance on Safety and Health of Work Under High Pressure
- Ordinance on Health Standards in the Office
- Guideline for Occupational Safety and Health Management Systems

Although there is more information in an ordinance, the guidance remains general. The expectation is to prevent disease and to actively maintain and enhance health. This is to be accomplished through having an occupational safety and health management system to identify and control risks and hazards. Japan also has a national initiative to reduce working hours as part of improving working conditions.

Additional English synopses of the national laws and supporting ordinances and guidelines are available through the Japan International Center for

Occupational Safety and Health (JICOSH) (www.jicosh.gr.jp). See below for more information.

National Institute of Industrial Safety (NIIS)

The NIIS (www.anken.go.jp) is a research branch of the Ministry of Health, Labour, and Welfare that focuses on safety issues. Ergonomics is a main research topic of this group.

National Institute of Industrial Health (NIIH)

This is a multidisciplinary research limb of the Ministry of Health, Labour, and Welfare that focuses on occupational diseases and to provide the government scientific and technical information related to industrial health (www.niih.go.jp). There are several main activities that are industrial-hygiene-oriented, as well as activities focusing on:

- Work management and human factor engineering in response to changes in working conditions
- Working capacity and fitness of women and the elderly
- Assessment of physical hazards

Japanese Standards Association (JSA)

The JSA (www.jsa.or.jp) is the main resource for purchasing voluntary standards. The association supports the Japanese Industrial Standards Committee (JISC), a standards development group that is the primary producer of national voluntary Japanese Industrial Standards (JISs). These JISs are numerous but most are very technical. ISO standards are also available through the JSA and are adopted by Japan according to the ISO policy for a contributing country.

Japan International Center for Occupational Safety and Health (JICOSH)

JICOSH is a useful resource, as its mission is outreach to industry of other nations. Therefore, their Web page (www. jicosh.gr.jp) is in English and they have some overviews of the industrial laws of Japan. There are also some useful links to other Japanese web sites.

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URL REFERENCES FOR DESIGNING FOR PEOPLE WITH DISABILITIES

ADA Accessibility Guidelines (ADAAG) Sections 1–4
http://www.access-board.gov/adaag/html/adaag.htm#4.2

The Americans with Disabilities Act of 1990
http://usdoj.gov/crt/ada/statute.html or www.eeoc.gov/laws/ada.html

ANSI A117.1–1998 Accessible and Usable Buildings and Facilities
http://webstore.ansi.org/ansidocstore/find.asp

Anthropometry for People with Disabilities (see references above)
http://www.access-board.gov/researchandtraining/anthropometry/biblio.html/anthro.html

Employers' Forum on Disability (UK)
http://employers-forum.co.uk/www/guests/info/factsheets/sheet1.htm

JAN's ADA Hot Links (Job Accommodation Network)
http://www.jan.wvu.edu/kinder/

URL REFERENCES IN STANDARDS SECTION

American Conference of Governmental Industrial Hygienists (ACGIH), USA
www.acgih.org

American Industrial Hygiene Association, USA
www.aiha.org

American National Standards Institute, USA
www.ansi.org

American Society of Mechanical Engineers (ASME), USA
www.asme.org

American Society for Testing and Materials (ASTM), USA
www.astm.org

British Standards Institute, UK
www.bsi-global.com

California Ergonomics Standard, USA
www.dir.ca.gov/title8/5110/html

Canadian Standards Association, Canada
www.csa.ca

Comcare Australia
www.comcare.gov.au

Department of Labor and Industries, Washington State, USA
www.lni.wa.gov/wisha

European Committee for Electrotechnical Standardization (CENELEC)
www.cenelec.org

European Committee for Standardization (CEN)
www.cenorm.be

European Telecommunications Standards Organization (ETSI)
www.etsi.org

European Union (EU)
www.europa.eu.int

General Printing Office (GPO)—USA
www.access.gpo.gov

Health and Safety Executive (HSE)—UK
www.hse.gov.uk

Human Factors and Ergonomics Society (HFES), USA
www.hfes.org

Institute for Human Factors and Ergonomics, USA
www.institute.hfes.org

International Civil Aviation Organization (ICAO)
www.icao.org

International Organization for Standardization (ISO)
www.iso.org

International Telecommunication Union (ITU)
www.itu.org

Institute of Electrical and Electronics Engineers (IEEE), USA
www.ieee.org

Japan International Center for Occupational Safety and Health (JICOSH)
www. jicosh.gr.jp

Japanese Standards Association (JSA)
www.jsa.or.jp

Ministry of Health, Labour and Welfare, Japan
www.mhlw.go.jp

National Institute of Industrial Health (NIIH), Japan
www.niih.go.jp

National Institute of Industrial Safety (NIIS), Japan
www. anken.go.jp

National Institute of Standards and Technology (NIST), USA
www.nist.gov

National Occupational Health and Safety Commission (NOHSC), Australia
www.nohsc.gov.au

National Safety Council, USA
www.nsc.org

New South Wales (NSW) WorkCover Authority, Australia
www.workcover.nsw.gov.au

Northern Territory Work Health Authority, Australia
www.nt.gov.au

Occupational Safety and Health Administration (OSHA)—USA
www.osha.gov

Occupational Safety and Health Administration (USA) and European Union (EU)
www.osha-slc.gov/us-eu

Ontario Government, Canada
www.gov.on.ca

Perinorm, private database of international, European, and national standards
www.perinorm.com

Queensland Division of Workplace Health and Safety, Australia
www.whs.qld.gov.au

Society of Automotive Engineers (SAE), USA
www.sae.org

South Australian WorkCover Authority
www.workcover.com

Standards Australia
www.standards.com.au

Victoria WorkCover Authority, Australia
www.workcover.vic.gov.au

Workers' Compensation Board of British Columbia, Canada
www.worksafebc.com

Workplace Standards Tasmania, Australia
www.wsa.tas.gov.au

WorkSafe Western Australia
www.safetyline.wa.gov.au

World Wide Web Consortium (W3C)
www.w3.org

2 Evaluation of Job Demands

Physically demanding work can lead to adverse outcomes that are broadly construed as overexertion injuries, fatigue, and overuse (cumulative trauma) disorders. In terms of time frame, the job demand may be examined as something occurring in a moment, over a short period (minutes to hours), or over longer periods (days to years). The evaluation of jobs, therefore, requires a framework that considers all these possibilities. Understanding the physical demands requires an understanding of human capacity, which is marked by a mix of anatomical (biomechanical) and physiological (muscle and cardiopulmonary) factors. Further, evaluation methods can range from simple methods for forming a preliminary judgment to more complex methods requiring much more effort and expertise. This section describes the umbrella framework, the methods to describe the physical demands of work and human capacity, and the assessment methods that have evolved from the understanding of demands and capacity.

Evaluation of work based on very short time intervals generally falls into the realm of muscle strength and biomechanics. That is, can this be done in a moment? Considerations of muscle strength provide insight to the population who may be able to exert a required force under the external constraints. Biomechanical analyses consider the internal forces that affect joints, tendons, and muscles. Biomechanical analyses may also extend the database for strength. For instance, an understanding of the moments around the elbow or shoulder can help interpret the effects of an unusual load and posture combination.

Over the period of minutes to hours, fatigue may play a larger role in job evaluation than biomechanical and strength limits. That is, can a specific effort be sustained for the required period, and is enough recovery time allowed to be able to repeat the effort? If the answer to either facet of the question is no, then fatigue can occur. The fatigue may be to specific muscle groups (local muscle fatigue) or may represent a cardiopulmonary insufficiency to support the metabolic demands (whole-body fatigue). In both cases, the considerations include three important factors: individual (or population) capacity for the effort, effort time, and recovery time.

The long-duration aspect of job evaluation considers the effects over days, weeks, and years. Most often, these effects are work-related musculoskeletal disorders (WRMSDs), and the discussion in this section will focus exclusively on them. The evaluation schemes consider primarily force, posture, and frequency, and may include duration and environmental factors such as vibration and temperature.

Approaches to job analysis vary in the degree of effort required of the analyst. Qualitative job analyses are methods that gather basic observational (qualitative) data about the job. Two classic formats for qualitative analysis are the job safety analysis and checklist. Semiquantitative job analysis relies on a mix of judgment data and/or easily obtained quantitative data. These data are processed through a simple set of decision rules to yield a classification or ranking of job demands or risk. Quantitative job analysis primarily requires objective data, with perhaps some qualitative data, and the data are used in a more demanding quantitative computation to yield a result. Generally, qualitative approaches are used to screen jobs. Those that may be problematic will

TABLE 2.1
Common Job Assessment Methods Grouped by Method Type

Qualitative Assessment Methods	Table/Figure/Section
Job safety analysis / job hazard analysis	Figure 2.15a, 2.15d
Checklist for assembly	Figure 2.14a
Checklist for manual materials handling	Figure 2.14b
Checklist for computer workstations	Figure 2.14c
Checklist for maintenance	Figure 2.14d
Checklist for laboratories	Figure 2.14e
Semiquantitative Assessment Methods	
MSD Analysis Guide (MAG)	Figures 2.15a-d
Rodgers Muscle Fatigue Assessment	Figure 2.16
Liberty Mutual (Snook) tables	Tables 2.6–2.9
Utah Back Compressive Force	Figure 2.17
Shoulder moment	Figure 2.18
ACGIH hand activity level (HAL) TLV	Figure 2.19
WISHA hand-arm vibration analysis	Figure 2.20
Quantitative Assessment Methods	
Biomechanical analyses	See the section on strength and biomechanics
Rohmert muscle endurance and recovery	See the section on static work
Dynamic work analysis	See the section on dynamic work
Heart rate assessment	See the section on heart rate analysis
NIOSH Revised Lifting Equation	Figure 2.22
Moore-Garg Strain Index	Figure 2.23
Vibration analysis—hand-arm (HAV)	Figure 8.12
Vibration analysis—whole body (WBV)	Figure 8.11

be assessed with semiquantitative methods. When detailed information about the risk factors on a job is necessary (e.g., for interventions), the quantitative methods provide the greatest insight into the level of risk and the interrelationships among the risk factors. As a general principle, it is inappropriate to design jobs (as opposed to evaluating jobs) based on qualitative and semiquantitative analyses of job demands. Job design is discussed in other sections of this book.

Table 2.1 is a list of selected job analysis methods grouped by the method type.

There are several reasons why a job analysis might be performed. These include:

- One or more overexertion or overuse injuries have been attributed to the job.
- Multiple complaints have been reported.
- Production problems such as poor quality and low productivity have been reported.
- Accidents involving people, equipment, or product have been associated with the job.
- Proactive job analysis has selected it.

The first two reasons would also suggest body regions that might be of particular interest, and this can focus the analysis. In fact, injuries and complaints might be sufficient reason to skip the qualitative job analysis step and proceed to an appropriate semiquantitative or quantitative method.

This chapter is divided into two parts. The first part describes some of the underlying theories and principles used in the assessment of job demands. The second provides the reader with analysis methods that may be used to assess job demands.

PRINCIPLES

Biomechanics

Biomechanics deals with the principles of physics as they relate to understanding forces and their effects on the human body. These forces include gravity, external loads and resistances, and the internal forces acting within our skeleton, muscles, and other tissues to accomplish intended activities, including work activities. The principles governing the interactions of these forces are relatively straightforward and were published by Sir Isaac Newton in 1687 (*Philosophiae Naturalis Principia Mathematica*). Although sophisticated systems for acquiring force and movement data can provide in-depth biomechanical analyses, these techniques are not easily applied to address specific work-related problems in the factory or office or on the construction site. However, ergonomics practitioners can use knowledge of biomechanical principles, in the general sense, to better understand and improve the ever-changing and challenging conditions in today's workplaces.

Like most other human activities, work activities can range from being immobile and static to being very active and dynamic. Neither extreme is desirable. This chapter begins with a consideration of the principles governing static situations related to posture and progresses through holding and positioning tasks to a brief discussion of dynamic work-related activities. The reader is referred to other works on biomechanics, such as Chaffin, Andersson, and Martin (1999), for a more comprehensive treatment of the concepts contained in this chapter.

Biomechanics of Posture

The inescapable force that acts on all of our body segments, all the time, is gravity. If our body segments are in direct contact with the planet (as when we are lying down) or are supported by an extension of it (as when we are sitting in a chair), no muscular or passive forces from ligaments are needed to maintain the position of that body part. The surface of the supporting structure (floor, chair, armrest, etc) provides the required equal and opposite reaction force so that no movement occurs. For these segments, the primary consideration becomes the distribution of the supporting force over the contact area, where pressure is equal to force per unit area. Not all body tissues do equally well at accepting pressure. The fat pad on the heel of the foot is especially adapted to accept high levels of pressure while standing and walking, and the ischial tuberosities of the pelvis get conditioned to bear weight while seated. However, the coccyx of the spine quickly becomes painful when exposed to high pressure during slouched sitting. Similarly, the tip of the elbow easily becomes irritated when leaning on a table or desk, and there is very little tolerance for supporting over 90 percent of body weight while kneeling.

The force of gravity can also be opposed vertically from above. A simple example is the arm passively hanging from one's side. The downward pull of gravity on the forearm and hand is opposed by the structures in and around the elbow joint. Similarly, at the shoulder, the pull of gravity on the entire arm is, for the most part, passively opposed by shoulder joint tissues.

The governing principle for all static conditions, including static human postures, is that the summation of all the forces in any one direction, in this case the vertical direction (gravity), must be zero. That is, there can be any number of forces acting on the segment, but they must all add up to zero, with the upward forces equaling the downward forces. The governing equation for these static conditions ($\Sigma F = 0$) is simply a special condition ($a = 0$) of the more general Newtonian principle that $\Sigma F = ma$; that is, the sum of the forces in any one direction equals the mass of the object times its linear acceleration in that direction. The same principle is true for any direction, not just the vertical direction considered so far.

Apart from these situations of direct (linear) support, either from below or from above, any other arrangement of body segments (posture) is likely to require active muscle effort to maintain, in addition to passive (resistive) forces from ligaments and/or other soft tissue. Depending on the posture, these forces can be considerable, and they are often accompanied by some unwanted, but necessary, physiological consequences, discussed below.

When the force of gravity does not act exactly through the center of a joint (and most often it doesn't), there is a tendency for rotation about the joint axis (called a moment or torque). The magnitude of the moment about a joint is the product of both the magnitude of the force (F) and the perpendicular distance ($D\perp$) from the axis of rotation, so that $M = FD\perp$. The farther the line of action of the gravitational force is from the joint center, the greater the moment caused by gravity. In the case of static posture, when no movement is occurring, the governing equation is $\Sigma M = 0$; that is, moments that tend to cause rotation about the joint in one direction (e.g., clockwise) must be exactly counterbalanced by moments that tend to cause rotation about the joint in the opposite direction (counterclockwise). As with the static linear situation for forces described above, the static rotational situation is simply a special condition ($\alpha = 0$) of the more general Newtonian principle that $\Sigma M = I\alpha$, that is, the sum of the moments in any one direction equals the moment of inertia (I) of the object times its angular acceleration (α) in that direction. A segment's moment of inertia depends on its mass and the distribution of that mass within the segment. For all practical purposes, I can be considered to be constant, much as we consider a segment's mass to be constant.

Figure 2.1 shows an example of a static head-neck posture associated with using a microscope. The force of gravity acts at the center of mass of the head (labeled as R, for resistance). In this example, we assume that the axis of rotation or fulcrum (the solid dot in the figure) is the atlanto-occipital joint, between the head and first cervical vertebra. The controlling force (F) is provided by the muscles in the back of the neck. The moment arm for counterclockwise rotation is the perpendicular distance from the action line of the force of gravity to the rotation axis (resistance arm, RA) and the moment arm for clockwise rotation is the distance from the line of pull of the muscle force to the rotation axis (force arm, FA). In this static position, these two moments must sum to zero ($\Sigma M = 0$). This means that R multiplied by RA must be equal to F multiplied by FA. If, by visual inspection of the figure, we estimate that the resistance arm (RA) is approximately twice as long as the force arm (FA), then F must be approximately twice as large as R to make the sum of the moments equal zero. If we further estimate that the head of a 150-pound person represents approximately 7 percent of the person's body mass, the gravitational force, R, is 10.5 pounds and, consequently, the force provided by the cervical spine muscles must be approximately 21 pounds. It is important to note that both R and F are acting in a downward direction on the first cervical vertebra. Thus, the compressive force on the atlanto-occipital joint is not just the "weight" of the head, but approximately three times that amount in this for-

FIGURE 2.1. Illustration of the biomechanics of the head and neck

wardly flexed posture. If the microscope user bends forward even more, the resistance arm increases, necessitating an increase in muscle effort and a proportional increase in joint compression. Conversely, if a more erect, less flexed head posture is assumed, the resistance arm is reduced and the muscle tension and joint compression are less. The head-neck posture shown in Figure 2.1 is similar to postures of computer users, sewing machine operators, many assembly workers, surgeons, dentists, and a host of other workers who do fine motor tasks requiring good visual acuity.

The same biomechanical principle ($\Sigma M = 0$) applies to any posture in which a body segment is not in a relaxed vertical alignment or is maintained away from the body. Examples of other anatomical regions that commonly experience posture-related problems are the lower back and the shoulder-arm. The posture of these regions is often strongly influenced by the height at which work tasks are located, as illustrated in Figure 2.2.

In Figure 2.2a, the worker must maintain a forward-leaning trunk posture in order to accomplish a task on a relatively low work surface. In this case, assume that gravity acts on the combined head-arms-trunk at the approximate location indicated by the arrow labeled R in the figure. If the low back (namely, the region of the third-fourth lumbar vertebrae, indicated by the solid dot in the figure) is considered the axis of rotation, the clockwise moment is the product of the gravitational force R and the resistance arm (RA), the perpendicular distance from R to the axis of rotation. To maintain this static work posture, an equal-and-opposite counterclockwise moment must be provided by the product of the force generated by the paraspinal muscles of the low back, F, and the perpendicular distance of this force to the axis of rotation, the force arm, FA. Again, by simple visual inspection, the resistance arm can

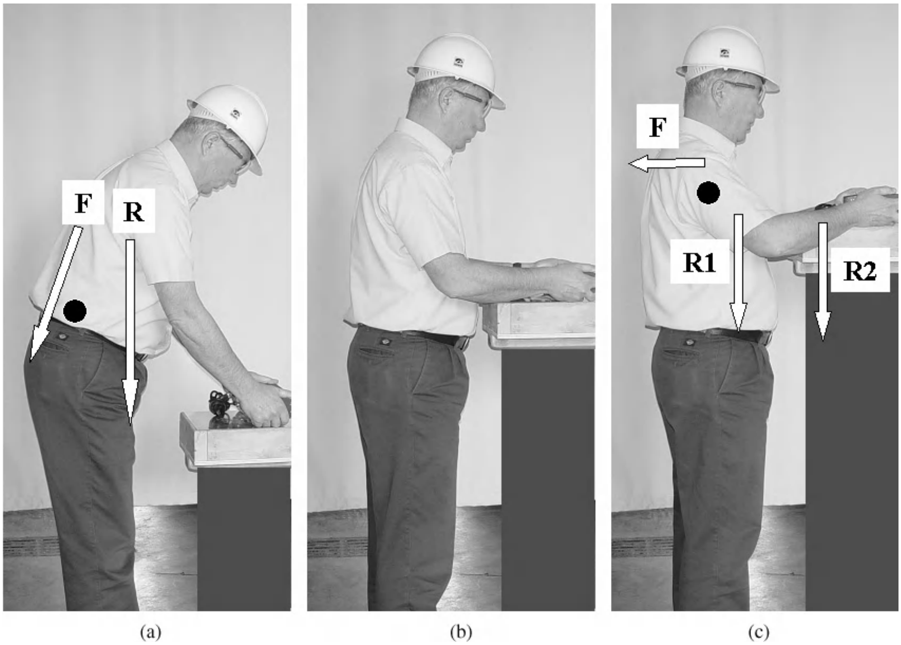


FIGURE 2.2. Effect of work surface height on posture and the biomechanics of the posture

be estimated as several times greater than the force arm. Consequently, the muscle effort, F, must be proportionally greater than R so that the sum of the moments equals zero. For the example of the posture illustrated in Figure 2.2a, assume that the resistance arm is four times greater than the force arm and that the resistance force is 50 percent of the weight of the 200-pound worker, or 100 pounds; then the force provided by the lumbar musculature must be approximately 400 pounds to maintain this working posture. As with the cervical spine example above, there are two important consequences of such a high level of muscle contraction: the total compressive force on the spine is five times the passive "weight" of the head-arms-trunk, and the lumbar muscles must contract continuously at relatively high levels increasing the chances of fatigue, pain, and reduced blood supply in the region. As with the example of the microscope user in Figure 2.1, as the worker maintains a progressively more flexed posture, the controlling musculature must produce progressively higher levels of tension. And conversely, more upright postures are associated with lower levels of muscle effort and less discomfort (Figures 2.2b, c).

The same principles apply to the shoulder. If the work task or the work surface is too high, the worker must maintain the arms in an elevated position, with the shoulder joint flexed forward or held out to the side (abducted). In Figure 2.2c, consider the upper extremity to be made up of two segments, the upper arm and the forearm-hand. There the force of gravity is assumed to act at the approximate center of mass of each segment, as indicated by the two downward arrows (R1 and R2). Each of these gravitational forces is acting at its respective perpendicular distance from the shoulder joint to contribute to a clockwise moment about the shoulder joint. To maintain this work posture, an equal and opposite counterclockwise moment must be provided by the force of the muscles crossing the top of the shoulder joint (deltoid and biceps brachii) (F) acting through a relatively short force arm. As the arm segments are moved farther away from the body, the ratio of the gravitational resistance arms to the force arm becomes progressively greater. As was the case with the neck flexion and forward leaning of the trunk, the muscles around the shoulder joint must contract more intensely to maintain postures with the arm flexed forward or out to the side. The same secondary effects are present: increased joint compression, reduced circulation, and muscular discomfort.

Biomechanics of Holding

In the previous consideration of biomechanical factors affecting postures of the neck, low back, and shoulder, the length of anatomical force arms are relatively fixed and small; consequently, it results in a mechanical disadvantage for most of the major muscle groups that control common work postures. Deviations from a relaxed, upright, balanced position require progressively greater effort to oppose the force of gravity on body segments. Unfortunately, muscles must work with the same anatomical disadvantages during exertional forces on the materials, tools, and other objects in the work environments, especially when postures already are placing high demands. From the point of view of biomechanical analysis, external loads represent additional forces and moments acting under the same Newtonian principles.

Holding and carrying objects are common work activities in many settings. In addition to the postural factors discussed above, the size and shape of an object can have important biomechanical consequences. Figure 2.3 shows two box-handling tasks in which the weight of the box is the same but the dimensions of the box are different. The box in Figure 2.3b is twice as wide as the box in Figure 2.3a. Because the distance from the axis of rotation of the lumbar spine to the edge of the box is the same in both cases, it is easily estimated that handling the larger box results in a 33 percent increase in the forward bending (clockwise) moment of the load and that there must be a proportionate increase in the muscular effort from the controlling lumbar paraspinal muscles (see figure legend for calculations). This increased effort would be even greater if the load were wider, or if the handler could not maintain an upright posture and had to bend forward over the load to grip the forward edge of the box to hold and carry it.

In Figure 2.4 three positions for an overhead drilling task are illustrated. The two lower downward arrows indicate the force of gravity on the upper arm and forearm-hand, and the third downward arrow represents the reaction force of the drill pushing back against the worker's hand. This reaction force includes both the weight of the drill and the reaction force from the sur-

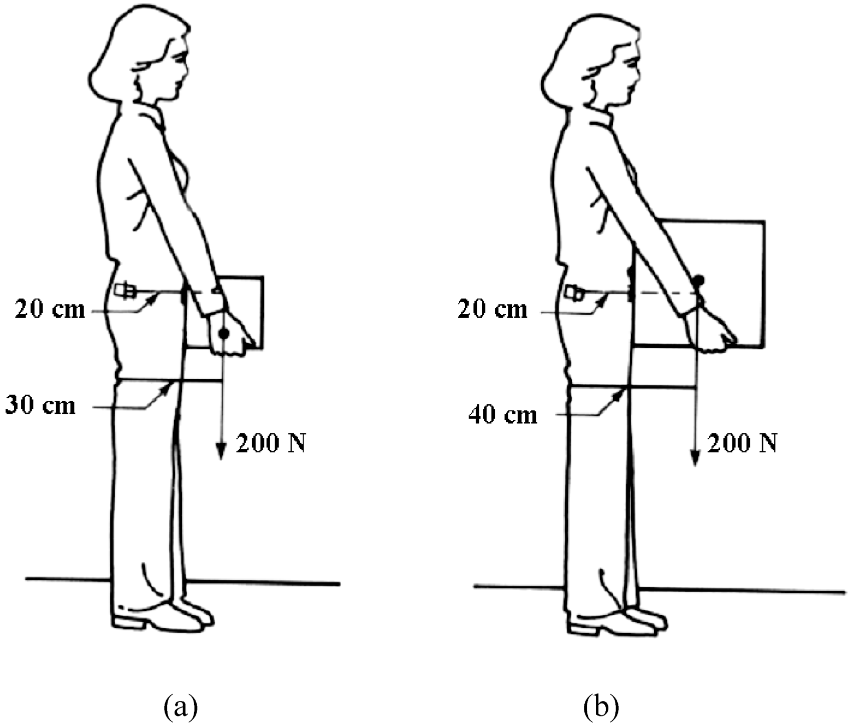


FIGURE 2.3. The influence of box size on the biomechanics of the back. The moment of the load in part (a) is M_a = 0.3 m x 200 N = 60 Nm, while in part (b), M_b = 0.4 m x 200 N = 80 Nm

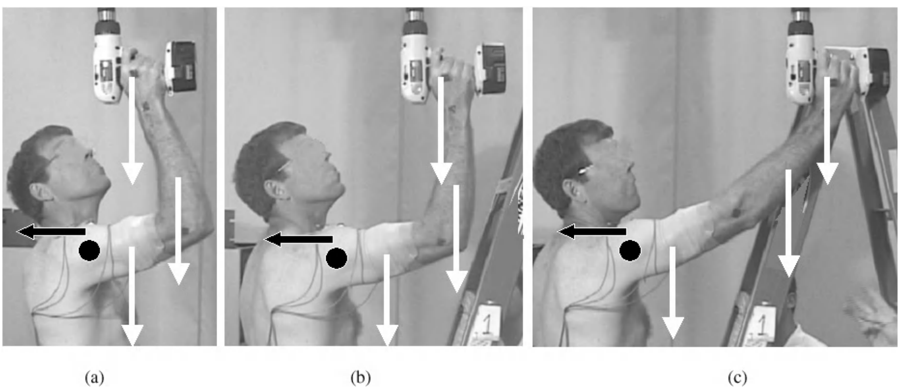


FIGURE 2.4. Illustration of overhead drilling in three postures

face being drilled. In this figure, the resultant clockwise torque is the sum of products of each of these resistive forces and their respective perpendicular resistance arms. The opposing counterclockwise moment must be provided by the product of the near-horizontal force of the shoulder muscles and the perpendicular force arm. A careful consideration of the figure reveals that the gravitational forces on the two arm segments and the force arm of the shoulder muscles are essentially constant, but the resistance arms of all three downward forces depend on the posture used to accomplish the task. As the worker increases his or her reach and, therefore, all three resistance arms, increasing effort from the controlling shoulder muscles is required. The results of a recent investigation by Anton and colleagues (2001) has documented a highly significant relationship between shoulder moment and shoulder muscle activation (EMG) while performing this task in different positions. In the three positions shown in the figure, the mean shoulder joint moment in the study of twenty people was reported to be (a) 13 Nm, (b) 21 Nm, and (c) 29 Nm. In the extended reach posture, the worker may be exerting far more muscular effort to maintain the arm and drill in position than to accomplish the drilling task.

The angle at which a muscle pulls on a skeletal segment varies as the angle of the joint it crosses changes. When the muscle pull is nearly perpendicular to the segment, the muscle produces the maximum moment for the effort exerted or, conversely, produces the desired external moment for the minimal muscle force. But as the joint angle changes and the angle of pull of the muscle becomes less perpendicular, the moment produced for any given muscle force is reduced as a trigonometric function of the angle of pull. In these instances, the force has two components, one component perpendicular to the segment, contributing to the external moment, and one parallel component, contributing to either compression or tension on the joint. Figure 2.5 illustrates these concepts for the action of the biceps across the elbow joint. As the elbow joint moves through its range of motion from an extended position, with the hand lowered, to a more flexed position, with the hand above elbow level, the angle of pull of the biceps changes. At a 90-degree elbow angle (Figure 2.5b), the moment arm is the longest, and the biceps tendon is most perpendicular. Therefore, at this angle the muscle can develop the greatest moment about the joint and we can exert the greatest upward pull at this angle. At angles greater than 90 degrees (Figure 2.5a), the moment arm of the biceps is reduced and some of the force is diverted along the forearm bones to cause upward compression at the elbow. Similarly, at elbow angles less than 90 degrees (Figure 2.5c), the moment arm of the biceps is also reduced and some of the force from the biceps causes upward tension at the elbow. As illustrated in Figure 2.5, as an alternative to visually estimating the force arm (perpendicular distance) of a muscle about a joint, the moment can be calculated using knowledge about the location and angle of the muscle's attachment to the segment and simple trigonometric relationships. The result is the same whether the moment is

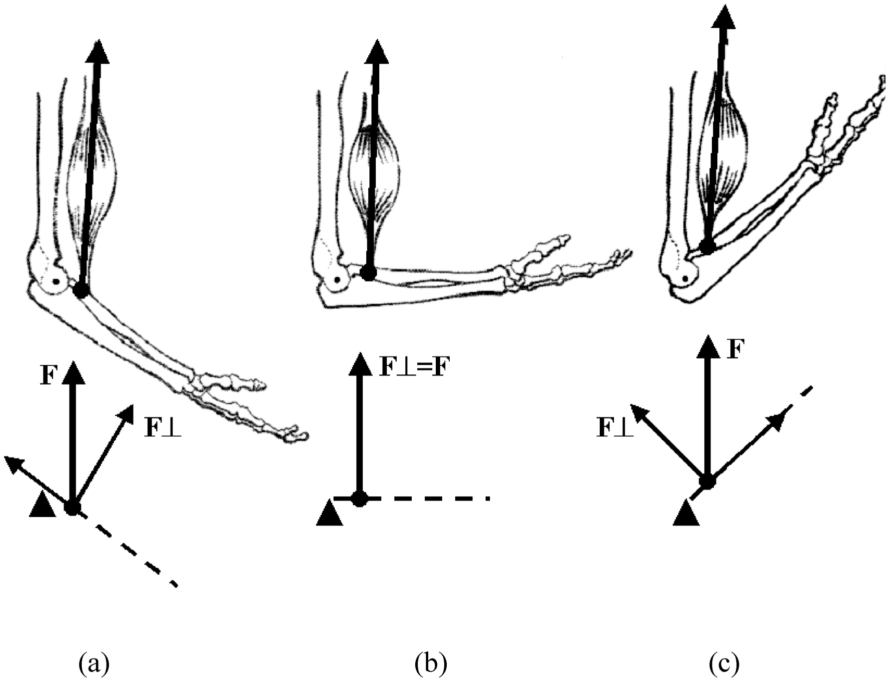


FIGURE 2.5. The effect of elbow angle on the ability of the muscle to exert a moment around the elbow

determined as the product of the entire muscle force and its perpendicular distance to the axis of rotation or as the product of the length from the muscle's attachment point to the joint axis and the perpendicular component of the force. The latter method has the advantage of also providing estimates of the compression or tension components acting along the axis of the segment and affecting the joint tissues.

In many cases, the angle of pull of a particular muscle group is much less variable than the biceps example and is limited to a range of angles causing a substantially larger compression-tension component than a rotational component of the muscle force. Looking more closely at tasks involving the shoulder, such as the overhead drilling task shown in Figure 2.4, the angle between the line of pull of the deltoid and the upper arm segment is clearly relatively small (see Figure 2.6). Because of this rather acute angle, much of the force exerted by this muscle group is contributing to compression of the shoulder joint compared to the perpendicular component that is contributing to the desired rotational component, that is, the external moment needed to accomplish the task. In the case of the deltoid muscles, the line of pull is relatively acute throughout the normal range of shoulder movement and becomes more perpendicular only at more extreme angles of shoulder flexion or abduction. Given the rela-

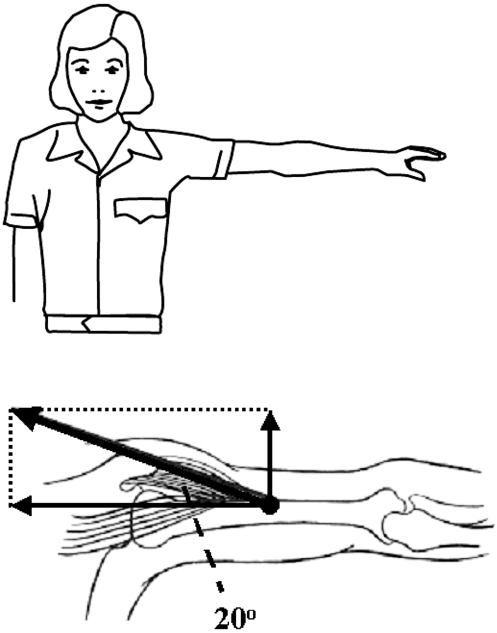


FIGURE 2.6. The angle of pull of the deltoid muscle resulting in a much smaller force of rotation (vertical arrow) than the overall force of the muscle

tively unstable nature of the shoulder joint, the stability obtained from large compressive components of the deltoid muscles may be very protective.

Biomechanics of Gripping

The discussion of holding above emphasized the biomechanics of back, shoulders, and elbows. Gripping is performed by the hands and has similar considerations for biomechanics. These considerations include the angle of pull of a muscle when gripping objects of different sizes, providing the link between the worker and the objects to be lifted, held, carried, pushed, pulled, or manipulated. The size of an object influences how it is grasped and how much grip force can be developed.

There are two basic types of grips: power grip and pinch grip. The pinch grip is characterized by opposition of the thumb and the distal joints of the fingers. The different types of pinch grips include:

- The tip pinch (using just the tips of the fingers and thumb, e.g., to hold a bead), sometimes classified as pulp 1 and pulp 2, depending on whether the index finger or the middle finger opposes the thumb
- The chuck pinch (used when holding pencils, etc.)
- The lateral pinch (using the thumb and the sides of the fingers, as for keys, etc.)

The power grip is used most often used when the object grasped is 3 cm (1.25 in.) or larger and includes the cylindrical grip, the spherical grip, and the hook grip/palmar grip. As the size of an object increases, one factor influencing the amount of force that can be exerted on the object is the angle of pull of the flexor tendons on the fingers and thumb. Figure 2.7 shows two different grip spans.

In the case of the smaller grip, the angle of the tendon pulling on the middle finger segment is approximately 60 degrees from perpendicular, while the angle of pull of the tendon on this segment, when using the larger grip span, is approximately 75 degrees from perpendicular. As shown by the calculations from the figure, for the smaller grip span, the perpendicular component of the force (F) that is directed at gripping an object is 0.68F and the component parallel to the segment, tending to compress (or stabilize) the joint, is 0.80F. In the case of the larger grip, however, the perpendicular component of the force that is directed at gripping an object is 0.33F and the component parallel to the segment, tending to compress (or stabilize) the joint, is 0.90F. The optimal grip spans are in the range of 4.5 to 9.5 cm (1.75 to 3.75 in.) (Petrofsky et al. 1980; SUNYAB-IE 1982–83; Greenberg and Chaffin 1976).

Similarly, for pinch grips the force that can be exerted declines greatly at spans less than 2.5 cm (1 in.) or more than 7.5 cm (3 in.) (Jones 1974). Whereas pinch grips do not involve the palm, and usually involve only the thumb and one other finger, the maximum strength in pinching is less than that with a power grip—typically about 25 percent of the power grip strength (Jones 1974). As the wrist angle changes, the pinch strength also changes, with the maximum force developed when the wrist is in neutral (Imrhan 1991) (see Figure 2.8).

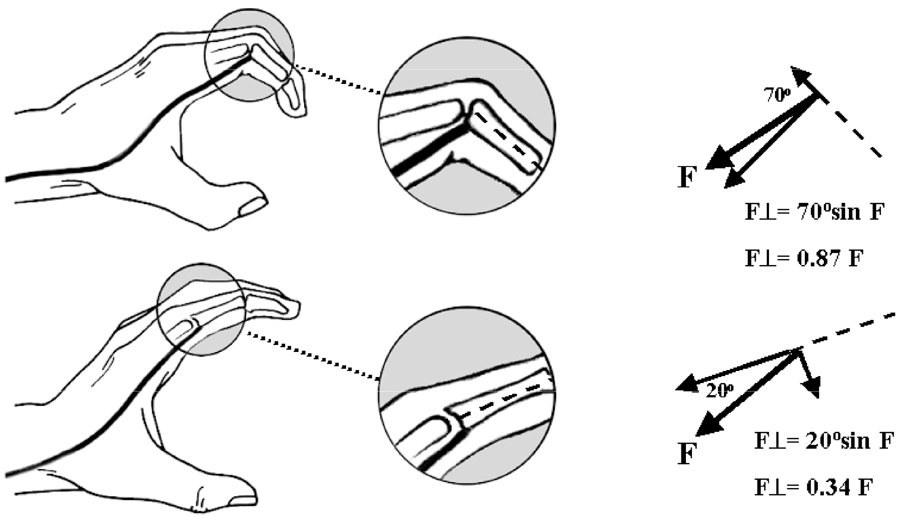


FIGURE 2.7. The biomechanics of grip span on force development

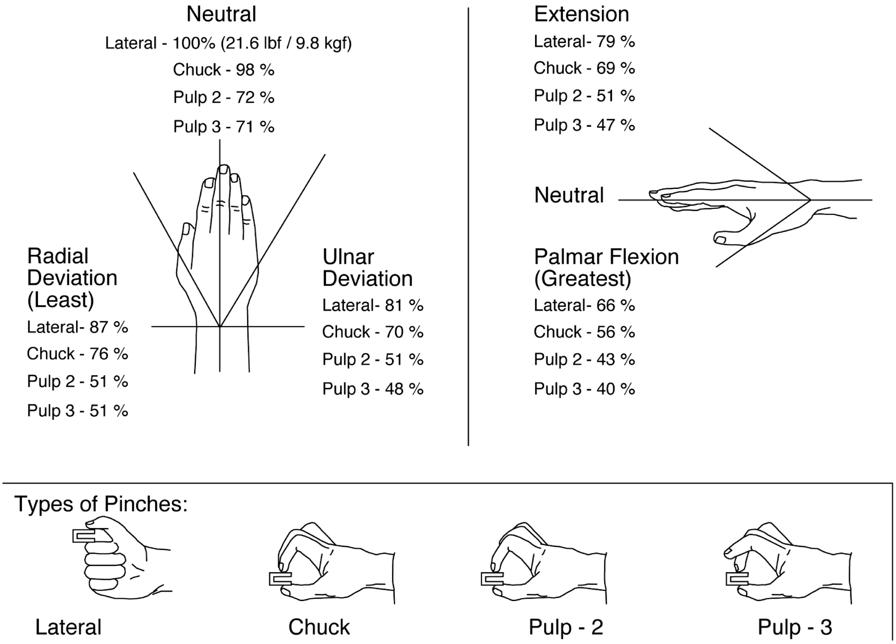


FIGURE 2.8. The influence of wrist angle on pinch strength (Imrhan 1991)

Table 2.2 gives an indication of the force generated in grasping and pinching and the force generated by the fingers in radial and ulnar deviation. Notice the decrease in strength when there is a deviation in the wrist.

Dynamic Motion

Most biomechanical analyses of work consider the posture and the load and make the assumption that the motion is slow and steady so that acceleration is treated as virtually zero ($a = 0$) as described above. The reality is that acceleration may not be negligible in many lifts, and this adds the required muscle force as described by Newton's Second Law of Motion. Figure 2.9 illustrates the compressive force on the back because of acceleration. Marras and colleagues (1993) have clearly demonstrated the link between rapid motion and the risk for back disorders. Similar risks may be assumed for other rapid movements around a joint.

Static Muscle Work

Static muscle work is a condition in which a muscle or group of muscles contracts for a sustained period. Sustained contractions occur when an object

TABLE 2.2
Hand Function Strengths for Men and Women (Chao et al., 1989)

		Functional Strength (kg)	
Type of function	n	Male	Female
Grasp	60	40 ± 9	23 ± 7
Tip pinch	124	6 ± 1	5 ± 1
Chuck pinch	60	6 ± 1	5 ± 1
Key pinch	84	11 ± 2	8 ± 1
Radial deviation of index finger	60	4 ± 1	3 ± 1
Radial deviation of middle finger	60	4 ± 2	3 ± 1
Radial deviation of ring finger	60	3 ± 1	2 ± 1
Radial deviation of little finger	60	2 ± 1	2 ± 1
Ulnar deviation of index finger	60	4 ± 1	3 ± 1
Ulnar deviation of middle finger	60	4 ± 2	3 ± 1
Ulnar deviation of ring finger	60	3 ± 2	2 ± 1
Ulnar deviation of little finger	60	3 ± 1	2 ± 1
Thumb abduction	47	4 ± 1	3 ± 1
Thumb adduction	47	7 ± 3	5 ± 2

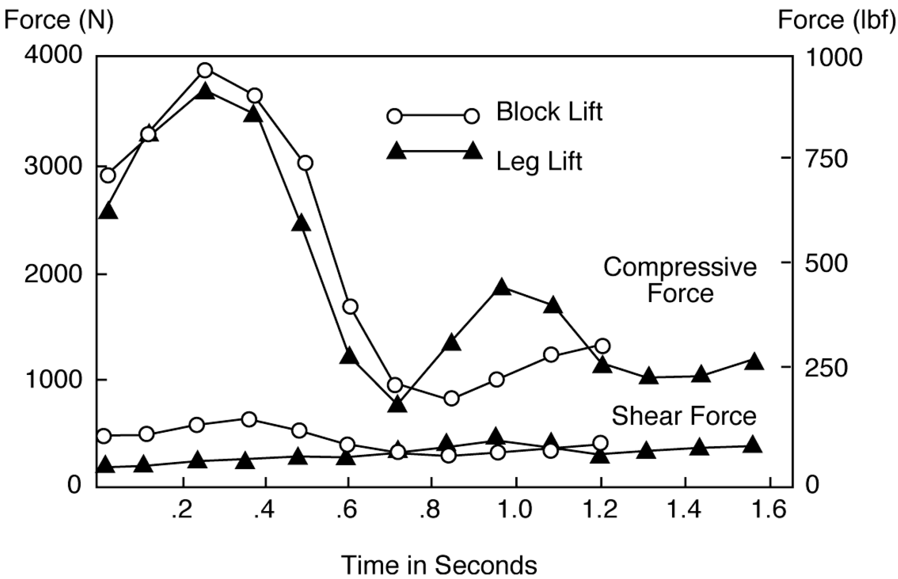


FIGURE 2.9. Compressive forces on the low back during back and leg lifting

must be held or a posture maintained. The characteristic outcome of static work is localized muscle fatigue. The greater the effort by a muscle group, the earlier the onset of fatigue. Local muscle fatigue has a marked effect on comfort and acceptability and may contribute to musculoskeletal disorders.

Rohmert (1965) and Scherrer and Monod (1960) have explored the relationship between level of effort and endurance time. Rohmert (1965) reported a relationship between level of effort and endurance time that is illustrated in Figure 2.10. The first thing to notice about the level of effort metric is that it is a relative measure, that is, the percentage of effort with respect to the individual's strength. This relative effort is described in the following paragraphs. Another feature of the relationship is the implication of endurance time. The endurance time is the maximum voluntary holding time, for which muscle discomfort has reached unacceptable levels.

The maximum voluntary contraction (MVC) is a measure of strength. The measure can be a maximal exertion of force reported as force (e.g., lb., kg, N) or as a moment around a joint (e.g., Newton-meters, foot-pounds, kilogram-meters). The percent maximum voluntary contraction (%MVC) is the percentage ratio of the applied force (as either a force or a resulting moment on a joint) to the MVC for the same muscle group in the same posture (and

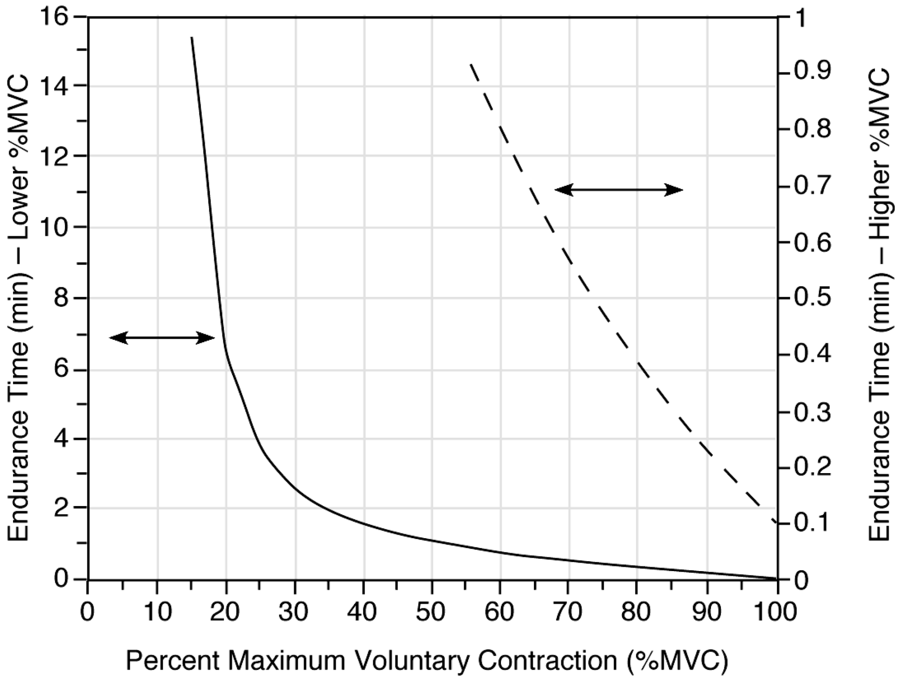


FIGURE 2.10. Curve based on Rohmert's relationship between %MVC (percentage of maximum voluntary contraction) and endurance time (minutes)

When using the upper curve, use the scale on the right; when using the lower curve, use the scale on the left.

expressed in the same units). Using the three overhead drilling examples of Figure 2.4, the shoulder moments are 13, 21, and 29 Nm. The average shoulder moments in a similar posture for nine young women were 21 Nm (Yates et al. 1980). The respective %MVCs would be 62 percent, 100 percent, and 138 percent. This means that the reaching posture of Figure 2.4c could not be done by the average young woman because it is greater than the MVC, the middle posture (Figure 2.4b) is at the MVC for the average young woman, and the posture with the flexed elbow is about two-thirds the MVC. At a 62 %MVC, the drilling could be supported for about 0.7 minute (40 seconds).

Rohmert (1973) also suggested a relationship between recovery allowance and the combination of %MVC and holding time. The relationships are illustrated in Figure 6.2 in Chapter 6. When any two of these are known or a given for a job, the third one is constrained to a specific value. For the 62 %MVC of the preceding paragraph, if the drilling was performed for 0.5 minute, the recovery allowance would be 600 percent, or about 3 minutes.

While the endurance time and recovery allowance curves suggest that a static exertion of less than 15 %MVC can be held indefinitely, it is likely that sustained contractions of less than 10 %MVC may lead to local muscle fatigue. In this regard, the Rohmert curves should be treated as a good first guess.

The potential for fatigue is the basis for the Rodgers Muscle Fatigue Assessment method, described later in this chapter.

Dynamic Work

Dynamic work is characterized by repeated brief contractions followed by relaxation of muscle groups. It is associated with body movement and usually accomplishes external work (defined as moving something through a distance against a resisting force). Dynamic work leads to physiological adjustments to accommodate the increased demand for oxygen and removal of carbon dioxide as well as the mobilization of energy stores such as carbohydrates and fats. A good measure of the dynamic work requirement is the rate of oxygen consumption and the rate of energy expenditure. While very short bursts of intense dynamic work can exhaust the active muscle group, the more typical outcome of demanding dynamic work is a sense of whole-body exhaustion from involvement of the cardiopulmonary systems. While it is less likely to have a direct effect on musculoskeletal disorders, whole-body fatigue will reduce productivity, lower psychomotor skills (which may lead to accidents and overexertion injuries), and reduce comfort and acceptability.

Åstrand and Rodahl (1977) published a classic representation of endurance time as a function of the relative rate of oxygen consumption. This is illustrated in Figure 6.3. The rate of oxygen consumption is normalized to the individual by expressing the rate of consumption as a fraction of the individual's maximum aerobic capacity. As expected, the maximum aerobic power, or the greatest rate of oxygen consumption the individual can support, can be sustained for only a brief period. As the relative demands decrease, the endurance time increases. Figure 2.11 provides a protective (lower-bound) relationship between relative rate of oxygen consumption and endurance time proposed by Bernard and Kenney (1994) based on a consideration of several investigators.

While the work demands were expressed in terms of rate of oxygen consumption in the preceding paragraph, they may also be expressed as energy expenditure where the consumption of 1 liter of oxygen has the equivalent energy expenditure of 5 kcal (McArdle, Katch, and Katch 2001).

To avoid exhaustion during the course of day, consideration must be given to recovery time. As a rule, the average demand over an eight-hour work day should not exceed 33 percent of maximum aerobic capacity (30 percent for ten hours and 25 percent for twelve hours), and none of the intermediate demands

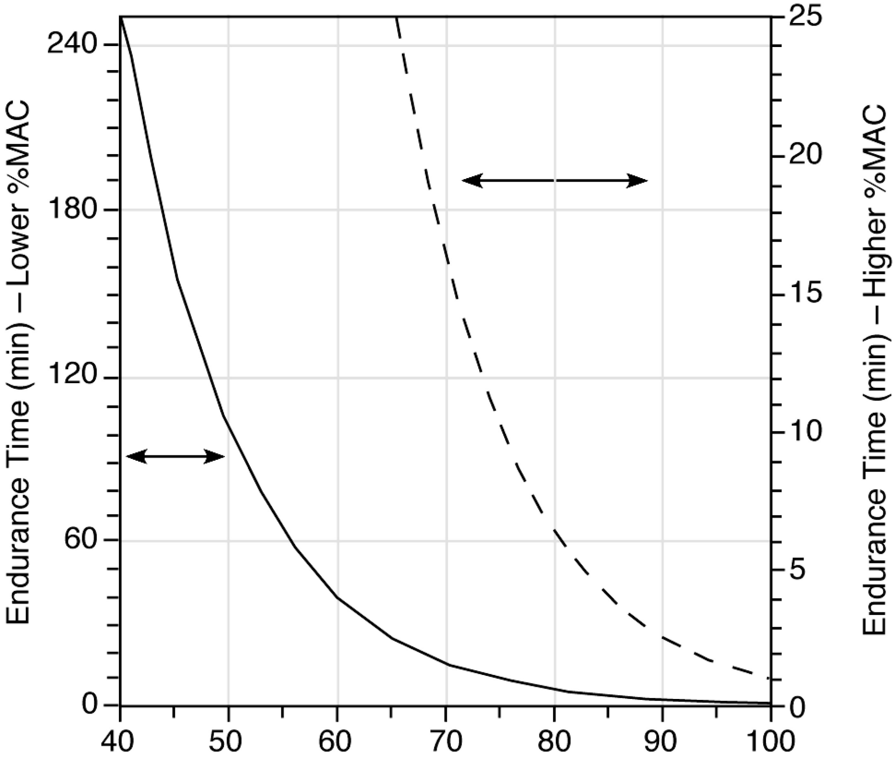


FIGURE 2.11. Relationship between endurance time (minutes) and relative metabolic demands (%MAC, percentage of maximum aerobic capacity) (Bernard and Kenney 1994)

When using the upper curve, use the scale on the right; when using the lower curve, use the scale on the left.

should exceed the endurance time. If there are demands that exceed the shift-long limit, a period of recovery is needed. Figure 6.4 and the section "Dynamic Work" in Chapter 6 provide work design guidance. The NIOSH lifting equation described in a following section uses a metabolic limit as one of the considerations.

A method to estimate the rate of energy expenditure is provided later in the "Analysis Methods" section of this chapter (the dynamic work method). Because there is a marked cardiovascular adjustment to dynamic work demands, methods to assess the physiological strain through heart rate is also described in the "Analysis Methods" section (Dynamic Work: Heart Rate Analysis on p. 180).

Psychophysical Scaling Methods

Psychophysical scaling methods are based on the assumption that "human subjects can make meaningful evaluations of the magnitude of their sensory experiences, at least under certain conditions" (Marks 1974; Noble and Robertson 1996). In ergonomics, this is an implicit assumption when psychophysical ratings are used to represent physiological and sensory changes introduced by job performance or use of tools in order to determine if they are designed within an acceptable range of an individual's work capacity.

Psychophysical Scales

Quantitative subjective evaluations are conducted with rating scales that can name, rank, differentiate, determine differences in magnitude, or define a relationship between and among sensations. In Table 2.3, examples of different scale types and the type of information they represent are presented.

The most commonly used scales in ergonomics are the category and interval scales. These scales are used either as unidimensional scales (that is, by themselves for one attribute of work) or in combinations as multidimensional scales (where several scales are used simultaneously for several different attributes of work). These kinds of scales can be used for product or intervention evaluation, as described in "Evaluation and Selection of Equipment" in Chapter 4.

The development and use of subjective scales requires some skill, and the advice of someone who is knowledgeable in psychometrics is invaluable. Follow the advice outlined in the "Forms and Surveys" section in Chapter 5.

Although subjective ratings are crucial to evaluate the effects of candidate designs on individuals, any subjective rating, regardless of the rating technique used, is influenced by environmental conditions, age, cognitive abilities, motivation, emotional states, and personality factors. Any interpretation of results must consider these factors.

TABLE 2.3
Examples of Scaling Methods (adapted from Cushman and Rosenberg 1991; Eastman Kodak Company 1983; Noble and Robertson 1996)

Scaling technique	Function	Type of information obtained
Nominal	Naming things	A number is assigned to an event or object with no quality attached to it. Example: ID numbers.
Ordinal	Ranking	A number is assigned to indicate that an event or object has more or less of a certain attribute. It does not provide information about how large or the magnitude of the difference. Example: Race results 1st, 2nd, 3rd etc.
Category	Ranking into defined attribute categories	A number is assigned to a special category of attributes of an event or object and the categories are ordered according to some rule. Example: 1 = easy; 2 = moderately easy 3 = difficult.
Interval	Ranking with regard to magnitude of quantity/ quality differences	A number is assigned to differentiate quantity/quality magnitude. Example: Fahrenheit and Celsius temperature scales.
Ratio	Names, ranks, tells magnitude differences and provides ratios	The scale starts with an absolute 0 and numbers are related to each other. Magnitude estimations. Example: a ruler.

Subjective Rating Methods

Many different techniques have been developed to collect subjective ratings of various psychological/physiological attributes of work(Cushman and Rosenberg 1991; Helander and Mukund 1991; Wilson and Corlett 1995). In Table 2.4 a few examples of these techniques are presented for the following areas: mental workload (Cooper and Harper 1969; Hart and Staveland 1988; Hill et al. 1992; Meshkati et al. 1995; Moroney, Biers, and Eggemeier 1995; Reid, Shingledecker, and Eggemeier 1981; Wierwille and Casali 1983); work stress (Cox and Mackay 1985; Gotts and Cox 1990); muscle fatigue (Ashberg 2000; Ashberg and Gamberale 1998; Ashberg, Gamberale, and Gustafsson 2000; Ashberg, Gamberale, and Kjellberg 1997); discomfort (Corlett and Bishop 1976; Hagberg et al. 1995; Wilson and Corlett 1995); and perceived exertion (Borg 1961; Borg 1998; Noble and Robertson 1996).

For more information on these techniques and other psychophysical methods, questionnaires, and surveillance data collection techniques, see the references presented above and to Cushman and Rosenberg 1991, Hagberg et al.,

TABLE 2.4
Rating Scales for Subjective Evaluations of Mental Workload, Work Stress, Fatigue, Discomfort, and Perceived Exertion

Type of evaluation	Type of scale	Comment
Mental work load scales	Cooper-Harper scale	
	SWAT (Subjective Workload Assessment Technique)	Widely used Not sensitive to low mental workloads Time-consuming
	NASA task load index (TLX)	Sensitive
	Overall workload scale (OW)	Sensitive
Work stress	Stress arousal checklist	Normative data available
	General well-being questionnaire	Normative data available for different age groups
Fatigue	Swedish Occupational Fatigue Inventory (SOFI)	Intensity of fatigue rated along five factors
Physical discomfort	Visual analog scales (VAS)	Often used in pain research
	Corlett and Bishop's body part diagram	Commonly used
	Borg CR10	Commonly used
Perceived exertion	Borg's RPE Borg's CR10	Commonly used

1995, Salvendy and Carayon 1997, and Wilson and Corlett 1995. For information about visual analogue scales, see Straker 2001.

Two of the most widely used subjective rating scales for physical demands in the workplace are the Borg scales of perceived exertion and discomfort, which are described in the next section.

Ratings of Perceived Exertion and Discomfort

The subjective perception of exertion and discomfort in industry, rehabilitation, and athletic training programs has been studied extensively with Borg scales (for reviews, see Borg 1998 and Noble and Robertson 1996). The RPE scale (Borg 1961; Borg 1962; Borg 1970) is primarily used for perceived exertion, and the CR10 scale (Borg 1982; Borg, Holmgren, and Lindblad 1981) is primarily for perceived discomfort and pain.

Figures 2.12 and 2.13 show the most recent versions of the RPE and CR10 scales, respectively, along with the previous (older) version for information and comparison. Both scales' verbal anchors (Borg and Lindblad 1976) have

Current Version

6	No exertion at all
7	
	Extremely light
8	
9	Very light
10	
11	Light
12	
13	Somewhat hard
14	
15	Hard (heavy)
16	
17	Very hard
18	
19	Extremely hard
20	Maximal exertion

Older Version

6	Extremely light
7	Very, very light
8	
9	Very light
10	
11	Fairly light
12	
13	Somewhat hard
14	
15	Hard
16	
17	Very hard
18	
19	Very, very hard
20	

FIGURE 2.12. Borg's RPE Scale
Used for rating perceived exertion. See Borg (1998) for instructions on how to use and interpret the scale. The older version is provided for comparison.

Current Version

0	Nothing at all—"no P"
0.3	
0.5	Extremely weak/just noticeable
1	Very weak
1.5	
2	Weak/light
2.5	
3	Moderate
4	
5	Strong/heavy
6	
7	Very strong
8	
9	
10	Extremely strong—"max P"
11	
•	Absolute maximum—highest possible

Older Version

0	Nothing at all
0.5	Extremely weak
1	Very weak
2	Weak
3	Moderate
4	
5	Strong
6	
7	Very strong
8	
9	
10	Extremely strong
•	Maximal

FIGURE 2.13. Borg's CR10 Scale
Used for rating pain and discomfort. See Borg (1998) for instructions on how to use and interpret the scale. The older version is provided for comparison.

been revised to improve the RPE scale's linearity with heart rate and the CR10 scale's bottom and ceiling effects. If other formats and anchors are found, they may be the previous versions or ones adapted by others.

For the correct usage of the scales, the user must go to the instructions and administration process prescribed by Borg (see Borg 1998 or the folders published by Borg on the RPE scale and the CR10 scale, which can be obtained directly from Borg Perception, Furuholmen 1027, 762 91 Rimbo, Sweden).

Perceived exertion has been defined by Noble and Robertson (1996) as "the act of detecting and interpreting sensations arising from the body during physical exertion," where the sensations arise from both the musculoskeletal and the cardiovascular systems (Pandolf 1978; Robertson 1982). Knowing an individual's perceived exertion levels during physical work provides information about demands that are placed on that individual's physical capacity. This is possible because the RPE and CR10 rating values correlate highly with changes in heart rate and oxygen consumption, which are indicators of physical capacity (for a review of the physiological mediators of perceived exertion, see Noble and Robertson 1996). As a result of this property, the RPE and the CR10 scales have been used as a substitute for physiological monitoring. The rating scales are less intrusive compared to, for example, a heart rate monitor, simple to administer, and yet allow collection of reliable and valid data. These scales can be used to aid in the collection of data for both semiquantitative and quantitative evaluation methods, discussed below.

Please note that errors have been made in both reproduction and administration of these scales. Borg (1998) states that this could result in a misrepresentation of what individuals subjectively rate. Changes in the scale design (for example, adding colors), wording, spacing of expressions, endpoints, or instructions (such as shortening and changing them) distort the scale values. "Changing the rating scale may be a way to manipulate the responses in order to avoid more accurate or real ones" (Borg 1998, p. 16). A change in the scale alters how well an individual's responses actually correlate with the physiological responses on which the scale is normally highly correlated. That can lead to a misjudgment of an employee's muscle fatigue or work capacity.

Table 2.5 presents examples of recent studies in which the RPE and/or the CR10 scales have been used to study perceived exertion and discomfort in industrial tasks performed both in the field and in the laboratory.

ANALYSIS METHODS

Qualitative Methods

Qualitative methods follow two paths. One path is professional judgment and experience. A walk-through survey is the quintessential example of professional judgment as a qualitative assessment. An informative supplement is some knowledge of the injury and accident history of the survey areas and

TABLE 2.5
Studies of Specific Tasks Using RPE and/or the CR10 Scales for Ratings of Perceived Exertion and Discomfort

Tasks studied	References
Manual handling tasks	(Ashfour et al. 1983)
Lifting patients	(Dehlin and Jaderberg 1982)
Repetitive submaximal lifting tasks	(Hagen et al. 1994)
Carpentry tasks	(Dimov et al. 2000)
Pushing and pulling	(Garcin et al. 1996)
Carrying heavy loads	(Goslin and Rorke 1986) (Wu and Chen 2001) (Wu 1997)
Repetitive lifting	(Capodaglio et al. 1996)
Self-paced and force-paced lifting	(Stalhammar et al. 1992)
Wood cutting	(Hagen et al. 1993)
Physical performance in protective clothing	(Murphy et al. 2001)
Farm work	(Nevala-Puranen and Sorensen 1997)
Dynamic work in hot conditions	(Randle and Legg 1985)
Driving screws, tool shape, work location	(Ulin et al. 1993a) (Ulin et al. 1993b) (Ulin et al. 1990)
Handle angle effects	(Wang et al. 2000)

conversations with those who work the jobs. The traditional job safety analysis (JSA) is a convenient structure to consider the risk factors of a job based on professional judgment. The analyst may identify some feature of the job as a hazard and either suggest further analysis or recommend possible solutions.

The other path is a checklist of job risk factors and a simple indication of sufficient presence or not. The checklist approach describes known job risk factors, may suggest the degree of presence necessary to be a threshold concern, and provides a method to indicate whether the threshold presence is associated with the job. The underlying principles of a checklist are simplicity and speed. The presence of a job risk factor means a further analysis using semiquantitative or quantitative methods, or the consideration of interventions. The decision depends on the judgment and practice of the ergonomist performing or reviewing the results.

Job Safety Analysis and Job Hazard Analysis

A typical job safety analysis (JSA) has a rather loose structure that relies heavily on experience. A typical job hazard analysis (JHA) has more structure in the identification of hazards, usually with a checklist of hazards that are considered. Those who use JHAs in the workplace may consider incorporating an ergonomics checklist into their process.

The typical JSA/JHA divides the job into somewhat homogeneous tasks. Within each task, possible or actual hazards associated with it are listed. For each of the hazards, one or more solutions are suggested. In preparation for a JSA/JHA, the analyst should become familiar with the injury history of the job from the OSHA records, workers compensation records, and first-aid logs. If a record of employee complaints is kept, this should also be consulted.

At the job site, an interview with one or more experienced operators is necessary. The operators can explain the steps taken to complete the work so that a task breakdown can be performed. The operators can also provide information on suspected hazards, including those that may exceed the limits of individuals and cause overexertion and overuse injuries. From the ergonomics point of view, the task demands should be examined with the following considerations in mind:

- Are there employees who do not have sufficient strength to perform a task?
- Are there employees who report significant muscle fatigue performing the work?
- Are there employees who become physically exhausted performing the work?
- Are there reports of work-related musculoskeletal disorders or symptoms associated with joints, muscles, and tendons?
- Are there high psychomotor and cognitive demands (i.e., long learning times) that may cause accidents?
- Are there poor workstation layout features that cause limits on motion, excessive motion, or postural fatigue?
- Are there environmental conditions, such as heat, cold, vibration, noise, or inadequate illumination, that may reduce performance?

Based on the above considerations, hazards that can be attributed to biomechanical and strength limits, fatigue limits, and risk of cumulative trauma as well anthropometric, psychological, and environmental limits are identified. The type of hazard and the body region affected can point toward tentative solutions, as well as follow-up analysis using semiquantitative and quantitative methods.

The Kodak MSD Analysis Guide (MAG) in Figure 2.15a provides a list of job risk factors that can be used in a JHA in order to consider issues related to ergonomics. These are oriented toward major body regions (back and legs, hands and wrists, elbows, shoulders, and neck), type of risk (contact stress, impacts, and vibration), and broader job factors (workstation design, tools and equipment, procedures and job demands, manual handling, and environment).

JSAs/JHAs are a powerful tool for understanding hazards that extend beyond the physical and psychological demands of the work. They require some training and experience in ergonomics, and diligent information gathering. Without knowledge and diligence, the results can be very inconsistent among analysts and may be very superficial. The MAG job risk factors list in Figure 2.15a can be used to reduce some of the variability in results.

Checklists

A checklist is a selected presentation of job risk factors broken into basic components. The checklist may also focus on a specific type of work or a particular group of job risk factors. The person or team using a checklist considers whether a particular job risk factor is present in the job or not. In this way, it is more structured than a job safety analysis and may cover more areas than a job hazard analysis. Depending on the checklist used, there will be considerations of strength, fatigue, and cumulative trauma disorders as well as environment. OSHA also provided a list of job risk factors associated with WRMSDs in its workplace standard for ergonomics (29CFR1910.900 2000), which was later vacated. A recent checklist designed for work-related musculoskeletal disorders was developed and distributed by the State of Washington Department of Labor and Industries for its 2000 Ergonomics Rule (WISHA 2000). Job risk factors have been well documented by NIOSH (1997a), National Academy of Sciences (1998), OSHA (1999), and Keyserling (2000a, 2000b).

Checklists have been constructed and offered here (Figures 2.14a-e) to cover some limited conditions: general assembly, manual materials handling, computer workstations, maintenance, and laboratory work. The general assembly list is used for workstations that require hand work with little handling of materials over 10 pounds. The materials handling checklist is applicable to jobs requiring the routine handling of objects of 10 or more pounds. If the workday contains more than four hours of computer work, individuals may choose to use the computer checklist. Maintenance work is more irregular than other types of manufacturing work and a checklist for those is provided in Figure 2.14d. For laboratory employees, the laboratory checklist may provide some insight. If a job risk factor is identified, further analysis or corrective action is recommended.

A useful source for checklists is the *Elements of Ergonomics Programs* published by NIOSH (1997b).

Job/Task: __________ Dept. ________ Date: ____ Analyst: ____
Before ____ *After (Controls Implemented)* ____

Directions: Review each condition for the job/task of interest and for each condition that frequently occurs, place an X in the "Concern" column as appropriate. Add comments as appropriate.

Condition	X if a Concern	Comments
POSTURES		
Prolonged standing or sitting (with poor back support)		
Prolonged kneeling/squatting/ crouching		
Trunk bending or twisting (front/ back/side)		
Neck bending or twisting (front/ back/side)		
Reaching in front of body, to side, or behind		
Upper arm(s) raised & unsupported (to the side)		
Hand(s) bent up/down left/right		
Forearm rotation		
Feet bent up/down left /right		
REPETITION		
High-speed process line or work presentation rates		
Similar motions every few seconds		
Observed signs of fatigue		
WORKSTATION DESIGN		
Work surface too high or low		
Location of materials promotes reaching		

FIGURE 2.14. Five checklists for (a) general assembly, (b) manual materials handling, (c) computer workstations, (d) maintenance, and (e) laboratory work (adapted from material developed by Chemical Manufacturers Association)

Condition	X if a Concern	Comments
Table/bench lack adequate toe / leg space		
Table/equipment places sharp edges on limbs, torso		
Chair lacks adequate lumbar support		
Chair lacks adequate/adjustable seat height		
Lack of an adequate footrest, antifatigue support mat		
Walking/stair/ladder use		
FORCE		
Excessive/heavy lifting/Lowering		
Excessive/heavy pushing/pulling		
Long-distance carrying		
Awkward dynamic (rapid) application of force		
Long-duration exertions (static work)		
Wide grasping or pinching grips		
Using palm/knee as hammer		
ENVIRONMENTAL		
Room temps/equipment/objects too hot/too cold		
Lighting is too bright or too dim		
Glare makes seeing the task difficult		
Noisy area/not isolated from noise		
Vibrations in work area		

FIGURE 2.14a *(Continued)*

Condition	X if a Concern	Comments
OTHER		
Inappropriate work techniques used		
Personal protective equipment needed but not available/used		
Tools cause non-neutral wrist/elbow/shoulder positions		
Tools require high force or create high torque/vibration		
Tool size or design inappropriate		
TOTAL SCORE (Optional)		*To score, add up the number of Xs identified.*

FIGURE 2.14a *(Continued)*

Semiquantitative Methods

Semiquantitative methods may require a little more effort to collect data, usually involve some processing of the data to reach a decision, may focus on a body region, and consider two or more contributing factors. Two paths direct the ergonomist to semiquantitative methods: a qualitative assessment that pointed toward a body region, and a professional judgment that the job risk factors are well enough known to suggest a semiquantitative method.

Of the semiquantitative methods, the Kodak MSD Analysis Guide and the Rodgers Muscle Fatigue Assessment are approaches for all body regions. Rapid Entire Body Assessment (REBA) (Hignett and McAtamney 2000) and its antecedent, the Rapid Upper Limb Assessment (RULA) (McAtamney and Corlett 1993), emphasize the upper extremities but include all body regions. REBA and RULA are generally well known but are not discussed further here. The remaining methods listed in Table 2.1 focus on one body region and should be selected with the guidance of a qualitative method or professional judgment. These methods are described below.

MSD Analysis Guide

The Kodak Musculoskeletal Disorder (MSD) Analysis Guide (MAG) is a structured method to look for MSD risk factors within a job, to prioritize them for further action, and to get at the root cause for the presence of the risk

Job/Task: ________________ Dept. ___________ Date: _____ Analyst: _____

Before _____ *After (Controls Implemented)* _____

Directions: Review each condition for the job/task of interest and for each condition that frequently occurs, place an X in the "Concern" column as appropriate. Add comments as appropriate.

Condition	X if a Concern	Comments
REPETITION		
High-speed process line or work presentation rates		
Similar motions every few seconds		
Observed signs of fatigue		
WORKSTATION DESIGN		
Work surface too high or low		
Location of materials promotes reaching		
Angle/orientation of containers promotes non-neutral positions		
Spacing between adjacent transfer surfaces promotes twisting		
Obstructions prevents direct access to load/unload points		
Obstacles on floor prevent a clear path of travel		
Floor surfaces are uneven, slippery, or sloping		
Hoists or other power lifting devices are needed but not available		
LIFTING AND LOWERING		
Heavy object to be handled		
Handling bulky or difficult-to-grasp objects		

FIGURE 2.14b Ergonomics Checklist—Material Handling (adapted from material developed by Chemical Manufacturers Association)

Condition	X if a Concern	Comments
Handling above the shoulders, below the knees		
Lifting to the side or unbalanced lifting		
Placing objects accurately/precisely		
Sudden, jerky movements during handling		
One-handed lifting		
Long-duration exertions (static work)		
PUSHING/PULLING/CARRYING		
Forceful pushing/pulling of carts or equipment required		
Brakes for stopping hand carts/ handling aids are needed but not available		
Carts or equipment design promotes non-neutral postures		
Long-distance carrying (carts not available)		
CONTAINERS/MATERIALS		
Lack adequate handles or gripping surfaces		
Are unbalanced, unstable, or contents shift		
Obstructs leg movement when being carried		

FIGURE 2.14b *(Continued)*

Condition	X if a Concern	Comments
OTHER		
Inappropriate work techniques used		
Buildup of process material /product increases worker effort		
Personal protective equipment needed but not available/used		
TOTAL SCORE (Optional)		*To score, add up the number of Xs identified.*

FIGURE 2.14b *(Continued)*

factor. This information is used to determine what the appropriate job modification would be. The data collection is organized by an annotated guide, shown in Figure 2.15a, and a worksheet, illustrated in Figure 2.15b.

After noting general information about the job, the analyst divides the job into individual tasks, similar to performing a job safety/hazard analysis. The task number and description are entered into the first two columns. The third column provides a space for the weight or forces that might be exerted as part of the task. If the combination of posture, force, and repetition as described in the analysis guide (Figure 2.15a) is observed, the risk factor is considered to be "present" and the appropriate action code is entered onto the analysis worksheet (Figure 2.15b). The action codes are listed in the fifth column of the analysis guide. Space is also provided for further description of the risk factors. If there is more than one risk factor per task, the task description should be repeated on the next line with the weight/force and action code for that risk factor.

The next step within a task is to enter the task frequency (the number of cycles divided by the time in minutes it takes to complete the number of cycles), the duration in seconds within a cycle that the risk factor is present or in the lifting zone, and the hours spent during the shift performing the task. The cumulative time within a shift can be computed as the product of the frequency, duration, and shift time. The resulting cumulative time is in minutes per shift and is entered into the worksheet.

Action codes A5–A8 have a weight or force limit instead of a time limit. For these action codes one need not fill in the columns concerning task frequency or risk duration within a cycle of hours spent doing the task. In the worksheet column 7 is used to capture the lifting zone for action code A6.

While you are seated at your computer workstation, use this checklist to analyze your workstation layout and posture.

1. Are you able to view your screen without tipping your head either forward or back? ___Yes
2. Are you looking straight ahead at your screen? ___Yes
3. Is your copyholder right next to your screen and at the same height and distance from your eyes? ___Yes
4. If you wear bifocals, do you have special glasses for computer work? ___Yes
5. Can you easily view your work without leaning forward? ___Yes
6. Are the screen contrast and brightness set correctly for your visual comfort? ___Yes
7. Is the screen free of any glare (reflections, white spots) from your work environment? ___Yes
8. Can you avoid bending your neck and/or hunching your shoulder to hold your phone? ___Yes
9. Are your shoulders relaxed and your arms down by your side as you use your keyboard/mouse? ___Yes
10. When you work, is your elbow at about 90°? ___Yes
11. Are your wrists almost straight (in a neutral posture) as you work? ___Yes
12. Is your work area free of any sharp edges against your forearm or wrist? ___Yes
13. Can you reach frequently used items (mouse, files, coffee mug, etc.) without stretching? ___Yes
14. Can you sit all the way back in your chair without pressure against the back of your knees? ___Yes
15. Does your chair provide good lumbar support? ___Yes
16. Are your feet fully supported by the floor or a footrest? ___Yes
17. Are you able to intersperse non-computer work (e.g., filing, copying) with your computer work? ___Yes
18. Do you take “micro-breaks” to stand up, stretch, and focus your eyes on something far away? ___Yes

If all your answers are yes, congratulations! You’re probably working fairly comfortably and are not experiencing computer-related problems. If you have any no responses, something about your workstation probably needs to be adjusted. Consult the other handouts for suggestions or call _________ .

Corporate Ergonomics
Health, Safety & Environment
Eastman Kodak Company
http://hse.kodak.com/ergo/

FIGURE 2.14c Computer Workstation Checklist

Job/Task: ________ Dept. ________ Date: ____ Analyst: ____
Before ____ *After (Controls Implemented)* ____

Directions: Review each condition for the job/task of interest and for each condition that frequently occurs, place an 'X' in the "Concern" column as appropriate. Add comments as appropriate to describe concern

Condition	X if a Concern	Comments
POSTURES		
Prolonged work in an awkward posture		
Prolonged kneeling/squatting/ crouching		
Trunk bending or twisting (front/ back/side)		
Reaching in front of body, to side, or behind		
Work elevated above shoulders		
Hand(s) bent up/down left/right		
Forearm rotation		
REPETITION		
Similar motions every few seconds		
Observed signs of fatigue		
Job occurs as result of emergency conditions		
Production is interrupted by maintenance work		
JOB DEMANDS		
Work area lacks adequate sitting/ standing surface		
Equipment/materials lacks adequate gripping surface		

FIGURE 2.14d Ergonomics Checklist—Equipment Service and Maintenance Work (adapted from material developed by Chemical Manufacturers Association)

Condition	X if a Concern	Comments
Obstacles prevents clear and easy access to service point		
Work is performed in restricted, confined space Fork trucks/power equipment needed but not available/accessible		
Equipment causes pressure points on body		
Excessive walking/stair/ladder use		
Floor surfaces are uneven, slippery, or sloping		
FORCE		
Excessive/heavy lifting/lowering		
Excessive/heavy pushing/pulling		
Equipment/materials must be manually carried to/from site		
Awkward/excessive application of force		
Forceful grips		
Wide grasping or pinching grips		
Using palm/knee as hammer		
TOOL USAGE		
Tool is inappropriate/not designed for the task		
Handle creates pressure points in the hand		
Handle diameter, span, or length is too small or too large		

FIGURE 2.14d *(Continued)*

Condition	X if a Concern	Comments
Activation of the tool requires prolonged use of finger or thumb		
Worker must exert force to operate/control the tool		
Worker experiences vibration and/or torque		
OTHER		
Room temps/equipment/objects too hot/too cold		
Lighting is too bright or too dim		
Noisy area/not isolated from noise		
Vibrations in work area		
Inappropriate work techniques used		
Personal protective equipment needed but not available		

FIGURE 2.14d *(Continued)*

The risk factor summary sheet (Figure 2.15c) is used to bring the data together. The work sheet is scanned for all the instances of one action code, say, A1. The cumulative time for each instance of A1 is summed together and entered on the summary sheet next to A1. The process is repeated for each action code. The recommended limit (as minutes for most of the action codes) is provided in the third column. The next step is to indicate in the fourth column whether the recommended limit is exceeded for each action code. Finally, calculate the ratio of the actual risk (column 2 on the summary sheet) to the recommended limit (column 3 on the summary sheet or column 6 on the analysis guide). All ratios that are equal to or greater than 1 are classified as "red units," and the associated action codes are classified as "red" risk factors. Red units can also be accumulated by summing ratios for risk factors for the same joint. For example, if the ratios for action codes B5 through B8 (see Figure 2.15a) sum up to 1 or more than 1, then there are red units associated with grasping.

There are two indices of ranking jobs. One is a simple count of the unique action codes that are present but below the exposure limit. This is entered on the analysis worksheet as the number of risk factors observed. The other is the sum of the red units, and this is entered on the analysis worksheet as the number of red units.

Job/Task: ______________ Dept. __________ Date: _____ Analyst: _____

Before _____ *After (Controls Implemented)* _____

Directions: Review each condition for the job/task of interest and for each condition that frequently occurs, place an X in the "Concern" column as appropriate. Add comments as appropriate.

Condition	X if a Concern	Comments
POSTURES		
Prolonged work in a fixed position		
Prolonged kneeling/squatting/ crouching		
Trunk bending or twisting (front/ back/side)		
Reaching in front of body, to side, or behind		
Hand(s) bent up/down left/right		
Forearm rotation		
REPETITION		
Times of peak demand exist during the shift/week		
Work is production-driven		
Similar motions every few seconds		
Observed signs of fatigue		
WORKSTATION DESIGN		
Work surface too high or low		
Location of materials promotes reaching		
Table/bench lack adequate toe/leg space		
Table/equipment places sharp edges on limbs, torso		

FIGURE 2.14e Ergonomics Checklist—Laboratory Work (adapted from material developed by Chemical Manufacturers Association)

Condition	X if a Concern	Comments
Chair lacks adequate lumbar support		
Chair lacks adequate/adjustable seat height		
Lack of an adequate footrest, antifatigue support mat		
Equipment design does not promote neutral postures		
FORCE		
Excessive/heavy lifting/lowering		
Excessive/heavy pushing/pulling		
Long-distance carrying		
Awkward/excessive application of force		
Equipment controls require forceful use of the fingertips		
Long-duration exertions (static work)		
Wide grasping or pinching grips		
INSTRUMENT USE		
Instrument design requires constant use of the fingertips or thumb		
Length of the instrument promotes reaching		
OTHER		
Room temps/equipment/objects too hot/too cold		
Lighting is too bright or too dim		
Glare makes seeing the task difficult		

FIGURE 2.14e *(Continued)*

Condition	X if a Concern	Comments
Noisy area/not isolated from noise		
Vibrations in work area, equipment		
Inappropriate work techniques used		
Personal protective equipment needed but not available		
TOTAL SCORE (Optional)		*To score, add up the number of Xs identified.*

FIGURE 2.14e *(Continued)*

Among different jobs, those with the highest number of red units should be considered before those with fewer. Within a job, each of the tasks that have red risk factors deserves more attention. If none of the action codes is marked as exceeding the recommended limit, the task has a low priority for change. For each red risk factor the analyst should determine the root cause(s) by investigating if it is the task frequency, duration, posture, or force components that drive the problem. This information is used (with the help of the preliminary contributory factors list in Figure 2.15d) to identify potential solutions.

In the ranking of jobs, the ergonomist should also consider the number of labor-hours per week or year associated with the jobs as well as the injury history and complaints.

Rodgers Muscle Fatigue Assessment

The Muscle Fatigue Assessment (MFA) was proposed by Rodgers (1988, 1992) as a means to assess the amount of fatigue that accumulates in muscles during various work patterns within a five-minute work period. The hypothesis was that a rapidly fatiguing muscle is more susceptible to injury and inflammation. With this in mind, if fatigue can be minimized, so should injuries and illnesses of the active muscles. This method for job analysis is most appropriate to evaluate the risk for fatigue accumulation in tasks that are performed for an hour or more and where awkward postures or frequent exertions are present. Based on the risk of fatigue, a "priority for change" score from low to very high can be assigned to the task. Figure 2.16 provides a format for this process.

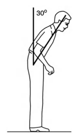
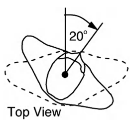
The first step is to divide the job into tasks and determine what percent of the shift each task is done. In addition, the analyst identifies which tasks are perceived as "difficult" by people on the job. The analysis is performed on the primary tasks (those done for more than 10 percent of the shift) and on any

Notes:

1. The MAG was designed to help people evaluate and prioritize jobs or job tasks in terms of work related MSD risk factors.
2. MAG helps to determine whether the work performed exceeds a certain magnitude for the major risk factors for MSDs (posture, force and repetition/lack of recovery).
3. For each job, sum up the total cumulative risk factor duration* for each risk factor before comparing it to the recommended limit. Those that exceed the limit have a high priority for redesign.

* Cumulative Risk Factor Duration = Task Frequency (cycles/min) X risk duration within each cycle (seconds) X hours spent doing the task (hours/shift)

A: Back and Legs

Visual Aid	Posture	Force	Repetition	Action Code	Recommended Limit
	Back Bent:	none	Less than 2 times per minute	A1	90 minutes
	Working with the back bent forward more than 30°	none	2 times per minute or more; or static contraction > 10 seconds	A2	60 minutes
	Twisted Back:	none	Less than 2 times per minute	A3	90 minutes
	Working with the back twisted more than 20°	none	2 times per minute or more; or static contraction > 10 seconds	A4	60 minutes
	Lifting: In any posture	More than 50 lbs (*at any one time*)	Less than once per hour	A5	50 lbs.

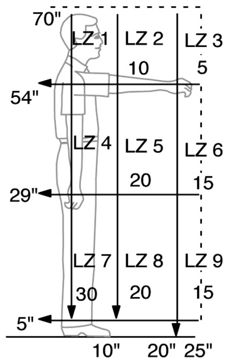
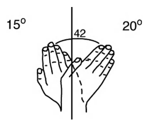
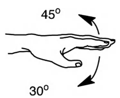
	Lifting: In the zones shown in the adjoining figure. (Based on NIOSH ’91 for a 50%ile heights, and 5%ile reach; modified by Kodak experience). The numbers in each Lifting Zone (LZ) indicate the recommended weight limit.		Once per hour or more	A6	0 (Zero) minutes
	Pushing-Pulling (whole body activity) (e.g. truck with total weight of 1000 lbs.):	More than 50 lbs. of initial force or 25 lbs. maintenance force		A7	50 lbs. initial 25 lbs. maintenance
	Carrying at waist level	20 lbs. or more	More than 30 feet each time or > 5 times / min.	A8	20 lbs.
	Carrying at waist level	20 lbs. or more	Less than 30 feet or < 5 times / min.	A9	2 hrs
	Squatting, crouching or kneeling	none	Static or dynamic	A10	2 hrs

FIGURE 2.15a Kodak Musculoskeletal Disorder (MSD) Analysis Guide (MAG): (a) analysis guide that describes job risk factors and thresholds for further consideration, (b) worksheet for task analysis and overall score, (c) risk factor summary sheet, and (d) contributory factors list

Visual Aid	Posture	Force	Repetition	Action Code	Recommended Limit
	Standing or walking on a hard surface (without anti-fatigue mats or insoles),	none	Static or dynamic	A11	4 hours
	Seated with back not in neutral, or without leg/foot support **OR** climbing stairs, ladders, forktruck access **OR** repetitive/forceful leg exertions	none	Static or dynamic	A12	2 hours

B: Hand and Wrist

Visual Aid	Posture	Force	Repetition	Action Code	Recommended Limit
 	Bent Wrist: *(hand bent down ° or more,* ***or*** *up 45° or more,* ***or*** *toward thumb 15° or more,* ***or*** *away thumb 20° or more).*	none	Less than 2 times per minute	B1	90 minutes
		With Force: Any level of force in any direction	Less than 2 times per minute	B2	40 minutes

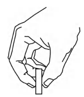
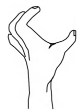
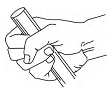
		none	2 times per minute or more; or static contraction > 10 seconds	B3	60 minutes
		With Force: Any level of force in any direction	2 times per minute or more; or static contraction > 10 seconds	B4	20 minutes
	Pinching with or without force (see visual aid)	none	Less than 2 times per minute	B5	90 minutes
	Wide grasp with or without force	With Force: Pinching with a force of 2 lbs or more per hand *(comparable to pinching half a ream of paper)* Or wide grasp with a force of 5 lbs or more per hand (eg. Holding a roll or first form) Or Gripping with a force of 10 or more pounds per hand, *(comparable to clamping light duty automotive jumper cables onto a battery)*	Less than 2 times per minute	B6	40 minutes
	Power grasp with force	none	2 times per minute or more; or static contraction > 10 seconds	B7	60 minutes
		With Force (See above)	2 times per minute or more; or static contraction > 10 seconds	B7	20 minutes

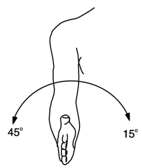
FIGURE 2.15a *(Continued)*

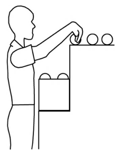
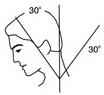
C: Computer Work—Intensive keying and mousing

	Posture	Force	Action Code	Recommended Limit
	Neutral Posture	none	C1	7 hrs
	Awkward posture (Including bent wrists, extended arms, tilted neck, back leaned forward)	none	C2	2 hrs

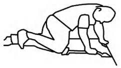
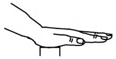
Notes: This is only meant for occasional use at equipment. For computer workstations use the Computer Checklist (Figure 2.14c).

D: Elbow, Shoulders and Neck

Visual Aid	Posture	Force	Repetition	Action Code	Recommended Limit
	Unsupported dynamic rotation of the forearm more than 45° in either direction (not a supported static position e.g. typing)	none	Less than 2 times per minute	D1	90 minutes
		While exerting a torque of 10 in-lbs or more	Less than 2 times per minute	D2	40 minutes
		none	2 times per minute or more; or static contraction > 10 seconds	D3	60 minutes
		While exerting a torque of 10 in-lbs or more	2 times per minute or more; or static contraction > 10 seconds	D4	20 minutes

	Working with the arms or elbows away from the body (in any direction)	none	Less than 2 times per minute	D5	
		While exerting force	Less than 2 times per minute	D6	60 minutes
		none	2 times per minute or more; or static contraction > 10 seconds	D7	
		With Force	2 times per minute or more; or static contraction > 10 seconds	D8	30 minutes
	Bent neck:	none	Less than 2 times per minute	D9	90 minutes
	Neck bent (up or down) 30° or more.	none	2 times per minute or more; or static contraction > 10 seconds	D10	60 minutes

E: Contact Stress / Repeated Impact / Vibration

Visual Aid	Posture	Force	Repetition	Action Code	Recommended Limit
	Any Posture: 	Using the hand (heel/base of palm) or knee as a hammer	More than once per 5 minutes	E1	2 hrs
	Any Posture:	Pressure against soft tissue (e.g. from a square edge / ridge)	Static or dynamic	E2	2 hrs
	Any Posture:	Using vibrating tools or equipment that typically have *high* vibration levels *(i.e. >10 m/s²* such as chain saws, jackhammers, percussive tools, riverting or chipping hammers)		E3	30 min.
	Any Posture:	Using vibrating tools or equipment that typically have *moderate* (i.e. 5 m/s^2 such as jig saws, grinders, or sanders)		E4	2 hrs

Notes:
1. The MAG is not a comprehensive list of risk factors, it focuses on the more common issues seen at Kodak.
2. MAG does not predict if/when someone will get an MSD from a particular job.

FIGURE 2.15a *(Continued)*

Job/Equipment/Workstation:	______	Date:	______
Organization & Division:	______	Analyst:	______
Department	______	Job Duration (avg # hours /person /week):	______
Total # of employees doing job in dept.:	______	# MSD incidents on this job in the last year:	______

Reason for evaluation ______ # of Risk Factors Observed ______ # Red Units ______

#	Task	Wt / Force (lb)	Action Codes	Risk Factors Observed	Task Frequency (cycles / min)	Risk Factor duration w/n cycle (sec) or in Lifting Zone (sec)	Hours spent doing task each shift	Cumulative Risk Factor duration over the shift (min)	Contributory Factors for each "Red" risk factor

FIGURE 2.15b Musculoskeletal Disorder (MSD) Analysis Worksheet

Job Title

Action Code	Cumulative Risk Factor Duration over the Job	Recommended Limit	Recommended Limit Exceeded? (Yes)	Ratio of Actual Risk to Recommended Limit	Recommended Fix for Red Risk Factor
A1		90			
A2		60			
A3		90			
A4		60			
A5		50			
A6		Limit for the appropriate Lifting Zone			
A7		50			
A8		20			
A9		120			
A10		120			
A11		240			
A12		120			
B1		90			
B2		40			
B3		60			
B4		20			
B5		90			
B6		40			
B7		60			
B8		20			
C1		420			
C2		120			

FIGURE 2.15c MSD Risk Factor Summary Sheet

Action Code	Cumulative Risk Factor Duration over the Job	Recommended Limit	Recommended Limit Exceeded? (Yes)	Ratio of Actual Risk to Recommended Limit	Recommended Fix for Red Risk Factor
D1		90			
D2		40			
D3		60			
D4		20			
D5		150			
D6		60			
D7		100			
D8		30			
D9		90			
D10		60			
E1		120			
E2		120			
E3		30			
E4		120			

FIGURE 2.15c *(Continued)*

tasks considered "difficult," no matter how much of the job they constitute. For each task and then for each body region within the task, the three MFA factors are assessed by assigning each factor a rating by category.

Space for description of effort level for the different body regions, continuous (single) effort duration, and effort frequency is provided on the data collection form. Within a body region, once an effort level is chosen to represent the task, the assignment of continuous effort time and efforts per minute should be associated with the chosen effort. For each of the MFA factors, the greatest level, 4, means that that factor alone is significant. If the effort level is high enough that most workers cannot accomplish it, if the continuous effort duration is greater than 30 seconds, or if the frequency is greater than fifteen per minute, there is sufficient reason to assign a 4 and a very high priority for change.

Workstation Design:
Work surface height causes non-neutral Postures
Workstation layout promotes twisting
Table/bench lacks adequate toe/leg space
Table bench has sharp edges to lean on
Chair lacks adequate support/adjustability
Lack of adequate footrest or anti-fatigue mat
Location of materials/**controls** promotes reaching/twisting/bending
Obstructions prevent direct access to work
Heavy materials are stored above shoulder height or below knuckle height
Displays not within visual comfort zone
Tool/Equipment Design
Tools/Equipment cause non-neutral wrist/elbow/shoulder positions
Handle diameter, span or length is too small/large
Handle creates pressure points in the hand
Tool has trailing air/electrical lines that interfere
Tool requires high force to control or operate
Tool creates high torque or vibration
Activation of tool requires prolonged use of finger or thumb
Tool not compatible with glove use
Tool is unbalanced/heavy
Equipment dimensions promote reaching
Tool/equipment not appropriate for task
Defective or worn Equipment
Equipment out of adjustment
Procedures or Job Demands
Excessive walking/stair climbing or ladder use
Few opportunities to change posture

FIGURE 2.15d Contributory Factors

Carrying not within guidelines
Lifting tasks not within guidelines
Work rate goes up and down over the week
Job occurs as a result of emergency conditions
Machine paced rates, buffer inadequate
Precision work
Inappropriate work techniques used
Inadequate work hardening
Handling parts, containers, carts/trucks
Size of the object (very small or awkwardly large)
Objects handled hot/cold/dirty
Unbalanced, unstable part, or contents that shift
No handles/handles in the wrong place/inadequate
Size of part obstructs leg movement when carried
Cart/truck shelf height causes bending/reaching
Wheels worn/bound/inappropriate
No brakes on the carts/trucks
Environmental Conditions
Work area hot/cold
High Humidity
Light is dim/uneven/too bright
Glare makes seeing difficult
Noise area—not isolated from noise
Insufficient or confined workspace
Obstacles prevent clear and easy access to load/unload or service the equipment
Obstacles on floor prevent a clear path of travel
Floor surfaces are uneven, slippery or sloping

FIGURE 2.15d *(Continued)*

Job		Analyst
Task	% of Shift Time	Date / /

	Effort Level (If the effort cannot be exerted by most people, enter 4 for Effort and VH for Priority)			*Scores*			*Priority*
Region	**Light—*1***	**Moderate—*2***	**Heavy—*3***	***Effort***	***Dur***	***Freq***	
Neck	Head turned partly to side, back or slightly forward	Head turned to side; head fully back; head forward about 20°	Same as Moderate but with force or weight; head stretched forward				
Shoulders	Arms slightly away from sides; arms extended with some support	Arms away from body, no support; working overhead	Exerting forces or holding weight with arms away from body or overhead	Right			
				Left			
Back	Leaning to side or bending arching back	Bending forward; no load; lifting moderately heavy loads near body; working overhead	Lifting or exerting force while twisting; high force or load while bending				
Arms/ Elbow	Arms away from body, no load; light forces lifting near body	Rotating arms while exerting moderate force	High forces exerted with rotation; lifting with arms extended	Right			
				Left			
Wrists/ Hands/ Fingers	Light forces or weights handled close to body; straight wrists; comfortable power grips	Grips with wide or narrow span; moderate risk angles, especially flexion; use of gloves with moderate forces	Pinch grips; strong wrist angles; slippery surfaces	Right			
				Left			

FIGURE 2.16. Rodgers Muscle Fatigue Assessment method, which includes a data collection sheet and interpretation table

	Effort Level (If the effort cannot be exerted by most people, enter 4 for Effort and VH for Priority)			*Scores*			*Priority*
Region	**Light—*1***	**Moderate—*2***	**Heavy—*3***	***Effort***	***Dur***	***Freq***	
Legs/ Knees	Standing, walking without bending or leaning; weight on both feet	Bending forward, learning on table; weight on one side; pivoting while exerting force	Exerting high force while pulling or lifting; crouching while exerting force	Right			
				Left			
Ankles/ Feet/Toes	Standing, walking without bending or leaning; weight on both feet	Bending forward, leaning on table; weight on one side; pivoting while exerting force	Exerting high force while pulling or lifting; crouching while exerting force	Right			
				Left			

Continuous Effort Duration	< 6 s **1**	6–20 s **2**	20–30 s **3**	> 30 s **4** (Enter VH for Priority)
Effort Frequency	< 1/min **1**	1–5/min **2**	> 5–15/min **3**	> 15/min **4** (Enter VH for Priority)

Category Scores Grouped by Priority for Change in the Order of Effort, Continuous Effort Duration and Frequency

The following table ranks the combinations of scores in increasing potential for fatigue, and, thereby, in increasing priority for change. The least fatiguing combinations are at the top left side of the table and the highest are at the end of the list on the right side of the table. When a solution is chosen to improve the work, it is important to rate the new task with the same tool to be sure the fatigue has been dropped to a lower level.

Low (L)	**Moderate (M)**	**High (H)**	**Very High (VH)**
111	123	223	323
112	132	313	331
113	213	321	332
211	222	322	4xx, x4x, xx4*
121	231		
212	232		
311	312		
122			
131			
221			

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*A category of 4 for Effort Level, Continuous Effort Duration or Frequency is automatically Very High (VH)

FIGURE 2.16 *(Continued)*

The priority for change is found by locating the combination of scores in the various categories in the table. Note that a combination of 3 for duration and 3 for frequency is not possible. The table provides an indication of relative risk for fatigue within a category. The earlier the combination of categories is in the list, the lower the fatigue should be (i.e., it is better).

Liberty Mutual Tables for Manual Materials Handling

Many jobs that contain risk factors for injury can be described as manual materials handling. The Liberty Mutual Tables for lifting/lowering, carrying, pushing, and pulling (Snook and Ciriello 1991) are semiquantitative methods that cover various aspects of manual materials handling. All of the studies were performed at the Liberty Mutual Research Center, where investigators have used a psychophysical technique to assess the acceptable load (lift/lower and carry) or force (push/pull) for some types of materials handling where other job factors, such as frequency and distance, were held constant. For a combination of job factors, the reported loads or forces were expressed as the percentage of the male and female populations that would find it acceptable. The values provided in Tables 2.6–2.9 are design goals based on conditions that are acceptable to 75 percent of women. This means that 25 percent of women would find the work unacceptable, and fewer men would report it as unacceptable. Over the years of experience with these tables, the 75-percent-acceptable-for-women level has evolved into the threshold above which further consideration should be given to the job.

Table 2.6 presents the lifting/lowering design goals. While lowering values in the original tables were slightly higher, the difference is not enough to warrant a different set of tables. The critical factors are the frequency of the lift, the location of the hands in front of the body, the distance of the lift, and the overall vertical region in which the lift occurs. The table is divided into three parts, each representing a vertical region (above the shoulders, or greater than 138 cm [54 in.]; between the shoulders and knuckles with the hands at the side, or 74 to 138 cm [29 to 54 in.]; and between the hands and the floor, or below 74 cm [29 in.]). Within a vertical region, the next considerations are the location of the hands and the vertical distance of the lift. The hand location is measured as the distance from the front of the body to the center point of the hands. The vertical distance of the lift should include the distance from the lowest point to the highest point of the lift or lower. Next, find the design goal for the nearest frequency of lift. If the vertical travel crosses over two vertical regions, first consider if most of the lift is in one region or if it is evenly divided between two. If it is mostly in one region, use that region; if not, select the region with the lower value of load.

The design goals for carrying are provided in Table 2.7. The investigators considered two hand positions for the carry. One was with the hands near waist height and the other with the elbows straight and the hands near the level of the hips. Without the elbow flexion needed for the bent elbows, the acceptable

TABLE 2.6
Design Goals (in kg) for Lifting and Lowering of Loads Based on the Liberty Mutual Tables for 75% Acceptable for Women (Snook and Ciriello 1991) (adapted from the tables published in Erogonomics pubnlished by Taylor & Francis Ltd., see http://www. tandf.co.uk/journals)

Above Shouler		Horizontal Distance (Front of Body to Load) [cm]								
		17			25			38		
		Distance of Lift [cm]			Distance of Lift [cm]			Distance of Lift [cm]		
Frequency of Lift		25	51	76	25	51	76	25	51	76
1/8 h	1/8 h	16	14	13	13	12	11	12	11	10
1/30 min	2/1 h	14	12	11	11	10	9	10	9	8
1/5 min	12/1 h	12	11	10	10	9	8	9	9	8
1/2 min	30/1 h	12	11	10	10	9	8	9	9	8
1/1 min	1/1 min	12	11	9	9	9	8	9	8	7
1/14 s	4.3/1 min	9	9	8	8	8	6	8	8	6
1/9 s	6.7/1 min	8	8	7	7	7	6	7	7	6
1/5 s	12/1 min	8	8	6	6	6	5	6	6	5

Knuckle to Shoulder		Horizontal Distance (Front of Body to Load) [cm]								
		17			25			38		
		Distance of Lift [cm]			Distance of Lift [cm]			Distance of Lift [cm]		
Frequency of Lift		25	51	76	25	51	76	25	51	76
1/8 h	1/8 h	18	17	15	17	15	14	17	15	14
1/30 min	2/1 h	16	14	13	14	13	12	14	13	12
1/5 min	12/1 h	14	13	12	13	12	11	13	12	11
1/2 min	30/1 h	14	13	12	13	12	11	13	12	11
1/1 min	1/1 min	13	12	11	12	11	10	12	11	10
1/14 s	4.3/1 min	11	11	9	9	9	8	9	9	8
1/9 s	6.7/1 min	10	10	8	8	8	7	8	8	7
1/5 s	12/1 min	9	9	7	7	7	6	7	7	6

Floor to Knuckle		Horizontal Distance (Front of Body to Load) [cm]								
		17			25			38		
		Distance of Lift [cm]			Distance of Lift [cm]			Distance of Lift [cm]		
Frequency of Lift		25	51	76	25	51	76	25	51	76
1/8 h	1/8 h	23	22	19	19	18	16	18	17	14
1/30 min	2/1 h	17	16	14	14	14	12	13	13	11
1/5 min	12/1 h	15	15	13	13	12	10	12	11	10
1/2 min	30/1 h	15	15	13	12	12	10	12	11	10
1/1 min	1/1 min	14	14	12	12	11	10	11	10	9
1/14 s	4.3/1 min	13	12	11	11	9	9	11	9	9
1/9 s	6.7/1 min	12	11	10	10	9	8	10	9	8
1/5 s	12/1 min	10	9	8	8	7	7	8	7	7

TABLE 2.7
Design Goals (in kg) for Carrying of Loads Based on the Liberty Mutual Tables for 75% Acceptable for Women (Snook and Ciriello 1991)(adapted from the tables published in *Ergonomics* published by Taylor & Francis Ltd., see http://www.tandf.co.uk/journals)

		Carrying at about waist height (elbows bent)		
		Distance of Carry [m]		
Frequency		**2.1**	**4.3**	**8.5**
1/8 h	1/8 h	21	21	19
1/30 min	2/1 h	16	16	14
1/5 min	12/1 h	16	16	14
1/2 min	30/1 h	15	15	14
1/1 min	1/1 min	15	15	14
1/20 s	3/1 min	14	12	12
1/10 s	6/1 min	13	11	Out of Range
		Carrying with arms extended below waist (elbows straight)		
		Distance of Carry [m]		
Frequency		**2.1**	**4.3**	**8.5**
1/8 h	1/8 h	25	23	23
1/30 min	2/1 h	19	17	17
1/5 min	12/1 h	19	17	17
1/2 min	30/1 h	18	16	16
1/1 min	1/1 min	18	16	16
1/20 s	3/1 min	17	13	14
1/10 s	6/1 min	16	11	Out of Range

loads increase. The tables have load values for combinations of three travel distances and seven frequencies. For the carrying distance, choose the column that is closest to the actual distance or interpolate between distances. For frequency, choose the one that most closely matches the observed frequency.

The design goals for pushing and for pulling are similar in the information needed to make an evaluation and in the layout of the tables (Tables 2.8 and 2.9). The first consideration is the height of the push or pull point. The high point is about 140 cm (55 in.), the middle point is about 92 cm (36 in.), and the low point is 60 cm (24 in). Choose the point closest to the one used in practice, and this points to the top, middle, or bottom section of the table. Six distances are provided; the one closest to the actual distance should be used, or an interpolated value of distance for a given frequency can be determined. There are combinations of frequencies and distances that are out of range of the original tables, and these are indicated by "OR." Finally, initial and sus-

TABLE 2.8

Design Goals for Horizontal Pushing with a Force Value in Newtons for the Initial Force to Start the Motion and the Sustained Force to Maintain the Motion Based on the Liberty Mutual Tables for 75% Acceptable for Women (Snook and Ciriello 1991)(adapted from the tables published in Ergonomics published by Taylor & Francis Ltd., see http://www.tandf.co.uk/journals)

High Push Point (hands about 140 cm)		Push Distance [m]											
		2.1		7.6		15.2		30.5		45.7		61.0	
Frequency		Initial	Sustained	Initial	Sustained	Initial	Sustained	Initial	Sustained	Initial	Sustained	Initial	Sustained
1/8 h	1/8 h	265	206	235	157	206	127	206	118	206	108	186	88
1/30 min	2/1 h	245	167	225	127	196	108	186	88	186	78	167	59
1/5 min	12/1 h	235	157	216	118	186	98	167	88	167	78	147	59
1/2 min	30/1 h	216	137	196	108	167	88	157	78	157	78	137	59
1/1 min	1/1 min	206	137	196	108	167	88	147	69	147	69	OR	OR
1/30 s	2/1 min	196	137	186	98	167	78	OR	OR	OR	OR	OR	OR
1/15 s	4/1 min	186	118	167	88	OR	*OR*	OR	OR	OR	OR	OR	OR
1/12 s	5/1 min	176	118	OR	OR	OR	OR	OR	OR	OR	OR	OR	OR
1/6 s	10/1 min	167	88	OR	OR	OR	OR	OR	OR	OR	OR	OR	OR

Middle Push Point (hands about 92 cm)		Push Distance [m]											
		2.1		7.6		15.2		30.5		45.7		61.0	
Frequency		Initial	Sustained	Initial	Sustained	Initial	Sustained	Initial	Sustained	Initial	Sustained	Initial	Sustained
1/8 h	1/8 h	265	186	245	167	206	137	206	127	206	118	186	88
1/30 min	2/1 h	245	157	225	127	196	108	186	98	186	88	167	69
1/5 min	12/1 h	235	147	216	127	186	108	176	88	176	78	157	59
1/2 min	30/1 h	216	127	196	108	167	98	157	88	157	78	147	59
1/1 min	1/1 min	206	127	196	108	167	88	147	78	147	69	OR	OR

TABLE 2.8 (Continued)

Middle Push Point (hands about 92 cm)		Push Distance [m]											
		2.1		7.6		15.2		30.5		45.7		61.0	
Frequency		Initial	Sustained	Initial	Sustained	Initial	Sustained	Initial	Sustained	Initial	Sustained	Initial	Sustained
1/30 s	2/1 min	196	127	186	98	157	78	OR	OR	OR	OR	OR	OR
1/15 s	4/1 min	186	118	167	88	OR	OR	OR	OR	OR	OR	OR	OR
1/12 s	5/1 min	176	108	OR	OR	OR	OR	OR	OR	OR	OR	OR	OR
1/6 s	10/1 min	167	78	OR	OR	OR	OR	OR	OR	OR	OR	OR	OR

Low Push Point (hands about 60 cm)		Push Distance [m]											
		2.1		7.6		15.2		30.5		45.7		61.0	
Frequency		Initial	Sustained	Initial	Sustained	Initial	Sustained	Initial	Sustained	Initial	Sustained	Initial	Sustained
1/8 h	1/8 h	206	167	206	147	176	127	176	118	176	108	157	78
1/30 min	2/1 h	196	137	196	118	167	98	157	88	157	78	137	59
1/5 min	12/1 h	186	127	186	118	157	98	147	78	147	78	127	59
1/2 min	30/1 h	167	118	167	108	147	88	137	78	137	69	118	59
1/1 min	1/1 min	167	108	167	98	137	88	127	69	127	69	OR	OR
1/30 s	2/1 min	157	108	157	98	127	78	OR	OR	OR	OR	OR	OR
1/15 s	4/1 min	147	98	137	78	OR	OR	OR	OR	OR	OR	OR	OR
1/12 s	5/1 min	147	88	OR	OR	OR	OR	OR	OR	OR	OR	OR	OR
1/6 s	10/1 min	137	69	OR	OR	OR	OR	OR	OR	OR	OR	OR	OR

OR = Out of range of table

TABLE 2.9
Design Goals for Pulling with a Force Value in Newtons for the Initial Force to Start the Motion and the Sustained Force to Maintain the Motion Based on the Liberty Mutual Tables for 75% Acceptable for Women (Snook and Ciriello 1991) (adapted from the tables published in *Ergonomics* published by Taylor & Francis Ltd., see http://www.tandf.co.uk/journals)

High Pull Point (hands about 140 cm)		Pull Distance [m]											
		2.1		7.6		15.2		30.5		45.7		61.0	
Frequency		Initial	Sustained	Initial	Sustained	Initial	Sustained	Initial	Sustained	Initial	Sustained	Initial	Sustained
1/8 h	1/8 h	255	196	235	176	196	147	196	137	196	118	176	98
1/30 min	2/1 h	245	157	216	137	186	118	176	98	176	88	157	98
1/5 min	12/1 h	235	147	206	127	176	108	167	98	167	88	147	69
1/2 min	30/1 h	206	137	186	118	157	98	157	88	157	88	137	69
1/1 min	1/1 min	196	127	186	118	157	98	137	78	137	78	OR	OR
1/30 s	2/1 min	196	127	176	108	137	88	OR	OR	OR	OR	OR	OR
1/15 s	4/1 min	186	118	157	88	OR	OR	OR	OR	OR	OR	OR	OR
1/12 s	5/1 min	186	118	OR	OR	OR	OR	OR	OR	OR	OR	OR	OR
1/6 s	10/1 min	157	78	OR	OR	OR	OR	OR	OR	OR	OR	OR	OR

Middle Pull Point (hands about 92 cm)		Pull Distance [m]											
		2.1		7.6		15.2		30.5		45.7		61.0	
Frequency		Initial	Sustained	Initial	Sustained	Initial	Sustained	Initial	Sustained	Initial	Sustained	Initial	Sustained
1/8 h	1/8 h	265	186	245	167	206	137	206	127	206	118	186	88
1/30 min	2/1 h	255	157	225	137	196	118	186	98	186	88	167	69
1/5 min	12/1 h	245	147	216	127	186	108	176	88	176	88	157	69
1/2 min	30/1 h	216	127	196	118	167	98	157	88	157	78	147	59
1/1 min	1/1 min	206	127	186	108	167	98	147	78	147	69	OR	OR

TABLE 2.9 (Continued)

Middle Pull Point (hands about 92 cm)		Pull Distance [m]											
		2.1		7.6		15.2		30.5		45.7		61.0	
Frequency		Initial	Sustained	Initial	Sustained	Initial	Sustained	Initial	Sustained	Initial	Sustained	Initial	Sustained
1/30 s	2/1 min	206	127	176	108	137	78	OR	OR	OR	OR	OR	OR
1/15 s	4/1 min	196	118	167	88	OR	OR	OR	OR	OR	OR	OR	OR
1/12 s	5/1 min	186	118	OR	OR	OR	OR	OR	OR	OR	OR	OR	OR
1/6 s	10/1 min	157	78	OR	OR	OR	OR	OR	OR	OR	OR	OR	OR

Low Pull Point (hands about 60 cm)		Pull Distance [m]											
		2.1		7.6		15.2		30.5		45.7		61.0	
Frequency		Initial	Sustained	Initial	Sustained	Initial	Sustained	Initial	Sustained	Initial	Sustained	Initial	Sustained
1/8 h	1/8 h	274	176	255	157	216	127	216	118	216	108	196	88
1/30 min	2/1 h	265	137	235	127	206	108	196	88	196	78	176	59
1/5 min	12/1 h	255	127	225	118	196	98	176	88	176	78	157	59
1/2 min	30/1 h	225	118	206	108	176	88	167	78	167	78	147	59
1/1 min	1/1 min	216	118	196	108	167	88	157	69	157	69	OR	OR
1/30 s	2/1 min	216	118	186	98	147	78	OR	OR	OR	OR	OR	OR
1/15 s	4/1 min	206	108	167	78	OR	OR	OR	OR	OR	OR	OR	OR
1/12 s	5/1 min	196	108	OR	OR	OR	OR	OR	OR	OR	OR	OR	OR
1/6 s	10/1 min	167	69	OR	OR	OR	OR	OR	OR	OR	OR	OR	OR

OR = Out of range of table

tained values are given in the tables. The initial value is the maximum acceptable force to start the object in motion. The lower, sustained force is the maximum force required to keep the object in motion against resistance or gravity. The pushing or pulling task exceeds the design goals when either the initial or sustained force is greater than the table value.

At the higher lifting/lowering frequencies and sustained travel for carrying, pushing, and pulling, the metabolic demands may be high even though the loads are less than the table values. In addition, sustained forces and loads greater than 540 N (25 lb.) for more than one minute may be limited by muscle fatigue.

University of Utah Back Compressive Force Model

An estimate of back compressive force can be obtained by the semiquantitative model of Bloswick (Bloswick and Villnave 2000). Both the moment around the back acting through the extensors and the weight of the body and load contribute to back compressive force. These effects can be estimated through the load, body weight, torso angle, and the distance that the load is held out from the body, as described in Figure 2.17. Bloswick describes the contributors as terms A, B, and C. Term A is the compression caused by the moment of the upper body weight. Term B is the compression caused by the load moment. Term C is the direct compressive component of upper body weight and load. Typically, terms A and B are the largest contributors and the ones most influenced by the job. For comparison, a limit of about 3,100 N (320 kg or 700 lb.) is consistent with the 770 lb. recommended by NIOSH with some allowance for estimation error. If the comparison limit is exceeded, a more detailed biomechanical model may be required for further analysis. Examples of these are those published by the University of Michigan and Ohio State University.

Shoulder Moment

The materials handling guidelines contained in the Liberty Mutual tables are somewhat protective of shoulders as well. For a specific focus on shoulders, Bloswick has suggested a semiquantitative method to assess shoulder moment and to compare the demand against shoulder strength of the 50th percentile, male and female (Bloswick and Villnave 2000). Following the principles described in "Biomechanics of Holding," earlier in this chapter, the moment around the shoulder is the sum of the moment of the load and the mass of the arms. The moment of the load, M_L, is the weight of the load (L) times the horizontal distance of the load from the shoulder joint (d_L):

$$M_L = L \times d_L$$

The moment attributed to the arm alone can be approximated as the weight of the arm and the horizontal distance that the hand is from the shoulder joint.

Job	Analyst
Task	Date

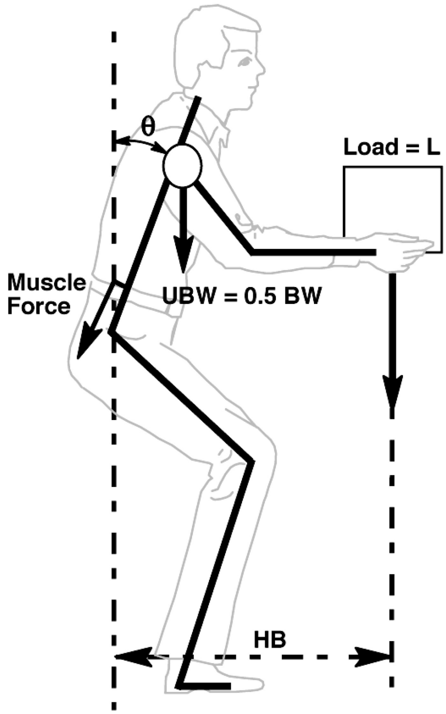
Measure			Symbol	Value
Body Weight [kg] Average body weight for an even gender distribution is 75 kg			BW	[kg]
Load [kg]			L	[kg]
Horizontal Distance [m] (Hands to Lower Back {L5-S1 Joint})			HB	[m]
Back Posture (Angle from Vertical)	**θ [°]**	**sin θ**	θ	[°]
Vertical	0	0.0		
Bent ¼ of the way	23	0.4	sin θ	[—]
Bent ½ of the way	45	0.7		
Bent ¾ of the way	67	0.9		
Horizontal	90	1.0		

Contributor	Computation	Value [N]
Back Posture A = 29(BW) sin θ	29 × ( ) × ( )	
Load Moment B = 190 (L × HB)	190 × ( ) × ( )	
Direct Compression C = 7.5{(BW) ÷ 2 + L}	7.5 × {( ) ÷ 2 + ( )}	
Estimated Compressive Force F_c = A + B + C	Sum computed values in last column. Comparison Value: 3,100 N	

If the estimated compressive forces exceed 3,100 N, consider a more detailed analysis or make changes.

Note: This is just an estimate and its accuracy varies with posture, especially as the hands move forward of the shoulders.

FIGURE 2.17 Estimation of Back Compressive Force (a representation of the model by Donald S. Bloswick at the University of Utah)



F_c (in Newtons) = $(29 \times BW \times \sin\theta) + (190 \times L \times HB) + 7.5 \times \{(BW \div 2) + L\}$
Where all distances are in meters, and mass is in kg.

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FIGURE 2.17 *(Continued)*

Bloswick estimates the moment due to the arm as:

$$M_A = 0.0115 \times BW \times d_L$$

where the arm weight is a fraction (0.0115) of body weight (BW).

While shoulder and elbow posture play roles in shoulder strength, a representative value for the 50th-percentile woman from the Bloswick tables is 325 in/lb. Using a coefficient of variation of 0.25 (Chaffin, Anderson, and Martin 1999), the 25th percentile (75 percent capable) of maximum shoulder moment for women is 31 N/m (270 in/lb or 310 kg/cm).

The estimation of shoulder moment is described in Figure 2.18. The ergonomist should consider the typically greatest shoulder moments, which might occur at the longer distances between shoulder joint and load or from heavier loads. If the estimated moment is greater than the criterion value, further evaluation is appropriate.

Circle Units of Measure	in-lb kg-cm N-m		
Data Entry		**Left**	**Right**
Horizontal Distance from Shoulder to Load	d_L		
Load	L		
Body Weight*	BW		
Computations			
Load Moment (= $d_L \times L$)	M_L		
Arm Moment (= $0.0115 \times d_L \times BW$)	M_A		
Total Moment ($M_L + M_A$)	M_T		
Criterion Moment for M_T	in-lb	270 in-lb	
	kg-cm	310 kg-cm	
	N-m	31 N-m	

*An average body weight for an even distribution of men and women is 165 lb, 75 kg, 730 N.

FIGURE 2.18. Shoulder moment method to evaluate the effect of materials handling on shoulder strength requirements

ACGIH TLV for Hand Activity Level

If job risk factors from the qualitative methods or professional judgment point toward the hands or elbows, a semiquantitative method to look further into the stress is the hand activity level offered by the American Conference of Governmental Industrial Hygienists (ACGIH) in its threshold limit value (TLV) for hand activity (2002). The evaluation is based on an assessment of hand activity and the level of effort for a typical posture while performing a short-cycle task. The data collection form in Figure 2.19 is an adaptation that guides the gathering of information on job risk. The first step is to identify the level of hand activity on a scale of 0 to 10, where 0 is virtually no activity and 10 is the highest imaginable hand activity. Hand activity accounts for the combined influences of effort repetition and effort duration in a qualitative assessment. Because it is a single scale with two factors, attention should be paid to both the repetitiveness, which is an indicator of frequency, and the duration of exertion, which indicates periods of sustained effort. As the opportunity for recovery decreases because of activity and duration, the scale value becomes higher.

The second step characterizes the effort level by noting the effort associated with a typically high force within the cycle of work. The normalized peak

ACGIH TLV for Hand Activity

Job	Analyst	Date
	Left	Right
Hand Activity Level (HAL) (See scale below)		
Normalized Peak Force (NPF) (See table below)		
Ratio = NPF / (10– HAL)		
Determine Result TLV = 0.78 AL = 0.56	> TLV ❑ AL to TLV ❑ < AL ❑	> TLV ❑ AL to TLV ❑ < AL ❑

Hand Activity Level Rating

0	2	4	6	8	10
Hands idle most of the time; no regular exertions	Consistent conspicuous long pauses, or very slow motions	Slow steady motion/ exertions; frequent brief pauses	Steady motion/ exertion; infrequent pauses	Rapid steady motion/ exertions; no regular pauses	Rapid steady motion/ difficulty keeping up or continuous exertion

Estimation of Normalized Peak Force for Hand Forces

%MVC	*Subjective Scale*		*Moore-Garg Observer Scale* (Alternative Method)	*NPF*
	Score	Verbal Anchor		
0	0	Nothing at all		0
5	0.5	Extremely Weak (Just Noticeable)	Barely Noticeable or Relaxed Effort	0.5
10	1	Very Weak		1
20	2	Weak (Light)	Noticeable or Definite Effort	2
30	3	Moderate		3
40	4		Obvious Effort, But Unchanged Facial Expression	4

FIGURE 2.19 Method to determine HAL TLV (adapted from American Conference of Governmental Industrial Hygienists (ACGIH®), *2002 TLVs® and BEIs® Book*. Copyright 2002. Reprinted with permission.

%MVC	*Subjective Scale*		*Moore-Garg Observer Scale* (Alternative Method)	*NPF*
	Score	Verbal Anchor		
50	5	Strong (Heavy)		5
60	6		Substantial Effort with Changed Facial Expression	6
70	7	Very Strong		7
80	8			8
90	9		Uses Shoulder or Truck for Force	9
100	10	Extremely Strong (almost maximum)		10

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FIGURE 2.19 *(Continued)*

force (NPF) is the relative level of effort on a scale of 0 to 10 that a person of average strength would exert in the same posture required by the task. Three methods are suggested here for assessing NPF: (1) percentage of maximum voluntary contraction, (2) subjective reports of perceived exertion, and (3) an observational method borrowed from the Moore-Garg Strain Index (1995). The quantitative method to determine NPF is to measure the typically high exertion (e.g., 90th percentile) and compare it to the average strength of the population for the same posture. Alternatively, the ACGIH suggests obtaining the average rating of perceived exertion for the typically high exertion based on the population of operators that may perform that job. For this approach, see the discussion of the Borg CR10 scale or the documentation for the hand activity level TLV (ACGIH 2002). Another alternative is to borrow the observation scale from the Moore-Garg Strain Index (see "Quantitative Methods") and relate it to the typically high exertion for a population of workers. The psychophysical and observational methods for determining NPF require an appreciation for the lower precision that is likely.

The third step is to compute the ratio of NPF to the value of 10 – HAL. Ratios that are less than the action level (AL) may be monitored but no further analysis is necessary without more evidence of problems. A figure greater than the TLV indicates that more analysis or job redesign is required. Between the AL and the TLV is a region of intermediate risk. For more information, see the TLV and associated documentation (ACGIH 2002). It is best to assume that the band of error around the hand activity scale and the NPF is ± 0.5 units, which makes this better as an evaluation tool than as a design tool.

WISHA Hand-Arm Vibration Analysis

Vibration of the hand and arms from oscillating tools is a risk for WRMSDs. Under the State of Washington Industrial Safety and Health Act (WISHA), the Department of Labor and Industries provides some guidance that was adapted for the analysis form shown in Figure 2.20. If either caution condition is present, a hazard may exist. To make the hazard decision, the level of vibration must be measured or data obtained from the manufacturer or the WISHA Web site. The level of vibration and the total exposure time are compared to the regions on the graph to determine if a hazard or caution level exists.

Quantitative Methods

Quantitative methods may require more effort to collect data, involve processing of the data to reach a decision, focus on a body region, and consider several contributing factors. While professional judgment may lead the ergonomist directly to a quantitative method, a qualitative or semiquantitative method would be a more efficient way when the severity of the risk factors is not clear.

Strength and Biomechanics

In the framework of job analysis at the beginning of this section, the first question raised was the ability and risk associated with a momentary effort. This question is addressed through an understanding of the strength requirements and biomechanics of the effort.

Strength data for various muscle groups and populations are available from the literature and from biomechanical models such as the University of Michigan 3D Static Strength Prediction Program (3DSSPP) (Chaffin, Anderson, and Martin 1999; www.engin.umich.edu/dept/ioe/3DSSPP/). Tables 1.13 to 1.18 provide a summary of many of these sources for different muscle groups and postures. A reasonable evaluation criterion is the 10th-percentile strength from the female population, which should represent about the 5th percentile of an evenly mixed population.

- When the mean (μ) and standard deviation (σ) of the female population is known:

$$\text{Criterion Value}_{\text{female}} = \mu - 1.28 \times \sigma$$

- If only the mean is known, a reasonable approximation of the standard deviation is:

$$\sigma_{\text{approx.}} = 0.30 \times \mu$$

- If the data are reported for a mixed population, then:

Job	Date
Notes	Analyst(s)

The hand-arm vibration analysis on the following page is performed when one or two of the Caution Level job risk factors in the following checklist are present. This checklist is taken from the adapted WISHA checklist.

Moderate to High Hand-Arm Vibration

Body Part	Physical Risk Factor	Duration	Check (□) as applicable
Hands, wrists, and elbows	Using impact wrenches, carpet strippers, chain saws, percussive tools (jackhammers, scalers, riveting or chipping hammers), or other hand tools that typically have high vibration levels	More than 30 minutes total per day	Caution □
	Using grinders, sanders, jigsaws, or other hand tools that typically have moderate vibration levels	More than 2 hours total per day	Caution □
	WISHA HAV Analysis—Perform if any Caution condition exists. Actual exposure time is greater than the Hazard Level Exposure Time (See separate worksheet)		Hazard □

Use the instructions below to determine if a hand-arm vibration hazard exists.

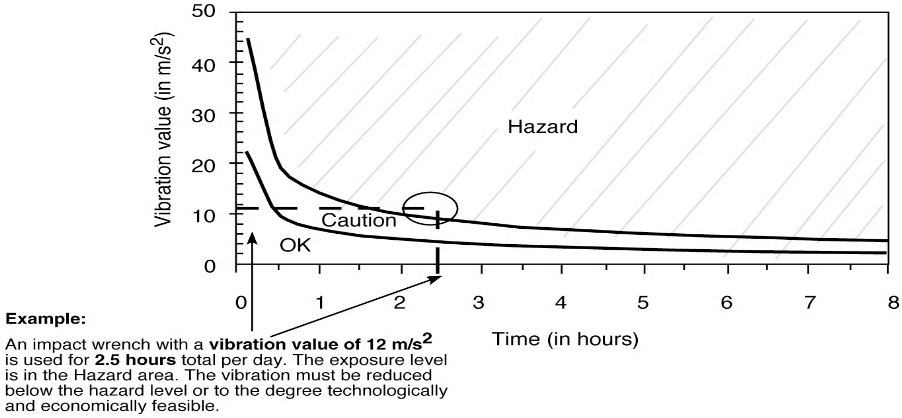
Step 1. Find the vibration value for the tool. (Get it from the manufacturer, look it up at the web site http://umetech.niwl.se/vibration/HAVHome.html, or measure the vibration yourself). The vibration value will be in units of meters per second squared (m/s^2). On the graph below find the point on the left side that is equal to the vibration value.

Step 2. Find out how many total hours per day the employee is using the tool and find that point on the bottom of the graph.

Step 3. Trace a line in from each of these two points until they cross.

Step 4. If that point lies in the crosshatched Hazard area above the upper curve, then the vibration hazard must be reduced below the hazard level or to the degree technologically and economically feasible. If the point lies between the two curves in the Caution area, then the job remains as a Caution Zone Job. If the point falls in the OK area below the bottom curve, then no further steps are required.

FIGURE 2.20. WISHA Hand-Arm Vibration Analysis



Adapted from State of Washington Department of Labor and Industries Ergonomics Rule
See *http://www.ini.wa.gov/wisha/ergo/ergorule.htm*
This version includes the hand-arm vibration section. See *www.hsc.usf.edu/~tbernard/ergotools* for electronic copy.

FIGURE 2.20. *(Continued)*

$$\text{Criterion Value}_{\text{mixed population}} = \mu - 1.64 \times \sigma$$

For instance, the weighted mean grip strength for women in Table 1.13 is 275 N. Because the standard deviation is not available, estimate it as:

$$\sigma_{\text{approx.}} = 0.30 \times \mu = 0.30 \times 275 = 83$$

The criterion grip strength becomes:

$$\text{Criterion Value}_{\text{female}} = \mu - 1.28 \times \sigma = 275 - 1.28 \times 83 = 170 \text{ N}$$

External moments around joints are another useful way of evaluating the strength demands of a task. This is illustrated in the discussion of Figure 2.4 in the "Static Work" section. It is on this principle that the analysis in the "Shoulder Moment" section is built. Using again the three overhead drilling examples of Figure 2.4, the shoulder moments are 13, 21, and 29 Nm. The average shoulder moment for women is 21 Nm (Yates 1980; Table 1.15). The criterion value would be 13 Nm (= 21 − [1.28 × 0.3 × 21]). This means that only the reaching posture of Figure 2.4a would be acceptable for most of the population, based on strength alone.

A number of biomechanical models for the low back are available—for instance, the one outlined in Chaffin, Anderson, and Martin 1999. These are particularly useful for the detailed analysis of a job demands and interventions.

Static Work: Endurance and Work/Recovery Cycles

The difference between the evaluation of a job based on strength and biomechanics and the evaluation of static work is the consideration of time. Strength and biomechanics has no time consideration; that is, the time frame is a moment and the limiting condition is whether there is sufficient strength or an inherent limit of the joint and tendon system. For static work, the concern is fatigue of the muscle group. While rare, it may be an endurance limit with one exertion that is sustained long enough to fatigue the muscle group. More often, it is the cumulative demand of exertions without sufficient recovery between them.

As with the strength limits discussed in the preceding section, the reference or criterion strength is the weakest person, usually taken as the 10th-percentile women. When the strength requirement of a task is taken as the percent of the required force divided by the criterion strength, an endurance limit is predicted by Rohmert's relationship described in Figure 2.10. For the example of the drilling, which in the most favorable posture illustrated required 100 percent of the criterion strength (%MVC), the maximum exertion time is a few seconds.

Using the example of the criterion grip strength of 170 N, if a grip had to be sustained for 30 seconds, the maximum force would depend on the %MVC associated with a 0.5-minute endurance time. From Figure 2.11, this would be about 70 percent. Therefore the criterion grip force would be:

$$170 \text{ N} \times 70\% \div 100\% = 120 \text{ N}$$

As noted above, these endurance times are approximate, and while the figure suggests that they are unlimited below 15 %MVC, this may not be the case.

The endurance limit is based on a one-time effort. If the effort is repeated, there needs to be an adequate recovery time between exertions. In the work design section, guidance is provided on adequate recovery time. From the design point of view, there are three factors that are available for job design: effort time, recovery time, and effort level. For job analysis, these are determined by the existing or proposed job. That is, the effort time, recovery time and absolute effort are known. The relative effort as %MVC is needed to complete the evaluation. %MVC is determined as the effort (i.e., force or moment) divided by the criterion force or moment and the fraction converted to percent. Once this is accomplished, Figure 6.2 is used to make the evaluation. For the effort (or contraction) time and the relative effort (%MVC), a minimum recovery time can be determined. If the minimum recovery time is greater than the allowed recovery time, local muscle fatigue may result and the job demands should be considered more closely with an eye toward redesign.

Dynamic Work: Endurance and Work/Recovery Cycles

The analysis of dynamic work is analogous to static work evaluation. It considers the relative demand of the work on the least fit individual based on population data as well as the work time and recovery time. The time frames are, however, longer—minutes to hours versus seconds to minutes for local muscle fatigue.

The criterion value for dynamic work is the aerobic capacity of the least fit person. As described in "Aerobic Work Capacities" in Chapter 1 and Figure 1.21, the 5th percentile for whole-body demands is about 21 ml/kg/min. In practice, a value of 27 ml/kg/min, about the 25th percentile, is a good criterion value, and this is the one recommended here. If the work involves the upper body (primarily arms and shoulders, and not the legs), the criterion value should be reduced to 19 ml/kg/min. The percent maximum aerobic capacity (%MAC) is the percent ratio of the oxygen demands of the work, a principal measure of dynamic work, and the criterion aerobic capacity.

The endurance time is illustrated in Figure 2.11. For instance, if the work demands require 15 ml/kg/min (e.g., walking at 90 m/min or 3.5 mph), the %MAC is 56 and the associated endurance time is about 60 minutes. If the required work time is greater than this, some consideration should be given to lowering the dynamic work demands. A method to estimate the metabolic demands is provided in the next section.

The time-weighted average of the metabolic demands should not exceed 33 percent, 30 percent, and 25 percent for shift lengths of eight, ten, and twelve hours, respectively. Considering shorter time intervals, the evaluator may consider any cycle of work and ask if the average metabolic demand expressed as the %MAC for the criterion aerobic capacity exceeds the allowed average. If it does, recovery is necessary. Recovery time for an eight-hour shift is illustrated in Figure 6.4.

As with static work analysis, an actual or prospective job can be described as a relative effort expressed as %MAC that is based on an average demand over the cycle of effort time plus recovery time allowed in the cycle. If the time-weighted average is greater than 33 %MAC (or 30 or 25) for an eight-hour shift (or ten-hour or twelve-hour, respectively), the demands may be sufficiently high as to cause fatigue.

Estimation of Metabolic Rate

Dynamic work is quantified by metabolic energy expenditure rate and oxygen consumption rate. Published data on the oxygen demands of work tasks may be used with caution to estimate workload (e.g., Passmore and Durnin 1955). Examples of tabled values are provided in Table 1.21. Over the years, methods have been developed to assess the physical effort (Bernard and Joseph 1994; Garg, Chaffin, and Herrin 1978); these are often based on elemental analyses of job tasks. Similarly, the method of workload estimation described here was developed to help quantify the physical effort levels of jobs for an evaluation of total job demands. When the results of this method were compared to direct measurement of oxygen consumption from twenty-one jobs, the correlation between total points and average oxygen consumption on the job was 0.83 (Rodgers, Caplan, and Nielsen 1976).

Physical effort stress can be assessed by identification of primary and supplementary job requirements by following the process described in Figure 2.21.

	% of Shift	Points*
Primary Activities—Degree of Effort* (Task sheet may be used to assist in data gathering)		
Light (total across all tasks)		
Moderate (total across all tasks)		
Heavy (total across all tasks)		
Total residual (see below)		
Total % of shift (should be 100%)		
Supplementary Activities—Efforts† (circle level of effort and enter number of points)		
Standing/walking	L M H	
Restrained posture	L M H	
Visual or auditory requirements most of the time; restricted head and neck posture (RHN)	L M H	
Fixed external pace	L M H	
Use of small muscle groups up to 1.8 kg or 4 lb	L M H	
Short-duration heavy effort (< 5% of time)	L M H	
Total points		
Oxygen consumption Oxygen consumption (L/min) = 0.012 × (total points − 9)		
Residual Activities		
Other physical activities (supplementary activities)		
Base/nonphysical		
Standby/waiting		
Paid lunch		
Breaks		
Total residual		

†See the data provided in the tables following (titled Degree of Effort and Assignment of Points).

FIGURE 2.21 Estimation of Average Oxygen Consumption for a Full Shift

Task Sheet for Assisted Data Gathering on Primary Activities

Tasks	Time or % of Cycle		
	Light	Moderate	Heavy
Total Time or % of Cycle			

% of Shift	Light	Moderate	Heavy
Total Time / Shift Time or (% of Cycle / % Work)			

Type of Effort	Degree of Effort					
	Light		Moderate		Heavy	
	Weight or Force	Ease of Handling	Weight or Force	Ease of Handling	Weight or Force	Ease of Handling
Lift/carry (weight)	1.8–4.5 kg (4–10 lbm)	Easy/ difficult	5–34 kg (11–75 lbm)	Easy	> 34 kg (75 lbm)	Easy
			5–18 kg (11–40 lbm)	Difficult	> 18 kg (> 40 lbm)	Difficult
Applications of force (force)	18–180 N (4–40 lbf)	Easy	181–335 N (> 40–75 lbf)	Easy	> 335 N (> 75 lbf)	Easy
			111–180 N (> 25–40 lbf)	Difficult	> 180 N (> 40 lbf)	Difficult
Climbing (weight)	18–110 N (4–40 lbf)	Difficult	5–18 kg (11–40 lbm)	Easy	> 18 kg (> 40 lbm)	Easy
	0–4.5 kg (0–10 lbm)	Easy/ difficult	5–11 kg (11–25 lbm)	Difficult	> 11 kg (> 25 lbm)	Difficult

- Examples of difficult handling are lifting and carrying a container of liquid, applying force or supporting a weight on a thin edge instead of a broad surface, or carrying a bulky object when climbing up a ladder.
- Easy handling usually suggests that there are well-designed handholds on the object and that it is compact and well balanced.

FIGURE 2.21 *(Continued)*

Assignment of Points
Primary Activities

Duration	Degree of Effort		
	Light *	Moderate **	Heavy
Occasional (5–25%)	10	16	26
Frequent (26–50%)	19	38	57
Constant (> 50%)	38	76	115

*Omit points for Light if any of the following occur:
Constant Heavy
Constant Moderate
Frequent Moderate and constant Heavy
**Omit points for Moderate effort if the following occurs:
Constant Heavy effort occurs

Supplementary Activities

Type of Effort	Level of Effort and Number of Points		
	Low	Moderate	High
	6	13	22
Standing/Walking	—	25–50% of time	> 50% of time
Restrained Posture (except neck and head)	Sit > 75% of time	Awkward posture > 5% of time	—
Visual or auditory requirements most of the time; Restricted head and neck posture (RHN)	Easily detected, no RHN	Easily detected, with RHN OR Hard to detect no RHN	Hard to detect with RHN
Fixed external pace	—	> 50% of time	—
Use of small muscle groups up to 1.8 kg or 4 lb	—	> 25–50% of time	> 50% of time
Short-duration heavy effort (< 5% of time)	—	Up to 23 kg Up to 50 lbm	> 23 kg > 50 lbm

FIGURE 2.21 *(Continued)*

The analyst finds the intensity of a given task, such as lifting or pushing, by choosing the effort level according to the weights lifted or forces exerted from the degree-of-effort table within the figure. Each job task is similarly analyzed, and the total time as a percent of shift for each level of effort is calculated. A task sheet is provided at the end of the figure to assist in data gathering for the primary activities. The points for primary effort are determined from the degree of effort and the percentage of shift. The balance of the shift includes all other types of activities (total residual). Residual time can be calculated according to the breakdown of activities in the bottom portion of the data collection form in Figure 2.21.

Supplementary effort is recognized via additional points for specific job activities not covered under primary effort. The ranges of weights handled and forces exerted are above recommended values described elsewhere in this book and should not be interpreted as acceptable.

An example illustrates the use of the primary requirements factor in analyzing a specific job. A chemical bagging job involves the following activities:

1. Placing empty bags (1 kg or 2.2 lb.) on loading chutes, sixty times per hour.
2. Pulling the filled bags (23 kg or 50 lb.) down the conveyor line, sixty per hour, forces of 90 newtons or 20 lbf
3. Lifting full bags off the conveyor and onto a pallet, sixty times per hour
4. Procuring supplies (sheaves of empty bags, 25 kg or 55 lb.), eight to ten times per shift
5. Dragging empty pallets to the conveyor area (forces of 180 newtons or 40 lbf), twelve times per shift

The frequent handling of empty bags, except in a sheaf, is not included since bag weight is less than 1.8 kg (4 lb.). The 25-kg (55-lb.) sheaf of bags is relatively easy to handle, so it falls into the moderate-effort category. Dragging the pallet is a moderate effort. Pulling the bag along the conveyor is a light effort. Lifting the bag onto the pallet is a heavy effort because the bag's contents will shift, making it difficult to handle, and the bag has to be turned from vertical to horizontal.

The percent of time in each effort category has to be determined from an activity analysis. In this instance, the large majority of the shift was spent in loading, pulling, and handling the bags; about two hours were spent on each activity each shift, on the average. The auxiliary-supplies handling tasks (pallets and bags) each took about twenty minutes per shift. In summary, then:

Light	Pulling bags for two hours
Moderate	Dragging pallets for twenty minutes; carrying sheaves of bags for twenty minutes
Heavy	Lifting bags for two hours
No effort	Loading empty bags for two hours

If total shift time is 480 minutes, the activity breakdown becomes:

Light	25 percent of time
Moderate	8 percent of time
Heavy	25 percent of time

This leaves 42 percent of the shift in work activities other than handling. These residual activities can be accounted for as:

Other physical effort	25 percent
Breaks	12 percent
Standby or non-physical activities	5 percent

There are 52 points for primary requirements assigned as follows:

25 percent light = 10 points
8 percent moderate = 16 points
5 percent heavy = 26 points

Supplementary requirements of jobs increase the job stress but are significant only at a given intensity (such as the visual attention required) or after a given duration, such as the external pacing. Points are given for each component that exists in a job. Included are points for short-duration heavy effort that occurs for less than 5 percent of the shift and receives no points under primary requirements. The 48 points for the supplementary activities are as follows:

Standing/walking, more than 50 percent of the time = 22 points
Repetitive use of small muscles, 25 percent of the time = 13 points
External pacing, more than 50 percent of the time =13 points

Once the points for the primary and supplementary requirements have been determined, they are added to find the total effort level of the job over an eight-hour shift. The total points for the bagging job come to 52 + 48, or 100. Using the relationship between oxygen consumption and points provided in Figure 2.21, the estimated metabolic demands of the bagging job are about 1.1 liters of oxygen per minute.

NIOSH Revised Lifting Equation

The National Institute for Occupational Safety and Health (NIOSH) first proposed guidelines for lifting in 1981 and updated them in 1991 (Waters et al. 1993) through a revision of the guidance for a recommended weight limit (RWL) for a lifting task. The Revised Lifting Equation as it is presented here is for a lifting task with similar loads, origins and destinations. NIOSH has published *Applications Manual for the Revised NIOSH Lifting Equation* (1994). The reader should consult this publication for the background, justification, detailed equations, and complex lifting tasks. The lifting equation is designed for manual materials handling in which both hands are used about equally; it specifically does not apply to shoveling and patient handling. It acknowledges that one-handed lifts are outside of the intended use.

The RWL and a related parameter, the Lifting Index, are used for the interpretation of results. Figure 2.22 provides a worksheet with supporting information to facilitate the determination of the RWL. The first step is to identify the lifting task and to note the location of the starting point (origin) and the ending point (destination). The first measurement is the horizontal distance from the center point of the ankles to the center of gravity of the load (usually between the two hands). This measurement is recorded for both the origin and destination. Next, the vertical distance from the floor to the origin and destination are measured and recorded. The next measurement is the vertical travel distance that the load has been moved. Usually this is the difference between the vertical distances of the origin and the destination, but it can be greater—for instance, if the load is moved over a barrier. The same value is entered for the origin and destination columns. The load coupling is a subjective decision about how well the load can be grasped and how stable it is. If the center of gravity is unlikely to shift and there are handles to grasp the load, the coupling is good. If there are no handholds and the material may shift in the container, then the coupling is poor. Fair is an intermediate decision. Frequency is the average number of lifts per minute (as measured over a fifteen-minute period) during the job. The last measurement is asymmetry, which is the number of degrees that the load is from the front of the body (i.e., how much twisting of the hips and trunk is necessary). The most critical measurements are the horizontal distance and the frequency. Uncertainty (or lower accuracy) in the other measurements does not affect the RWL very much.

The RWL is computed as a load constant, which is 51 lb or 23 kg, multiplied by a series of six multipliers that have values that range from 0 to 1. The next step is to find the multipliers associated with each of the measurements that were recorded on the worksheet. The first supporting graph has the multipliers for horizontal distance (HM), vertical distance (VM), and vertical distance of travel (DM). For each of these multipliers and for both the origin and destination, the value is found by noting the distance in inches along the horizontal axis and moving up to the appropriate curve. The multiplier value is read to the left on the vertical axis. As can be seen from the graph, the multiplier with the greatest range is the horizontal multiplier, and hence it has greater importance. The coupling multiplier depends somewhat on whether the load is handled from below the waist (either at the origin or at the destination). A supporting table for the coupling multiplier (CM) is provided in the figure. The frequency multiplier (FM) depends on how long that the task is performed during the day and, for the higher frequencies, whether it is performed above or below the waist. If it is done for less than one hour a day, the

NIOSH Revised Lifting Equation

Factor	Code	Origin		Destination	
		Value	Multiplier	Value	Multiplier
Horizontal distance from the ankles [in]	HM				
Vertical distance from the floor [in]	VM				
Vertical distance load moved [in]	DM				
Load coupling: good, fair, poor	CM	G F P		G F P	
Frequency [lifts/min]	FM				
Asymmetry [°]	AM				
Load constant [lb]	LC		51		51
RWL = HM × VM × DM × CM × FM × AM × LC		**Multiply the multipliers together and enter at RWL below**		**Multiply the multipliers together and enter at RWL below**	
Recommended weight limit (lb)	RWL				
Load lifted [lb]	L				
Lifting index LI = L/RWL	LI				

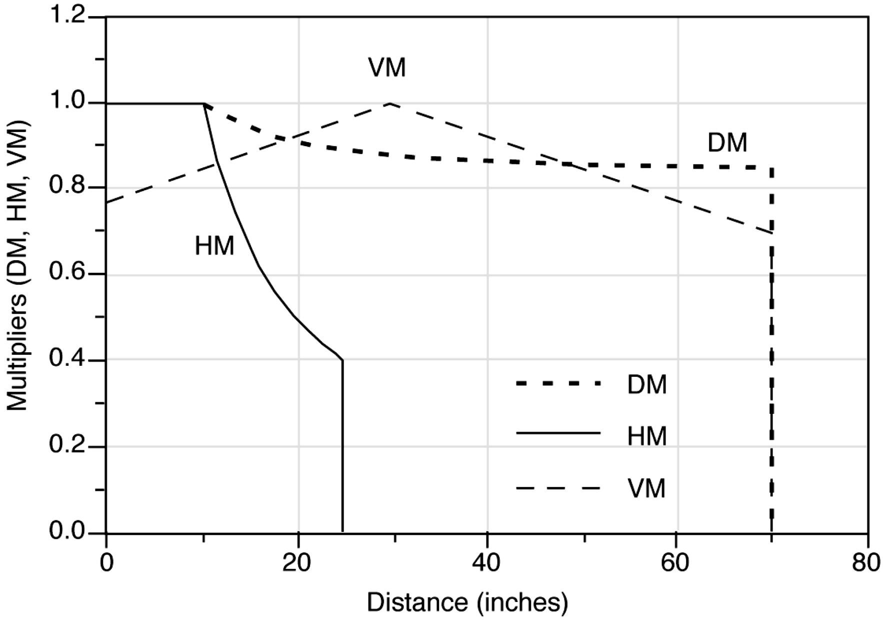
For applications documentation, see the following for a .pdf file: http://www.cdc.gov/niosh/94–110.html

FIGURE 2.22

upper (dashed) curve is used. At the frequencies above twelve per minute and below the waist (< 30 in), the light dashed curve is used. In similar fashion, if the task is performed for one to two hours a day, the middle (solid) curve is followed, with a similar break at ten per minute for lower lifts. Finally, if the task is performed for two to eight hours, the bottom (short dash) curve is used, with a break at 8 per minute for the lower lifts (below 30 in.). Note also that the FM is very sensitive to frequency and therefore is the other very important factor in computing RWL.

The RWL is computed for both the origin and the destination by multiply-

Multipliers for Horizontal (HM) and Vertical (VM) Positions and the Vertical Travel Distance (DM)

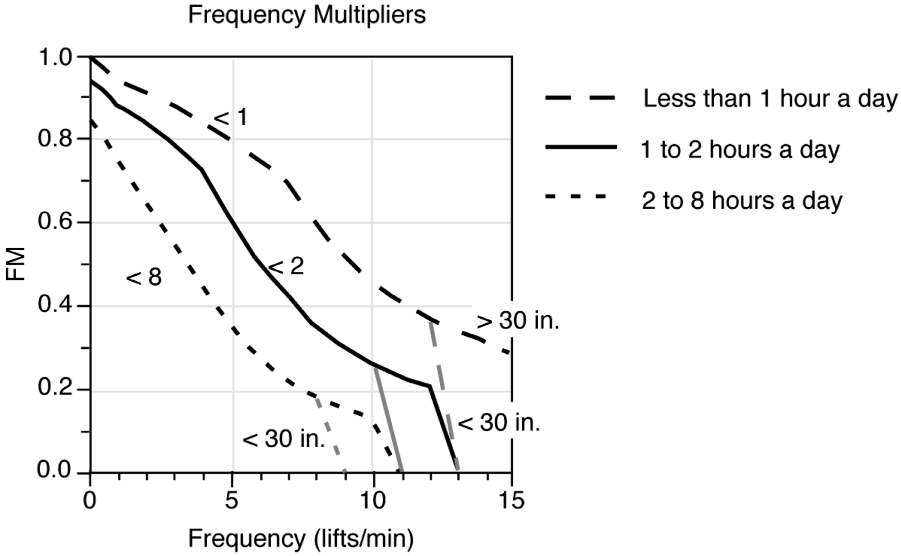


Coupling Multiplier

Coupling	Hand Position at Origin or Destination	
	< 30 inches	> 30 inches
Good	1.00	1.00
Fair	0.95	1.00
Poor	0.90	0.90

FIGURE 2.22 *(Continued)*

ing the six multiplier values together with the load constant. The Lifting Index (LI) is found by dividing the average load handled in this task by the RWL. The greater of the two LIs, origin or destination, is used to represent the task. If there is no control of the load at the destination, such as dropping it, only the origin needs to be considered. An LI of 1 or less is generally accepted as a safe lift with respect to the risk of back injury. Back injuries are clearly associated with LIs greater than 3, which mean that these require immediate attention. There is some evidence that the risk of injuries and the reporting of symptoms will occur much lower than an LI of 3 when there is standing or walking for more than six hours in the day.



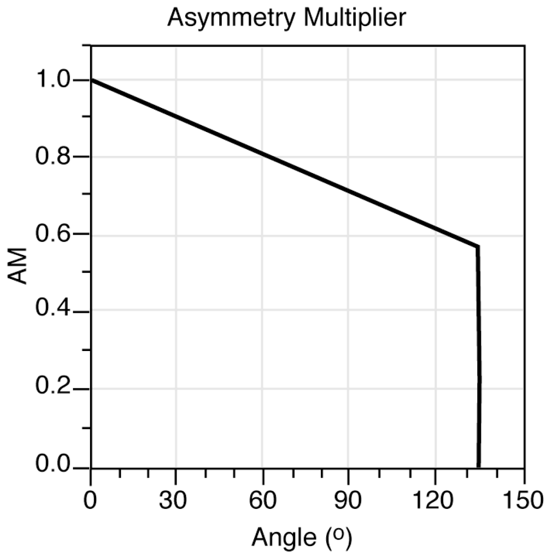


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FIGURE 2.22 *(Continued)*

Task	Analyst
	Date / /

Strain Index	Find rating for each risk factor and multiply them together	SI < 3: safe SI between 3 and 5: uncertain SI between 5 and 7: some risk SI > 7: hazardous			
Risk Factor	**Rating criterion**	**Observation**	**Ratings**	**Left**	**Right**
Intensity of Exertion [Borg Scale values in brackets]	Light	Barely noticeable or relaxed effort [0–2]	1		
	Somewhat hard	Noticeable or definite effort [3]	3		
	Hard	Obvious effort; unchanged expression[4–5]	6		
	Very hard	Substantial effort; changed expression [6–7]	9		
	Near maximal	Uses shoulder or trunk for force [8–10]	13		
Duration of Exertion (% of Cycle)	< 10%		0.5		
	10–29%		1.0		
	30–49%		1.5		
	50–79%		2.0		
	> 80%		3.0		
Efforts Per Minute	< 4		0.5		
	4–8		1.0		
	9–14		1.5		
	15–19		2.0		
	> 20		3.0		
Hand/ Wrist Posture	Very good	Perfectly neutral	1.0		
	Good	Near neutral	1.0		
	Fair	Non-neutral	1.5		
	Bad	Marked deviation	2.0		
	Very bad	Near extreme	3.0		

FIGURE 2.23 Moore-Garg Strain Index

Strain Index	Find rating for each risk factor and multiply them together	SI < 3: safe SI between 3 and 5: uncertain SI between 5 and 7: some risk SI > 7: hazardous			
Risk Factor	**Rating criterion**	**Observation**	**Ratings**	**Left**	**Right**
Speed of Work	Very slow	Extremely relaxed pace	1.0		
	Slow	Taking one's own time	1.0		
	Fair	Normal speed of motion	1.0		
	Fast	Rushed, but able to keep up	1.5		
	Very fast	Rushed and barely/unable to keep up	2.0		
Duration of Task Per Day (hours)	< 1		0.25		
	1–2		0.50		
	2–4		0.75		
	4–8		1.00		
	< 8		1.50		

FIGURE 2.23 *(Continued)*

Moore-Garg Strain Index

The Strain Index was proposed by Moore and Garg (1995) as a means to assess jobs for risk of work-related musculoskeletal disorders (WRMSDs) of the distal upper extremities (hand, wrist, elbow). The three primary risk factors that are considered are the intensity of the effort, the duration of the effort over the cycle of work, and the frequency of efforts. Three other factors modify the risk assessment: wrist posture, speed of work, and duration of task over the day. The Strain Index is intended to include both observational and measured data and to look very closely at a job. For this reason it is included as a quantitative method, and its value is best when used this way. Figure 2.23 is a worksheet that is an adaptation of the method originally proposed.

The Strain Index is computed as a series of six multipliers (called "ratings" in the worksheet) with values that range from 0.25 to 13. The magnitude of the multipliers provides some insight into the importance of each risk factor. For a given task that dominates the work under consideration, the worksheet provides entries for the left and right hands.

Intensity of exertion, the strongest driver of the Strain Index, is an observational factor. Care should be taken, because there is a tendency to overstate this factor. Another important consideration for intensity of exertion is an adjustment for posture. In the following description of levels, the analyst should appreciate that the level of effort depends on posture (e.g., the same external force exerted by the fingers in a neutral posture will require more exertion with a deviated wrist).

Light effort is frequently observed in industrial tasks that are appropriate to the Strain Index, and represents a range of %MVCs (associated with the posture) of 0 to 25. Somewhat hard (from 25 to 35 %MVC) is also common. Less common are hard (from 35 to 55 %MVC) and very hard (from 55 to 75 %MVC). A near maximal exertion is rare, and requires more than 75 %MVC and very noticeable shoulder and trunk involvement. After observing each hand, place the rating for each hand in the spaces provided.

Duration of exertion and efforts per minute are quantitative measures. Duration of exertion is best measured using a stopwatch to note the total time during a work cycle in which the muscles are active (under load) for a given intensity of effort. The percent of the cycle is then computed as the duration of exertion divided by the cycle time (expressed in percents). The number of efforts is counted, and the frequency is the number of efforts divided by the cycle time in minutes. For each of these and for each hand, place the appropriate rating in the spaces provided on the worksheet.

Hand/wrist posture and speed of work are observational data. While posture is accounted for in intensity of exertion, it is also factored into the Strain Index here, but with smaller ratings. A very good and good posture appear to be very near the neutral posture for the hand and wrist and do not carry any additional risk. Fair is a noticeable deviation of the wrist, while an evaluation of bad is a clear deviation and one of very bad is a near extreme deviation from a neutral posture.

Speed of work accounts for an additional loading of the muscles and tendons when the work is rushed. Therefore, the observed speed of work—from extremely relaxed pace to normal speed of motion—has a rating of 1.0 and a fine distinction is not required. Fast indicates an ability to keep the pace, but there is little margin for delays or time for pauses. Rushed is associated with a near maximal pace.

The duration of the task per day is known from the work assignments and length of shift. This recognizes the benefits of performing the task for less than whole shifts and risk for working longer than eight hours.

The Strain Index is computed for each hand as the product of the six ratings that were noted on the worksheet. A single decision point for prioritizing the job for modification at a Strain Index of 5 appears to be emerging from further use of the Strain Index. Values greater than 7 clearly deserve more attention.

Dynamic Work: Heart Rate Analysis

The heart rate, usually expressed in beats per minute, is the most convenient physiological measure of job stress. Increased rates can reflect the stress of the following types of job conditions (Brouha 1970; Lehmann 1962; Sternbach 1966):

- Physical effort
- Environmental heat and/or humidity
- Psychological stress and/or time pressure
- Some types of decision making and perceptual work
- Other environmental factors (such as some chemicals, noise)
- Combinations of the above factors

In addition, the heart rate reflects an individual's capacity for the work. The ease of use and low cost of heart rate data loggers and pulse meters makes using heart rate assessment practical for the workplace. This section describes the information on physical work demands, mainly associated with dynamic work, that can be collected from monitoring the heart rates of people in the workplace. Because of interindividual variability, the analysis of heart rate (HR) is most useful if the person studied on the job is typical of most other people or, preferably, represents the least aerobically fit. Because people also vary in their physiological responses to job stress, one approach to ensuring that the job demands are being properly assessed is to measure several people on the same job. The analysis will also show how people adapt to the work demands depending on their capacity for work. For instance, the length of the recovery periods between work periods will determine how low the heart rate falls and, therefore, how high it will go during the next work period.

Figure 2.24 shows a typical heart rate trace by monitoring a person doing a physically demanding job on a shipping dock for four hours. The level and pattern of the heart rate demonstrates the large amount of information such a trace provides. The horizontal dotted line (A) at 124 beats per minute represents the average heart rate over the four-hour period. Peak heart rates at B, C, D, and E are associated with manual handling of shipping cases of the product for three to five minutes at a time. The resting heart rate at the beginning of the shift is shown at the left of the graph (F). Several recovery heart rates during paperwork (G) and breaks (H) are also indicated. A line sloping upward to the right (I) near the center of the graph indicates incomplete recovery with a gradually rising recovery heart rate level as the intermittent heavy lifting work continues. Each of these measures can be used to assess the demands of jobs on workers.

Most often heart rate data are evaluated as absolute values. An alternative way of looking at heart rate responses is the average heart rate (HR_{ave}) as an elevation above rest (HR_{rest}) in relation to predicted maximum heart rate (HR_{max}) (Bernard and Kenney 1994). HR_{max} can be roughly estimated by subtracting a person's age from 220 (Åstrand and Rodahl 1977). To estimate the percent of the maximum HR range ($\%HR_{range}$) required by a job or job activity:

$$\%HR_{range} = 100\% \times (HR_{ave} - HR_{rest}) / (\text{Predicted } HR_{max} - HR_{rest})$$

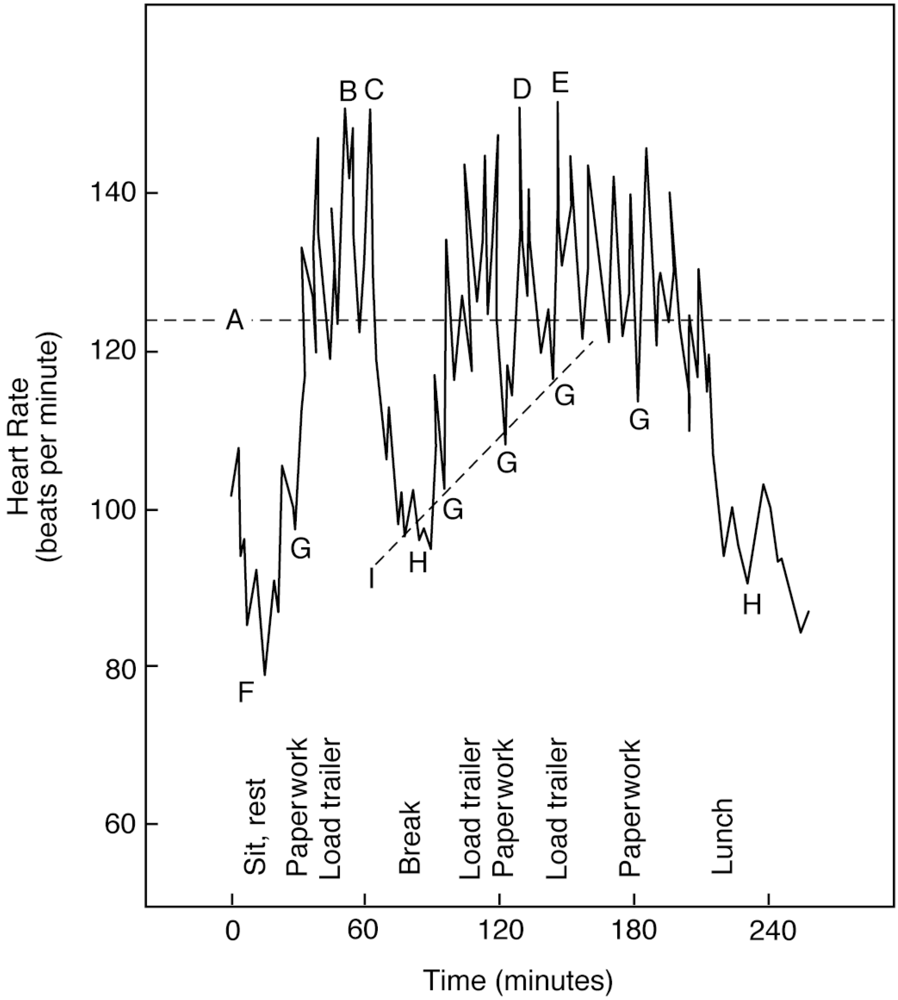

FIGURE 2.24. Pattern of heart rate response to work on a loading dock

For many tasks, the $\%HR_{range}$ is closely related to the percent of maximum aerobic capacity (%MAC) required to perform the work. This is especially true if moderate to heavy whole-body work, such as lifting boxes onto pallets, is done in temperate workplaces. Therefore, if more than 33 $\%HR_{range}$ for whole-body work is required during the shift, the typical worker is likely to become fatigued. In most instances, people will structure their work to include lighter activities that reduce the average effort level to 33 $\%HR_{range}$ or less. When a worker does not have control over work pace, as can happen during work on a machine-paced task, workloads requiring more than 33 $\%HR_{range}$ are more likely to occur. By expressing the heart rate responses of an individual on the job in relation to his or her fitness level, you can determine the percentage of the potential workforce that may find the job difficult based on its total and peak demands. For instance, a handling task that requires 40 percent of aerobic capacity for a very fit person will be too difficult for most people. If it takes, on the average, 30 percent of the capacity of a person who has below-average fitness, most people should be able to do it without excessive fatigue.

When other environmental stressors such as heat stress are present, the HR_{rest} helps to indicate the level of those stresses (Bernard and Kenney 1994). The equivalent %MAC can be used to assess how much of the heart rate response is associated with the physical workload. The difference between the HR_{rest} and %MAC can also indicate the nonphysical stress level. Studies of the same activity (driving a fire truck) under training and emergency conditions, for example, show $\%HR_{range}$ of 30 and 50, respectively. The emergency stress, therefore, was calculated to account for (50 – 30)/50, or about 40 percent of the total heart rate elevation.

This approach to distinguishing different job stresses is useful in defining the most effective intervention for reducing job stress. For example, a job in which a person must lift cases in a hot environment can be improved either by reducing the lifting requirements or by cooling the environment. If the lifting task is relatively heavy and difficult in any environment, simply reducing the heat level may not be the most effective intervention. Reducing the workload through redesign of the handling task could result in increased productivity and permit the hotter environment to be more easily tolerated, especially if heat is only a factor in the summer months.

An increase in resting heart rate over time is often an indication of a fatiguing work pattern indicating incomplete recovery from work (Brouha 1967; Bernard and Kenney 1994). Figure 2.24 shows this gradually increasing heart rate level on a job where heat was present and the workload was heavy and intermittent. The increasing level of resting heart rate (between activities) as the shift proceeds can be attributed to heat stress or increasing levels of fatigue. From the heart rate trace, it is possible to determine the duration of elevation of the heart rate above the usual levels as well as the magnitude of the increase.

To assess the peak loads in a job, one has to look at both the intensity and the duration of the load. A one-minute heart rate of 150 beats per minute, for instance, may be less stressful than a 5-minute heart rate of 130 beats per minute. On the other hand, a one-minute heart rate of 180 beats per minute for a person over 40 years of age would be undesirable because it could represent a maximum level of work for the heart.

After a period of heavy effort, heat exposure, or an emergency, the elevated heart rate will drop toward its resting level. The rate of fall of the heart rate is a function of the individual's cardiovascular fitness, the duration of the previous stress, the nature of the activity done, and the environmental conditions during the recovery period. Other factors also influence the rate and level of recovery of the heart rate on the job. In field job studies, the heart rate recovery can be used to estimate an individual's capacity to perform the work. A fast recovery rate after a physically demanding task indicates adequate capacity of the individual to perform the work, whereas a sustained or slowly falling heart rate indicates insufficient capacity. Generally, a recovery heart rate, taken one minute after stopping work and sitting, of less than 110 beats per minute indicates good recovery. A recovery heart rate of more than 120 beats per minute means that the job has caused, or will cause if continued, excessive cardiovascular strain. Recovery heart rates between 110 and 120 may be indicative of impending excessive strain.

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3 Workplace Design

Guidelines for the design of workplaces and workstations are presented in this chapter. Subjects discussed include layout, seating, clearances, and adjustments to accommodate individual differences in size and strength.

A workplace is a location where a person or people perform tasks for a relatively long period. These periods may be interspersed with other activities that require the person to leave the workplace, such as procuring work supplies or disposing of the finished product. A workstation is one of a series of workplaces that may be occupied or used by the same person sequentially when performing his or her job. The part or product is moved between stations either by equipment (such as conveyors) or by the operator. Workstations may also be locations where a person performs a task for short durations, such as monitoring or recording information from instrument panels. Additional information on controls and displays may be found in Chapter 4, "Equipment Design."

Workplaces should be designed so that most people can safely and effectively perform the required tasks. Reaches, size, muscle strength, and visual capabilities have to be considered when developing design criteria (see "For Whom Do We Design?" in Chapter 1). Although reaches can be extended by stretching or leaning, and muscle strengths increased by provision of tools or other aids, designing workplaces to fit most people's capabilities helps to reduce unnecessary job stress and increase productive work.

Seven major topics are discussed in this chapter:

- General workplace layout and dimensions
- Computer workstations
- Laboratory workspaces
- Visual work dimensions
- Aisles, ramps, and stairs
- Conveyors
- Adjustable workstations

GENERAL WORKPLACE LAYOUT AND DIMENSIONS

The way a production or office area is laid out can have an effect on how efficiently people do their jobs. The design of a large production system, for instance, can determine the staffing needs of an operation. Extended travel distances and lack of space to store supplies or to inventory product can put excessive time pressure on an operator who is trying to keep a machine running.

Some general considerations when laying out a production workplace or office area are as follows:

- Services needed by several people should be placed in a central location.
- The communications needs of different operations should be evaluated, and people or workplaces should be located to maximize communication.
- Lines of sight and other visual requirements for operations should be kept clear. For example, it is important to be able to see from a control console to manufacturing equipment.
- Noisy, heat-producing, odor-producing, or visually distracting operations should be modified or located to minimize their effects on other operations.
- The work area should be arranged so the product can flow through it, preferably in one direction, with minimal rehandling.
- Workstations should be designed to permit people a minimum separation of 122 cm (48 in.), with 244 cm (96 in.) being more desirable (Hall 1966).
- Postural flexibility and change should be provided. A person should not be restricted to a workplace in such a way that he or she cannot change posture during the shift.

There are three major categories of workplace: sitting, standing, and sit/stand. Choice of the appropriate one depends on the task to be performed. Table 3.1 indicates the recommended workplaces for combinations of tasks often found in industry.

Some general characteristics of workplaces in each of the three categories are summarized below.

Sitting workplaces are best in the following situations:

- All items needed in the short-term task cycle can be easily supplied and handled within the seated workspace.
- The items being handled do not require the hands to work at an average level of more than 15 cm (6 in.) above the work surface.
- No large forces are required, such as handling weights greater than 4.5 kg (10 lb.) (adapted from Rehnlund 1973). These large forces may be eliminated by using mechanical assists.
- Fine assembly or writing tasks are done for a majority of the shift.

Standing workplaces will be the best alternative in the following circumstances:

- If the workplace or workstation does not have knee clearance for a seated operation.

TABLE 3.1
Choice of Workplace by Task Variables (developed from information in Ely, Thomson, and Orlansky 1963b; Murrell 1965; Rehnlund 1973; Woodson 1981).

Parameters	Heavy Load or Forces	Intermittent Work	Extended Work Envelope	Variable Tasks	Variable Surface Height	Repetitive Movements	Visual Attention	Fine Manipulation	Duration > 4 hrs
Heavy Load or Forces		ST	ST	ST	ST	ST	ST	ST	ST/C
Intermittent Work			ST	ST	ST	S or ST	S or ST	S or ST	S or ST
Extended Work Envelope				St	ST	ST	ST	ST	ST/C
Variable Tasks					ST	ST	ST	ST	ST/C
Variable Surface Height						S	S	S	S
Repetitive Movements							S	S	S
Visual Attention								S	S
Fine Manipulation									S
Duration > 4 hrs									

Note: S = sitting; ST = standing; ST/C = standing, with chair available
Job and workplace characteristics are looked at, two at a time, in relation to the preferred workplace choice: sitting, standing, or standing with a chair provided. More than one type of workplace may be acceptable for these task combinations; the most appropriate choice is indicated.

- Objects weighing more than 4.5 kg (10 lb) are handled.
- High, low, or extended reaches, such as those in front of the body, are frequently required.
- Operations are physically separated and require frequent movement between workstations.
- Downward forces must be exerted, as in wrapping and packing operations.

In operations where a standing workplace is used for a majority of the shift, provision should be made for sitting down during machine or other slack time. It is desirable to minimize static standing operations by having the operator move outside the immediate work area several times per hour (see "The Standing Work Area"). Such movement, however, should not be made a regularly occurring part of a short-duration, highly repetitive work cycle. Provision of floor mats at the workplace also reduces discomfort for people whose job requires them to stand all day. Where safety considerations prevent the use of floor mats, shoes with cushioned soles may increase a person's comfort in a standing workplace.

Whereas jobs may combine elements that favor each type of workplace, some priorities have to be established between or among the tasks. Some guidelines for this choice are as follows:

- The duration for each task should be assessed. Those that make up the majority of the work time should take precedence in establishing the type of workplace used.
- If critical visual tasks are involved, workplace choice should be geared to them, especially if they are a major part of the job.

In addition to general guidelines for the selection and design of sitting and standing workplaces, this section gives information about the design of two specific types of workplaces: computer workstations and chemical hoods and glove boxes. Computer workstations may require extended visual work along with keyboard and mouse use. Chemical hoods and glove boxes require the operator to work behind a protective barrier or in gloves attached to arm ports. These special requirements should be considered in the design process.

Sitting Workplaces

The Seated Work Area

Seated operators generally work in the space above the working surface. For the determination of where parts or controls may be located, it is necessary to visualize a three-dimensional space in front of the operator (Figure 3.1).

The maximum forward reach of a woman with short arms (5th percentile) is shown in Figure 3.2. As the reach is located farther to the right of the body's

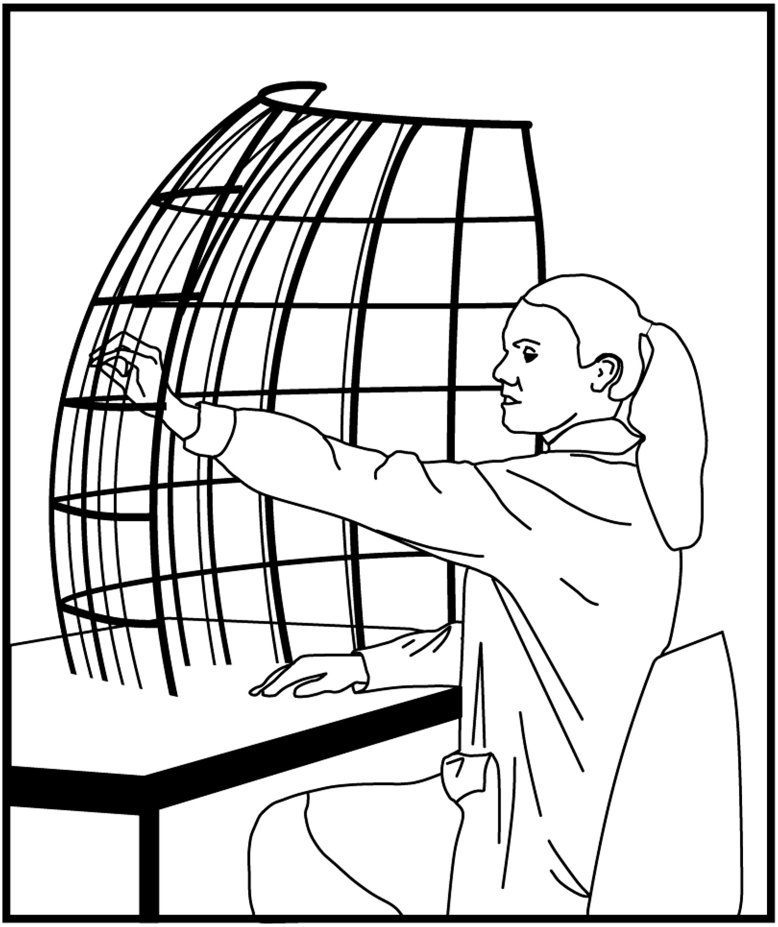


FIGURE 3.1 The Seated Workspace
The operator is seated behind a three-dimensional model that represents the reach capability of a person with short arms (5th percentile). The reach distances are shown for several different heights above the working surface. The operator's chair has been adjusted so that the work surface is at elbow height. The reaches are from the front of the workplace without leaning forward or stretching. See Figure 3.2 for the reach distances.

centerline in the usual work posture, the forward reach capability is also reduced. The dimensions shown are that for the work area on the right side only. The workspace on the left can be treated as a mirror image of the right.

For example, if a workplace is used to pack small items into a kit, the distance from the center of the workplace to each supply bin should be designed to be within this seated arm reach workspace. Suppose that eight items had to be clustered around the kit assembly area, and at least a 25 × 25 cm (10 × 10 in.) work area was needed in front of the operator. Supply bins would then be more than 25 cm (10 in.) in front of the operator near the work surface. For

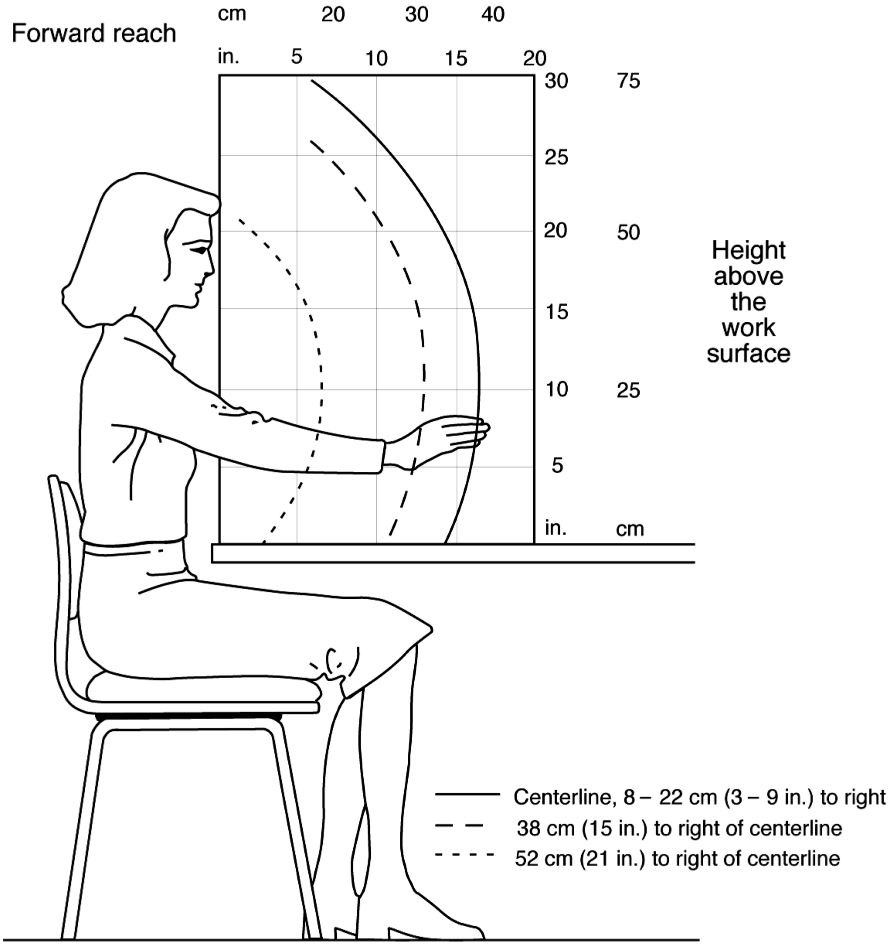


FIGURE 3.2 Forward Reach Capability of a Small Operator, Seated (developed from data in Faulkner and Day 1970)

Three curves describe the seated reach workspace for a 5th-percentile female's right hand. The view is from the side, similar to the angle in Figure 3.1. The forward reach capability (horizontal axis) is affected by the height of the hands above the work surface (vertical axis) and by the arm's distance to the right of the body's centerline, as indicated by the three curves defined at the bottom of the figure. At 25 cm (10 in.) above the work surface, for example, the forward reach is 41 cm (16 in.) if the arm is within 23 cm (9 in.) of the centerline; if it is moved 53 cm (21 in.) to the right, forward reach falls to 18 cm (7 in.).

the most efficient work motions, the bins should be placed within 41 cm (16 in.) to the right or left of the center of the workplace and not more than 50 cm (20 in.) above the surface (preferably lower). To avoid fatiguing the shoulder muscles, one might decide to keep the procurement of items from supply bins 25 cm (10 in.) above the work surface. This technique would limit the comfortable reach distance to the left or right of the body's centerline to 41 cm (16 in.) and to about 36 cm (14 in.) in front of the operator. Although more extended reaches can be made occasionally (a few times an hour), such as leaning forward or to the side to procure something outside the work area, they should not be incorporated into a highly repetitive assembly task such as kit assembly.

Because these values represent people with less reach capability, it is advisable to add an 8-cm (3-in.) foldout extension to the front of the workplace or to provide a chair with adjustable armrests. These armrests permit people with long forearms to rest their arms during repetitive assembly or inspection operations.

Any object that is to be frequently grasped or procured should be located within 15–36 cm (6–14 in.) of the front of the work surface. These ranges are the distances from which small objects can be procured without requiring the operator to bend forward. Large or heavy objects will need to be located closer to the front of the workplace.

Seated Workplace Height

The correct seated working height depends on the nature of the tasks being performed. A majority of manual tasks, such as writing and light assembly, are most easily performed if the work is at elbow height. If the job requires perception of fine detail, it may be necessary to raise the work to bring it closer to the eyes.

Seated workplaces should be provided with adjustable chairs and footrests. The recommended workplace dimensions for most seated tasks are shown in Figure 3.3. Workplaces for people in wheelchairs should also follow these guidelines. Sitting wells should be at least 81 cm (32 in.) wide under the work surface (Mueller 1979). If possible, the sitting well should also be 100 cm (39 in.) deep, to allow the user to stretch his or her legs when sitting.

For specialized workplaces (i.e., where manipulative tasks require only small arm, hand, and finger movements), the task should be located according to its visual requirements. It should be possible to raise the work surface or arm supports to function as elbow supports. Sitting workplaces that are raised to provide arm support, extra storage space, or more convenience to the operator should not be raised to more than 91 cm (36 in.) above the floor (Champney 1975; Faulkner 1968). A footrest must be provided.

Standing Workplaces

The Standing Work Area

Standing operators often work in an area around a machine instead of at a given workplace. Even when the operator is free to move about, all handled items and controls should be positioned to eliminate excessive reaches, stooping and bending, twisting the body, and unnatural head positions because of

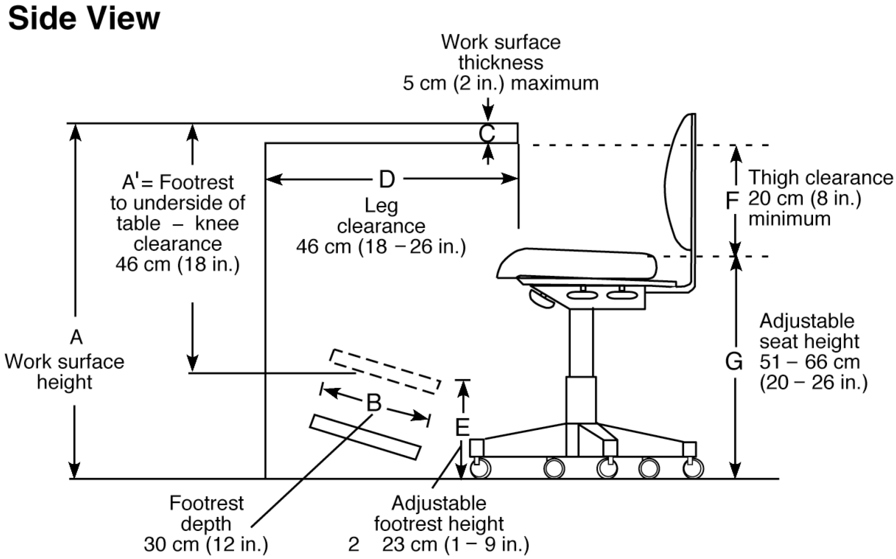


FIGURE 3.3 Recommended Dimensions for a Seated Workplace with a Footrest (adapted from Champney 1975; Faulkner 1968)
The heights, clearances, and work surface thickness of a seated workplace with a footrest and an adjustable chair are given. These design guidelines ensure that most people will be able to work comfortably at the workplace. Based on the work surface height the chair (G) and footrest (E) heights should be adjustable to provide adequate thigh clearance (F) and leg comfort. Forward leg clearances: D is the recommended distance under the work surface. Seat and footrest adjustabilities are important in accommodating differences in size of people using a seated workplace. A′ indicates the minimum knee clearance required between the underside of the worksurface and the top of the footrest when set at its highest position.

visual requirements. Figures 3.4 and 3.5 illustrate the standing workplace area for forward reaches with one arm and both arms without bending the trunk forward.

The reach of the left arm can be considered a mirror image of the pattern for the right arm. Without excessive stretching or leaning forward, most people can reach about 46 cm (18 in.) directly in front of the arm, as long as the object is 110 to 165 cm (43 to 65 in.) above the floor and not more than 46 cm (18 in.) to the side of the body centerline. At further distances to the side or heights less than or greater than the above range, forward reach capability falls off. The operator can achieve an extended reach only by leaning, stretching, stooping, or crouching; these postures can all produce fatigue if they have to be assumed frequently or maintained for periods longer than a minute.

For tasks where two hands must be used, such as steadying and controlling an object or manipulating dual controls, the acceptable forward reaches

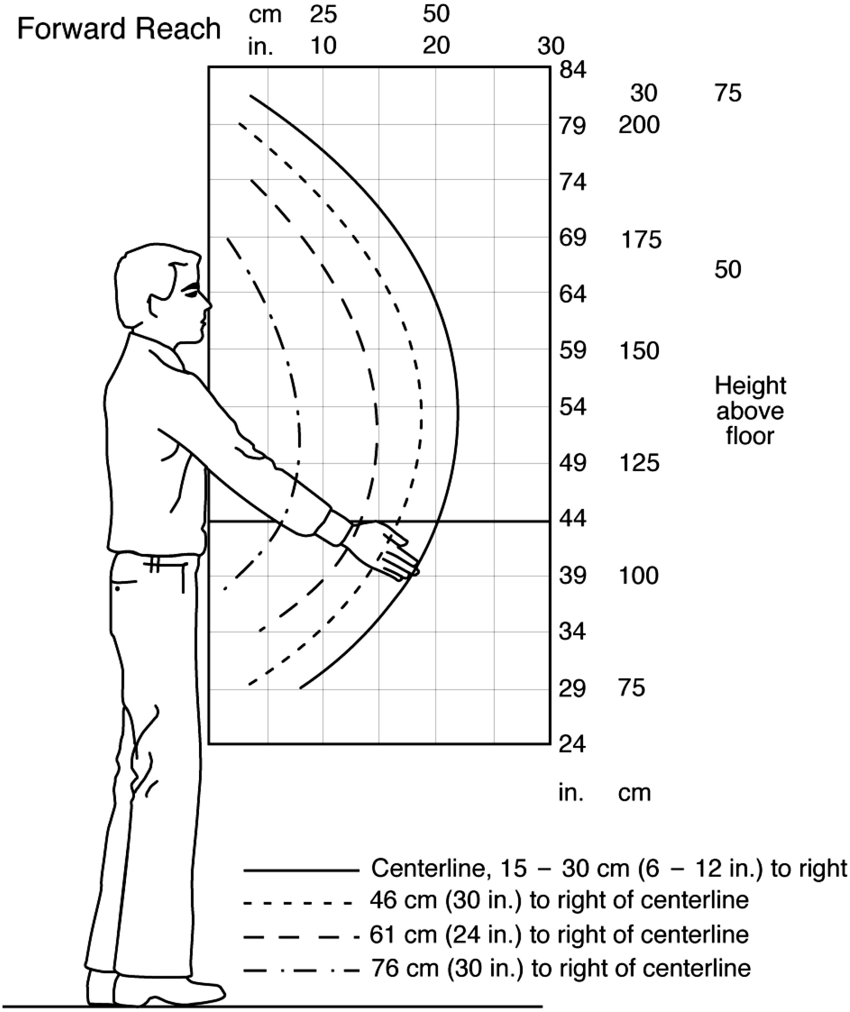


FIGURE 3.4 The Standing Reach Area, One Arm (adapted from Muller-Borer 1981)
Four curves describe the forward reach from the front of the body at different heights of the hand above the floor for a 5th-percentile person (see Chapter 6, Appendix A). Distances are in centimeters (cm) and inches (in.). No leaning forward was permitted. The four curves represent forward reaches at different distances to the right of the body's centerline, as described at the bottom of the graph. The outermost curve shows the forward reach capability within 30 cm (12 in.) of the center of the body. Once the arm is positioned more than 30 cm (12 in.) to the right, there is a rapid reduction in forward reach capability at all heights above the floor. The dark line at 112 cm (44 in.) on the horizontal axis illustrates, by its intersection with the four curves, this reduction in forward reach with lateral arm movement; maximum forward reach falls from 51 cm (20 in.) to 15 cm (6 in.) as the arm moves 76 cm (30 in.) to the right. The left arm's forward reach capability can be considered to be the same, using distance to the left of the body's centerline to define the four curves.

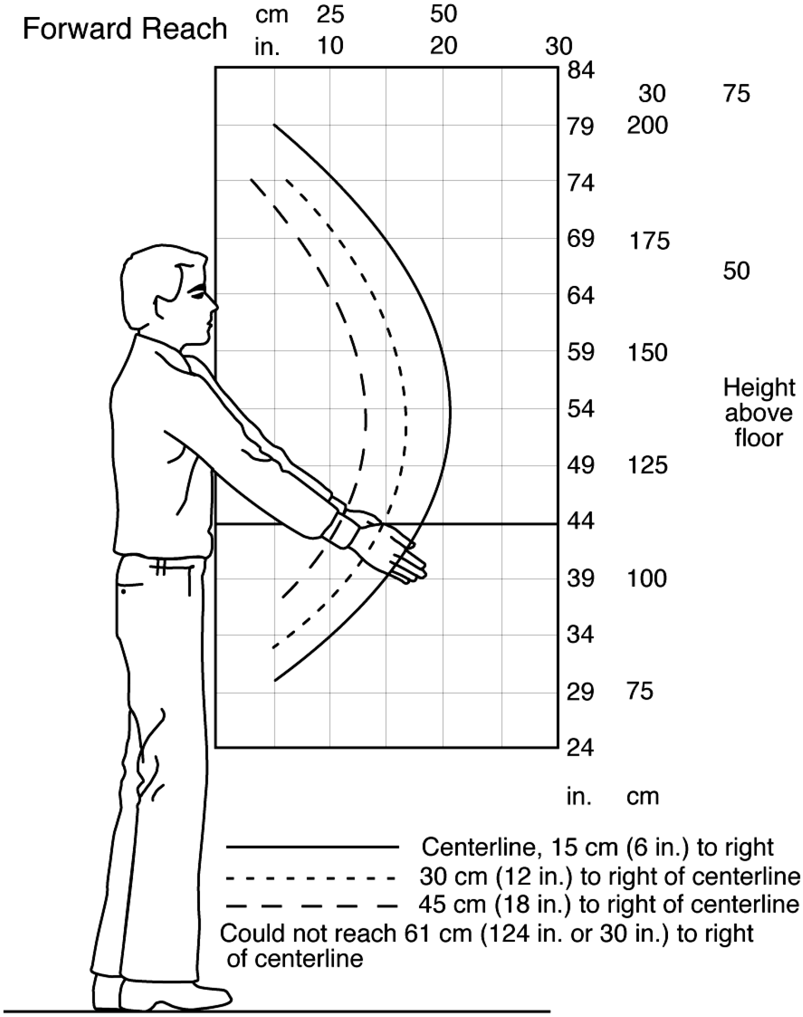


FIGURE 3.5 The Standing Reach Area, Two Arms (adapted from Muller-Borer 1981) *Three curves describe the forward reach from the front of the body for both arms together at different heights of the hands above the floor. Distances are in centimeters (cm) and inches (in.). No bending or leaning forward was permitted. The three curves describe forward reach capability at 15, 30, and 46 cm (6, 12, and 18 in.) to the right of the body's centerline. Reaches greater than 46 cm (18 in.) to the right could not be done because the left arm could not reach that far. The dark line at 112 cm (44 in.) illustrates, by its intersection with the three curves, how forward reach decreases as the arm moves laterally; it falls from 51 cm (20 in.) to 36 cm (14 in.) with a 46-cm (18-in.) move to the right of the centerline. Forward reach is only marginally shorter for two-handed tasks than it is for one-handed tasks within the 46-cm (18-in.) lateral limit (see Figure 2.5), except at the lowest and highest points above the floor.*

are somewhat less than those for one-handed tasks. Because of restriction of arm movement across the body, the most extensive forward reaches (about 51 cm, or 20 in.) are within 15 cm (6 in.) of either side of the body centerline. The furthest two-handed reaches to the side are only about 46 cm (18 in.) from the body centerline; at this point only 25–36 cm (10–14 in.) of forward reach is possible without bending forward (at a working height of 110–165 cm). Please note that most working *surfaces* are less than 110 cm (43 in.) off the floor, so functional forward reach will be less. If the arm has to be bent (e.g., to orient a tool), then at a working height of 100 cm (39 in.), the functional forward reach is at least 20 cm (8 in.)

For occasional standing tasks where sustained activity is not required (such as activating a switch or marking a record), forward reach can be extended by bending forward over a work surface. If the bend can be made at the hips, an additional 36 cm (14 in.) of forward reach can be obtained. If the bend has to be made at the waist, as in leaning over an 89-cm (35-in.) barrier, forward reach can be extended only 20 cm (8 in.) (Muller-Borer 1981). For more anthropometric data on reach capability, see “For Whom Do We Design?” in Chapter 1.

Standing Workplace Height

Standing workplaces should be designed according to the dimensions indicated in Figure 3.6. The optimal working height of the hands (A) is determined by compromise based on analysis of the total work sequence, as follows:

- For light assembly, writing, and packing tasks, the optimal working height of the hands (A) is 107 cm (42 in.).
- For tasks requiring large downward or sideward forces, such as casing operations and using a planning tool, the working height of the hands (A) should be at 91 cm (36 in.). For heavy force exertions, lowering heights to about 76 cm (30 in.) may be appropriate.
- For tasks requiring large upward forces, as in clearing machine jams and removing components, the optimal working height of the hands (A) is 81 cm (32 in.).
- Visually demanding tasks should have the items placed above elbow height by at least 5–10 cm (2–4 in.) to reduce the stress on the neck.
- The difference (B) between optimal working height (A) and the table surface height (C) is determined by the size of the objects being handled. Thus, several values may result for B, each dependent on the particular item being handled and the optimal work method. Distance B should be adjustable to the height that allows the hands to be at the levels recommended for A above most of the time. Bench cutouts or elevations should be provided to accommodate particular instruments that would be awkward to operate if placed on the bench surface.

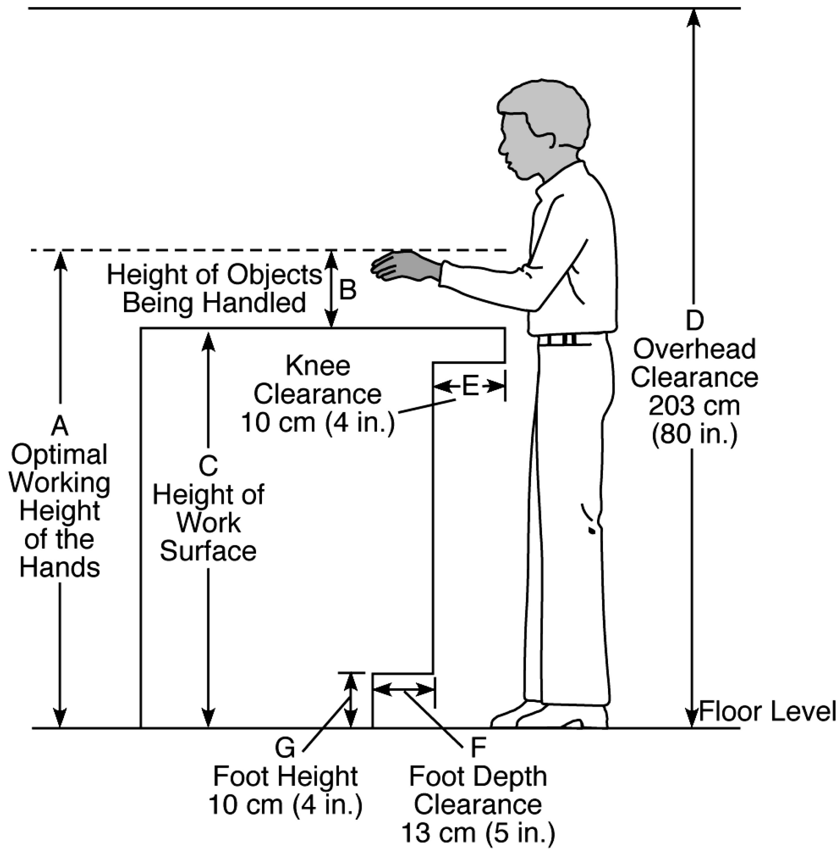


FIGURE 3.6 Recommended Standing Workplace Dimensions (adapted from Champney 1975; Faulkner 1970; additional information from Kroemer 1971)
Workplace height (C) and overhead (D), knee (E), and foot (F and G) clearances are indicated for a typical standing workbench. The knee and foot clearances (E, F, and G) permit the operator to stand with knees bent and feet pointed straight ahead. Work height (C) varies according to the type of task being performed, the size of the objects worked on (B), and the location of the hands when doing it (A). Height A is the optimal working height of the hands, B is the typical height of the objects being assembled, packed, or repaired, and C is the height of the work surface without a product on it. Guidelines for determining the proper standing workplace height for a given task are further explained in the text.

- Distance C is the height of the table and equals A minus B. Note that if different sizes of items are handled, several locations in the work area may be at different heights. If jobs requiring different sizes of items must be done at the same workplace, either an adjustable-height workbench should be used or the height should be based on the most frequently used items.

In most workplaces, whether seated or standing, there is a tendency to use the space under the work surface for storage, thereby reducing the leg clearance. Cabinetry and storage shelves should be located so that they do not interfere with the clearances previously indicated in Figures 3.3 and 3.6.

To summarize, workplaces and workspaces should be designed so that:

- Workplaces, controls, and tools are easily accessible to the operator with the least reach.
- Body clearances are sufficient for the larger users.
- Working hands are:
  - At elbow height for most tasks
  - Below elbow height for tasks requiring force
  - Slightly above elbow height for visually demanding tasks
- Employees will not have to do a lot of body twisting or get into awkward working postures in order to get their work done.

COMPUTER WORKSTATIONS

Computers are ubiquitous at work, in homes, and in schools. Today, in the US, 53.5 percent of the work force uses a computer at work, 51 percent of all households, and 99 percent of all schools in the United States (Hipple and Kosanovich 2001; Newburger 2001; National Center for Educational Statistics 2000a, 2000b).

All computer users have a challenging task in selecting computer equipment and workstation designs, as there are numerous computers, input devices, and displays to choose from and a myriad of computer furniture designs. To select equipment and design workspaces that will result in a good fit between the computer users, the tasks performed, and the psychosocial environment they work within is a complex process that requires careful analysis of all components in a work environment. For in-depth information about how to analyze the interactions between and within all these components, see Dainoff 2000; Dainoff and Mark 2001; and Dainoff, Mark, and Gardner 1999.

The goal of this section is to provide practical analysis techniques and strategies to create an office environment where the risks for developing musculoskeletal and visual discomfort during computer work are avoided. Techniques for addressing psychosocial stressors is presented in Chapter 6.

Selection of Computer Equipment

Selecting computer equipment that best matches task and job characteristics is not a simple quest. The optimal computer equipment configurations change continuously as new technologies develop. However, regardless of what new technology becomes available, the following questions need to be asked in guiding the selection process (see also "Checklists" in Chapter 2):

FIGURE 3.7 Computers—desktop, docking station, laptop

- What is the length of time the computer is used in the office, at home, or during travel?
- What is the length of continuous typing time at the different work locations (office, home, travel)?
- How are input devices other than the keyboard used?
- What are the visual demands?

See Figure 3.7 for the basic configurations for a computer workstation. Typically they are:

- Desktop computer: separate display, separate keyboard with attached numeric pad, mouse, hard drive in either floor or desk model
- Docking station: separate display, docking station hard drive with laptop module, separate keyboard with numeric pad attached, mouse; carrying bag for the laptop
- Laptop: display and keyboard are attached; carrying bag for the laptop

Table 3.2 presents factors to consider when choosing between these configurations.

Please note that before the final decision on equipment for a computer workstation is made, the physical dimensions of the work surface and the computer user's visual needs should also be considered, especially when using larger monitors. When choosing furniture, ensure that the specific chair design parameters will be compatible with the desk and keyboard trays or other input device support surfaces (BSR/HFES 100 2002), as well as with the work tasks.

Workstation Design

When a new computer workstation is designed, specific anthropometric dimensions need to be considered. However, there are several different methods for using anthropometric data, and each has theoretical as well as practical limitations (Robinette and McConville 1981). If body dimensions are simply added—for example, 95th-percentile popliteal height plus 95th-percentile thigh clearance—the resulting leg clearance dimension will not accommodate 95 percent of the population as intended (Kroemer, Kroemer, and

TABLE 3.2
Factors to Consider When Choosing Between a Desktop, a Docking Station, and a Laptop Computer (adapted from material developed by Inger M. Williams for Corporate Ergonomics, Eastman Kodak Company, 2000)

	Desktop Computer	Desktop with Docking Station	Laptop
Time doing computer work in the office	Computer work > 6 hours/day Approximately 25–30 hours/week in the office	Computer work > 6 hours/day Approximately < 25 hours/week in the office Telecommuting, business travel	Extended periods of corporate travel, audits, sales, marketing, field engineer work Continuous typing < 2 hours at any location
Additional equipment needed due to specific task demands	Large display size for graphics, large spreadsheets, use of many applications simultaneously	Same large display requirements as for the desktop If using the computer >2 hours continuously at home or while traveling, a separate keyboard is needed at these locations also	Same separate keyboard requirements as for the docking station computer
Office workstation requirements	Minimum work surface depth 36" See below for accessories to add adjustability	Minimum work surface depth 36" Need extra space for docking platform and hard drive to ensure the display is located at proper eye height	Minimum work surface depth 24" Special attention needed to glare from overhead light on the tilted display
Advantages	One permanent setup that can be tailored once to individual's needs; requires very few fine-tuning adjustments	Few adjustments regularly needed to set up workstation in the office Flexible work environment	Flexible work environment
Disadvantages	Only for office use	Added equipment required for certain types of tasks	Same as for the docking station Small viewing area Potential conflict between musculoskeletal and visual needs

Kroemer-Elbert 1997; Nemeth and Dainoff 1997). Nemeth and Dainoff (1997) have shown that if popliteal height plus seated thigh clearance height minus buttocks-to-knee length and abdominal depth is used to calculate leg clearance for an inclined seat pan, only 52.2 percent of the males and 66.7 percent of the females would be accommodated. In addition, all dimensions within, for example, the 5th percentile cannot be combined to create a "5th-percentile individual" because this type of person most likely does not exist. An individual with a 5th-percentile forearm-to-hand length could have a 37th-percentile shoulder-to-elbow length and a 65th-percentile elbow rest height.

However, using the anthropometric data presented below is a starting point in the design process. An optimal computer workstation design process includes not only proper application of the anthropometric data and an understanding of their limitations, but also an analysis of task demands, communication patterns, and the individual's potential postural and visual constraints. "Optimizing individual workstation components (i.e. seat height, gaze angle) without taking into account the interactive effects of such components on each other can easily result in an overall outcome which is suboptimal" (Dainoff 2000, p. 1137). For more information on how to conceptualize and use an integrated design process, see Dainoff 2000; Dainoff and Mark 2001; Dainoff, Mark, and Gardner 1999.

Table 3.3 shows which body dimensions are taken into account and how they are applied in the design of computer workstations.

Anthropometric dimensions for the 5th-, 50th-, and 95th-percentile female and male populations and for the 5th-, 50th-, and 95th-percentile mixed male/female populations are presented in Chapter 1. The anthropometric data that are relevant for office workstation design are presented below together with the recommended workstation dimensions.

Work Surface Dimensions and Design

According to the draft BSR/HFES 100 standard (2002), for computer workstations the workstation dimensions should be able to accommodate the range of postures often observed at computer workstations. This range is represented by four "reference postures," as shown in Figure 3.8.

When selecting a work surface, the following physical dimensions should be considered:

- Clearances under the work surface
- Work surface height (including work surface thickness, input device thickness, and monitor size)
- Width and depth of the work surface
- Type of work surface

When an adjustable work surface is selected, the following factors should also be considered (BSR/HFES 100 2002):

TABLE 3.3
Anthropometric Dimensions to Use in Seated and Standing Computer Workstation Design (adapted from ISO 9241 Part 5 by Inger M. Williams)

Anthropometric Dimension	How Used to Determine Workstation Dimensions
Height of bottom of corner of scapula (height of the shoulder blades)	Seat backrest height to ensure that it does not interfere when the shoulder blades move and when turning to the side or rear
Eye height, sitting	Monitor height and monitor size for viewing angle and viewing distance to ensure there is no unnecessary load on neck, shoulders, and upper spine at seated workstations
Shoulder height	Often used together with arm length to determine where objects in the workstation can be located
Elbow height, sitting	Armrest height to ensure comfortable elbow and shoulder position
Thigh height	Seat to underside of work surface to ensure there is enough space to change seated postures
Popliteal height	Seat height to ensure the seat pan does not put pressure on underside of thighs
Buttock-to-knee length	Kneehole depth to ensure there is enough space to vary lower body postures
Buttock-to-popliteal length	Seat depth to ensure there is no compression at the back of the knee and allow proper use of backrest
Buttock-abdomen length	To ensure that it is possible to get close to the work surface
Elbow-to-elbow breadth	Distance between armrests to ensure arms are not cramped and that it is easy to get in and out of the chair
Hip breadth	Seat width to ensure changes in postures can be made
Eye height, standing	Monitor height and size to determine viewing angle and viewing distance to ensure there is no unnecessary load on neck, shoulders, and upper spine at standing workstations
Elbow height, standing	Standing workstation work surface height

- The control mechanisms should not interfere with foot and leg clearances or with typical work activities.
- The adjustment mechanisms should minimize the risk of pinching between the surfaces and should have a locking device to prevent unwanted adjustments.

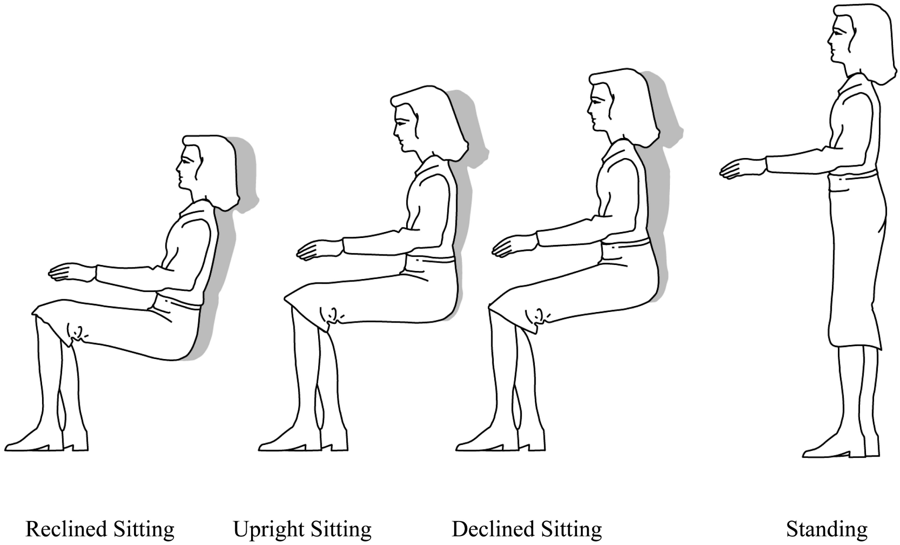


FIGURE 3.8 Four Reference Postures
These four reference postures are meant to represent the range of postures observed at computer workstations (BSR/HFES 100 [2002 draft]). Please note that these are just examples; actual postures may vary from the figures shown.

CLEARANCES UNDER THE WORK SURFACE Recommended clearances under the work surface for a seated workstation are shown in Table 3.4. The anthropometric dimensions used to derive these data are also presented.

Recommended clearances under the work surface for a standing workstation are shown in Table 3.4. The anthropometric dimensions used to derive these data are also presented.

WORK SURFACE HEIGHT The limiting factor in determining the lowest admissible work surface height is the leg clearance dimensions, as discussed above. However, once the dimensions shown in Table 3.4 are taken into account, the following variables should also be considered:

- Work surface thickness should be added to the clearance dimension.
- In addition to work surface thickness, input device thickness should be added to determine the final height of an input device surface. In the BIFMA guidelines (2001), an input device thickness of 2.5 cm (1 in.) is assumed.
- Input devices and displays may require different work surface heights to accommodate the user's typing posture, as well as the user's viewing distance and viewing angle (Anshel 1998).

Generally, the recommended work surface height is derived using resting elbow height and eye height as baselines for both the seated and standing workplaces (see Table 3.6).

TABLE 3.4
Clearance Dimensions Under the Work Surface at a Seated Workstation, in cm (in.) (adapted from BSR/HFES 100 2002)

	Recommended Workstation	Other Considerations	Anthropometric Dimension Used to Derive Clearances
Height clearance for thighs and lower legs	50–69 cm (20–27 in.). 72 cm (28.5 in.) for a nonadjustable work surface at the front edge. An adjustable work surface should be adjustable between 50–72 cm (19.5–28 in.). At 44 cm (17 in.) rearward from the front edge of the work surface the clearance should be no less than 64 cm (25 in.).	Shoe allowance has been added. ISO recommends 3 cm (1.2 in.).	Thigh height plus popliteal height. Thigh clearance is measured from the sitting surface to the highest point on the top of the right thigh. Popliteal height is measured from the foot support surface to the back of the right knee.
Height clearance for knee height	50–64 cm (19.6–25 in.) at 44 cm (17 in.) rearward from the front edge of the work surface	Shoe allowance is added. ISO recommends 3 cm (1.2 in.).	Knee height, measured from the foot support level to the top of the knee cap while seated with legs at 90° angle.
Depth clearance for knees	43 cm (17.5 in.).	These dimensions allows for changes in posture.	Buttock-to-knee length minus abdominal extension depth.Buttock-to-knee length is measured from the back of the buttocks to the front of the right knee. Abdominal extension depth is measured from the front of the abdomen to the back at the same level.
Width clearances for thighs	52 cm (20.5 in.).	Clothing and movement are added. ISO recommends 2.5 cm (1 in.) for medium clothing and 4.5 cm (1.8 in.) for movement.	Hip breadth, measured between the lateral points of the hips or the thighs, whichever is broader.
Height clearances at foot level	11 cm (4.5 in.). If a footrest is used, the clearance is measured from the top of the footrest. This clearance dimension applies also to a standing workstation.	Shoe allowance has been added. ISO recommends 3 cm (1.2 in.).	Foot height, measured from the standing surface to the malleolus on the outside of the right ankle.
Depth clearance at foot level	60 cm (23.5 in.). Additional clearance space is required to allow for leg extension.	The depth clearance is measured from the front edge of the input device surface and extends toward the back of the work surface. These dimensions do not allow for any space to extend the legs under the work surface or any postural changes	Buttock-to-popliteal length plus foot length minus abdominal extension depth. Buttock-to-popliteal length is measured from the back of the buttocks to the back of the right knee.

TABLE 3.5
Clearance Dimensions Under the Work Surface for a Standing Workstation, in cm (in.) (adapted from BSR/HFES 100 2002)

	Recommended workstation	Other Considerations	Anthropometric Dimension Used to Derive Clearances
Height clearance at foot level	11 cm (4.5 in.)	Shoe allowance has been added. ISO recommends 3 cm (1.2 in.). If a footrest is used, the clearance should be measured from the top of the support surface.	Foot height, measured from the standing surface to the malleolus on the outside of the right ankle.
Depth clearance at foot level	10 cm (4 in.)	No allowance has been added for shoes.	This dimension is derived from seated depth clearance recommendations.
Width clearance at foot level	50 cm (20 in.)	An allowance of 7.0 cm (3 in.) for movement and clothing has been added (recommended by BIFMA).	Hip breadth, measured between the hips or the thighs, whichever is broader.

Many variables affect optimal work surface height for a display. The following factors should be considered in addition to the center of display height given above:

- Eyeglass prescriptions, especially for bifocal and trifocal users
- Computer display size (13 in., 15 in., 17 in., or 21 in.)
- Computer tilt angle
- Viewing distance (minimum recommended viewing distance is 40 cm (15.7 in.).
- Viewing angle to see the entire monitor (recommended between 0° and 60° below eye level)

It is practical in the office, as a first approximation, to use the top of the monitor as a reference point and when setting up the monitor for viewing angle and distance (Chengalur 2002). Information on calculating viewing angle and distance is given in "Visual Work Dimensions" in this chapter. These calculations assume the display is not tilted. Note that when a fixed surface height of 72 cm (28.5 in.) is used, it limits the choice of monitor size that can comfortably accommodate most computer users' visual needs.

TABLE 3.6
Recommended Work Surface Height for Input Devices in a Seated and Standing Workstation, in cm (in.) (adapted from BSR/HFES 100 2002)

	Recommended Workstation	Other considerations	Anthropometric Dimension Used to Derive Clearances
Input device work surface height for a seated workstation	56–72 cm (22–28.5 in.) if surface is adjustable. 72 cm (28.5 in.) for a nonadjustable surface.	Shoe allowance of 3.0 cm (1.2 in.) has been added and input device thickness of 2.5 cm (1 in.) subtracted from the anthropometric dimensions. If using a fixed-height surface, a height-adjustable chair should be used and a footrest made available	Popliteal height plus seated elbow rest height. Elbow rest height is measured from the seat pan to the bottom of the right elbow when forearm and upper arm are at a 90° angle.
Input device work surface height for a standing workstation	95–118 cm (37–46.5 in.) for an adjustable surface. If the surface is both height and tilt adjustable it should range between 78 and 118 cm (30.5–46.5 in.). A non-adjustable work surface should be within this range or at 107 cm (42 in.)	Shoe allowance of 3 cm (1.2 in.) has been added and input device thickness of 2.5 cm (1 in.) subtracted from the anthropometric dimensions Please note that with a fixed-height surface, other equipment to adjust input device and/or VDT height will be required to accommodate most of the population.	Standing elbow rest height, measured from the standing surface to the lowest point on the elbow when the forearm and upper arm are at a 90° angle.

DEPTH AND WIDTH OF WORK SURFACE Standard office desks are commonly 76 cm (30 in.) deep and come in a variety of widths. With the introduction of 17-in., 19-in., and 21-in. CRT displays, which are approximately 51 cm (20 in.) deep, choice of work surface depth became an issue. In addition, the depth must allow for forearms resting on surface in front of the keyboard and for adjustments of viewing distance to the display.

The optimal work surface size depends on depth and width of the display, depth and width of the keyboard, depth and width of mouse space (mouse with or without mouse pad), and space needed for paper documents and writing (see Figure 3.9). For just a keyboard and mouse, the minimum work surface width should be 70 cm (27.5 in.) (BSR/HFES 100 2002).

For writing tasks, an area 30 cm (12 in.) wide and 41 cm (16 in.) deep, preferably 76 cm (30 in.) in both directions, is recommended to allow for adequate writing space (Cushman and Crist 1979).

Extra space allowance must also be added if other equipment such as telephones, calculators, or dictating machines are present. If these are used frequently, they need to be placed within a comfortable reach distance (see the previous section for optimal reach distances).

TYPE OF WORK SURFACE In Figure 3.10 the most commonly used work surfaces for computer work in the office are shown.

As a general note, the edges and corners of the work surface should be rounded (minimum radius 3 mm or 0.1 in.) and have a nonreflective surface (BSR/HFES 100). Work surfaces that move relative to each other should be designed to minimize the risk of pinching the user's fingers, arms, or legs.

Two work surfaces that adjust independently, one for input devices and one for the display, are optimal, provided that the display surface is deep enough to accommodate a large monitor and the input device surface is wide enough to accommodate both keyboard and mouse with mouse pad. A deeper desk might be required if a larger monitor (typically the 17–21-in. CRT- type monitor) is used, to allow for adjustments of viewing distance and viewing angle. If a large monitor is considered for a standard-size desk, a flat panel display is a better choice than a CRT.

In general, one work surface allows flexibility and will usually cost less. A single surface could accommodate future changes in computer equipment designs. When needed, height-adjustable chairs, footrests, keyboard trays, and/or monitor holders can be added for adjustability.

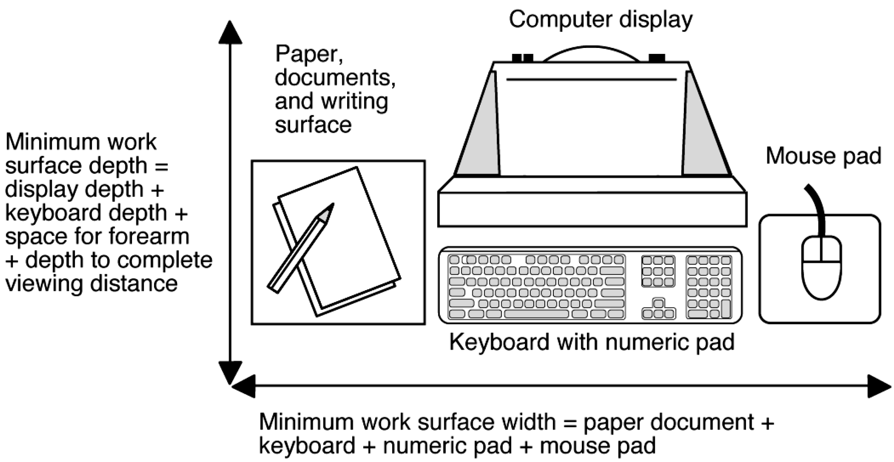


FIGURE 3.9 Dimensions for Work Surface Widths for a Computer Workstation

Regular single-surface desk	Desk with separate surface for keyboard, both fixed heights	Desk with fixed monitor surface but adjustable keyboard tray	Desk with both surfaces adjustable

FIGURE 3.10 Examples of Types of Work Surfaces in a Computer Work Station

If multiple surfaces are to be used, the following issues should be addressed:

- The input device surface should not interfere with the armrest on the chair.
- If a keyboard tray is used, thigh and lower leg clearance as well as width clearance for thighs should be taken into account to ensure that the keyboard tray's mounting mechanisms and support arm do not interfere.
- The input device surface should be wide enough to accommodate both a keyboard and a mouse with a mouse pad.
- The input device surface should accommodate both right- and left-handed individuals.
- Bifocal wearers who are using the lower section of their bifocals might need to place the display surface lower than their input device surface in order to achieve the correct viewing angle.

Summary of Dimensions for Computer Workstations

Figures 3.11 and 3.12 summarize the recommended dimensions for seated and standing workstations, respectively.

Workstation Layout

Computers are used increasingly in all environments. The issues discussed above apply to all work environments. The layout of the workstation in a specific environment involves not only the dimensions of the workstation but also the placement of the workstation itself in the room, and the arrangement of the computer equipment and other work material on the work surface.

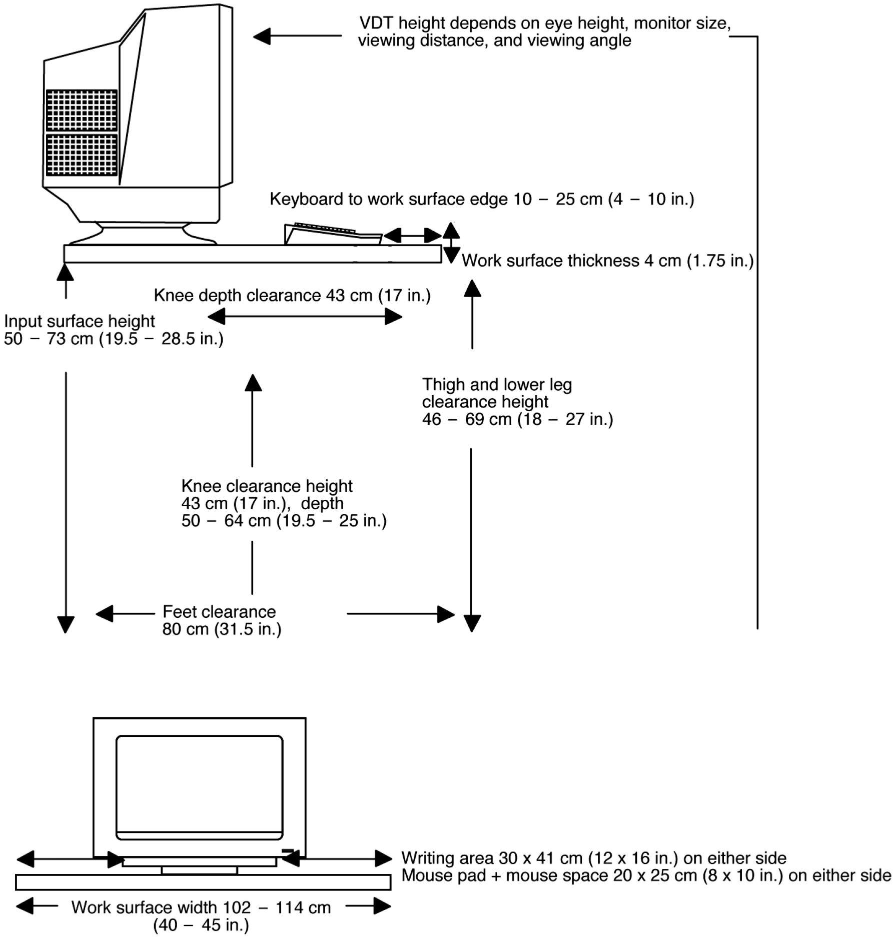


FIGURE 3.11 Seated VDT Workplace Dimensions

Workstation Placement

The main factors to consider when locating a computer workstation in a workplace are the need to protect the user from noise, the need for privacy, and the need to reduce glare. ISO 9241/6 (1999) gives some good guidelines on different layouts for office work with computers. If an enclosed office is not possible, noise can be best reduced through high panels, or by directing noise sources away from the computer workstation. Privacy needs vary, and the individual user should be considered when setting up the workstation. In order to reduce glare, the computer workstation should be arranged in relation to windows and overhead lights, as shown in Figure 3.13.

Glare lowers the contrast on the display and reduces the visibility of the text. In Table 3.7 other ways to reduce glare are presented.

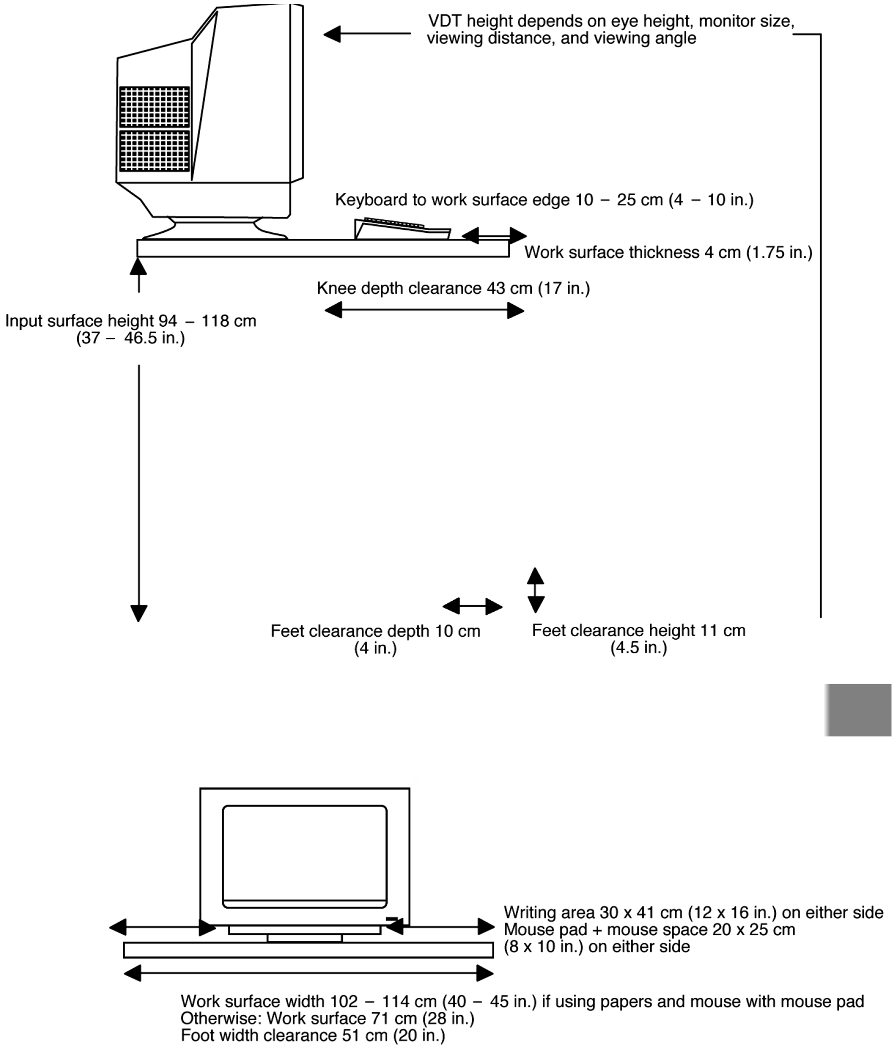


FIGURE 3.12 Standing VDT Workplace Dimensions

If glare cannot be controlled at the source, antiglare filters can be used. Table 3.8 shows some of the advantages and disadvantages associated with each. However, the best choice is antiglare-coated monitors that do not require an extra antiglare filter. There are no glare problems associated with liquid crystal displays (LCDs), though there may be directionality problems.

Computer Equipment and Work Material Layout

Most of the time the computer monitor is square with the keyboard, that is, the keyboard is symmetric with the monitor. If the VDT user is using only the

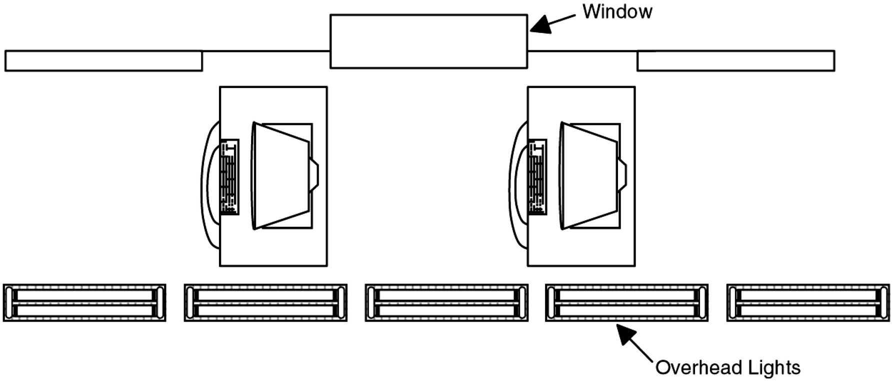


FIGURE 3.13 Workstation Orientation

TABLE 3.7
Reducing the Impact of Various Sources of Glare

Potential Glare Source	How to Reduce Impact
Sunlight	Tinted windows; vertical blinds; reorient workstation or tilt monitor; add glare guarding or hood
Overhead fluorescent lights	Parabolic louvers; reorient workstation or tilt monitor; remove or relocate light fixtures; use a positive display; add glare guarding or hood
Task lights	Shield added to lampshade; select a unidirectional light; reorient lamp
Glossy surfaces	If walls, repaint; if desk surface, cover

alphanumeric part of the keyboard, not the number pad, the right hand will be in a slight ulnar abduction when typing. Grandjean (1987) demonstrated that the larger the ulnar abduction, the more tiredness, pain, and cramps would develop. Therefore, consider the following when placing the computer equipment on the work surface:

- When only the alphanumeric portion of the keyboard is used, center it with the center of the monitor.
- When only the mouse is used, move the keyboard to the side and bring the mouse to a comfortable position in front of the active arm.
- If the primary task is to view paper documents, these documents should be placed straight ahead of the user and the monitor should be moved to the side.
- If both the monitor and the paper documents are viewed equally often,

TABLE 3.8
Advantages and Disadvantages of Antiglare Filters (adapted from AT&T Bell Laboratories 1983 by Inger M. Williams, 1994)

Type of filter	Advantages	Disadvantages
Neutral-density filters	Increases contrast of the characters, but filters need to be treated with etchings, frosting, quarter wave, or thin film to reduce specular reflections	Decreases perceived brightness of the characters
Colored filters	Same as for neutral-density filters	Same as for neutral-density filters
Circular polarizers	Increases contrast of the characters better than neutral-density filters, but specular reflections can be severe if not properly treated	Specular reflections possibly introduced by the filter itself
Micromesh filters	Increases contrast without introducing new reflections	Display must be viewed straight ahead, as viewing from the side makes characters appear dim; collects dust easily and must be kept clean

angle them so that they can both be read easily when the computer user looks straight ahead.

- Place printers some distance away from the computer workstation itself to encourage the user to get up and walk away from the computer. This provides a natural break from a static seated position.
- As mentioned above, frequently used equipment such as phones, calculators, dictating machines, or touchpad displays should be located within a comfortable reach distance (see the previous section for reach distance dimensions).

LABORATORIES

A laboratory can be used for a variety of functions, such as analytical processes, where pipettes, chemical hoods, and glove boxes may be used; microscope work; and computer-related tasks. As the biotechnology field has grown, there has been a corresponding increase in the number of laboratories, and there is a greater awareness of the importance of ergonomics in laboratories, including a rising concern over physical stresses for those who work there (Lang 1994; Avers 1996; Lee and Ryan 1996; McGlothlin and Hales 1997; Kreczy, Kofler, and Gschwendtner 1999).

Problems in laboratories often arise when equipment is installed on a traditional standing-height laboratory bench without consideration for the nature of the equipment or the tasks that are involved to operate the equipment. The typical laboratory bench is ill-suited for computer use or microscope work without modifications. Many basic laboratory tasks are also a challenge to perform at a bench because of the height of the equipment being used. A traditional laboratory bench height varies according to the type of laboratory, so the bench height chosen should be suitable for the working height of the hands of most of the bench tasks. However, at times when tall vessels are used, the arms are often raised to shoulder height to accomplish the task, for example, when pipetting into tall test tubes. A combination of workplace design, task design, and work organization principles should be applied to ensure the health and safety of the person performing laboratory tasks.

General Principles of Laboratory Bench Design

The following guidelines for laboratory benches and installing large equipment in the laboratory should be considered:

Workbench

(Also see the sections on seated and standing workstations, microscope workstations, and computer workstations.)

- Determine the appropriate bench height for a general laboratory. Typically, the bench height range is 81–96 cm (32–38 in.) and the appropriate height should allow most tasks to be performed in a comfortable working posture. The height depends on the type of laboratory (and therefore the tasks being conducted there) and the size of equipment that generally is used.
- Design the laboratory to allow for:
  - Designated workstation areas suited to the tasks that are conducted.
  - Standing bench height that allows most tasks to be performed comfortably.
  - Sit/stand at the workbench.
  - Sitting workstations for sustained activities, such as microscope work.
- Provide adequate leg and thigh clearance at the designated sitting and sit/stand areas. Make sure to keep leg wells clear, and ensure there are no aprons (or bench fronts) and drawers at the sitting areas. These aprons and drawers may vary from 10–15 cm (4–6 in.) in height and can significantly reduce thigh clearance or prevent raising a chair to an appropriate work height (see Figure 3.14).
- Provide a footrest or foot rail in a sitting or sit/stand well. This gives the user a choice and allows for a change of position between the foot rail

and the foot ring that is attached to the laboratory chair. Chair foot rings are often not easy to adjust, and so people with shorter legs may not be able to reach them comfortably.

- Provide an adjustable-height laboratory seat with a supportive back. If armrests are present, ensure that they are adjustable and padded and can be moved out of the way when necessary.
- Design a toe recess in the benches that are at standing height. The recess should be a minimum of 10 cm (4 in.) high and 10 cm (4 in.) depth and run the length of the working area.
- Pad sharp edges, especially at areas where the task may provoke leaning against the bench.
- Provide antifatigue matting in areas of prolonged standing.

Equipment Installation

Avoid installing large laboratory equipment on top of the workbench, as this usually places the point of user interface at an awkward height and reach. Instead, consider the following guidelines (see also the section on standing workstations and dimensions for visual work):

- Modify the height of the workbench, or provide an alternative support for large laboratory equipment so that the working height and reach of the hands to operate the equipment is comfortable while standing, without provoking awkward postures.
- If the working height is too high, provide a platform in the area so that the equipment may be operated effectively.

FIGURE 3.14 An illustration of the lack of thigh clearance when sitting at a bench that has drawers along the top edge of the leg well

- When determining the work height, take into consideration the visual demands of the tasks.
- When appropriate, provide lifting aids for heavy components of processing machines, for example, heavy centrifuge cores or agitation machines.

Equipment Layout

The layout of the equipment can make a difference to the postures adopted for a task. The following are some general reminders of good practice that help keep workflow efficient and tasks more comfortable and safer to perform.

- Locate the various pieces of equipment so that work can be performed in a logical sequence and can be conducted with a comfortable flow and patterns of movement of the body.
- Arrange equipment within easy reach and so that it can be used with a neutral posture of the body. For example, microtome machines that slice samples for histology slides can be angled on the bench for more comfortable wrist postures.
- Use organizer accessories—for example, pipette carousels—for quicker access to equipment and good housekeeping.
- Place waste bins in convenient locations. If the use is frequent, consider using smaller containers that are close by, perhaps on the bench itself, and periodically empty those containers into the large waste bin.
- Prop up laboratory procedures or other reference material so that it is easy to read and clears bench space. A clear cookbook holder can work well, as it also protects the materials from splashes.
- Tip and/or raise work to attain a comfortable working posture.
- Use devices that reduce sustained activity, such as reverse tweezers, which are squeezed to open them and when released will hold an object.

Containment Cabinets and Glove Boxes

Containment cabinets and glove boxes (also known as biological, biosafety, or isolation cabinets, chemical hoods, and clean and dry boxes) are used frequently in industrial, university, and governmental laboratories, as well as in manufacturing processes. They are used to protect a person from direct contact with a chemical, or to protect a product from environmental contamination.

The performance of tasks in a cabinet or a glove box is constrained by the plastic shields, armholes, or gloves (as shown in Figure 3.15); arm movements are restricted, and the operator usually has to lean forward. There are also visual restrictions that may interact with the postural limitations to make an otherwise easy task very awkward to perform. In most chemical handling tasks the operator is wearing gloves, further reducing his or her dexterity. Sit-

FIGURE 3.15 A constant humidity containment cabinet/glove box.

ting at containment cabinets is often difficult because of the lack of knee space and thigh clearance. The type of work to be done in the cabinet or the glove box will determine how severely these factors affect the operator's ability to do the task.

Chemical shields are also used in some laboratories to protect the face. If too wide, these can also provoke awkward arm and hand movements, and sometimes the shield interferes with vision. The screen should be no greater than 46 cm (18 in.) wide so that constant static loading of the shoulders is not required to perform the job.

Lighting is a general concern when using either containment cabinets or glove boxes. Discoloration or deterioration of the material through which the person has to look may affect visual quality. Laboratory lights or sunlight may be a source of glare from the shields, especially if the cabinet or glove box window is at an angle. Guidelines for lighting are similar to those for visual display terminals; see the section on lighting in Chapter 8.

There are numerous guidelines for and classifications of glove boxes and containment cabinets that specify ventilation, seals, glove attachment, necessary services inside the contained area, and cleaning and decontamination facilities. The ergonomics considerations are less well developed.

Containment Cabinets

The same general principles for the design of workplaces apply to containment cabinets. See the previous sections on standing and sitting workplaces. Some specific guidelines for improving ergonomics issues at containment cabinets are given below:

- Modify the cabinets by moving the locations of equipment underneath them, such as pipes and pumps, to allow for knee space below cabinets that do not have adequate clearance. Leg clearance of 66 cm (26 in.) is desirable.
- Provide an adjustable chair that allows the seat back to come forward and the seat pan to tilt forward. This should allow the person to sit with the knees considerably lower than the hips and so get closer to the cabinet.
- Provide articulating arm supports that could attach to the chair or to the cabinet.
- If there is leg space, provide a footrest for short-legged users.
- Consider the organization and placement of materials within the cabinet. Keep the working materials as close as possible. Reaches should be kept within 15–41 cm (6–16 in.) from the front of the work surface for seated operations and within 51 cm (20 in.) for standing operations. Arrange the materials by logical sequences of movements and task steps, which will reduce the possibility of accidents.
- Choose instruments that are short; for example use short pipettes because of the difficult arm access into the cabinet. To reduce sustained activity and for safety, use assistive devices such as clamps to hold test tubes and beakers. Usually gloves are worn that reduce dexterity and friction between objects being held, thereby increasing the grip forces exerted (Shih et al. 2001).
- Minimize lifting and manipulating heavy items. Consider alternative means to transfer contents from large vessels other than lifting the vessel, such as pumps or gravity feeds that could be set up before conducting the task. If large vessels are used, place them on a dolly with lockable casters so that the vessel can be pulled close to the outside edge for lifting in and out of the cabinet.
- Control the time on the task to reduce sustained postures or very repetitive activities.
- When upgrading the containment cabinet, consider designs that build in features, such as recessed waste receptacles and convenient placement of petcocks and electrical controls. Such features can reduce the reach distances and lower the working height of the hands, as well as improve efficiency.
- Rotate tasks to reduce the potential for prolonged activities at a containment cabinet.

Glove Boxes

Glove boxes are designed for standing or sitting tasks, although seated workplaces are preferred. Many of the functional issues of containment cabinets also pertain to glove boxes. The arms of the person are more constrained in a glove box, as they are encased in sleeves (as shown in Figure 3.15). This also means the person is drawn closer to the work than the glove box comfortably allows.

There are two main types of commercial glove boxes available: a low-profile glove box with a vertical glove port panel below the glass viewing panel, and a high-profile glove box with glove ports set into the sloping glass front. The latter design is advantageous for visually demanding tasks.

The same general principles for the design of workplaces apply to glove boxes. See the earlier sections on Standing and Sitting Workplaces. Some of the factors that should be considered in the design of a glove box are:

- Height of the glove port, or opening. If standing, the center of the glove ports should be 117 cm (46 in.) above the floor (Rodgers 2001). This height should be comfortable for most people, as it allows taller operators to make the reaches and gives shorter operators something to rest their arms on. A platform may be needed to accommodate short operators.
- Glove port diameter (usually about 20 cm [8 in.]).
- Separation between the glove ports (usually 38–48 cm [15–19 in.] apart, center to center).
- Reach limitations. The reach should be kept within 15–41 cm (6–16 in.) from the front of the work surface for seated operations and within 51 cm (20 in.) for standing operations.
- Biomechanical constraints (very task-dependent).
- Visual constraints. When possible, the window should be sloped back about 15° and be 137–168 cm (54–66 in.) above the floor.
- Seat height adjustability of at least 15 cm (6 in.) and thigh clearance so that at the highest seat setting the legs are not wedged against the underside of the glove box.
- Glove type and size.
- Location of switches and controls. Enable the operator to adjust the chair height without removing his or her hands from the gloves. Often, different aspects of a task can be performed best from different heights. Hands-free height adjustments, such as by foot pedal or a forearm switch, save time and allow a good posture to be adopted, reducing the potential for fatigue.
- Location of pass-through compartments into and out of the box.
- Access for cleaning, decontamination, or product changes.

- Design of tools, trays, and containers to be used inside the box.
- Probable task durations (time of continuous work in the gloves). If the glove box is used regularly and for a majority of a shift, the work should be a seated operation.

Restricted arm movement is a particular issue in glove box design. The shoulder and elbow ranges of motion are restricted, putting more stress on the smaller muscles of the hands and wrists. Moving an object from side to side is difficult, and it is especially awkward to pass an object through a side pass-through port. Consequently, techniques to reduce handling of objects in the box are desirable. The following are some suggestions to reduce handling:

- Conveyors to supply and remove product (unless contamination is an issue). Leg clearance should not be compromised by the mechanism.
- Air pumps to remove liquids from stock bottles so that liquids need not be poured manually.
- Trays or containers to permit parts or product to be moved into, out of, and around the inside of the box conveniently.
- Small platforms of different heights inside the box. The platforms should be movable so that the operator can adjust the height of an operation, permitting a comfortable working posture.

Microscope Workstations

Typical laboratory workstations are not conducive to the prolonged use of microscopes. Several studies of microscope use have reported neck, back, forearm, wrist, and visual discomfort or pain among the users (Fischer and Wick 1991; Helander, Grossmith, and Prabhu 1991; James 1995; Caskey 1999; Kreczy, Kofler, and Gschwendtner 1999). When using a microscope, the position of the eyes and hands are fixed by the location of the eyepiece and the controls. The distance between the eyepiece and hand controls of a microscope is usually several inches less than the anthropometric difference of the position of the eyes (with the head flexed at 20–30°) and the hands at a comfortable position level with the elbows (James 1995). Therefore, it should not be surprising that the poor design of a microscope workstation, as well as microscopes themselves, can provoke the following problems:

- An extremely flexed neck and forward head if the eyepiece is too low, or an over-stretched neck if the microscope is high
- The body leaning forward to reach the microscope
- A hunched upper body if the microscope is too low
- The arms held up without support, or elbows leaning against the sharp edge of the table
- Bent wrists to use the controls;

- The legs and thighs being cramped if there is insufficient clearance below the work surface, as is often the case at laboratory benches because of the aprons or a drawer or cupboard in the sitting well
- Visual complaints

Figure 3.16 illustrates a microscope adjusted by piling books underneath. Helander, Grossmith, and Prabhu (1991) recommend several measures that could be taken to improve microscope work in industrial inspection tasks. Many of the following recommendations are also pertinent for laboratory microscopy:

- Design products to minimize the use of microscopes. Ergonomists should work closely with product designers to reduce unnecessary work elements in assembly and inspection.
- Use visual projection systems. This technique can be useful in laboratory settings as well as for industrial inspection. Cell counting is one example of intense laboratory microscopy that lends itself well to computer projection. This can be combined with the use of keyboard entry to count, rather than use of a manual counter.
- Analyze productivity implications of the degree of magnification. The more magnification that is required, the slower the task of inspection, so that a speed/accuracy trade-off for the degree of magnification should be made.
- Train inexperienced operators. Although microscope users may be well trained in the technical aspects of the task, they also need to be trained in the adjustable features of the workstation and ergonomics principles so that they can best set up their workstation and microscope. The

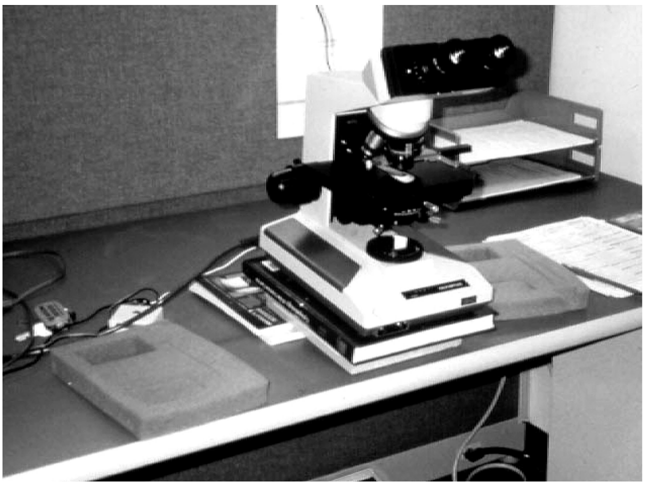


FIGURE 3.16 A microscope adjusted for height and angle by using books. Foam pads are present on either side to cushion the elbows.

importance of dynamic work postures, job or task rotation (when possible), and rest breaks should be emphasized.

- Screen operators for visual defects that could heighten their visual fatigue from using a microscope. Helander, Grossmith, and Prabhu (1991) endorse screening operators for astigmatism greater than 1.5 diopters.
- Procure ergonomically designed microscope workstations and microscopes (detailed below).

Standing Workstation

Prolonged use of a microscope should be at a well-designed seated workstation. However, on occasion microscopes may be used when standing for short reference activities or if the task requires considerable movement between microscope uses (Fischer and Wick 1991). Despite the short time at the task, microscopes that are used while standing should be set at appropriate heights.

When standing to look through a microscope that is on a laboratory bench, the back is bent forward and the neck is in an awkward extended posture. A practical solution is to place the microscope on a height-adjustable monitor holder. The height adjustment feature allows either tall or short employees to use the microscope at a comfortable height. The microscope itself should be improved as suggested below, and the arms supported.

Seated Workstation

Ideally, for a seated microscope task the table and chair should be fully adjustable, the microscope position should adjust horizontally and vertically, and the eyepieces should be able to be altered in length and angle. However, even with this degree of adjustability there are some inherent issues with many microscopes that provoke postural compromise. As noted above, the distance between the eyepiece and hand controls of a microscope is usually several centimeters less than that needed for comfortable use. This discrepancy between the design of the microscope and the desired setup cannot be entirely made up by adjusting the table and chair.

WORKSTATION MODIFICATIONS

- Ensure that the workstation conforms to general seated workstation guidelines. This is often not the case in laboratories because of the aprons or drawers that compromise the thigh clearance; these should be removed.
- Modify the bench or table with an optional extension out toward the user, so that the microscope can be brought as close as possible. A cutout in the bench can accomplish the same goal of bringing the user

and microscope closer together. An alternative is to have expandable sections between the eyepiece and objectives.

- Provide a height-adjustable chair with an adjustable back support that can be set to 90°, as most users of microscopes sit upright.
- Provide a footrest under the workstation; do not rely only on a foot rail attached to a chair.
- Provide a padded forearm ramp, or articulating armrests so that the arms are supported as they reach up for the controls. Some of the padded supports that come with a microscope are too close to the microscope to be of value (because of the width of the shoulders), but there are some independent arm supports commercially available.

MICROSCOPE MODIFICATIONS

- Make customized modifications to the microscope. James (1995) reported success in soliciting a local microscope repair company to modify the microscopes. One modification the company made was to increase the distance between the eyepiece and stage adjustment controls with an extension piece.
- Some in-house modifications can be made to improve a microscope, including raising the microscope on a platform so that the eyepiece is at a comfortable height and tilting the microscope if the eyepiece is not at an appropriate angle. There are commercial platforms available.
- Modify the microscope by using alternative component parts, if available for the model, such as:
  - An eyepiece that has an adjustable angle in a range of 0–30°.
  - A platform that easily adjusts vertically and horizontally.
  - An expandable piece between the objective and eyepiece (if this is not available, spacers can sometimes be used, or a teacher's eyepiece, which is often longer).
- An adjustable interpupillary distance (IPD) of a range 46–78 mm (1.5–3 in.), preferably scaled on the eyepiece in millimeter increments. It should be convenient to lock in the preferred distance. In addition, with such an IPD range, the convergence angle of the microscope should be 3–10°.

Liquid Dispensing Stations

Liquid dispensing entails the filling, transport, and emptying of containers in the laboratory. Of particular issue are large bottle dispensers, carboys, and dispensing jugs. A common difficulty in the laboratory is lifting large containers to place on high shelves above the laboratory bench (see Figure 7.12 for an example of this) A discussion of the material handling issues associated with such stations is in "Carboy and Large Bottle Handling" in Chapter 7).

VISUAL WORK DIMENSIONS

We obtain much of the information about how to do our work from our eyes. For many tasks, the visual requirement is a primary one. When it is difficult to see, we almost automatically lean forward, tilt the head forward, extend the neck, and squint. We assume these postures in order to improve visibility of a visual target by shortening the viewing distance and improving focusing ability. The problem of seeing may arise from poor viewing conditions and/or because the visual target's physical properties are at the visual threshold. Ergonomic designs, therefore, need to take into account the visual system capabilities and limitations to ensure high visual performance with low stress on the musculoskeletal system.

If the workplace is being designed for fine visual tasks, the objects being viewed should be 15 to 25 cm (6 to 10 in.) above the recommended working surface height (Champney 1975). If magnifiers are used, they should be designed or located to avoid stretching the neck. If magnification is 8X or less, fiber-optic magnifiers should be considered for inspecting flat products.

Occasionally a compromise must be made to accommodate the needs of both the visual system and the musculoskeletal system, especially during sustained visual tasks such as VDT work, fine assembly, and the use of touch screens.

The four main factors to consider when determining the required dimensions of a workstation for visually demanding work are:

- Visual field
- Viewing angle
- Viewing distance
- Size of the visual target

Each is discussed separately in the sections that follow.

Visual Field

The size of the visual field in a normal setting is important in such tasks as:

- Monitoring two or more lights on a large display (in a control room)
- Detecting warning lights (in a control room)
- Visual search tasks (in visual inspection)
- Driving (cars and trucks as well as equipment such as forklifts)

The sensitivity of the stationary eye to different regions of the visual field varies. The size of the visual field where the sharpest image of an object is obtained is a 1° area right around the center of fixation, in the fovea (Boff, Kaufman, and Thomas 1986). Eye movements ensure that a critical visual target always is focused within this region. Outside the fovea, up to about 30° from the center of fixation, seeing clearly requires that objects be ten times larger than they would in the center of fixation (Woodson, Tillman, and Tillman 1992). From a 1° to 40° area from the center of fixation, small movements of objects as well as very dim lights can easily be detected (Boff, Kaufman, and Thomas 1986). If dim lights must be seen, it is best to look away from the target and use the peripheral visual field to detect them.

When the head is still, the eyes can comfortably deviate 15° right or left and up or down to direct the fovea to visual targets, providing a 30° visual field cone around the line of sight (see below under "Viewing Angle"). If frequent changes of gaze between two equally important visual targets are equally critical, they should be located within this 30° cone (see Figure 3.17). This does not necessarily reduce head movements because the eye-head movement is individually determined and task-specific (Hayhoe 2002). Head movements are elicited when the visual target is located outside the visual field cone.

In a work environment, the following factors, apart from the visual target's physical properties, affect the usable size of the visual field:

- If a person has vision in only one eye (monocular viewing)
- Age (speed of attention shifts)
- Heavy spectacle frames
- Frames of safety glasses
- Corrective lens types
- Glare from the edges of eyeglasses without frames

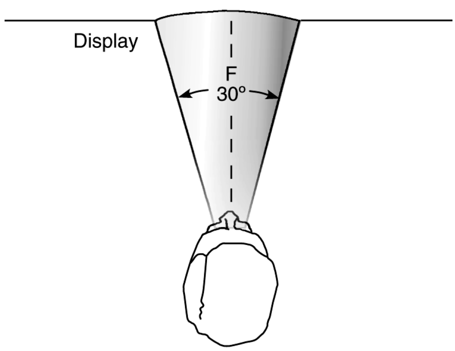


FIGURE 3.17 Visual Cone

- Opaque side shields in safety glasses
- No training to attend to peripheral vision

Viewing Angle

Line of sight is defined as "the line connecting the point of fixation and center of entrance pupil to the fixating eye" (*Dictionary of Visual Science,* as referenced by Whitestone and Robinette 1997). Viewing angle is the angle formed between this line of sight and a reference line. It is important to clearly define the reference line when the viewing angle is specified, because it can be measured either relative to the horizontal in the external world or relative to an internal imaginary line between the ear and the eye. Different sources in the literature use different reference lines, making it sometimes difficult to properly apply the angles given. One commonly used line is the Frankfurt line, which goes through the front of the ear (the tragion) to the lowest part of the right eye socket (Ranke 1884; Whitestone and Robinette 1997); the other is the ear-eye line, which goes through the right ear hole through to the outer corner of the right eye (Kroemer 1986). The Frankfurt line is 4° above horizontal; the eye-ear line is 11° above the Frankfurt line and thus 15° above the horizontal (Ankrum and Nemeth 1995); see Figure 3.18. These numbers are helpful to keep in mind when interpreting recommendations on visual target location from other references.

Most often, eye level means eye height, and this is the reference point for what is defined as horizontal. The Natick anthropometric database (Gordon et al. 1989) shows that:

- Standing eye height ranges between 132.5 and 191.2 cm (52.2–75.3 in.).
- Seated eye height ranges between 64.0 and 90.3 cm (25.2–35.6 in.).
- Shoe height (3 cm = 1.2 in.) should be added to the standing eye height,

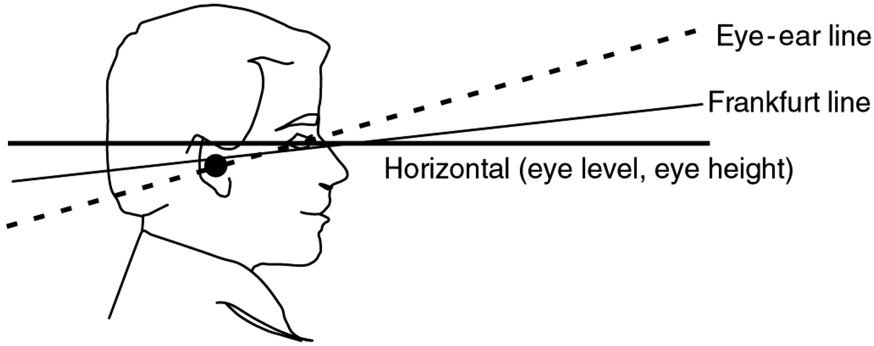


FIGURE 3.18 Reference Line of Sight: Frankfurt Line, Eye-Ear Line, Horizontal

and a slump factor (4 cm = 1.5 in.) subtracted from the seated eye height.

This should not be thought of as equal to comfortable viewing. In general, a normal resting line of sight is 15° below horizontal when looking at distant targets; approximately 5° of this angle is accounted for by a normal head tilt (Grandjean 1983; Morgan et al. 1963). At closer viewing distances a larger viewing angle is preferred (Heuer et al. 1991). This means that the best location of an important viewing area is 15° below horizontal and not at eye level. Figure 3-19 shows the formula for calculating viewing distance X and viewing angle D° when the object is a certain height (A) below eye level.

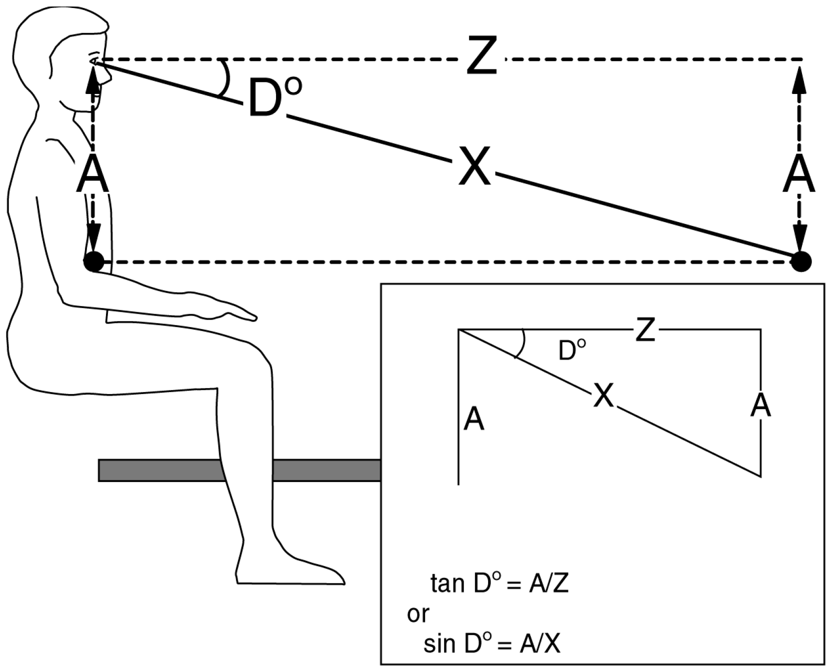


FIGURE 3.19 Calculating the viewing distance and viewing angle (adapted from material developed by Inger Williams and Erika Williams, 2002)

A is object height below eye level

X is viewing distance at angle D

Z is horizontal viewing distance

Example 1: To predict viewing angle required:

If an object is 10" below eye level and the horizontal distance from the eye to the object is 27", then A = 10" and Z = 27". Viewing angle D° = tan-1 10/27 = 20°.

OR:

If an object is 10" below eye level and the viewing distance is 18", then A = 10" and X = 18". Viewing angle D° = sin-1 10/18 = 34°.

Note: If this calculation is done for a VDT, the whole screen should fit within the viewing angles recommended (see "Selection of Computer Equipment").

A viewing angle of at least 15° below horizontal has also been found to be a good compromise between visual and musculoskeletal needs (Burgess-Limerick, Mon-Williams and Coppard 2000; Sommerich, Joines, and Psihogios 2001; Villanueva et al. 1997). Sommerich, Joines, and Psihogios (2001) found that a 17.5° angle below horizontal at viewing distances ranging between 75 and 83 cm (29.5–32.7 in.) results in lower muscle activity in neck and head muscles as compared to viewing angles at horizontal and 35° below horizontal.

The following variables must be considered to determine optimal viewing angle for sustained and demanding visual tasks (for example, reading, VDT work, inspection, and fine assembly):

- When identifying eye height and thus eye level, a normal slump factor of 4 cm (1.5 in.) should be deducted from a seated upright eye height dimension (Pheasant 1998).
- The neck angle should not exceed 20–30° (Chaffin, Andersson, and Martin 1999).
- In a seated position, the head and neck are not naturally held upright and level with horizontal but are at a 10–13° forward tilt angle from an erect vertical upright head position (Hsiao and Keyserling 1991; Woodson, Ranc, and Conover 1992).
- The preferred downward gaze angle increases (as measured from the horizontal) as the viewing distance becomes shorter (Heuer et al. 1991).
- Fine motor assembly tasks need to be placed at closer viewing distances and will therefore be performed with larger viewing and neck and head angles. This will increase strain on head and neck muscles more than, for example, VDT work. It is therefore important to encourage frequent rest breaks in such tasks (see Chapter 6).

To reduce excessive neck, trunk, and viewing angles during sustained and demanding visual tasks, a slanted work surface or a slant board can be used. A slant of only 10° has been found to reduce neck extensor load moment by as much as 21 percent (deWall et al. 1991; Feudenthal et al. 1991). A three-ring binder may serve as a temporary assist device; see Figure 3-20.

A downward viewing angle is recommended also for the following reasons:

- The load on the extraocular muscles is reduced as the resting position of convergence (see explanation below) moves inward (Heuer and Owens 1989).
- The ocular surface area becomes smaller, reducing the risk for developing dry eyes (Sotoyama et al. 1995; Tsubota and Nakamori 1993).
- The risks of developing visual fatigue, headaches, and eyestrain are reduced (Owens and Wolf-Kelly 1987; Tyrrell and Leibowitz 1990).

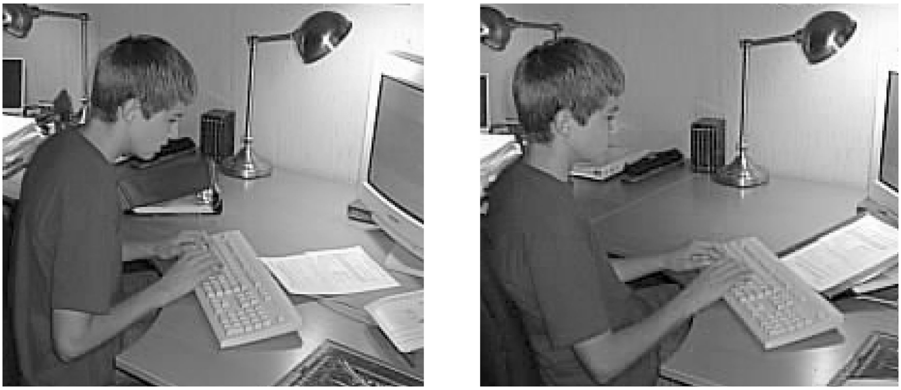


FIGURE 3.20 Slanting Work to Reduce Stress on the Neck

Viewing Distance

To see objects clearly, the eye must accommodate (change the curvature of the lens to focus the image on the retina at the back of the eye) and fuse the two slightly different images from the two eyes into one image. The resting position of the eyes, when no effort is exerted to focus and fuse a visual target, corresponds to an average distance of 59 cm (23 in.) in a student population (Leibowitz and Owens 1975; Owens 1984). This resting position gradually moves to longer viewing distances with age (Hedman and Briem 1984). Several studies have shown that visual performance is optimal when the visual task is placed at a distance that corresponds to an individual's resting position (Johnson 1976; Owens 1980; Raymond, Lindblad, and Leibowitz 1984; von Lau and Mutze 1952). The location of the resting position of the eyes varies greatly between individuals. Demanding visual tasks should be located at an individual's resting position to reduce the risk for developing visual fatigue.

Size of Visual Targets

Viewing distance determines what size the visual target is to the eye. The measuring unit is degrees or minutes of arc. This formula is used to calculate the angle an object subtends in degrees in the eye:

$$\theta = \tan^{-1} (\text{size of visual object / viewing distance to object})$$

All measurement units must be in meters. To obtain minutes of arc, multiply θ by 60.

The further a visual target is moved away from the eye, the smaller its visual angle. For text to be read comfortably at a common reading distance of

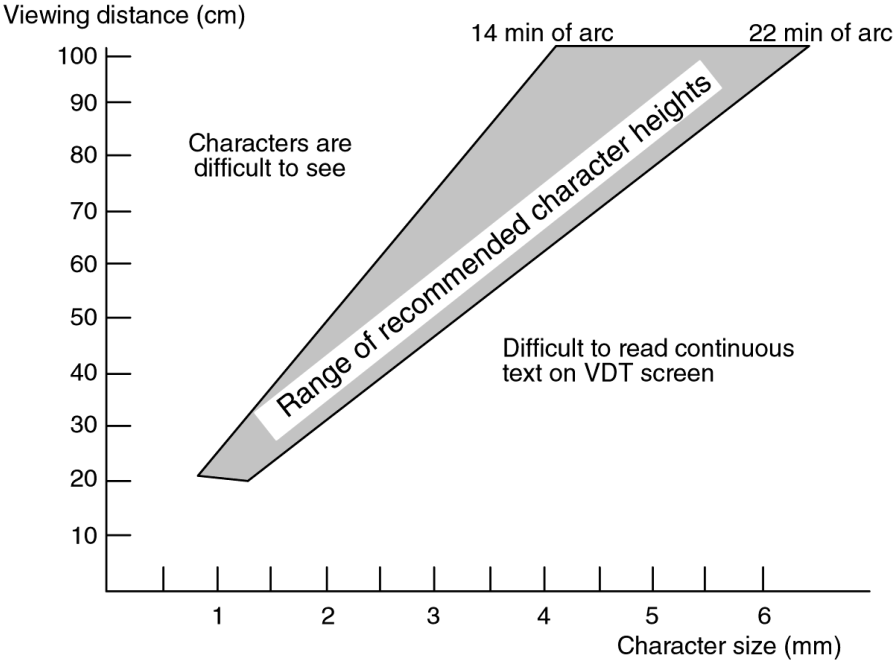


FIGURE 3.21 Size of Visual Target at Different Viewing Distances (based on material developed by Inger M. Williams, 1989)

approximately 50 cm (20 in.), character height should be between 3 and 4.3 mm (0.12 and 0.17 in.) (Grandjean 1987). This corresponds to a visual angle of 20 minutes of arc. It is commonly recommended that the preferred character height for most tasks be between 20 and 22 minutes of arc; the smallest should be 14 minutes of arc. In Figure 3-21, the physical size of characters at various viewing distances for character heights of 14 minutes and 22 minutes of arc is shown.

If the visual angle of an object is less than 3 minutes of arc, magnifiers should used (North 1993).

FLOORS, RAMPS, AND STAIRS

The accumulation of equipment, supplies, and product in workplace aisles is a common problem in some operations. Aisles and corridors should be designed to meet minimum clearance guidelines when the system is running at full capacity. Figures 3.22 and 3.23 provide guidelines for minimum clearances in aisles and corridors.

Some parts of corridors and aisles may be designated as *marshaling areas,* where trucks, carts, and products on pallets are stored before being taken to

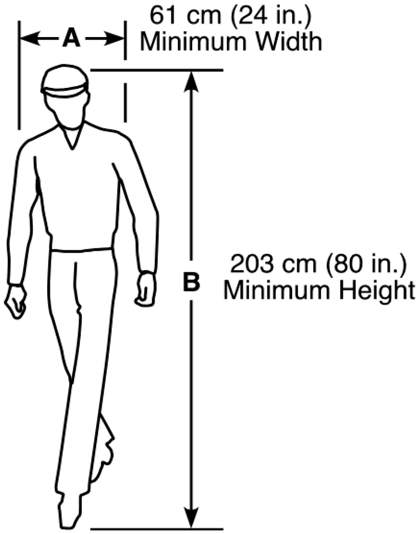


FIGURE 3.22 Minimum Clearances for Walking (adapted from Thomson et al. 1963)
The minimum amount of space needed to permit a person to walk normally is shown. The minimum width (A) includes about 5 cm (2 in.) of clearance on either side of the shoulders of a very broad-shouldered person. The aisle clearance recommendation of 92 cm (36 in.), given in Figure 3.23, should be used for clearances whenever possible instead of this minimum value. Vertical clearance (minimum height 80 in.) should be measured from the floor or working surface; the dimension given will accommodate a very tall person wearing thick-soled shoes and a hard hat.

the workplace or warehouse. Space requirements for these areas should be determined not just by the size of the items stored but also by the needs for maneuvering handling equipment used there. This maneuvering room can add as much as 25 percent more to the space requirements in some operations.

For aisles in warehouses or storage areas where high-stacking fork trucks are used, aisle width should be about 5–10 percent greater than the values given in Figure 3.23. The visual demands of judging distance in the high lifts may require the truck to be positioned farther from the shelves than would be the case for lower lifts (Drury 1974).

Some additional guidelines for the design of aisles and corridors are given below (Thomson 1972):

- Avoid blind corners. Arrange machinery and workplaces to allow visibility around corners. Use a mirror if necessary.
- Locate paths for minimum distances, using flowcharts or diagrams to indicate where the densest traffic will be.
- Mark traffic guides (aisle limits, arrows) on floors, walls, or ceilings.
- Design aisles, machinery, and workplaces to avoid the possibility of employees brushing up against equipment and inadvertently activating switches or knocking unattached objects to the floor.

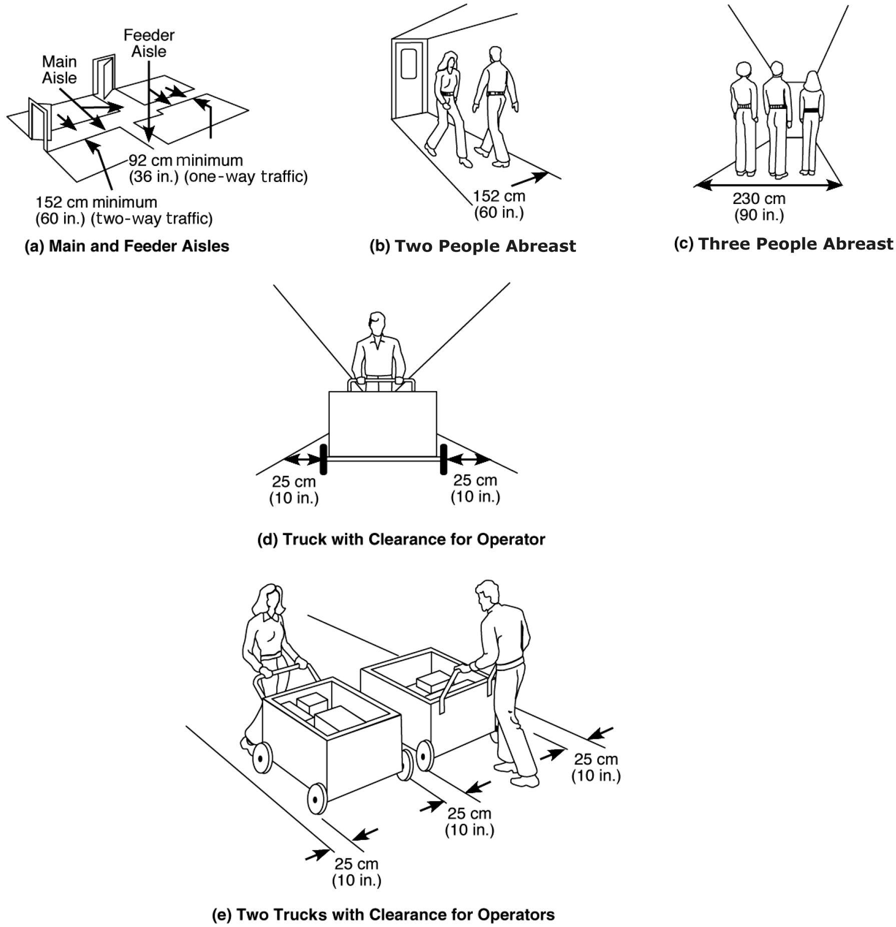


FIGURE 3.23 Minimum Clearances for Aisles and Corridors (adapted from Thomson et al. 1963; Woodson, Tillman and Tillman 1992; Access Board 1998)
The aisle widths shown in these illustrations are the minimum values for traffic and for handling trucks in production areas. Main aisles should be wider than feeder aisles (see part a). Both widths should be determined by the traffic needs (see parts b and c) but should not be less than the values given in part a. Where trucks and carts are used, there should be 25 cm (10 in.) of clearance on either side of them (see part d) and between them if there is two-way traffic in the corridor (see part e). Minimum aisle width will be set by truck width, clearance needs, and the traffic pattern in the production area.

- Avoid having doors open into corridors. Occasionally there is no alternative, such as in the case of fire doors or a small utility closet in an aisle. In these instances use folding, sliding, or recessed doors if possible.
- Keep aisles clear. Do not allow structural support columns or production equipment to protrude into the aisle space.
- Where possible, avoid locating an aisle against a wall, because this location permits access only from one side.

- Avoid one-way traffic restrictions in aisles. They are practically unenforceable.

Floors

The characteristics of floors in the workplace can determine the potential for slip-and-trip incidents, the forces required to move carts, trucks, or products manually, and the comfort of the people working at standing workplaces. The choice of floor material, how it is maintained, and what footwear the people working in the area are wearing will influence worker safety and performance.

Floor Material

The following factors are usually considered when a floor material is chosen:

- Cost
- Architectural considerations (load-bearing characteristics)
- Aesthetics (appearance)
- Durability
- Nature of work being done
- Maintenance needs

In addition to these factors, attention should be paid to the slipperiness of the floor surface both when dry and when wet from spilled materials or cleaning operations. Install runners, skid strips, grooves, or abrasive coatings to reduce the potential for slip-and-trip incidents, particularly in areas where wet floors are common, such as liquid-chemical preparation areas or cleaning stations (Archea, Collins, and Stahl 1979; "Answers to the Problem" 1980; Brock 1996). Too much slip-resistant material on a floor, however, may make walking or handling of carts and trucks more difficult. The difficulty arises from the increased frictional resistance to the sliding that occurs naturally as part of walking or maneuvering a vehicle manually.

Grates are sometimes used over floors in order to raise the operators during handling operations or to permit them to remain relatively dry during cleaning operations. Floors with grates can significantly increase the force requirements for the operator manually handling trucks and carts, though. Larger casters and wider treads are often needed on the carts to compensate for this increased resistance to motion (Lippert 1954).

Rugs or mats can be used in the workplace to improve the comfort of standing operations, reduce ambient noise levels, reduce breakage in some assembly operations, or improve the appearance of a work area. While they are most often considered beneficial, rugs and mats have increased resistance to rolling motion and therefore make the manual movement of carts, trucks, or other objects across them difficult. The mat or rug should contrast with the floor color so that its edges are clear and do not produce a trip hazard. The edges should be tapered down to the floor to make the transition between floor and rug smoother ("Floor Mats and Runners" 1981).

Cushioned mats (commonly referred to as antifatigue mats) are used often in standing workplaces. Such mats have been found to lower the perceived fatigue and discomfort in the lower extremities when standing for long periods of time (Redfern and Cham 2000). Currently, there are no definitive guidelines on the mat properties that are associated with minimum fatigue, although it appears that thicker mats and those with higher elasticity and stiffness decrease reported fatigue (Redfern and Chaffin 1995). A mat that is very compressible (18 percent of thickness) can also lead to an increased reporting of discomfort (Rys and Konz 1994).

Areas where reduced light levels make visual identification of floor coverings difficult should have full floor coverage, up to entrance and exit doors, or other architectural cues to mark where the floor-to-mat or floor-to-rug transition occurs. These cues may include support columns, panels, or workplace delimiters.

Entrances to buildings from the outdoors should have mats to reduce tracking in of water, snow, or mud in inclement weather. Ideally, the mats should be long enough to permit about ten steps to be taken (about 6 m [20 ft.]) before the regular floor surface is stepped on. In many buildings, it is not possible to provide this much space when a stair flight is present just inside the door. Use of stair mats or a roughened portion on the stair step to improve traction can reduce the potential for slip-and-trip incidents (Asher 1977).

Floor Maintenance

The maintenance of floors may be divided into three categories:

- Housekeeping, such as cleaning up spills and removing dropped objects.
- Cleaning, such as waxing, vacuuming, and scrubbing.
- Repairing, such as filling cracks, repainting, and replacing rugs or mats.

Although the latter two categories are important to ensure that the floors are properly cared for, it is improper housekeeping that frequently contributes to slips and trips (Doering 1974, 1981). Choice of floor material according to the type of work being done can help reduce housekeeping problems, as indicated in the following list:

- Rubber or cocoa-fiber mats may be used at outdoor entrances to buildings. These mats help remove dirt, water, or snow from shoes, so less is carried into the work area.
- Gratings or open rubber mats may be used on floors in areas where water is commonly present, as in cleaning stations or chemical preparation workplaces. By raising the worker above pools of water, gratings or

mats reduce the amount of water tracked to other workplaces in the area.

- Mats may be placed at an assembly workstation where parts may be dropped on the floor. Rug, mat, and floor colors should be chosen to contrast with the items that could be dropped on them. Thus dropped parts would be visible and more likely to be cleaned or picked up. This scheme would be feasible in workplaces where only a few operations are done or where few items are involved.

Attention to three other workplace characteristics may also reduce housekeeping problems in a work area:

- A small catch trough, a depression near the front of the work surface to catch parts before they fall to the floor, may reduce housekeeping problems on floors. Figure 3.24 illustrates a catch trough at a seated workplace.
- Cracks, depressions, or other irregularities in a floor's surface may require much greater forces from operators moving hand trucks or carts manually. The effort needed to dislodge a truck from a floor crack, for instance, may result in product spilling from the truck. This spill could present a slip-or-trip hazard if it is not quickly cleaned up. Floor surfaces should be kept in good repair, especially in areas where trucks or equipment are moved.
- Regular cleaning to reduce the accumulation of dirt, excess wax, or other materials is also needed, because these substances make the surface uneven and may contribute to handling or slip-and-trip incidents.

Footwear

(The material in this section was developed from information in Day and Nielsen 1978 and Shorten 1993.)

Footwear should be selected based on the floor surface, the standing requirements of the job, the nature of the work being done, and the potential for exposure to environmental hazards such as electric shock. For instance, cleaning operations where wax strippers are used on linoleum floors result in very slippery floors. See Figure 3.25 for guidelines on choosing shoes.

When a worker has to exert large forces (greater than 222 N [50 lbf]) to move an object, the slippage of the shoe soles on the floor may determine how much force can be exerted. Provision of a rigid support in the floor that will not be a trip hazard but against which the operator can push to avoid slipping makes force exertion easier (Kroemer 1969; Kroemer and Robinson 1971).

Aside from slip-and-trip considerations, footwear can be chosen to improve comfort in standing operations. Shoes with well-cushioned insteps and soles can be worn in areas where floor mats cannot be used. Using cushioned insoles

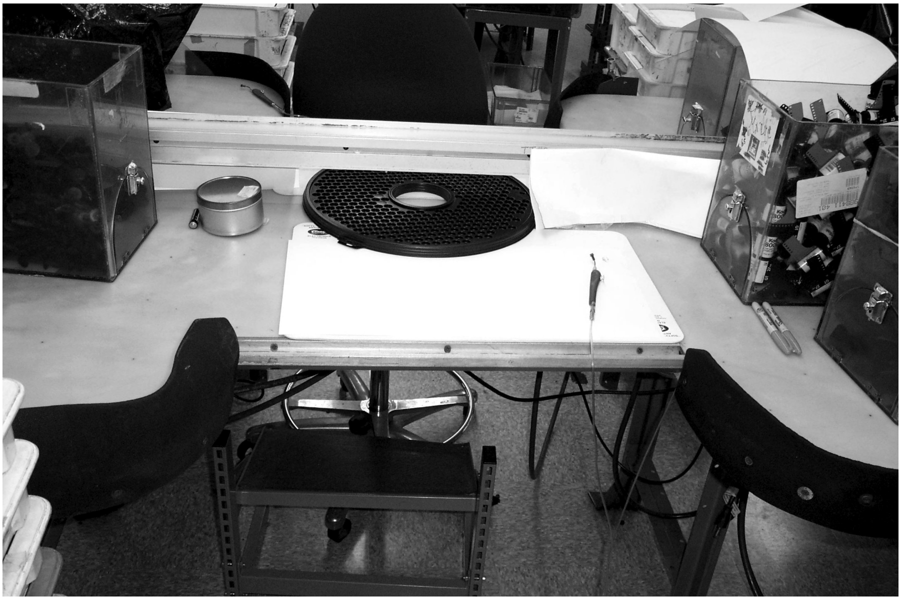


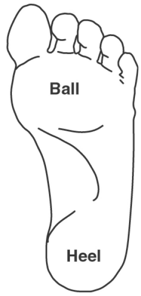
FIGURE 3.24 Workplace Catch Trough
The front surface of this workplace has been cut out to permit the operator to move closer to the conveyor, which runs along the far side. Semicircular cutouts such as this one may be suitable in assembly work stations; storage bins for parts can be clustered around the assembly area within the seated reach space (see Figure 3.2). The front surface of the workplace includes a small indentation that will capture small parts before they roll off the edge onto the floor. The trough should be sloped gradually, without sharp edges, so that it does not represent a pressure point for the operator's forearms during the assembly task.

has also been shown to decrease fatigue in such situations. Insoles, however, do not last the life of the shoe and may need to be replaced every six months to a year.

Ramps

Ramps are found in accessways to buildings and are used to join two areas with different floor heights (joining two buildings, or joining a special-purpose room, such as a computer facility, with its neighboring rooms). The slope of the ramp should be kept below 4.75° (1:12 grade) so that wheelchair users can negotiate it without excessive effort (Tica and Shaw 1974; ADA Accessibility Guidelines for Buildings and Facilities 1998). Where there is not enough space to provide a low-sloped ramp, powered equipment is recommended. For truck and cart handling, a ramp slope of 15° (27 percent grade) marks the point where powered equipment is recommended over manual handling (Corlett et al. 1972).

➢ DO CHOOSE ≺



Wide shoes or shoes shaped like athletic shoes. They are better for your feet than narrow shoes or shoes with higher heels.

Shoes that are adjustable, i.e., have laces or Velcro closures. Slip-on types of shoes are not recommended for work use.

Shoes that are fitted for both length and width.

Shoes with cushioning under the heel and the balls of the toes.

A shoe with a midsole foam layer 3/5" to 3/4" thick in the heel and 1/5" to 2/5" thick in the forefoot (front of the foot). Or use a thinner (less than 3/5"), flexible, soft insole inside the shoe (choose a larger-sized shoe to accommodate the extra thickness).

Shoes that are flexible—e.g., shoes with deep horizontal grooves in the sole and shoes with lightweight upper materials in the forefoot region.

Shoes that will reduce the possibility of slipping. For indoor surfaces, choose a shoe with a flat rubber outsole with a herringbone or similar low-profile pattern.

Shoes that have a perforated or mesh upper for good ventilation.

WORKING IN HOT AREAS:

Shoes that are well ventilated, i.e., fit well and have a low ankle with mesh inserts or perforations on the uppers. If this is not possible (e.g., if it is necessary to wear construction boots or shoes meant for working in chemical areas), then wear socks that pull the moisture away from the skin surface.

➢ DON'T CHOOSE ≺

Shoes with high heels (1" or greater). High heels have been linked to a variety of musculoskeletal problems. However, small heels (1/4" to 1/3" for a men's size 9, scaled to other sizes) decrease the strain on the Achilles tendon and allow more comfortable standing and walking.

High-cut ankles (e.g., boots or basketball shoes). They should be used only if specifically required, such as in construction work or tasks on unstable surfaces. Shoes that are properly fitted and have low heels, firm cushioning, and a stiff external or internal heel counter will provide enough stability for most general purposes.

Shoes made with stiff material or with thick soles or cup soles (soles that wrap around the side of the shoe).

Shoes with leather soles. However, if you will be working in wet or dusty areas, don't choose shoes with polyurethane soles.

FIGURE 3.25 Guidelines for Footwear (Shorten 1993)

Because it is more difficult to walk up ramps than to walk up stairs, ramps should have a nonskid surface and handrails on each side. Figure 3.26 illustrates a ramp for pedestrian and vehicle use.

Many times, a ramp leads to a door. Doors often move outward (toward the ramp) because they are the fire exit from the buildings or rooms to the outside. Pulling a door toward oneself while resisting the rolling motion of a cart, truck, or wheelchair down the ramp can lead to awkward postures and increased potential for accidents. Manually handled equipment should be provided with a brake to assist the operator in negotiating doors on ramps.

Ramps should not be located directly in line with floor openings (pits) or

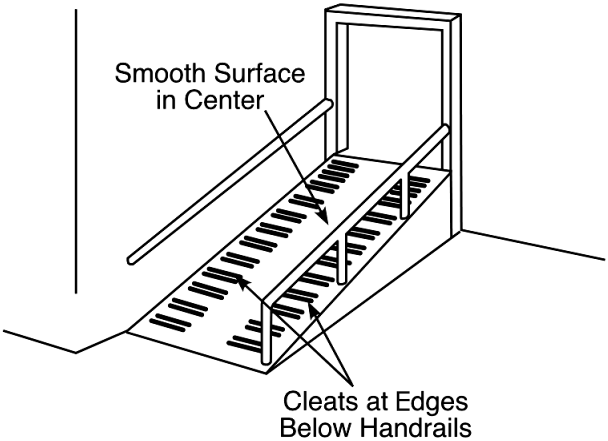


FIGURE 3.26 Ramp Design for Pedestrian and Vehicular Traffic (adapted from Thomson et al. 1963)
The ramp illustrated can be used by both pedestrians (at the sides) and trucks (in the center). Because the ramp must accommodate truck traffic, its center is smooth. Steps have been formed near the handrails by ridges or cleats to provide stability for the pedestrian's feet when ascending and descending the ramp. The width of these steps should not be less than 61 cm (24 in.).

stairwells. If a piece of equipment rolls away from a handler on a ramp, it should be able to come to a gradual stop on a flat surface without endangering people working in the area or damaging itself or other equipment.

Stairs and Ladders

Falls from ladders or on stairs are one of the leading causes of injury and death in the United States (National Safety Council 2000). Attention to the design of stairs and ladders cannot be expected to eliminate all of these incidents because many are related to inattention or risk-taking behavior (Templar, Mullet, and Archea 1976). However, good design can reduce the potential for misstepping or provide a person about to fall with a way to retrieve balance.

Stairs

Detailed recommendations for stair design have been developed by federal, state, and local building code and safety organizations ("Part 1910.24, Fixed Industrial Stairs" 2001; Archea, Collins, and Stahl 1979; Carson et al. 1978). These recommendations should be referred to when a specific design has been developed in order to be certain that it meets existing regulations.

Stair designs have become integrated so completely into the aesthetics of architecture that some new human factors problems have been created relative to anticipated stair riser height and tread width. Designs that are pleasing to

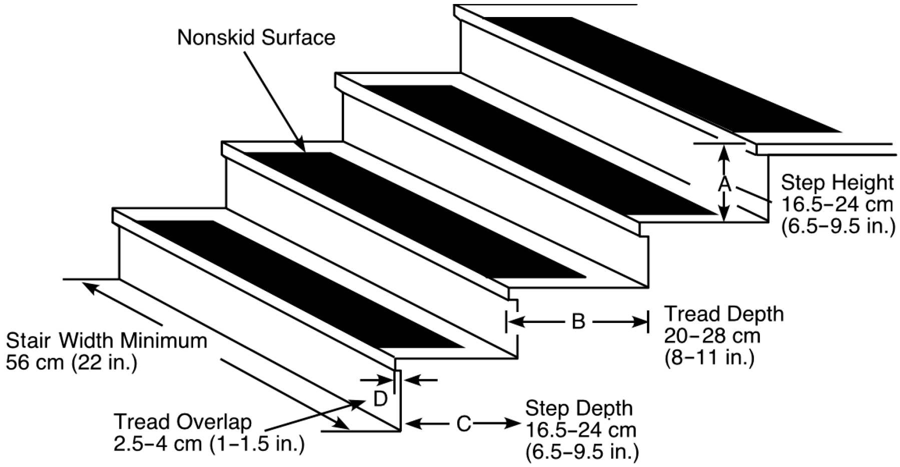


FIGURE 3.27 Fixed Stairway Design (adapted from Thomson et al. 1963; Part 1910.24, Fixed Industrial Stairs" 2001)
A fixed stairway should follow the guidelines for step height (A), step depth (C), and tread depth (B) shown here. The tread should overlap the riser horizontally (D) by 2.5–4 cm (1–1.5 in.). A nonskid surface is recommended for the front surface of each tread. The edge of each step should be distinct, particularly in low light situations.

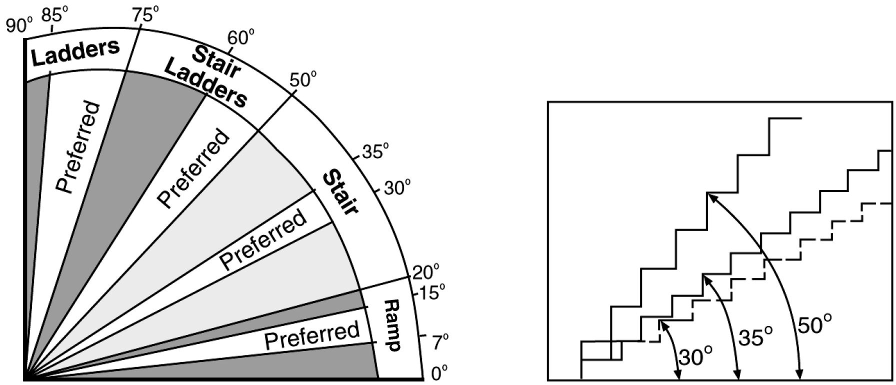
the eye may be hazardous because they do not take into account normal walking gait or expected step height (Templar, Mullet, and Archea 1976). A stairway that is not difficult to ascend may be very difficult to descend.

STAIR DIMENSIONS Figure 3.27 illustrates a typical fixed stairway section, with recommended dimensions for riser height, tread depth, and tread width.

The slope of a staircase should be approximately 30–35° from the floor (Thomson et al. 1963; U.S. Department of Defense 1998). Because stairway slope will affect the mechanics of walking on stairs, tread depth and riser height will have to be adjusted accordingly. Table 3.9 shows this relationship. Figure 3.28 shows how stair slope is measured.

STAIR SURFACES To minimize the opportunity for slipping on stairs, a nonskid surface is often placed on the leading edge of each tread. This surface can be a strip of metal, hard rubber, or synthetic material, or a special paint that resists sliding of the foot and increases the stair user's stability. These nonskid surfaces should be maintained regularly, especially in areas of heavy traffic.

Outdoor stairways or stairways in work areas where water is frequently on the walk surfaces (as in chemical-making areas) should have a means to direct the water away from the treads. This feature helps to prevent the accumulation of water, slush, or snow on the stairs, all of which could result in increased slip hazard for stair users.



(a) Slope and Type of Structure (b) Fixed Stair Slope

FIGURE 3.28 Fixed Stair Slope Range (adapted from Thomson et al. 1958)
The maximal range of a fixed stair slope is 20°–50°. The optimal range is 30°–35°. Slopes below 20° are for ramps; slopes above 50° are for stair ladders. These slopes are shown in part a. The optimal and maximum slopes for stairways are further illustrated in part b. The extremes of this range result in awkward and more strenuous stepping requirements, because the tread and riser design do not match most people's normal gait (see Table 3.9).

TABLE 3.9
Effect of Fixed Stair Slope on Recommended Riser Height and Tread Depth ("Part 1910.24, Fixed Industrial Stairs" 2001a.)

Column 1 presents a selection of slopes, in degrees, that cover the common range (30°–50°) for a fixed stair. Columns 2 and 3 indicate the combinations of riser height and tread depth that would be needed to accommodate each slope. At higher slopes the riser and tread designs become less optimal.

	Riser Height		Tread Depth	
Slope (°)	Cm	In.	Cm	In.
30	16	6.5	28	11.0
35	18	7.2	26	10.2
40	20	8.0	24	9.5
45	22	8.8	22	8.8
50	24	9.5	20	8.0

VISUAL CONSIDERATIONS IN STAIR DESIGN

Stair safety problems are frequently associated with misstepping and catching a heel on the edge of a step. Visual distractions in the stairway may contribute to stair user inattention and, thereby, to an increased potential for misstepping. The following factors should be considered to improve stairway visibility:

- Use a color or hue on the edge of the tread (the nonskid material) that contrasts with the rest of the tread.

- ◆ Use matte, not high-gloss, finishes on the steps so that overhead lighting or daylight does not create sources of glare for the stair user (see "Lighting" in Chapter 8).
- ◆ Do not use carpeting patterns that are visually distracting and so might disguise differences in depth, such as narrow stripes of strongly contrasting colors.
- ◆ Use a handrail that contrasts with wall and stair colors. A handrail of contrasting color is an easier target to focus on when descending the stairs, providing a sensation of improved stability for some people.

HANDRAILS The design of handrails is often affected by architectural as well as functional considerations. A handrail should be graceful enough to add to the aesthetics of the staircase, but it must be functional enough to allow it to be grasped in the event of a slip or to be used routinely in ascending or descending the stairs. Figure 3.29 presents guidelines for the height and grasp characteristics of handrails.

In addition to a handrail, open stairways should incorporate a guardrail at about 38 cm (15 in.) above the stair surface so that a person who slips cannot fall off the side of the staircase.

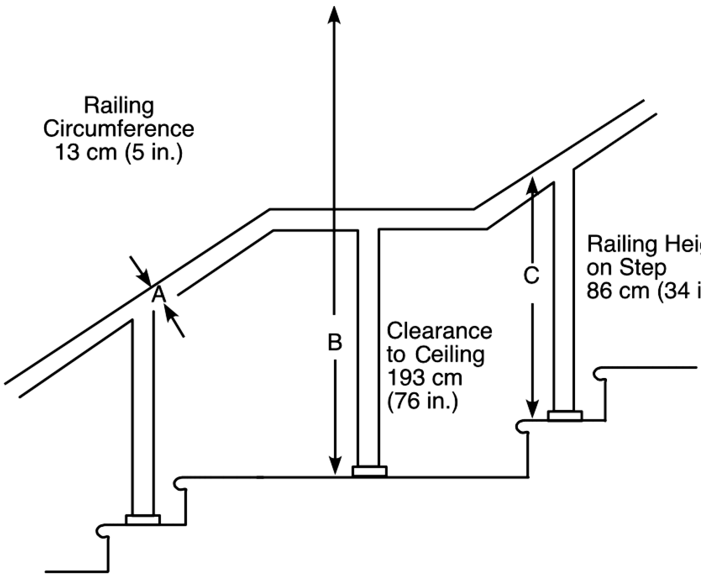


FIGURE 3.29 Handrail Design Guidelines (adapted from Thomson et al. 1963; U.S. Department of Defense 1998; Access Board 1998; Part 1910.24, "Fixed Industrial Stairs" 2001; Tilley 1993)

Guidelines for handrail design on fixed stairs are given. Railing circumference (A) should not exceed 15 cm (6 in.). Indentations allow easier grasping of the railing in the event that a person loses balance when descending or ascending the stairway. Provide a 5-cm (2-in.) clearance (for the hand) around the rail if it is attached to a wall.

Ladders and Step Stools

A ladder is usually thought of as portable and is generally used to move vertically up slopes in excess of 75° above the floor. Stair ladders also exist, which are fixed ladders, usually with a slope between 50° and 75° (Thomson et al. 1963; U.S. Department of Defense 1998). Stair ladders are frequently found in workplaces where large processing equipment, such as reactors or extruding machines, requires operators to move between several levels on an occasional basis. Fixed ladders usually have handrails, whereas movable ones may not. As is the case for stairways, the slope of the stair ladder will determine the appropriate riser height and tread depth. The more vertical it is, the shallower the tread and the higher the recommended riser height.

Detailed recommendations for stair design have been developed by federal, state, and local building code and safety organizations ("Part 1910.27, Fixed Ladders" 2001). These recommendations should be referred to when a specific design has been developed, in order to be certain that it meets existing regulations. Figure 3.30 summarizes the recommended dimensions for stair ladder and ladder design and selection.

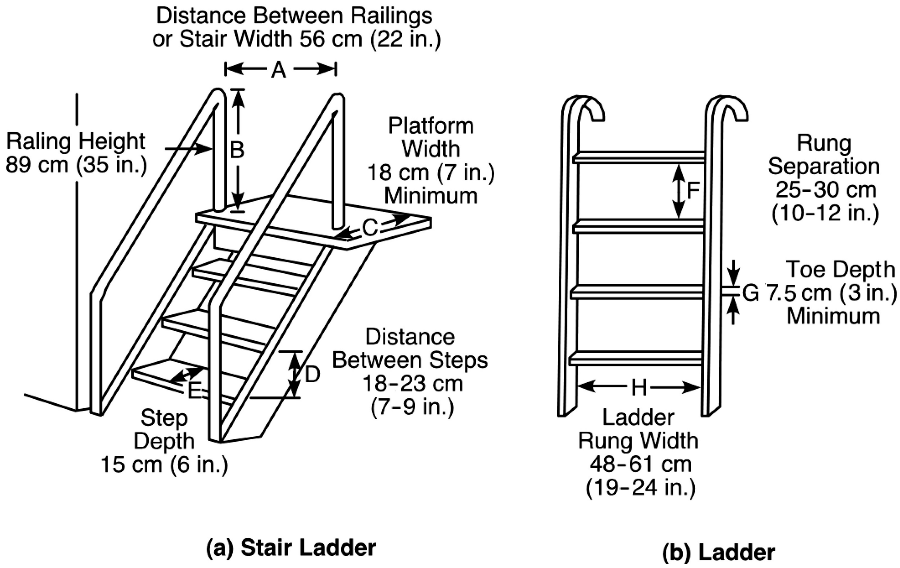


FIGURE 3.30 Design of Stair Ladders and Ladders (developed from information in Part 1910.27, "Fixed Ladders" 2001; Thomson et al. 1963; Woodson, Tillman, and Tillman 1992; U.S. Department of Defense 1998)

The recommended step depth (E), distance between steps (D), distance between the railings (A), railing height (B), and minimum platform width (C) are shown for stair ladders (part a). Stair ladders have a slope greater than 50° and usually less than 75°. The rung width (H) and separation (F) and minimum toe depth (G) for a vertical ladder are shown in part b. The rungs should be flattened on the top to provide stable footing.

There are a large number of step stools and portable stairs (short ladders) used in the workplace to help access high shelves or parts of production machinery. Figure 3.31 illustrates a stepstool and one of these shorter ladders. The ladder should be designed or selected according to the guidelines given above for stair ladders. Stairs with retractable casters (which become very stable as soon as a person stands on them) have the added advantage of being very easy to move around the workplace. Thus they may be used more frequently than stairs that have to be carried or dragged into position. Caution is needed if a retractable-caster stair or stepladder is used in an operation where the user has to do extended forward reaches, since the rear casters may not remain recessed in this posture.

CONVEYORS

Conveyors are often used to link workplaces in a manufacturing system. Products and supplies are carried and moved in and out of the workplace in assembly, storage, transportation, and supply operations. For some situations, assembly work is done directly on the conveyor. The type, location, height, width, and pace of conveyors can all influence the way a person works by

(a) (b)

FIGURE 3.31 Portable Stairs and a Step Stool

Reaching items above shoulder height or lifting materials up to shelves above 127 cm (50 in.) is made easier with portable step stools or stairs. These devices may be two steps about 30 cm (12 in.) high each, as seen in part a, or a small stairway with railings, as seen in part b. The small stairway has retractable casters and four fixed supports. The casters permit the stairs to be moved around the workplace easily; the fixed supports provide a secure base once a person has stepped on the stairway.

determining the postures and strengths required and the amount of time pressure involved. Large manufacturing systems incorporate automatic assembly with hand assembly operations, making the impact of conveyor design greater with regard to both workplace dimensions and pacing.

The following information should be used when installing conveyors in manufacturing and service areas:

- Conveyors should be accessible from both sides, especially in locations where large, heavy products are transported and where jams can occur.
- Crossovers or gates in conveyors should be provided where people need to move in and out of workplaces or where supplies are handled by hand pallets, trucks, or hoists. The gates should be counterweighted and easy to raise and should lock into place when down or fully raised.
- Conveyor height and width for a given operation should be determined by the size of the units carried and by hand location when working on the product (Figure 3.32). The guidelines for work height of the hands in standing workplaces also apply to conveyors in standing tasks. Conveyor heights of 69 to 79 cm (27 to 31 in.) are often used in casing operations or other finishing areas. The seated workplace dimensions given in Figures 3.3 and 3.4 should be used when assembly work is done on conveyors. Large drums (208L [55 gal.]) on a filling line are best transferred on conveyors close to the floor so that they can be chimed (rolled on edge) on and off the conveyor to pallets.
- Conveyors in sequential-assembly workplaces should be located within the sitting or standing arm reach areas discussed earlier in this chapter. Leg and knee clearance should be adequate for seated work. Whenever possible, the operator should be able to slide, rather than lift, the part or tray on and off the conveyor.
- In work areas where the conveyors carry the assembly task and are run either continuously or at a preset rate (as in the case of pulse conveyors or computer-controlled assembly workplaces), the conveyor rate should be set as a compromise between the most- and least-skilled operators. At conveyor speeds greater than 10 m/min (32 ft./min), susceptible people may develop conveyor sickness symptoms such as nausea and dizziness (T.G. and R.L. 1975).
- Since unloading conveyors has been shown to be three times as likely to result in overexertion as loading them (Cohen 1979), a space should be provided that can be used to temporarily accumulate parts or trays after sliding them from the conveyor. This arrangement removes some of the pace pressure from the operator and permits more careful handling of materials from and to the conveyor.
- For sequential-assembly work, the operators should be allowed to influence the pacing of the task by having the nest (or part) stop in front of them to give them control over its release.

(a) Seated inspection at a conveyor (b) Loading a conveyor

FIGURE 3.32 Workplaces at a Conveyor

In shipping or receiving operations, when bulk materials and cases are handled, snake conveyors for truck and railroad car loading or similar conveyors that permit some flexibility in locating them (e.g., retractable conveyors with skate wheels) should be used. Wherever possible, the manufacturing process and the shipping operations should be linked to minimize the need to rehandle product. Continuous conveyors should be designed to move product to the shipping area without interfering with other activities on the work floor.

ADJUSTABLE WORKSTATIONS

People vary in size and strength. Thus, no one design can be optimal for all people. Adjustable workplaces or pieces of equipment that accommodate individual differences are, therefore, very desirable. Chapter 1 includes information on the anthropometric characteristics of industrial and military populations. These data are used to assess the impact of a proposed or existing design on the potential workforce. Most workplaces require attention to more than one anthropometric characteristic. The design of seated glove boxes, for instance, has to consider forward reach, shoulder breadth, visual angles, hip-to-thigh length, thigh breadth, and upper arm circumference. If designed for a person with either 5th-percentile (short) or 99th-percentile (long) reach, it would probably be unsuitable for most people (McConville and Churchill 1976).

A good fit between the person and the task can be obtained by making the workplace adjustable. The needed adjustment can be achieved in one or more ways: the work surface can be raised or lowered, the person can change position, a tool can be moved or used to extend a reach, or the product or object being worked on can be relocated or reoriented.

Although adjustable features are provided in the workplace, they may not be used. Use depends on how much time and effort are needed to make the changes and on perceived benefits to the operator. Not every person will need to employ the adjustment. However, if the adjustment is there, more people will be comfortable in the workplace. An aid that is shared between widely spaced workplaces, such as a drum truck or stacker truck, may not be taken advantage of by an operator because it will take too long to procure. Availability and accessibility of the aid, such as an air hoist or elevator, will also determine its use. Examples of three levels of adjustability are given in Table 3.10.

Flexibility is not the same as adjustability, although it is a desirable workplace feature. A flexible workplace is one that can be readily changed or modified to accommodate a product or task change. Once the change is made, the workplace remains fixed. Flexibility is particularly useful in an area where frequent product changes occur.

TABLE 3.10
Levels of Adjustability

Level	Characteristics	Examples
High	Instantaneous (<5 seconds) Continuous Powered or mechanical assist	Pneumatic chair Air hoist Spring-loaded palletizers
Moderate	Takes 5 to 30 seconds Incremental adjustment Manual effort	Chain hoist Pallet truck foot pedal Fold-out steps Adjustable lighting fixtures Mechanically adjusted chairs
Low	Takes more than 30 seconds Only two levels of adjustment Manual effort: pushing or lifting	Sliding, wing-nut chair or footrest adjustment Panel-hung furniture Manually rotated palletizers Adjustable shelving or parts holders

Adjusting the Workplace

The shape, location, and orientation of the workplace are determined by the overall layout of the production line. How the person interfaces with the workplace may be influenced by these factors.

Shape

Where a forward reach in excess of 40 cm (16 in.) is required (e.g., disposing of a product to a work surface behind a 50-cm [20 in.] conveyor), a semicircular cutout can be made in the workplace to bring the operator closer to the reach point (Figure 3.24 illustrates an example of such a cutout). The cutout can be made only if the requirements for workspace in front of the operator are small. An additional advantage of this cutout is that aisle space behind the operator is increased when the chair is pulled into the workplace.

Location: Height and Distance

A drafting board or an adjustable-height table is especially useful at a standing workplace, because the angle or height (or both) may be varied to accommodate people of different sizes. To be effective, the adjustment mechanism has to be easily found and activated. Tilting the work surface toward the operator in some tasks may reduce the reach. All job requirements should be evaluated, however, to ensure that none would be affected negatively by use of the tilt capability.

Orientation

Positioning of the workplace in relation to a conveyor line or other flow of materials can affect the reach and strength required to procure and dispose of product. Orienting the work surface at a 45° or 90° angle to the conveyor has been used to reduce the reach when the worker is lifting heavy objects. The suitability of such an orientation has to be evaluated in terms of all the tasks performed; visual and communication needs should also be considered.

Adjusting the Person Relative to the Workplace

Height adjustment of the work surface is often not feasible because many services to the workplace, such as pipes, vents, and conduits, are rigidly attached to it. In this event, people can be located on an adjustable chair or platform or given footrests, armrests, or other aids to improve their interaction with a non-adjustable work surface.

Chairs

Vertical adjustment can be achieved by changing chair or seat height. Some horizontal adjustment may be obtained with chair casters and swivel seats, which extend a person's reach by extending his or her range. It is important for a chair to provide correct posture and comfort and features compatible with the workplace and task. Poor seating can lead to fatigue, poor performance, and interference with work. The dimensions shown in Figure 3.33 summarize characteristics that should be looked for in selecting a chair for a workplace.

The operator in a production workplace should be provided with a chair that has the following characteristics (Faulkner 1967, 1968, 1970):

- An easily adjusted seat height, such as is found in a pneumatic chair
- An easily adjusted backrest giving lumbar support with up-and-down as well as in-and-out movement

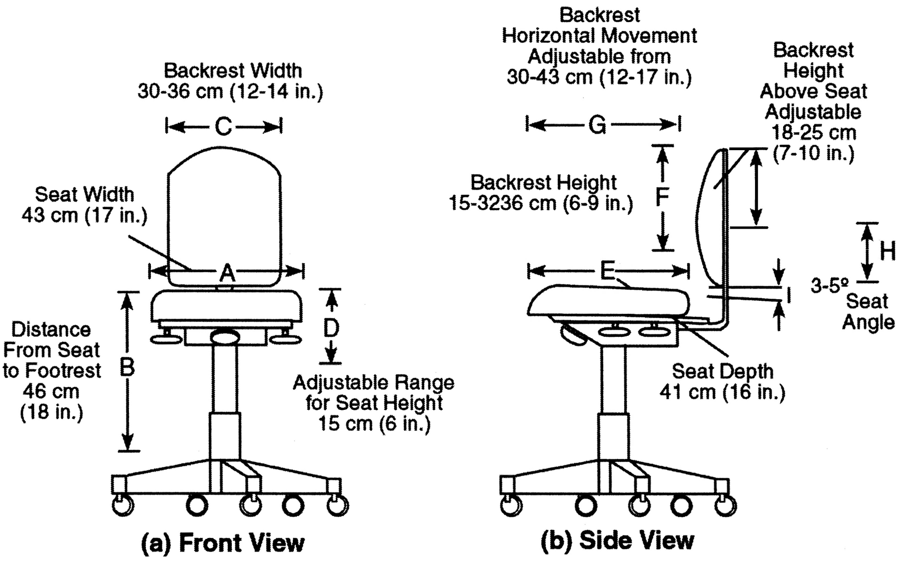


FIGURE 3.33 Recommended Chair Characteristics (developed from information in Akerblom 1954; "Seating in Industry" 1974; Faulkner 1967, 1968, 1970; Floyd and Roberts 1958; Grandjean 1995)

Dimensions for chair seat width (A), depth (E), vertical adjustability (D), and angle (I) and for backrest width (C), height (F), and vertical (H) and horizontal (G) adjustability relative to the chair seat are given, using both front (part a) and side (part b) views. The backrest should be adjustable horizontally from 30 to 43 cm (12 to 17 in.), by either a slide-adjust or a spring, and vertically from 18 to 25 cm (7 to 10 in.). This adjustability is needed to provide back support during different types of seated work. The seat should be adjustable within at least a 15-cm (6-in.) range. The height above the floor of the chair seat with this adjustment range will be determined by the type of workplace, with or without a footrest (see Figure 3.3). The 46-cm (18-in.) distance between the chair seat and the footrest should be maintained by having the footrest move vertically 15 cm (6 in.) with the seat.

- A backrest narrow enough so that an operator's arms and rib cage do not strike it if the torso is rotated during a work cycle
- A seat with a rounded edge and upholstered in woven fabric to improve comfort in the warmer months

Chairs with casters are suitable for seated workplaces without footrests. Seat height should not be adjusted to more than 51 cm (20 in.) above the floor in order to maintain stability.

Current chairs often offer the option of seat tilt. The seat on such chairs can be tilted forward 5–20° (depending on the design). Some studies have shown that tilting the seat can help reduce lower leg and back discomfort, particularly if the chair seat is free-floating (rocks) (Mandal 1981; Naqvi 1994; Udo, Fujimura, and Yoshinaga 1999; Stranden 2000).

For a computer workstation, the following guidelines may be followed (HFES 1988):

- Chair seat height should be between 40 and 54 cm (16–21 in.).
- Seat depth should be between 38 and 43 cm (15–17 in.) to allow contact with the lumbar support.
- Seat width should be at least 46 cm (18 in.) at the center, and the front edge of the seat should be rounded.
- Seat pan angle should be between 0º and 10º (if adjustable, the choice should cover this range).
- Angle between seat pan and backrest should be between 90 and 105º.
- Seatback should be at least 30 cm (12 in.) wide.

Support Stools, Swing-Bracket Stools, and Other Props

A chair or stool used at a sit/stand workplace must be very stable; for instance, five legs are preferred to four, with a wide base. A swing-bracket stool can also be used as a support stool or prop; the operator leans against the seat rather than sitting on it, thereby getting postural relief during an extended standing operation. It is important that the prop be located so that the operator may continue performing the job. Props like this can be helpful in extending monitoring activities. Such props, however, should not be used as a substitute for a chair, it will gain little acceptance if presented as such. Figure 3.34 illustrates a number of props that can be used in industrial workplaces, including a foot rail, padded arm rail, jump seat, and prop stool.

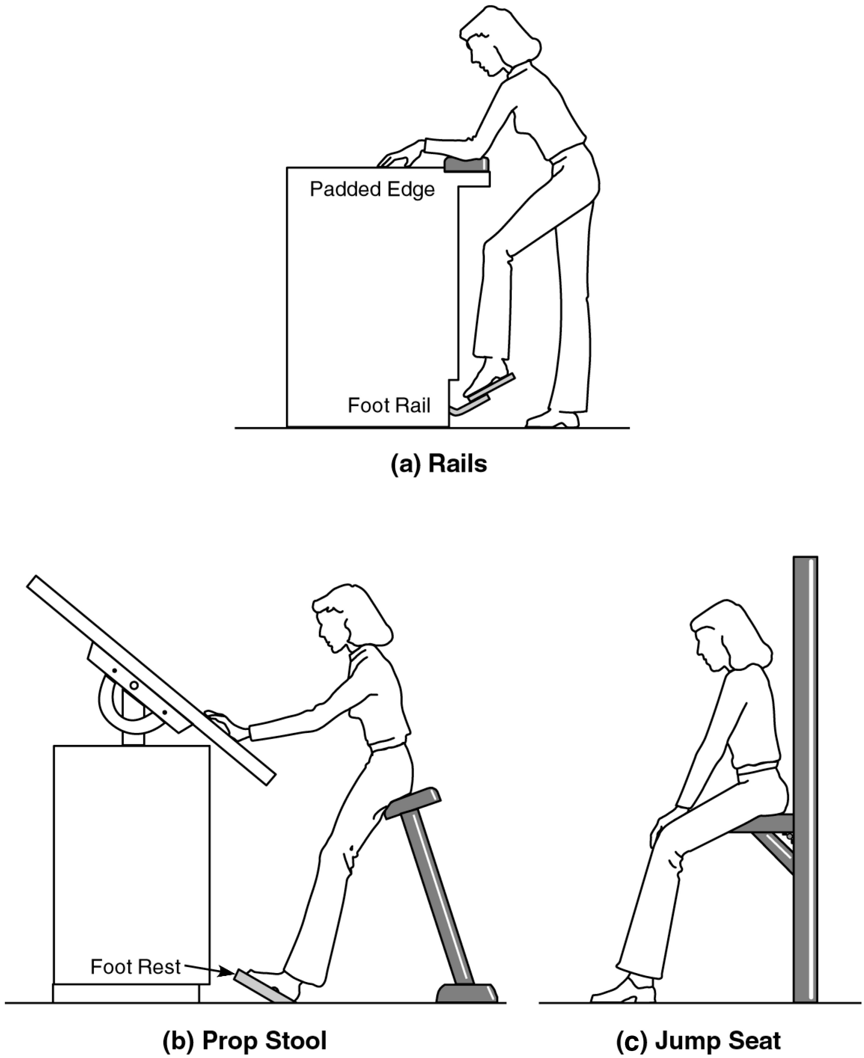


FIGURE 3.34 Other Props for Operators in Standing Workplaces
Four types of props that can be used to aid operators in predominantly standing workplaces are shown. The foot and arm rails (part a) provide ways to rest the legs, one at a time, and the arms, by cushioning the elbow. The jump seat (part c) is not adjustable, but it provides a temporary seat for an operator during a break in the work cycle or for a short monitoring activity.

Platforms, Step-Ups, and Mechanical Lifts

Another means of adjusting a person to the workplace is to use a platform or step-up stool. These aids do not provide a change in posture, as the props discussed above do, and they may present a tripping hazard to people unfamiliar with a work area. Ideally, such a platform or step-up stool should be retractable—designed to be moved out of the way when not in use. In areas where low light levels predominate, full-floor platforms present less of a tripping hazard, but these devices may not be acceptable if materials-handling equipment such as a pallet truck has to be used in the area.

For areas where it is necessary to work above head height for extended periods, a mechanical lift or elevating platform can raise the person to reduce arm and shoulder fatigue. Riding trucks with mechanical lifts are often used in warehousing and construction or maintenance activities.

Footrests

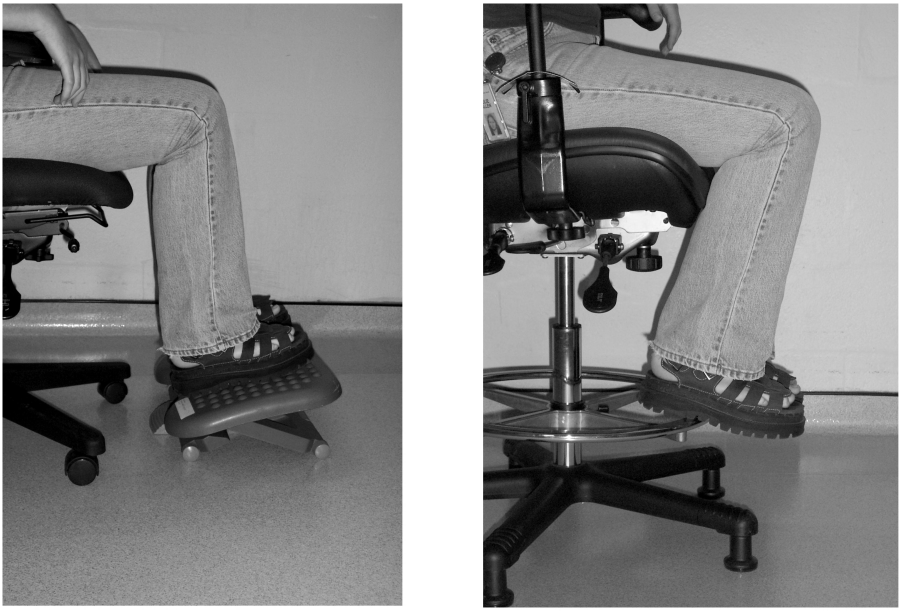
For accommodation of all sizes of operators, a workplace should include an adjustable footrest. An adjustable chair, by itself, is insufficient, because achieving the best height for working at the work surface may leave the feet unsupported. This puts pressure on the underside of the thighs, which is uncomfortable.

Some of the types of footrests available are (see Figure 3.35) a portable footrest or platform, a chair foot ring, and a footrest built into a workbench. For the workplace where a low chair is used and the feet are close to the floor, a portable, angled footrest can be used. With the chair adjusted to the correct working height, people with short legs can use the footrest to reduce discomfort on the underside of their thighs.

Whatever type of footrest is provided, it must be easily adjustable. Rings on a chair are acceptable only if they are height-adjustable. If the seat is raised, a person with short legs may not be able to reach a fixed foot ring. Some chairs are manufactured with foot rings that move with the seat as it is adjusted, and others have foot rings that can be adjusted independently. Because foot rings are generally close to the center post of the chair, the operator has to position the legs backward to use them and cannot operate foot pedal controls from them.

Portable footrests must be large enough to support the soles of both feet. A surface of 30 × 41 cm (12 × 16 in.) should be adequate. If the footrest is built into the workplace, it should be 30 cm (12 in.) deep and wide enough to reach across the width of the seat well. The footrest inclination should not exceed 30° (Roebuck, Kroemer, and Thomson 1975). Its top should be covered with a nonskid material to reduce slippage. Bars, brackets, or narrow strips are not adequate footrests.

It is usually best to build the footrest into the workplace. A board whose height can be varied in 5 cm (2 in.) increments (like a bookshelf or refrigerator shelf) is satisfactory for most situations.



(a) (b)

FIGURE 3.35 Examples of Footrests for Seated Workplaces
Two types of footrests are illustrated. Part a shows an adjustable platform that is set on the floor under a seated workplace; it can be moved to the most comfortable location by the operator. A footrest on an adjustable chair is shown in part b. These footrests are often not easily adjustable, making them less suitable for people with short legs whose work requires them to use their chair at the upper range of its adjustability.

Armrests

Armrests should be provided in assembly or repair tasks when the arm has to be held away from the body or is not moved extensively during the work cycle. A soft foam or plastic cushion on the armrest, covered with a nonsoiling fabric, will permit easy movement of the forearm and avoid discomfort from hard edges (Kellerman, van Wely, and Willems 1963). The armrests should be located near the front surface of the workplace but should be easily movable to fit the variety of tasks an operator may have to do. They should be 5–8 cm (2–3 in.) wide and should tilt without having to be readjusted manually. Wrist supports can also be useful in delicate assembly work to steady the hands.

Adjusting the Workpiece or the Product

Adjusting or repositioning the workpiece or product enables the operator to maintain a comfortable working posture while continuing a series of tasks. The workpiece can be adjusted or held in a fixture, parts can be supplied in a revolving supply bin, or the product can be adjusted on a leveling device such as a lift table.

Jigs, Clamps, and Vises

It is often necessary to hold a workpiece still while an operation is done on it. If one hand is primarily needed for holding, use of a fixture can improve the efficiency of an assembly operation by reducing static effort. Jigs, clamps, and vises are fixtures that can be used to hold a workpiece. When rotation is added, with a swivel ball and joint, for example, and motion along a track is allowed for translational movement, fixtures can become an indispensable tool to an assembler. Location of the fixture in the workplace should not require awkward reaches. These can best be avoided by making the location adjustable, for example, by mounting the fixture on a sliding track.

Circuit Board Assembly

Boards or holders are available on which larger parts can be mounted. These boards permit a wide range of motions so that the operator does not have to use awkward hand and wrist motions to complete parts of the assembly. They are often used in electrical circuit board assembly operations (Figure 3.36). For other applications a tilting-easel workplace may be useful.

Parts Bins

In tasks where a large number of parts are used, such as electronic assembly operations, a revolving bin is sometimes useful to improve accessibility of parts ("Part III: Small Parts Containers" 1959). In workplaces where parts storage space is limited, a multitiered set of bins can reduce the need for extended and awkward reaches. It can also use otherwise inaccessible space. Parts bins that tip forward for easy access are also available.
Figure 3.37 shows parts bins used in an assembly task workstation.

Lift Tables, Levelators, and Similar Equipment

In pallet loading and some packing operations, the product height can be adjusted by using a lift table, as shown in Figure 3.38. A levelator, lowerator, stacker, or forklift truck can also be used. Where powered equipment cannot be used or justified economically, use of a wooden platform or two or three stacked pallets to provide increased height often adjusts the product sufficiently. See Chapter 7 for more information.

Adjusting the Tool (Design and Location of Tools)

There are many tasks where tools are used to perform operations that the hand cannot do, to add strength to the hand, or to increase the arm reach

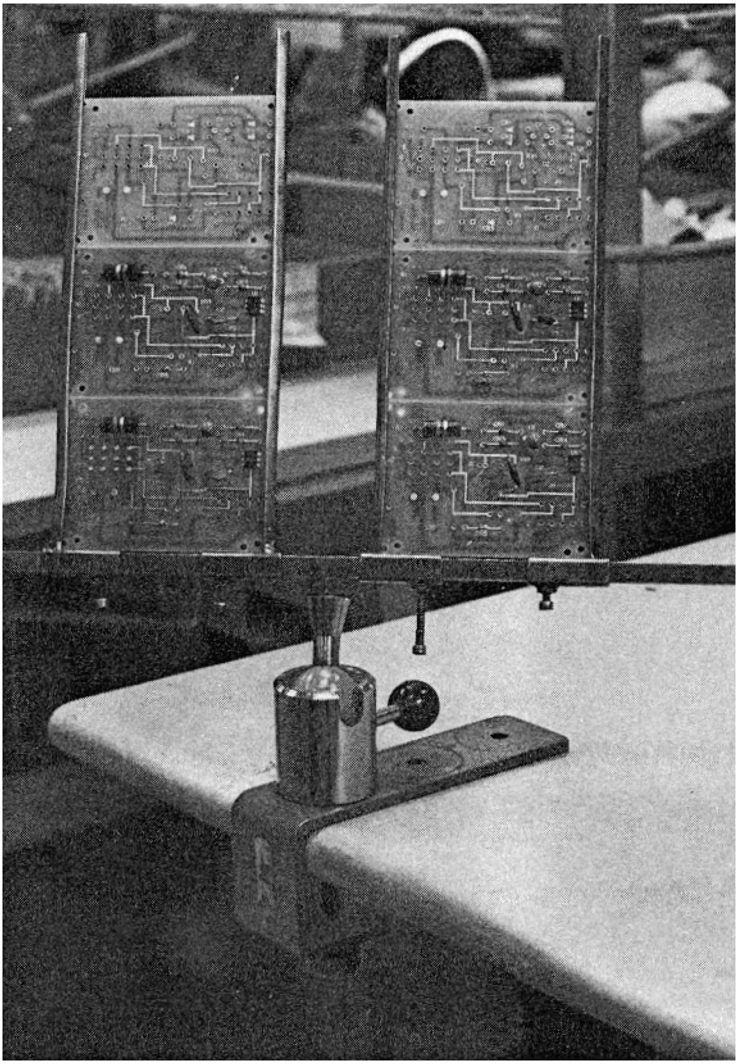


FIGURE 3.36 Circuit Board Assembly Aid

The boards are attached to a ball-and-socket fixture that allows them to be rotated to, and fixed in, a multitude of positions. This feature permits the operator to move from one side of the boards to the other without having to repeatedly remove and replace the units. The boards are held in position by the fixture, so the operator has two hands available for the assembly task.

capability. Power wrenches or screwdrivers, for instance, are used in many assembly operations. The weight of the tool is enough to recommend that it be supported from above, but the way in which that support is given can force the hand into an awkward position during assembly tasks. Whenever possible, the tool should be supported so it has several degrees of motion. For example, a hose should be attached with a universal swivel joint and should be on a track

FIGURE 3.37 Parts Bins for Small Parts Assembly
Small parts are stored in individual bins at the workplace. They are located directly in front of the operator within the seated arm-reach space (see Figure 3.2). Incoming and outgoing product is stored to the sides of the assembly area. Such bins are especially recommended where confusion between parts can occur and where many parts are used. An overhead support for a powered screwdriver is also shown. This support permits the assembler to bring the screwdriver down to the work as needed; the tension reel (at the top of the photograph) lifts the tool out of the way when it is not in use.

FIGURE 3.38 Lift Table for Adjusting the Height of a Pallet
A lift table that can be adjusted vertically is shown at a palletizing station. A pallet is placed on the table; its height is then adjusted to permit the operator to transfer product horizontally or downward to it from the conveyor line or workplace.

or spring with a low-tension reel, which allows the operator to move it through 180°–270° without having to fight the power cord (see Figure 3.37).

For more details on the design of the hand tool itself, refer to Chapter 4.

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4 Equipment Design

The design of equipment can have profound effects on the safety and performance of people at work. There are four main aspects of equipment design that should be considered by the ergonomist:

- Overall considerations (such as physical demands and safety)
- Maintainability
- Design of the displays
- Design of controls

In addition, two other related topics are discussed in this chapter:

- Hand tools
- Selection and evaluation of equipment

For a system to operate successfully, the efficient operation of a machine is not enough; the machines must be usable within the constraints of the system operator. Further, not only should the system be usable, but it should also demand enough attention and skill to be rewarding. Usability of the system can be addressed through good equipment design; however, the latter issues are within the realm of job enrichment and work organization, and will not be discussed in this chapter.

The goal of the ergonomist is designing equipment to be within the strength, endurance, reach, sensory, and information-processing capabilities of a large number of people. This is not always possible, sometimes because of time pressures in the design phase or the need to use off-the-shelf components. Reliable equipment often continues to be used even if the operator interface is ergonomically deficient. Further, these poor designs are sometimes perpetuated when a company chooses to save money by making copies of existing reliable machines rather than redesigning them.

The time to think about how the operator will interact with the equipment is at the concept stage. Such issues cannot be tackled effectively or incorporated as easily into an existing design. If the ergonomist's role in the design process is purely that of a reviewer, only deficiencies can be identified. It is often too late to make more than nominal changes to improve operator interface, thereby reducing the productivity of the equipment.

Human beings are the most flexible part of a system, and operators may be able to work around the design deficiencies of the equipment. However, this requires extra effort on the part of the user, leaving less time and energy for other tasks, thereby underutilizing the human resources.

OVERALL CONSIDERATIONS

As vital systems in the manufacturing system, production machines can be designed to improve the performance of the human system element in two ways: first, by appropriately allocating tasks to people or machines, and second, by designing equipment within the capabilities of people, in order to optimize their performance. Functions are typically allocated by taking into consideration (Mital et al. 1994):

- Physical demands (or the ability of the human to perform the task reliably)
- Sensory and information processing demands
- Safety considerations
- Feasibility and cost

Physical Capability

When designing equipment, emphasis should be placed on ensuring that those tasks allocated to humans can be performed optimally. The strength and reach information in "For Whom Do We Design" in Chapter 1 as well as the workstation design and layout information in Chapter 3 should be used when generating specifications for equipment.

The alternative to designing equipment within the reach and strength capacities of the industrial population is to select the people whose anthropometric characteristics make them suitable for the operation of a given piece of machinery. Because the selection of people to fit job demands requires special testing and validation of the selection criteria for each job (EEOC 1978), proper job design is the preferred approach. Figure 4.1 illustrates the difficulties of selecting operators to operate a modern industrial lathe. The lathe controls are located so that the ideal operator for this job would be 1.4 m (4.5 ft.) tall, have a shoulder breadth of 0.6 m (2 ft.), and have an arm span of 2.4 m (8 ft.). Individuals possessing these characteristics may have the required reaches and strengths yet lack communicative skills and have an unbridled passion for bananas.

A short summary of the salient guidelines follows:

- Forward reaches should be kept within 46 cm (18 in.) of the front of the body (measured at the ankles whenever possible).
- Objects weighing more than 10 kg (22 lb.) should be handled between 25 and 100 cm (10 and 39 in.) above the floor.

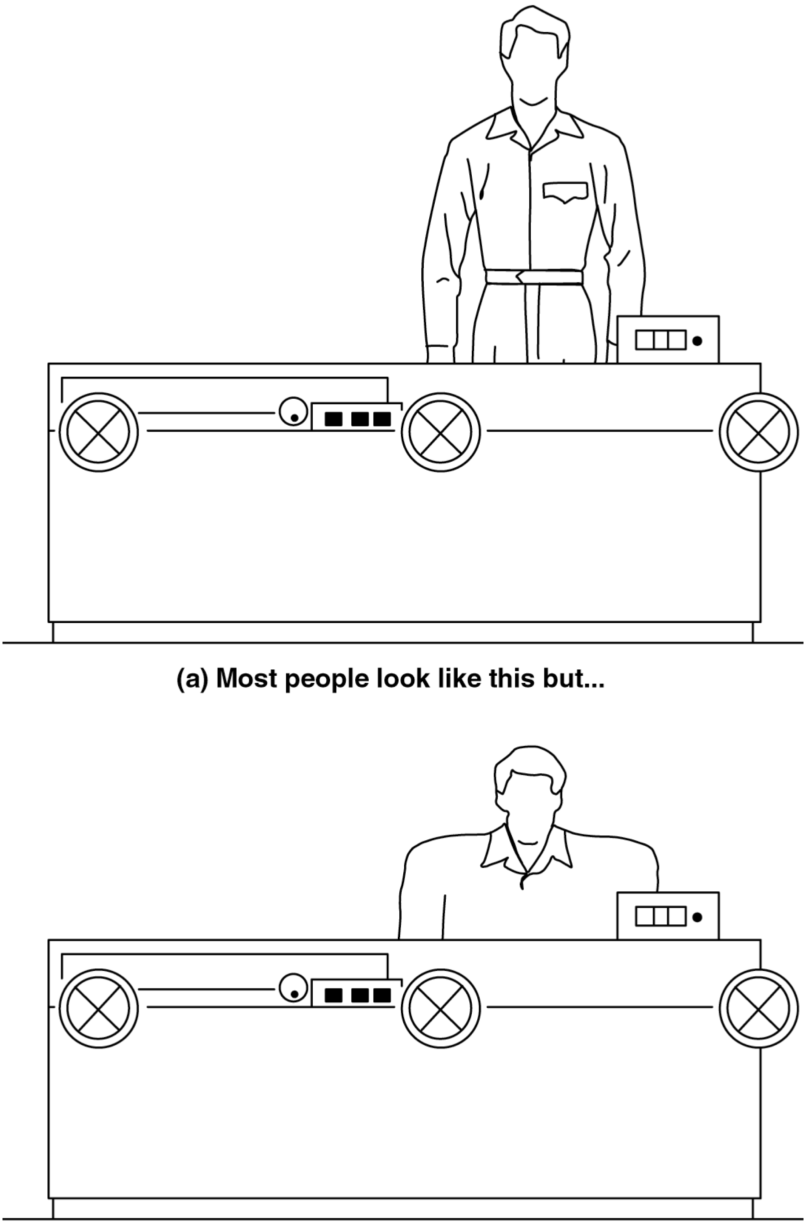


FIGURE 4.1 Industrial Lathe Design: Human Interface (adapted from Singleton 1962)

The drawing in (a) shows the location of controls for an industrial lathe in relation to a typical person's body size. Many of the controls are below waist height and at more than arm's reach from the center of the workplace. The drawing in (b) predicts what a person would have to look like in order to possess the reach and visual control capabilities needed to comfortably operate this lathe.

- The higher the lift and the farther in front of the body it is, the less the weight that can be handled. Provide either automatic equipment (such as air conveyors) or aids to operators (such as platforms or hoists) when production machine supplies must be loaded into hoppers that are more than 100 cm (39 in.) above the floor. Similar approaches are desirable if the load to be supported is more than 36 cm (14 in.) in front of the body.
- At seated workplaces (e.g., machine consoles) 100 cm (39 in.) of forward leg room is recommended. Work surface height should be about 65 cm (26 in.) above the floor; an adjustable-height chair should be provided.
- Upward reaches should be no more than 60 cm (24 in.) above the chair seat.

Environment and Safety

Accidents are often ascribed to human error. Poor equipment design may often be a major contributor to human error by requiring operators to work to the limits of their capabilities for information handling, perception, or exertion of strength. Awkward lifting and twisting and similar overexertions may be produced by systems designed with excessive reaches or inadequate clearances. If human factors principles are incorporated into the design of production equipment, the system should be easier to operate and, thereby, safer and more effective.

The following suggestions should improve the safety of machinery and remove the operator's burden of being constantly aware of possible hazards:

- Provide handles on components weighing more than 4.5 kg (10 lb).
- Avoid or guard against pinch points.
- Provide protection against accidental activation of control switches. This protection can be achieved both by shielding the control so that it cannot be activated if struck by another part of the body or by equipment moving through the area and by locating the controls in the workplace so that accidental activation is unlikely.
- Provide lockouts on machine controls to ensure that others cannot start the machine when it is being maintained or cleaned.
- Provide lock-ins on ladders, stands, and telescoping extensions to prevent their inadvertent collapse.
- Round off sharp edges and corners to reduce impact injuries.
- Provide guardrails around platforms used for monitoring or maintenance activities.
- Keep machine parts out of aisles so that tripping hazards are reduced.
- Provide aids (color coding, lighting, standard location) for readily accessing, identifying, and activating emergency equipment.

- Provide an environment with controlled levels of heat, humidity, noise, illumination, and chemical and physical substances so that the operator can perform the job without undue risk. See Chapter 8 for further information.
- Design reaches and clearances within the guidelines presented in Chapters 1 and 3.
- Keep lifts between 25 and 130 cm (10 and 51 in.) above the floor. Design supply stations so that bulk materials can be slid or automatically conveyed instead of requiring lifting.

MAINTAINABILITY

The material in this section was developed from information in Chapanis et al. 1963, Crawford and Altman 1972, and U.S. Department of Defense 1998.

Production equipment should be designed from the start with maintainability in mind. As systems become more complex and interdependent, evaluation of maintenance needs and the provision of aids to troubleshoot problems in a timely manner become even more important. The best source of information about maintenance needs are the maintenance mechanics, who are most affected by poor design. In the planning of a system, the following questions should be dealt with to ensure an effective maintenance program:

- What must the system do, and how reliable must it be?
- What routine and nonroutine kinds of service are needed? What are the criteria for overhaul or replacement?
- Where will maintenance be done? On the machine? In a shop? By contract or in-house mechanics?
- How much time will be available for completing maintenance activities? Will the mechanic be working under time stress?
- What information is needed to permit the mechanic or machine operator to make trade-offs among factors such as cost, speed, reliability, labor, and flexibility?
- Has a maintainability concept document been established for each piece of production equipment? This document should include the following:
  - A review of the maintenance program
  - Information from other concerned areas in the organization
  - Maintenance criteria for the designers and developers of the system

Areas to Consider When Planning Maintainability Requirements

There are five general areas to consider when planning the maintainability requirements of a production system. These areas are presented below with general guidelines for each.

Prime Equipment

- Use modular units that can be easily disconnected at one or two points, so that they can be removed for repair or maintenance.
- Design replaceable units that are independent and interchangeable. Removing and replacing one unit should not require extensive adjustment of other units.
- Provide easy access to test points and internal parts of the equipment.
- Provide self-checking features or test points for checking by auxiliary equipment.

Test Equipment

Design production machinery systems so they may be checked with readily available, standard test equipment. If this cannot be done, design and build special test equipment that will be available when the prime equipment is ready to use. Consider access points for test equipment when designing the equipment and planning the layout.

Maintenance Manuals

- Write up the maintenance procedure with aid from the system designers and experienced service personnel.
- Provide the maintenance manual at the time the equipment is ready for use.
- List all of the steps necessary to maintain the equipment. Use illustrations, descriptive material, checklists, and diagrams.
- Keep the manual up to date.

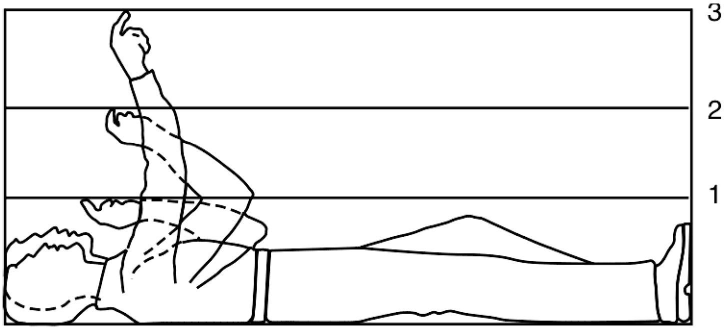
Tools

- Use standard tools wherever possible.
- Minimize the number of different tools needed to repair or service the equipment.

Installation and Accessibility

Design the equipment so that it may be easily serviced in the location where it is installed. Use the guidelines for reaches and strengths included in "For Whom Do We Design?" in Chapter 1 and the information on clearance around the machine in Chapter 3.

Clearances should be calculated to accommodate the largest worker. It should be possible for large workers to fit easily into a workspace. Some espe-



Position	Minimum Dimensions	
	Vertical	Horizontal
Lying for inspection—1	46 cm (18 in.)	193 cm (76 in.)
Restricted space for small tools and minor adjustments; power from elbow extension not possible—2	61 cm (24 in.)	193 cm (76 in.)
Space for reasonable arm extension; power tools 152–203 mm (6–8-in.) in length could be used—3	81 cm (32 in.)	193 cm (76 in.)

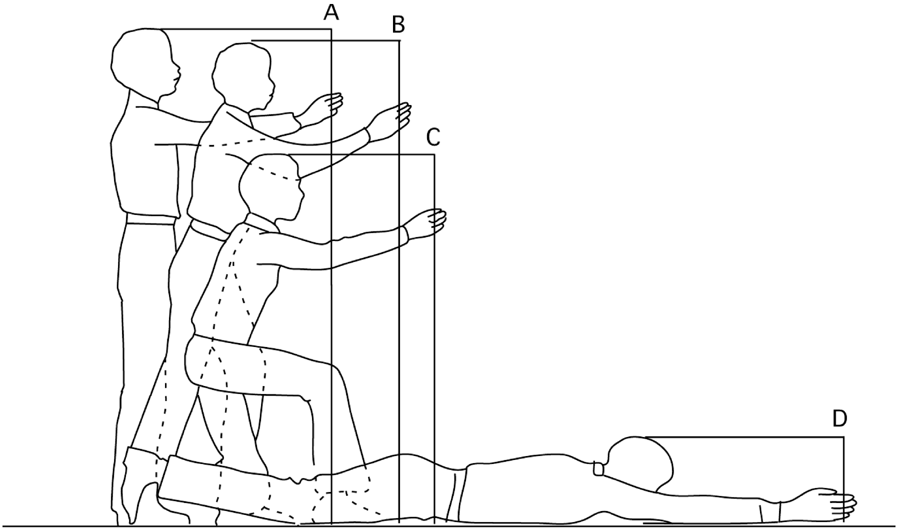
FIGURE 4.2. Work area clearances, horizontal (developed from information in Croney 1971; Hertzberg, Emanuel, and Alexander 1956; Rigby, Cooper, and Spickard 1961)

cially critical clearances should accommodate the 99th-percentile worker and have a safety margin to spare. Minimum clearances for several activities are shown in Figures 4.2 through 4.7.

In Figure 4.6 minimum access port dimensions are 33 by 58 cm (13 by 23 in.). These dimensions just allow a large person to move through the port. A 76-cm (30-in.) diameter port (e.g., a manhole) permits arm and leg bending as well.

Some general guidelines to follow for accessibility (U.S. Army 1975; U.S. Department of Defense 1998):

- A horizontal clearance of at least 117 cm (46 in.) should be provided beside a piece of equipment that requires on-site maintenance.
- A vertical clearance of 203 cm (80 in.) should be provided above any piece of equipment that requires overhead maintenance.
- Space should be provided around components that may have to be removed. A minimum of 4.5 cm (1.8 in.) around each side of the component to be grasped is recommended.



Position	Minimum Dimensions	
	Vertical	Horizontal
A. Standing	203 cm (80 in.)	76 cm (30 in.)
B. Standing, legs braced	203 cm (80 in.)	102 cm (40 in.)
C. Kneeling	122 cm (48 in.)	117 cm (46 in.)
D. Lying prone, arms outstretched	46 cm (18 in.)	243 cm (96 in.)

Note: Breadth should be at least 61 cm (24 in.), as given in Figure 3.22 Horizontal distances are measured from the back of the rear foot to the outstretched hand's knuckles.

FIGURE 4.3. Work area clearances, upright and prone (adapted from Alexander and Clauser 1965; Croney 1971; Hertzberg, Emanuel, and Alexander 1956; Rigby, Cooper, and Spickard, 1961)

- Provide access to components that will need maintenance, preferably through openings large enough to accommodate both hands and to permit visual access as well (Fig. 4.5).
- Consider what the maintenance tasks require in terms of tool use, exertion of force, and depth of reach when determining the dimensions of access ports. A diameter of 20 cm (8 in.) is needed for one-handed tasks requiring force exertion.
- Locate access ports so that they do not expose the maintenance operator to hot surfaces, electrical current, or sharp edges.

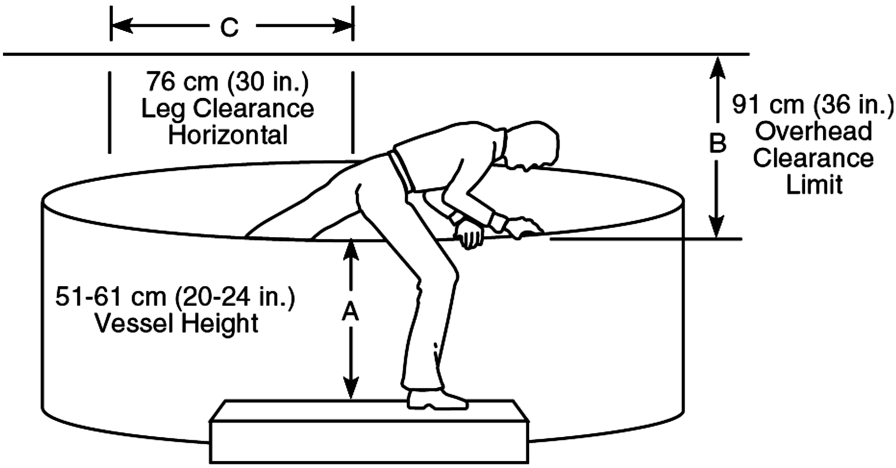


FIGURE 4.4 Clearances for Entering Open Top Vessels (adapted from Pugsley 1975)
The dimensions of the work area around an open-top vessel, such as a chemical reactor or a tank, are shown. The distance between the walking surface (often a platform on the floor) and the top of the vessel (A) can be about 10 cm (4 in.) less and still accommodate most workers. The clearance above the vessel to any overhead obstruction (B), such as pipes or an overhead hoist, is needed to minimize the operator's risk of bumping his or her head and shoulders. The horizontal distance from the point where the operator enters the vessel to the nearest vertical barrier (C) should be at least 76 cm (30 in.) to permit leg extension.

- Locate access ports so the maintenance operator can see the appropriate displays when making adjustments. This often means providing access ports on the front rather than on the back of the equipment.

Connectors and Couplings

Provide access port covers that are easy to remove and, if possible, hinged. When open, the covers should not block other components that may have to be manipulated or seen.

- On access covers, provide fasteners that are easy to operate with gloved hands; a tongue-and-slot design is recommended (Fig. 4.8a).
- Keep to a minimum the number of turns needed to remove or replace a component (usually less than ten turns).
- Use a hex (six-sided) bolt with a slot as a screw fastener so that it may be removed by either a screwdriver or a wrench (Fig. 4.8b).
- Provide electrical connectors with easily detached self-locking connectors that can be actuated with one hand.
- Keep the replaceable seals for couplings between pipes visible to ensure that they are replaced during assembly or repair.

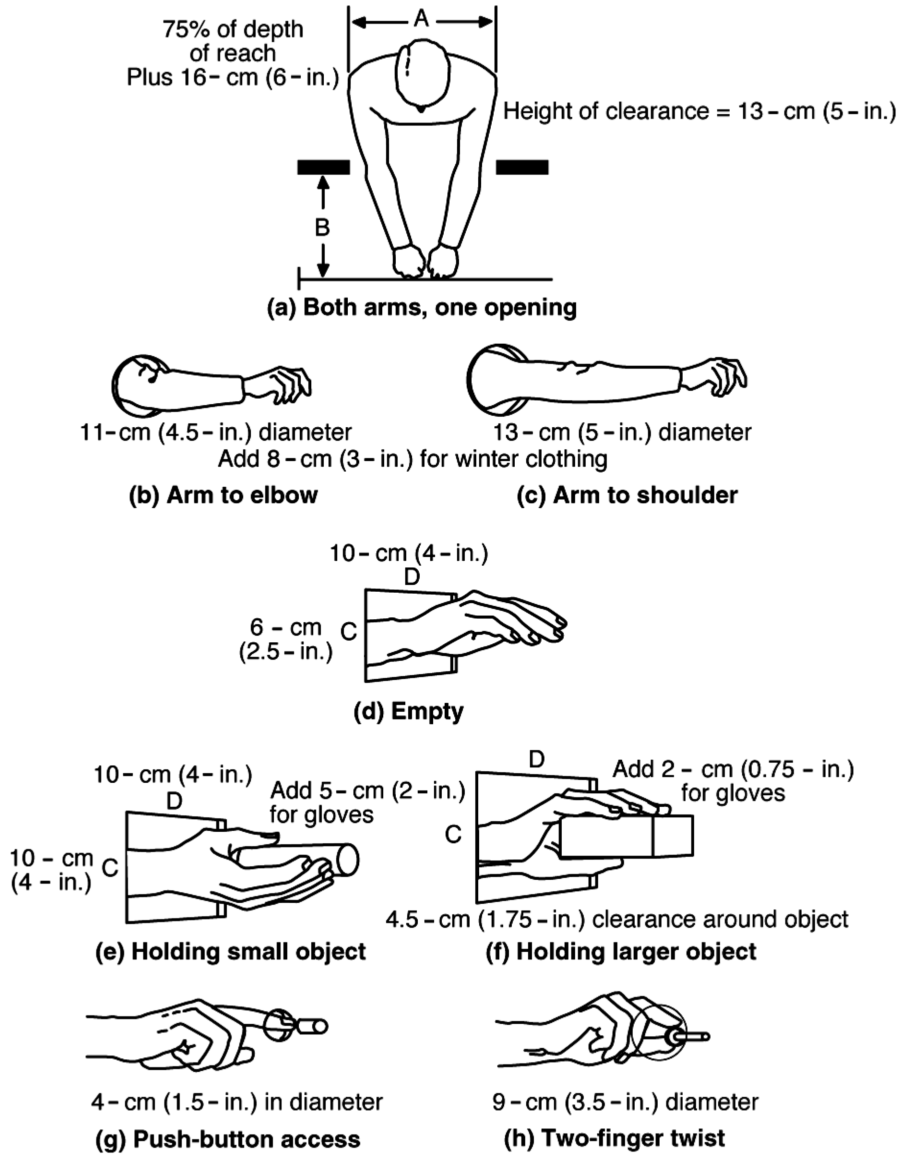


FIGURE 4.5 Selected Clearances for Arms and Hands (adapted from Kennedy and Filler 1966; Woodson and Conover 1964; U.S. Department of Defense 1998)

The dimensions for access ports in equipment that will permit the finger, hand, arm, or both arms to enter are given. If both arms must enter (a), a minimum of 61 cm (24 in.) of horizontal clearance (A) is needed to provide a 61-cm (24-in.) forward reach (B). The port diameters for arm-to-elbow (b) and arm-to-shoulder (c) access must be increased if the operation is done under conditions where heavy clothing is worn. Height (C) and width (D) clearances for the hand when empty or holding an object are given in (d), (e), and (f). These values should be increased by 2 cm (0.75 in.) if work gloves are worn. The access diameters shown in (g) and (h) are for one- or two-finger access. The size of the part being adjusted will determine the proper diameter of the two-finger access port; the larger the part, the larger the opening needed to access it.

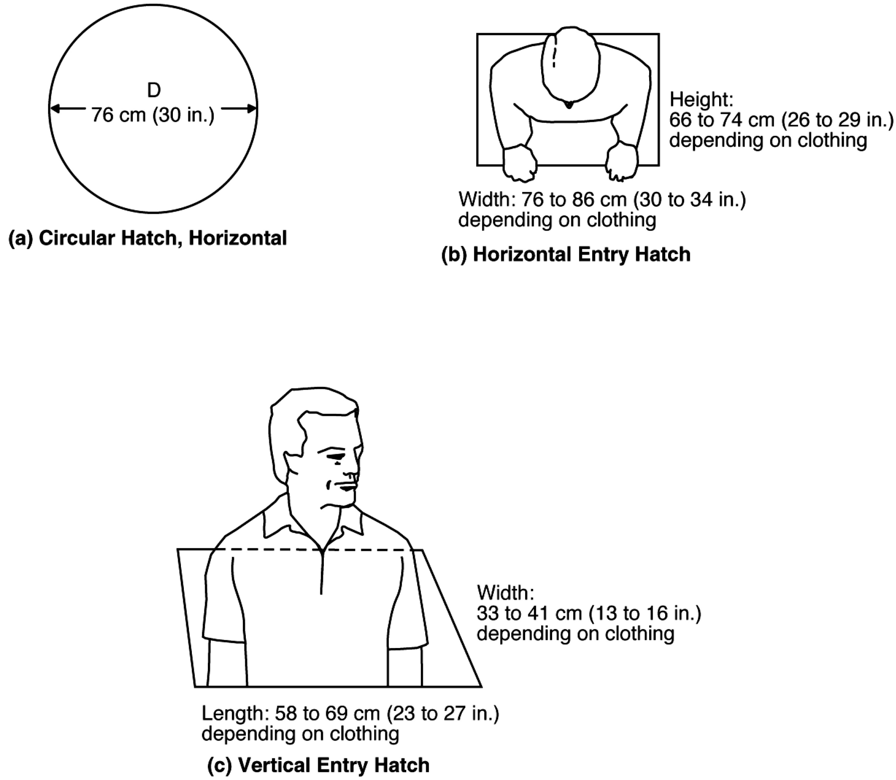


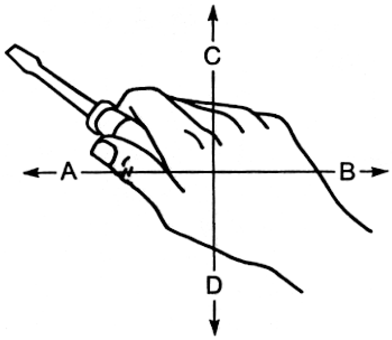
FIGURE 4.6 Minimum Full-body Access-port Clearances (adapted from U.S. Department of Defense 1998)
Minimum dimensions for three full-body access ports are shown: a horizontal, circular hatch (a), such as a pipe; a rectangular, horizontal, or side-entry hatch (b); and a rectangular, vertical port for top or bottom entry (c). People wearing heavy clothing may need more clearance than shown here.

- Design the fasteners for covers over components so they are easily accessible and visible from the maintenance operator's usual work posture.

Labeling

For general guidelines on labeling, see Chapter 5. For maintenance, the following factors should be kept in mind (U.S. Army 1975).

- Use labels to identify potential hazards (hot surfaces, electrical current); make them apparent to the casual operator or maintenance worker.
- Use labels to identify test points and to present critical information for specific maintenance procedures. Keep the message short and clear.
- Place the labels where they will not be obliterated by dirt or oil.
- Follow the stereotypes for label placement relative to the controls or test points (see the section on controls later in this chapter).



Hand Action	Minimum Dimensions for Hand Clearance			
	A, Left	B, Right	C, Up	D, Down
Turning screwdriver (20-cm [8-in.] length) or spinate wrench (15-cm [6-in.] length)	38 mm (1.5 in.)	62 mm (2.4 in.)	62 mm (2.4 in.)	42 mm (1.7 in.)
Grasping, turning, and cutting with needle-nose pliers (14-cm [5-in.] length) or wire cutters (13-cm [5-in.] length)	53 mm (2.1 in.)	73 mm (2.9 in.)	46 mm (1.8 in.)	68 mm (2.7 in.)
Turning socket wrench (10-mm [3/8-in.] base, 7-cm [3.2 in.] shaft)	54 mm (2.1 in.)	83 mm (3.2 in.)	83 mm (3.2 in.)	73 mm (2.9 in.)
Turning Allen wrench (5-cm [2-in.] length)	36 mm (1.4 in.)	86 mm (3.4 in.)	94 mm (3.7 in.)	64 mm (2.5 in.)

Clearances assume that multiple rotations are needed.

FIGURE 4.7. Minimum clearances for the working hand (adapted from Baker, McKendry, and Grant, 1960)

- ◆ Label access ports with information about what components can be reached through them.
- ◆ If fasteners are not familiar or do not follow the usual movement stereotypes, label them to indicate how they should be operated.

DESIGN OF DISPLAYS

In order for production equipment to run efficiently, the operator needs to be kept informed of the status of the machine and should be able to respond appropriately to such information by using the controls on the machine. The

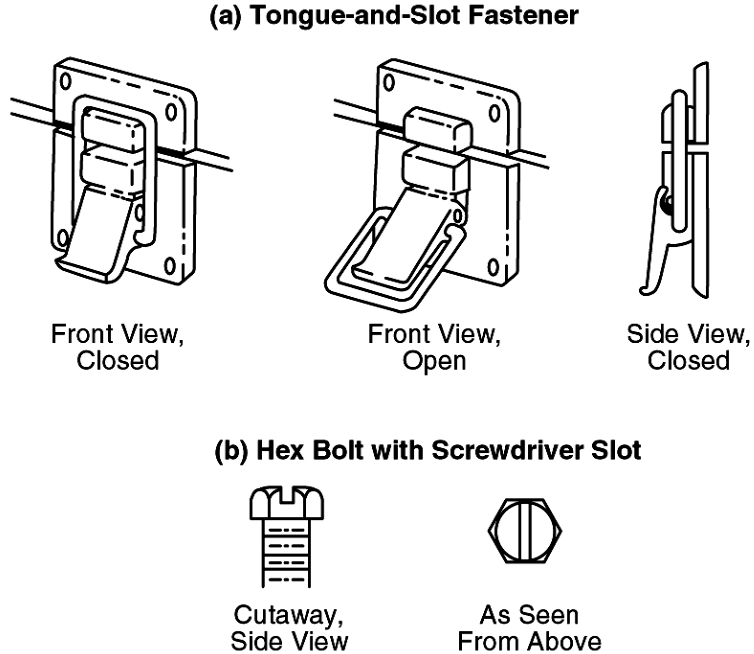


FIGURE 4.8 Examples of Fasteners (adapted from Woodson 1981)

following sections provide information and guidelines that can be used in the design of displays and controls to improve operator efficiency and reduce error opportunities.

The purpose of a display in a production system is to give information to the operator about the functional condition of the equipment or the process. The information can be categorized as follows:

- Need to know
- Nice to know
- Historical

Information is sometimes displayed in a confusing format, with less critical data obscuring the presence of information on which action must be taken. The guidelines in this section enhance the transmission of information from a display to an operator in order to improve operator efficiency and reduce potential errors.

Because the purpose of a display is to notify the operator of a situation, two prime concerns in designing the display are to make information (the signal) easily detectable and to have it indicate clearly any required actions. The operator may experience a decrement in monitoring and detection performance over the work shift related to the repetitiveness of the task and the frequency of appearance of signals to be detected. Table 4.1 indicates factors that

TABLE 4.1
Task Conditions Affecting Signal Detectability During Extended Monitoring (adapted from Van Cott and Warrick 1972; Wickens, Gordon, and Liu 1997)

Features that increase the probability of detecting a signal

- Provide good training and experience of the nature of the signals.
- Use simultaneous presentation of signals (e.g., audio and visual).
- Provide redundant representations of signal (more than simultaneous).
- Differentially amplify the signal (more than the noise).
- Make the signal dynamic.
- Provide two operators for monitoring; allow them to communicate freely.
- Provide 10 minutes of rest or alternative activity for every 30 minutes of monitoring.
- Provide knowledge of results (unless the observer then perceives more accurate probability of a signal, in which case a response bias may occur).
- Introduce artificial signals to which there must be a response. These signals should be the same as real signals. Provide feedback to the operator on detection of the artificial signals.
- Provide a refresher of the standard of discriminations to be found, when appropriate, such as the types of flaws in a cloth for an inspection task.
- Vary the environmental stimulation inversely to the task stimulation.

Features to avoid

- Avoid too many or too few signals to be detected and responded to.
- Reduce the likelihood of introducing a secondary display monitoring task.
- Prevent introducing artificial signals for which a response is not required.
- Do not instruct the operator to report only signals of which there is no doubt.

contribute to signal detectability. The contents of the table also apply to any form of detection, such as seeing a defect during an inspection task.

Modes of Display

There are several modes by which information from displays is conveyed to an operator:

- Tactile/haptic
- Auditory
- Visual

Tactile/Haptic Mode

Tactile and haptic (feel) modes are being used more often as people are bombarded with more information—for example, the vibration setting on cell phones that alert the user to a call. Since the passing of the Americans with Disabilities Act in the United States (see "United States and International Standards Related to Ergonomics" in Chapter 1) Braille has been incorporated more consistently into public interfaces, such as elevator controls and automatic teller machines. Tactile and haptic modes may also be employed when there is high ambient noise or vision is obscured. Haptic sense gives a person the knowledge of shape and it is closely combined with the proprioceptive sense of fingers. Shape coding on controls may be critical to identification of those controls when vision is limited or under task duress, rather than depending on visual cues. Similarly, tactile feedback of controls is important to communicate to the user that the control has been activated and by how much. (See "Design of Controls" in this chapter for more information.)

Auditory and Visual Modes

These are the most commonly used modes in displays. In most instances, auditory presentation is used to alert an operator or user. Occasionally the auditory signal is the prime display, such as the ringing of a telephone. Auditory presentation is preferred for simple messages in areas where people move around frequently and where response time must be rapid. Usually auditory displays supplement visual presentation by drawing the operator's attention to the visual display that provides detail of the system. Auditory displays are particularly well suited to represent infrequently occurring information where it is necessary to gain the operator's attention.

Visual presentation is preferred for complex messages in noisy environments where response time is not critical. Table 4.2 summarizes general guidelines of when to use either a visual or auditory display.

Equipment Visual Displays

Visual displays are often categorized into either static or dynamic displays. There are three basic kinds of dynamic display: light, instrument, and electronic. With more computer driven systems, the static/dynamic differentiation is lessening. Another way to categorize visual displays is to consider information transfer from equipment to person versus person to person (see Table 4.3 for examples of the two categories). Person-to-person information transfer by signs and labels is discussed in "Information Transfer" in Chapter 5.

Once an operator's attention has been called to a display, the information from that display should be readable and understandable so that the operator can take the appropriate action. There are several ways in which visual displays can be used in a production system. Table 4.4 includes some of these uses and suggests the display type most appropriate for each. Some examples of the displays indicated in Table 4.4 are illustrated in Fig. 4.9.

TABLE 4.2
Visual Versus Auditory Presentation of Communication in a Production Environment (adapted from Deatherage 1972; Ivergard 1999)

Use visual presentation if:

- The person's job allows him or her to remain in one position
- The message does not call for immediate action
- The message is complex
- The message is long
- The message will be referred to later
- The auditory system of the person is overburdened
- The message deals with location in space
- The receiving location is too noisy

Use auditory presentation if:

- The person's job requires him or her to move about continually
- The message calls for immediate action, as auditory alarms can be detected from any direction
- The message is simple
- The message is short
- The message will not be referred to later
- The visual system of the person is overburdened
- The message deals with events in time
- The receiving location is too bright or if preservation of dark adaptation is necessary
- The signal is originally acoustic
- The operator lacks training and experience of coded messages
- The situation is stressful and additional attention-getting is needed

Use tonal presentation rather than speech if:

- The operator is trained to understand coded messages
- In situations where it is difficult to hear speech (tones can be heard in situations where speech is inaudible)
- Where it is undesirable or unnecessary for others to understand the message
- If the operator's job involves constant talking
- In cases where speech could interfere with other speech messages

The design and installation of a visual display affects the performance of the operator of the equipment or production system. Factors such as the distance an operator is from a display when it is read, the number of displays on a single console, the readability of the dials, and the ambient illumination should be considered when selecting and installing displays. The guidelines presented below may be used in ordering dials and other displays off the shelf and in identifying potential problems in the design of display panels in the workplace. Dynamic representational information is most often communicated on a visual display terminal (VDT).

TABLE 4.3
Categories and Examples of Visual Displays

Categories of Visual Displays	Examples
Static or Person-to-person information transfer	Information that tends to remain fixed for a time, e.g., labels, signs, placards
Dynamic or Equipment-to-person information transfer	Information that is changing or subject to change, e.g., light displays, instruments such as dials and gauges, electronic displays such as head-up and computer displays

TABLE 4.4
Types of Information Displayed and Recommended Displays for Each (adapted from Grether and Baker 1972)

Information Type	Preferred Display	Comments	Examples in Industry
Quantitative reading	Digital readout or counter	Minimum reading time Minimum error potential	Numbers of units produced on a production machine
Qualitative reading	Moving pointer or graph	Position easy to detect, trends apparent	Temperature changes in a work area
Check reading	Moving pointer	Deviation from normal easily detected	Pressure gauges on a utilities console
Adjustment	Moving pointer or digital readout	Direct relation between pointer movement and motion of control, accuracy	Calibration charts on test equipment
Status reading	Lights	Color-coded, indication of status (e.g., "on")	Consoles in production lines
Operating instructions	Annunciator lights	Engraved with action required, blinking for warnings	Manufacturing lines in major production systems

Light Displays

A basic lamp display is usually color-coded and sometimes size-coded, according to function and level of urgency. For example, a small red light may indicate a malfunction, but a larger one may indicate an emergency condition. Red is typically danger, warning, fire; yellow or amber is used for caution,

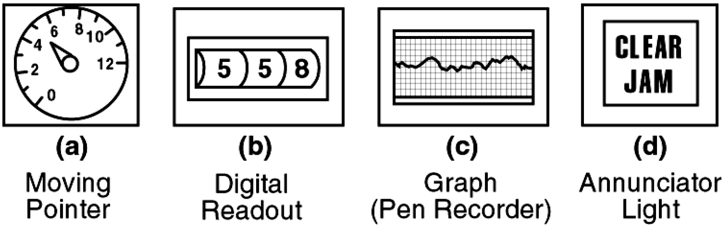


FIGURE 4.9 Examples of Visual Display
Four types of displays are shown: (a) a moving pointer, best for qualitative or check readings and some adjustments; (b) a digital readout, best for quantitative readings; (c) a graph (pen recording), best for detecting trends and qualitative readings; (d) an annunciator light, best for giving operating instructions on a control panel where many functions are monitored.

slow, power on; and green indicates go, ready, functioning correctly. A light display may also be an annunciator light that has written instruction on the light, such as "clear jam" (see Fig. 4.9). Annunciator lights are often push-button controls.

Instrument Displays

Although systems are becoming progressively more complex, traditional display instruments remain part of most production systems. For quantitative (numeric) readings a digital readout is preferable to a dial; the operator does not have to consider scale markings on a digital readout, so there is less room for error. However, this is the case only if the information change is slow and a definitive number is required. Through design, a dial can provide qualitative and quantitative information by color-coding zones or using target zones. The following are basic guidelines for dials, gauges, and digital readouts (adapted from Sanders and McCormick 1987; Woodson, Tillman, and Tillman 1992; Ivergard 1999).

DIALS AND GAUGES The following guidelines are for dials; however, most of the information pertains to gauges and electronically generated versions of dials and gauges as well. The design of the features of visual instrument displays directly influences the ability of people to make quick and accurate readings.

- ◆ Generally use an instrument with a moving pointer against a fixed scale rather than vice versa, unless the range is very large, in which case the moving scale behind the instrument panel can be extensive.
- ◆ Generally speaking, circular or semicircular dials are preferable to rectangular gauges, although rectangular gauges take up less room.
- ◆ Make the direction of increasing value clockwise for a dial, left to right for a horizontal gauge, and bottom to top for a vertical gauge.

- Avoid the need for interpolation for quantitative readings. Choose the best scale that provides the degree of precision required but with a maximum of only nine markings between numbers. For each numbered interval there should be only two, four, or five marked intervals in between, to avoid too many marks.
- Use whole numbers on the main graduation marks and progressions in units of one, two, or five. Definitely avoid increasing by units of three and four. Orient numbers upright, not radially.
- Place zero at the nine o'clock or twelve o'clock position on a round dial with a continuous scale. If the scale does not fill the perimeter, locate it so that the space is at the lower part of the dial, or put the zero at the six o'clock or twelve o'clock position.
- Ensure the markings are of sufficient thickness to be discernable from the viewing distance. Figure 4.10 provides military recommended dimensions for 71 cm (28 in.) viewing distance. Proportions should be kept the same for greater or small distances; that is, multiply each dimension by the viewing distance, or

$$\text{Dimension at Distance Y} = \text{Dimension at 28 in.} \times \frac{Y}{28}$$

- Choose the dial diameter (inside the scale markings) based on the number of graduations and the viewing distance. Table 4.5 provides dial diameter size for some numbers of scale marks and various viewing distances. Note how impractical the size can be as number of marks increases. Other forms of display such as a digital readout may be more appropriate. These diameter sizes are based on the marks being an appropriate width, as discussed above.

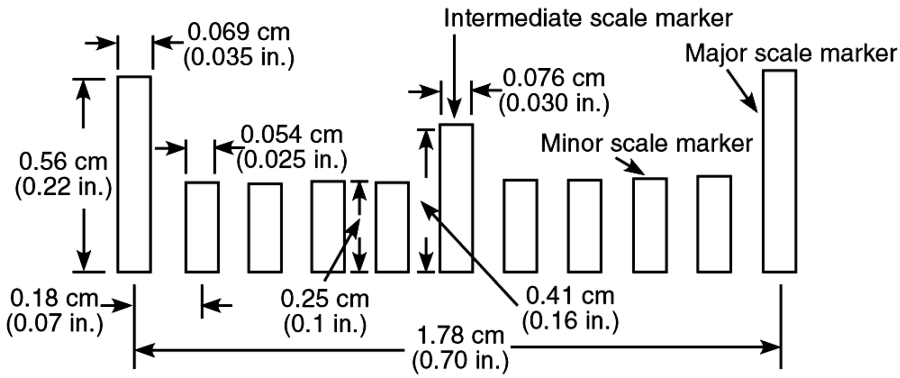


FIGURE 4.10 Recommended scale mark dimensions for 71 cm (28 in) viewing distance (based on MIL-HDBK-759A and adapted from Woodson, Tillman, and Tillman 1992)

TABLE 4.5
Minimum Diameter of Inner Ring Inside the Scale Markings of a Dial at Various Viewing Distances (adapted from Woodson, Tillman, and Tillman 1992)

No. of Scale Marks	Viewing Distance				
	50 cm (20 in.)	91 cm (3 ft.)	1.8 m (6 ft.)	3.6 m (12 ft.)	6 m (20 ft.)
50		3.3 cm (1.3 in.)	6.6 cm (2.6 in.)	13 cm (5.0 in.)	23 cm (9.0 in.)
100	3.5 cm (1.4 in.)	6.6 (2.6)	12.7 (5.0)	25.4 (10.0)	43.2 (17.0)
150	5.1 (2.0)	9.9 (3.9)	20.3 (8.0)	38.0 (15.0)	66.0 (26.0)
200	7.4 (2.9)	12.7 (5.0)	25.4 (10.0)	53.3 (21.0)	86.4 (34.0)
250	8.9 (3.5)	16.3 (6.4)	33.0 (13.0)	66.0 (26.0)	109.2 (43.0)
300	10.2 (4.0)	19.5 (7.7)	38.0 (15.0)	78.7 (31.0)	129.5 (51.0)
350	12.7 (5.0)	22.9 (9.0)	45.7 (18.0)	91.4 (36.0)	152.4 (60.0)

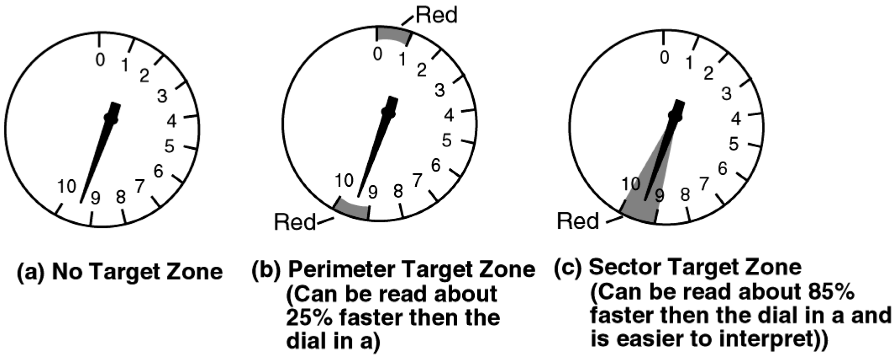


FIGURE 4.11 Target zone markings on dials (adapted from Kurke 1956)
Three dials are shown, two with markings to indicate abnormal functioning or conditions to which an operator has to respond. In (a) the abnormal function zone is not marked, so an operator has to be trained to recognize when a potential problem exists. In (b) the two zones of concern are marked by a red rectangle at the outer edge of the dial. The pointer can be seen against the light-colored dial; its tip points to the red zone when readings indicate abnormal function. In (c) the entire dial is colored red within the zone of abnormal function, making it very obvious when the pointer falls in this sector. Response time is faster for the dial in (c) than for those in (a) and (b).

- Select dials with target zone markings to permit more rapid reading (Fig. 4.11).
- Use white markings, pointers, and numbers on a black background for displays to be used with reduced ambient illumination.
- Use simple fonts and legible printing so that the displays can be easily read. See "Labels and Signs" in Chapter 5.
- The pointer should (adapted from Sanders and McCormick1987; Ivergard 1999):

- Reach the major scale marker but not overlap the smaller scale markers
- Lie as close to the surface of the dial as possible (to avoid parallax errors)
- Be pointed at the end with a tip angle of about 20 degrees
- Have the same color from the pivot to the tip as the scale, with the remaining part, which should be as short as possible, the same color as the dial face

DIGITAL Digital readouts are read most quickly and accurately when only precise quantitative information, such as a check reading, is required and the rate of change is not too fast. This is because the operator does not have to interpret scale markings, so there is less opportunity for error. However, digital instruments take longer to read if qualitative information is required, such as whether the value is increasing or decreasing, because more interpretation is necessary. Unless only precise quantitative information is required, digital displays should be redundant with an analog display.

Guidelines for font and character size in relation to viewing distance are given in "Labels and Signs" in Chapter 5 and can be used for digital displays.

INSTALLATION OF INSTRUMENT DISPLAYS Displays should be installed on a monitoring panel or on production equipment to minimize the potential for operator error. The following guidelines relate to factors in the display environment that should be controlled:

- Avoid shadows on the display face from adjacent protrusions or from the bezel (cover rim) of an inset indicator.
- Avoid optical distortion from the glass cover plate and glare from light sources.
- Align a group of dials uniformly when check reading is required so that all pointers are in the same position for the normal conditions. This allows the operator to quickly scan for a pointer that is out of the usual pattern of orientation.
- Provide adjacent indicators on a machine control panel with the same layout of marks and numbers (Fig. 4.12).
- Orient indicators so that they are perpendicular to the operator's line of sight. This design should reduce parallax errors when pointers are read.
- Avoid use of color coding on the indicator if colored ambient illumination provides poor color rendition (e.g., photographic safelights or sodium vapor illumination).
- Locate frequently used indicators at standing workplaces between 107 and 157 cm (42 and 62 in.) from the floor, but as close to 152 cm (60 in.) as possible. Less frequently read indicators may be above or below this height range. For seated workplaces, locate the primary displays no

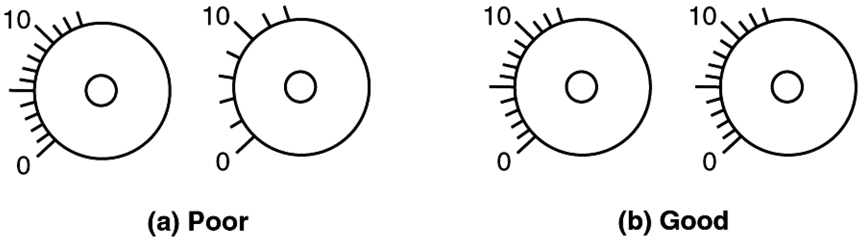


FIGURE 4.12 Examples of poor and good display panel dial design (adapted from Woodson, Tillman, and Tillman 1992)
Conformity in the choice of dial markings for adjacent indicators reduces the opportunity for making errors when reading dials with moving pointers. The example in (b) is good because each dial is marked with the same scale. The example in (a) is poor because one scale is marked in units and the other has a mark every two units. This situation increases the possibility of misreading the dials, particularly if the processes being monitored are similar.

higher than 50 cm (20 in.) above the work surface or 80 cm (32 in.) above seat height.

- Provide adequate levels of illumination (see "Lighting and Color" in Chapter 8).
- Label the displays clearly. Follow the guidelines in "Labels and Signs" in Chapter 5.
- Remove or cover unused displays, because they can divert attention from functioning units.
- Avoid too many displays and controls too close together.
- Arrange related displays and controls together and with logical functional compatibility.
- Group functionally related controls and displays (see section on labeling and coding).

Electronic Displays

Electronic displays are emissive displays that give off light, reflective displays are seen because light is falling on them. Therefore, the visibility issues for the two groups of displays are different.

There are three general categories of information to consider when presenting information on an electronic display: organization of information, design of graphical objects, and coding techniques. There are many ways to present the information, but the general attributes of all presentation methods should have (ISO 9241-12; Cakir 1999):

- Clarity (conveyed quickly and accurately)
- Discriminability (distinguished accurately)
- Conciseness (minimal extraneous information)
- Consistency (same information presented the same way throughout application, according to user's expectations)

- ◆ Detectability (user's attention is directed toward information)
- ◆ Legibility (easy to read)
- ◆ Comprehensibility (clearly understandable, unambiguous, interpretable, and recognizable)

There are several types of electronic displays. The most common types are discussed below.

LIGHT-EMITTING DIODE (LED) Conventional displays can be electronically displayed by several means. The most common method is light-emitting diodes (LED), which may be as simple as an annunciator light or put together in a matrix to form a display, for example, a digital readout. Some guidelines for such displays are:

- ◆ Minimize the use of segmented alphanumerics. Segmented numbers, typically seen in calculators, are less legible than the NAMEL font (a font designed by the Navy Aeronautical Medical Equipment Laboratory) because the characters are too similar and they can be easily confused if there is phosphor persistence (Fig. 4.13). Most displays (regardless of technology) now use font variations that use the principles of character and number distinctiveness of the NAMEL font.
- ◆ Use a dot matrix character style, at least 5 × 7 and preferably 7 × 7 or 7 × 9, for the most accuracy.
- ◆ Provide the following geometry for the numerals and letters displayed:
  - A width-to-height ratio of about 0.6 to 0.8.
  - A distance between digits of 1.1 to 1.4 times the stroke width.
  - Vertical numbers rather than slanted ones.
  - A dot spacing of about 0.4 to 0.6 mm (0.02 to 0.025 in.).

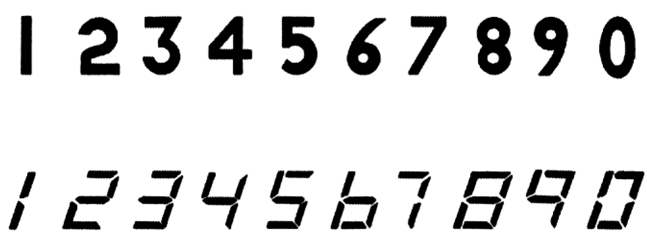


FIGURE 4.13 Segmented and NAMEL font (adapted from Plath 1970; McCormick and Sanders 1982)

NAMEL is a name for a font style designed by the Navy Aeronautical Medical Equipment Laboratory MIL-M-18012B.

The upper line of numbers is in the NAMEL font, which was designed for its legibility; it should provide less opportunity for error when operators are making readings. Segmented numbers (seen in the lower line) are less legible and may be misread in situations where fast readings are needed. For example, when numbers are changing rapidly on an electronic display, some persistence in the display phosphor may make it difficult to distinguish between the numbers 6 and 8.

- Select a display that does not persist so long that an operator is unable to read current values of numbers if they are changing rapidly.
- Choose a display with lines for describing the characters that are sharp, that are not diffused, and have equal brightness throughout.
- Provide for wide-range viewing angles to ensure full visibility of all characters without any background noise. Be sure obstructions do not prevent characters from being seen from all angles.
- Minimize internal reflections, unlit images, or distractions from the background of the display unit.
- Minimize glare on the display by adjusting the direction of ambient illumination, using shields or filters or both, and locating the displays away from glare sources.

CATHODE RAY TUBE (CRT) The typical visual display terminal (VDT) monitor that is not flat is a cathode ray tube. The monitor screen is the front of the tube and is lined with phosphor. An electron beam is emitted through the tube and swept across the phosphor at varying intensities. The differently charged electrons in the tube hit the phosphor that glows at the correct luminance level for that part of the picture.

Computer-controlled production systems are commonplace and production operators have to keep up with increasing complexity of manufacturing systems. Purchasing the computer system is less an issue of choosing the right CRT with certain characteristics, but rather what type of VDT technology. Many CRTs perform according to the standards of Visual Display Requirements ISO 9241-3 (International Standards Organization standard) and other technical standards set by the industry. (See "United States and International Standards Related to Ergonomics" in Chapter 1.) There are a few features specified in ISO 9241-3 that are difficult to meet—for example, flicker-free standards to which positive, 60-Hz-refresh-rate monitors do not conform. ISO specifications for flat-panel displays are being developed as ISO 13406. Many physical performance features of the VDT can only be determined in a laboratory (Cakir 1999). Even when certain technological characteristics are specified in ergonomics guides, they are determined under controlled conditions such as viewing at a certain distance under particular ambient lighting conditions.

LIQUID CRYSTAL DISPLAY (LCD) LCDs are made up of dipoles (crystals) suspended in a thin layer of liquid. When an electrical potential is applied across the liquid, the crystals align to form a polarizing filter. The combination of the polarized crystals and polarized cover plate holds back the light and provides the display. This technology is widely used for equipment such as notebook computers, flat-panel computer monitors, personal digital assistants (PDAs), and touch screens.

LCD OR CRT? If a company has chosen a specific technical system from an original equipment manufacturer, the type of VDT may be designated. Vision systems that magnify an area or for real-time monitoring are often CRT televisions. If there is a choice of display, consider some of the pros and cons of LCD and CRT displays.

There are several important practical advantages of LCDs over CRT monitors (Krantz, Silverstein, and Yeh 1992; Hollands et al. 2001; Ziefle 2001):

- LCDs maintain superior contrast under bright light conditions as LCDs have much lower surface reflectance than CRTs.
- Active matrix LCDs, which use a semiconductor device to hold the display at each pixel, further attenuate internal reflection of ambient light compared to non-active-matrix LCDs.
- LCDs do not have the flicker characteristics of CRTs that are known to be responsible for performance decrement and visual strain. Therefore, performance on LCDs is better than on CRTs.
- There is indication that performance of older workers is better with LCDs compared to CRTs, which is important as the majority of the workforce is over thirty years old. (Performance of the visual system and its subfunctions starts to decline significantly at about thirty-five years of age.)
- The weight, volume and footprint, and power requirements of LCDs are much lower than those of CRTs.
- LCDs are less susceptible to electromagnetic interference.

On the other hand, CRTs are better than LCDs at a wider viewing angle (off axis). Wide-angle viewing of LCDs reduces luminance and distorts color. However, some new techniques are being developed to improve the off-axis luminance from a LCD pixel (Hollands et al. 2001). The effect of wide-angle viewing is important if the screen is shared or if multiple screens are used where off-axis viewing is likely. Flat-panel monitors should have height and angle adjustability similar to a CRT, to allow for perpendicular viewing.

Notebook computers use flat-panel displays and studies are indicating that visual comfort may be inferior with portable computers compared to a desktop CRT display because of the reduced luminance from the angle of the screen in conjunction with suboptimal workstation set up (Villanueva et al. 2000). An active matrix display is preferred as it allows a greater viewing angle, so the screen can be better adjusted for viewing (see "Computer Workstations" in Chapter 3 for details on appropriate setup).

PLASMA DISPLAY PANEL (PDP) Plasma display panels (PDP) use the same neon-based gas as in cathode ray tubes, sandwiched between two layers of glass. When a voltage is applied across an intersection of conductors the gas becomes ionized (i.e., plasma state) and emits a spot of light at the intersection. This technology is used in the new flat-panel television screens.

Generally, new VDTs that are developed continue to improve in character generation stability, resolution, and clarity. Improved resolution is important to both manufacturers and users as more information can be displayed and it becomes more readable and visually comfortable (Ziefle 1998). Most VDTs are now color displays. Color can enhance performance if the color is prudently used in the design (Hollands et al. 2001). If the software overuses color and coding is poor, there can be a negative effect on performance. The software for the VDT of a system can be a very hard purchasing decision and is especially critical for an effective system. Even with the best current technology, there are cognitive and visual demands that continue to be investigated. The VDT must be considered within the overall system, as the users' capabilities, task design, workstation, installation, and environment all affect their interaction with the VDT.

Installation of Displays

The environment has a major effect on a display. Despite no reflective glare from a LCD, there can still be a mismatch between external scene luminance and the display luminance that will influence the readaptation of the eye to a screen (Krantz, Silverstein, and Yeh 1992). Particular attention should be given to lighting if CRTs are used, including vision system displays. See Chapter 8 for further discussion on lighting and other environmental issues.

The location of a computer in relation to the production system must be considered in the overall design of the system. This is more likely to occur when designing with a user-centered approach. Invariably, the display is not used independently of a traditional bank of controls and displays, or of checking on the plant floor itself through a window. The control workstation should be set up to allow for line-of-sight view of other pertinent aspects of the system while at the control station. On an equipment level, a similar principle applies: locate the displays and controls where the operator will be performing his or her task and at the same time has a line-of sight view of critical components of the system. If necessary, redundancy should be built in: either indicator lights or vision systems to present information at the control station point, or the VDTs and controls should be available in two locations if the operator has to be at either end of a machine. At the point of control the operator needs to have the all the information to operate the system efficiently.

DESIGN OF CONTROLS

Information is presented to an operator by some form of display, be it a dynamic visual display such as a VDT or an annunciator light; a static display such as labels, signs, or instructions (see "Information Transfer" in Chapter 5);

or an auditory alarm or tactile display. The operator's response to any display is through controls and data entry devices. This could be a switch, lever, pedal, keyboard, stylus—anything used by a person to affect performance of a system. Performance can be enhanced if the controls operate as one expects them to (they follow "population stereotypes"), if they are dimensioned to fit the human body, and if their operating characteristics are within the strengths and precision capabilities of most people.

Unconventional controls, using speech, eye and head movements, gestures, and electromyography, have mostly been used by the disabled. However, these are evolving, with some technologies entering the mainstream, such as speech-based controls with office computers. Other technologies may be commonplace in the future as computers become smaller and more mobile (Calhoun, Grigsby, and LaDue 2001). The more common conventional controls, including computer input devices, are discussed in this section, as well as some speech-based controls.

Behavioral Stereotypes

People expect things to behave in a certain way when they are operating controls or when they are in certain environments. Although it is possible to educate people to operate systems that do not follow the stereotypes, their performance may deteriorate when placed in an emergency situation. Stereotypes can change because of changes in technology or because new stereotypes are established.

General Population Stereotypes

The following are a few examples of expectations of the environment (Woodson and Conover 1964; Woodson, Tillman, and Tillman 1992).

- Very loud sounds, or sounds repeated in rapid succession, and visual displays that blink or are very bright imply urgency and excitement.
- Speech sounds are expected to be at approximately head height and in front of a person.
- Seat heights are expected to be at least 40 cm (15.5. in.) above the floor in production workplaces and offices.
- Very large or dark objects imply heaviness. Small or light-colored objects imply lightness. Large, heavy objects are expected to be at the bottom and small, light ones at the top.
- Red signifies stop or danger, yellow indicates caution, green indicates go or on, and a flashing blue indicates an emergency control vehicle, such as a police car.
- Coolness is associated with blue-green colors; warmth is associated with yellows and reds.

Control Movement Stereotypes

There are stereotype movement expectations of controls and associated displays. A long established principle (Warrick's principle) remains pertinent today: an operator usually moves a control so that the part of it nearest the display moves in the direction he or she is trying to move the display's indicator (Warrick 1947; Woodson and Conover 1964; Thylen 1966; Brebner and Sandow 1976). This principle is one of movement compatibility. Spatial compatibility is similar, in that an operator expects a control that is next to a display to be related to that display.

General movement expectations of controls are shown in Table 4.6. The information should be taken in the context of the culture of the United States and used with caution and checked against other cultural expectations if adopted by other countries. For example, a switch that is in the up position is understood as on in the United States and Germany, but the convention is reversed in the United Kingdom (Murrell 1965). Therefore, clear labels should be used on equipment that violates local stereotypes for movement.

There may be trade- or situation-specific stereotypes (such as left-handed threads on certain gas cylinders) that should be incorporated into the design of production systems in order to minimize confusion with existing equipment.

Emergency controls should be given careful attention to ensure that stereotypes are not violated, so that they are quick and easy to use with minimal deci-

TABLE 4.6
General Movement Expectations of Controls (adapted from Alexander 1976; Woodson, Tillman, and Tillman 1992)

Function	Direction of Control Movement
*On/start/engage	*Up, right, forward, press†
*Off/stop/disengage	*Down, left, rearward, pull†
Right	right, clockwise
Left	left, counterclockwise
Up	Up,rearward
Down	Down, forward
Retract (raising)	Up, rearward, counterclockwise, pull
Extend (lowering)	Down, forward, clockwise, push
Increase	Up,right, forward, clockwise‡
Decrease	Down, left, rearward, counterclockwise‡
Open (liquids, gases, doors)	Down,left, counterclockwise
Close (liquids, gases, doors)	Up, right, clockwise

*"Up" for "on" is a United States cultural stereotype.

†Pulling a knob is an exception, e.g., pulling a throttle control is "on" and pushing is "off."

‡Valves, handles, or wheels controlling liquids or gases, and other threaded controls, turn left or counterclockwise for on/increase and right or clockwise for off/decrease.

sion making by the operator. Because handedness could influence the expected direction of movement of a knob, emergency controls should be clearly marked to indicate the proper direction of rotation (Chapanis and Gropper 1968).

Display and Control Relationship Stereotypes (Compatibility)

Figure 4.14 shows an example of a control panel illustrating many of the points made below about the relationship between the displays and controls.

- The direction of movement of a control should correspond with the direction of movement of the display. For example, when a rotary control is moved right, the display pointer should move right if it is a dial, or up if it is a vertical scale.
- The stereotype expectation of a control should be matched by the display. For example, a right-handed or clockwise turn of a rotary control suggests an increase, so the display should record an increase with the pointer going the same direction. If the pointer is fixed and the scale moves, the direction of scale movement should be to the left or downward so that the increasing values are still going upward or to the right (Hoyos 1974, cited in Kroemer and Grandjean 1997).
- There should be an obvious physical relationship between a control and the related display.
  - Display instruments should be located as close as possible to the controls that affect them. For many designs, the control should be mounted just below its display, permitting both to share one label denoting the function.
  - The layout of the controls should be similar to the layout of the displays, especially if they are on separate panels.
  - Use coding to indicate relationships, such as color or demarcations.
  - The controls and displays should be close enough together to permit the operator to see both without assuming an awkward posture.
  - For concentric controls (two or three rotary knobs stacked on one another), the smallest control's display should be nearest the control or on the left, and the largest knob's display should be farthest or to the right (Bradley 1966). Color-coding of the knobs and displays is recommended.
- Arrange controls and displays in sequence of operation. The sequential arrangement should be from left to right and top to bottom.
- Functionally group controls and displays.
  - Use coding to differentiate the groups, such as a color background, using space between the groups, labeling, or delineating with a line surrounding the group.
  - Operators expect each similar set of controls to operate identically. If

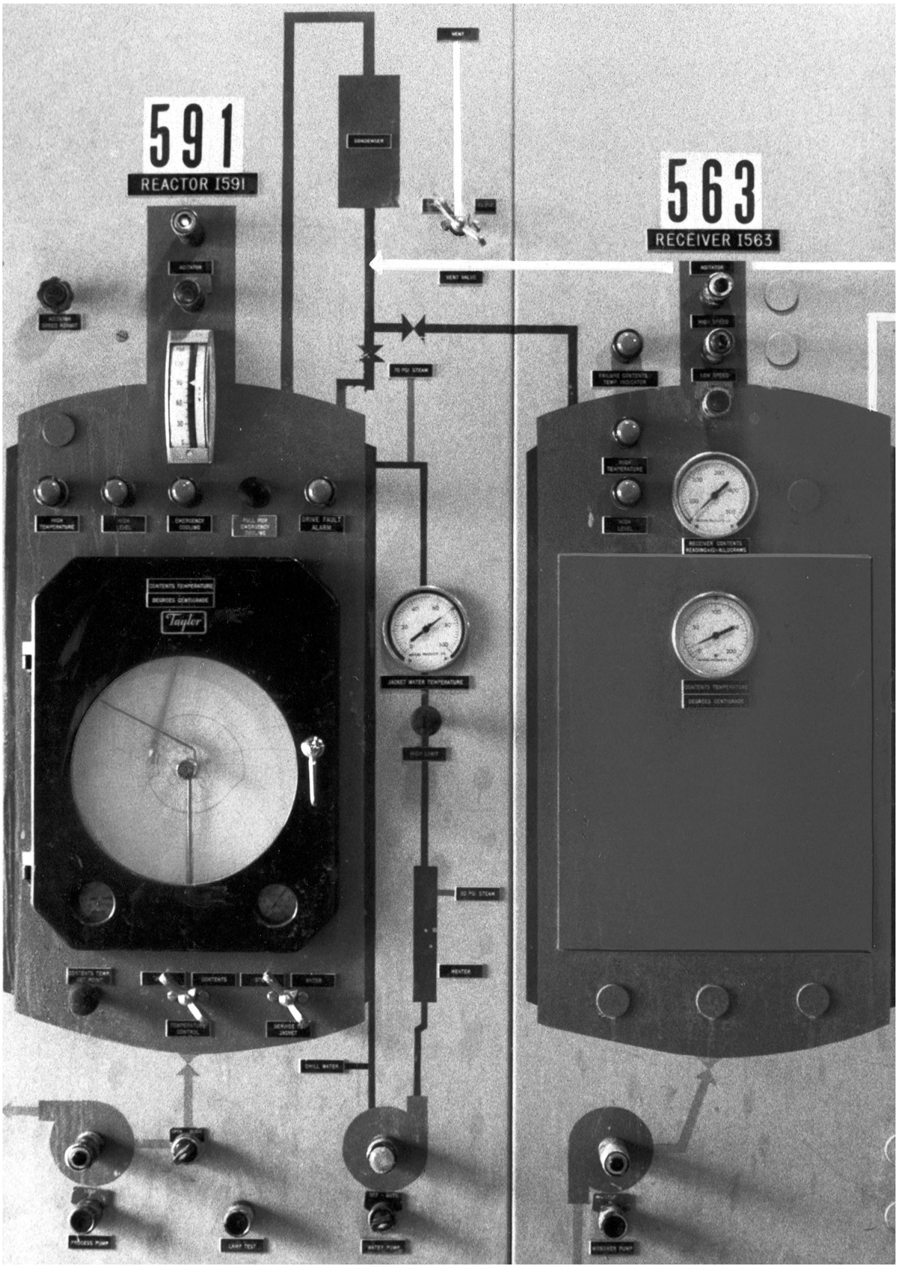


FIGURE 4.14 Arrangements of controlling knobs and their displays on a control panel

The location of controls in relation to their displays is illustrated on a production machine control panel. Color or graphics can be used to indicate controls and displays that belong together. Location of the control so that it is easily identified with its display, as shown at the bottom of this picture, will reduce the possibility of the operator taking an incorrect action in an emergency situation.

similar sets are located on each side of a console, ensure those sets are not arranged as mirror images (Seminara, Gonzalez, and Parsons 1977; Greenberg 1980). The rare exception would be if the controls were operated simultaneously.

- Organize by frequency of use. The most frequently used displays and controls should be in prime operating space, within a 30° visual cone (see "Workstation Design" in Chapter 3). Emergency controls should also be in the prime operating space.
- Labeling of controls and displays should allow for operator needs (Ely, Thomson, and Orlansky 1963a):
  - The need to read control settings while making adjustments, such as with a discrete setting on a rotary selector switch (each setting should be labeled).
  - The need to see the display while using the control to change a setting.
  - The need to identify some controls quickly in order to respond to emergencies appropriately. Color coding can be used to identify high-priority controls.
  - The need to have a consistent location for labels relative to displays and controls between workstations or machine sections.
- For displays that have controls directly beneath, one label can be used for the group. The label is usually placed to the right of or below the control.

Design, Selection, and Location of Controls

As mentioned earlier, a control is anything—a switch, lever, pedal, button, knob, or keyboard—used by a person to affect performance of a system. Even the simplest control has several characteristics that affect the ease, speed, and accuracy of its use. The most important characteristics are the following:

- Displacement, linear or angular
- Operating force
- Friction, inertia, or other drag
- Number of positions
- Direction of movement
- Detents and/or stops
- Appropriate identification
- Compatibility with displays
- Size

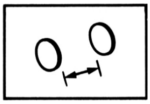
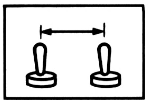
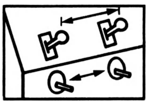
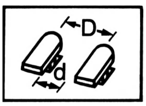
Displacement is the amount the control has to be moved or rotated to change a setting. All of these characteristics should be considered in relation to the specific workplace when selecting a control. Detailed suggestions for the design of controls and their relationship to the workplace will be found later in this section. First some general guidelines for control selection and layout are presented (Ely, Thomson, and Orlansky 1963b; Chapanis and Kinkade 1972; Sanders and McCormick 1987; Woodson, Tillman, and Tillman 1992; Bullinger, Kern, and Braun 1997).

Location

Information about appropriate heights for displays and controls can be found in Chapter 3. Generally, the most frequently used controls should be in easy reach. All controls should be placed or guarded so that they will not be accidentally activated. More specific recommendations for the location of controls are:

- Keep the number of controls to a minimum. The movements required to activate them should be as simple and easy to perform as possible, except where resistance should be incorporated to prevent accidental activation.
- Arrange the controls at the workplace so that the operator can frequently adjust posture, especially if extended hours of monitoring are required.
- If one hand or foot must operate several controls in sequence, arrange the controls to allow for continuous movement through an arc (if this arrangement does not violate any of the basic rules of control location).
- Assign to the hands controls that require precision or high-speed operation. When there is only one major control that, at times, must be operated by either hand or both hands, place it in front of the operator, midway between the hands.
- Handedness is important only if a task requires skill or dexterity. If the control requires a precision movement, place it on the right, given that most people (about 90 percent of the population) are right-handed (Barsley 1970).
- Assign to the feet controls that require the application of large forces; otherwise, provide the controls with power assists.
- Distinguish between emergency controls and displays and those that are required for normal operations, using the following techniques: separation, color coding, clear labeling, or guarding. In some instances an emergency mode or special operating position can be built directly into the normal control through the use of a detent, an emergency alarm, or a spring that can be actuated only by exceeding a minimum force. Emergency controls should be easily accessible and within 30° of the operator's normal one of sight.
- If the same relative groupings for major controls and displays cannot be kept, make any exception drastic and obvious.
- To prevent accidental activation of a control, place it away from other frequently used controls, recess it, or surround it with a shield.

TABLE 4.7
Recommended Separations for Various Types of Controls (adapted from Bradley 1954)

Control	Type of Use	Measurement of Separation	Recommended Separation: Minimum mm	Minimum in.	Desirable mm	Desirable in.
Push Button	One Finger (Randomly)		12	½	51	2
	One Finger (Sequentially)		6	¼	25	1
	Different Fingers (Randomly or Sequentially)		12	½	12	½
Toggle Switch	One Finger (Randomly)		20	¾	51	2
	One Finger (Sequentially)		12	½	25	1
	Different Fingers (Randomly or Sequentially)		16	⅝	20	¾
Crank and Lever	One Hand (Randomly)		51	2	100	4
	Two Hands (Simultaneously)		76	3	127	5
Knob	One Hand (Randomly)		25	1	51	2
	Two Hands (Simultaneously)		76	3	127	5
Pedal	One Foot (Randomly)		d = 100 D = 203	4 8	152 254	6 10
	One Foot (Sequentially)		d = 51 D = 152	2 6	100 203	4 8

Separation distances are defined from the centers or the sides of the controls.

Spacing

Table 4.7 contains recommendations for the separation of common controls on a panel.

For other combinations of controls the following factors should be considered (Ely, Thomson, and Orlansky 1963a):

- Whether use of the controls is simultaneous or sequential
- What part of the body is being used
- Size of the control and the amount of movement (displacement or rotation)
- Need for blind reaching (having to reach the control and grab it without seeing it)
- Consequences of inadvertently using the wrong control
- Whether personal protective equipment is used, such as gloves that might hinder control manipulation
- Environmental factors, such as cold or heat or wetness, that might hinder control manipulation

Shape Coding

Varying the shape, size, and type of controls on a complex control panel may assist the operator in identifying a specific control quickly and can reduce the potential for error. Shape coding is desirable in areas of reduced illumination, where vision is blocked (for example, by parts of production equipment), or when job requirements force the operator to look elsewhere. Size coding is less satisfactory. To distinguish controls by size might make the dimensions of several of them inappropriate for the exertion of force or for the precision movements needed. With shape coding of knobs, three to five shapes can be distinguished without visual cues (see the section on coding in person-to-person information transfer).

Control Resistance

The material in this section was developed from information compiled in Ely, Thomson, and Orlansky 1963a and Chapanis and Kinkade 1972.

Some force must always be applied to make a control move. The resistance of the control and device to which it is coupled may be elastic (spring loading), as in a power tool trigger; static and sliding friction, as in a rheostat; viscous damping, as in a dashpot to control motion; inertial, as on a seat belt reel; or combinations of the above. Depending on the kind and amount of resistance, the following effects on performance can occur:

- Altered precision and speed of control operation
- Changes in the feel of the control
- Changes in the smoothness of control movement
- Altered susceptibility of the control to accidental activation and the effects of shock and vibration

The control resistance should be assessed when selecting or designing controls for specific operations. All controls should be large enough to grasp or activate without exceeding a pressure greater than 150 kilopascals (kPa), or 22 pounds per square inch (psi), on the skin (Rehnlund 1973).

Additional guidelines for control resistance and design of the control's

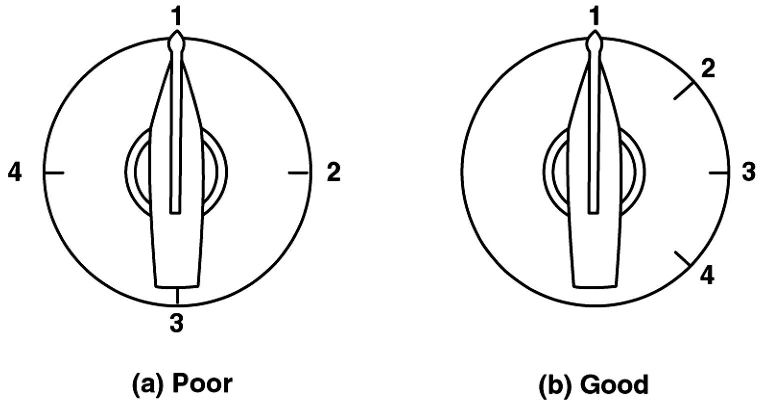


FIGURE 4.15 Examples of poor and good control movement design (adapted from Ely, Thomson, and Orlansky 1963a)

operation are given below (Damon, Stoudt, and McFarland 1963; Chapanis and Kinkade 1972)

- Design control movements to be as short as possible, consistent with the requirements of accuracy and feel. Figure 4.15 illustrates this principle for a bar-type knob.
- Provide a positive indication of control activation so that malfunction will be obvious to the operator.
- Provide feedback to the operator from the system that the desired equipment response has taken place.
- Design control surfaces to prevent slippage by the foot, finger, or hand activating them. Knurls or indentations on knobs and roughened rather than smooth surfaces for foot pedals and for some buttons are desirable. The choice of knurling and indentation will be a function of the frequency of activation and the forces required.
- Provide an arm or foot support if precise, sustained positioning of controls is required. Avoid static loading of the arm or leg muscles.
- Use controls with enough resistance to reduce the possibility of inadvertent activation by the weight of a hand or foot. The force required to activate a control can be greater if it is activated infrequently or for short periods than if it must be activated for long periods or frequently.
- Provide artificial resistances if power assists are used to aid the operator in activating a control.
- Provide a backrest or similar support if a seated operator must push with a force greater than 22 N (5 lbf) on a one-hand control.
- Design the workplace so that the operator can move the trunk and entire body if both hands are required to exert more than 135 N (30 lbf) through more than 38 cm (15 in.) in the fore-and-aft plane.

- ◆ Fit control design to the speed, force, and accuracy capabilities of most people, not just the most capable operators. The values given for forces in Table 4.9 have been selected to include the less strong portion of the working population.
- ◆ Pay particular attention to the force requirements for activation of infrequently used controls, such as control valves on liquid or solvent lines. Locate these valves from 50 to 100 cm (20 to 39 in.) above the floor whenever possible, so that they are accessible and maximum strengths can be applied to them.

Although the information in this section will aid in the selection and location of controls, each application will have its own requirements. An excellent approach to determining the best design is to simulate it and run an experiment to test its suitability, using psychometric measures (see "Psychophysical Scaling Methods" in Chapter 2).

Types of Controls

The following factors will determine which control is most suitable for a given application:

- ◆ Speed and accuracy of the response needed
- ◆ Space available
- ◆ Ease of use
- ◆ Readability in an array of similar controls
- ◆ Demands of other tasks performed simultaneously with control operation

Table 4.8 rates some of the more common controls for several of these factors. Further details of control characteristics and uses for toggle switches, push buttons, rotary selection switches, knobs, cranks, levers, valves, handwheels, and foot pedals are shown in Table 4.9.

Computer Input Devices

There are several types of computer input devices, including the keyboard, mouse, trackball, touch pad, graphic tablets, joystick, and voice. A stylus or finger touch is used directly on a screen for a touch-screen display. Certain input devices are best suited for particular functions such as alphanumeric entry, cursor positioning, or drafting. Table 4.10 summarizes the types of uses for different input devices. All input devices require integration into the design of the VDT workstation and the organizational and task requirements (see Chapter 6).

TABLE 4.8
Characteristics of Common Controls (adapted from Damon, Stoudt, and McFarland 1963; Murrell 1965; Chapanis and Kinkade 1972)

Control	Suitability where speed of operation is required	Suitability where accuracy of operation is required	Space required to mount control	Ease of operation in array of like controls	Ease of check reading in array of like controls
Toggle switch (on-off)	Good	Good	Small	Good	Good
Rocker switch	Good	Good	Small	Good	Fair[1]
Push button	Good	Unsuitable	Small	Good	Poor[1]
Legend switch	Good	Good	Small	Good	Good
Rotary selector switch (discrete steps)	Good	Good	Medium	Poor	Good
Knob	Unsuitable	Fair	Small-Medium	Poor	Good
Crank	Fair	Poor	Medium-Large	Poor	Poor[2]
Handwheel	Poor	Good	Large	Good	Good
Lever	Good	Poor (H) Fair (V)	Medium-Large	Good	Good
Foot pedal	Good	Poor	Large	Poor	Poor

[1]Except where control lights up for "on."
[2]Assumes control makes more than one revolution.
H = horizontal
V = vertical

The ratings are based on typical examples of each control type, not on the extremes of performance in each range.

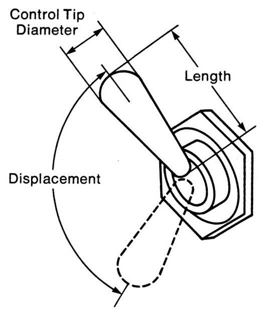
Keyboard

Conventional keyboards have become fairly standardized, with typical characteristics, such as tactile feedback and activation force, being kept within an acceptable range. Although these characteristics can make a difference to the user, they are not easily assessed in the field. Most consumers are making the choice between a conventional and an alternative keyboard and the features that either group of keyboards may offer.

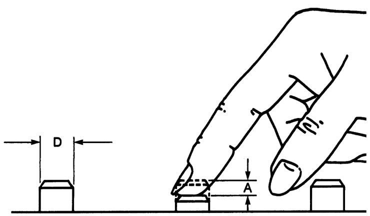
TYPES OF KEYBOARD Standard or conventional keyboards are ones with the keys in a straight line across the board, typically in a QWERTY format, so

TABLE 4.9
Design Parameters for Controls

(1) Toggle Switches *(Source: U.S. Department of Defense 1998)*



Parameter	Recommended Design Values (Minimum—Maximum)		Comments
Control tip diameter	3–25 mm	0.12–1.00 in.	Most commonly used when an operation has only two options (on or off) and when control panel space is limited. Three positions (e.g., off, low, high) cannot be operated with as much speed as two positions. The minimum resistance is specified to reduce the potential for accidental activation of the switch.
Length			
Normal	12–50 mm	0.5–2.0 in.	
If operator wears gloves	38–50 mm	1.5–2.0 in.	
Displacement			
2-position switch	30°–120°		
3-position switch	18°–60°		
Resistance			
Normal	3–11 N	10–40 oz	
If control tip is small	3–5 N	10–16 oz	



Parameter	Recommended Design Values (Minimum—Maximum)		Comments
Diameter (D)			Distinctions are drawn between push buttons operated with the index or middle finger and those activated by the thumb or palm. Maximum diameter is not indicated for the latter condition because it varies with the location of the push button in the workplace. Force and displacement values recommended for product design are much lower as older populations, often with arthritis, need to be considered. (Rahman, Sprigle, and Sharit 1998)
Fingertip activation	10–19 mm	0.4–0.75 in.	
Palm or thumb activation	19–NA mm	0.75–NA in.	
Emergency push buttons	not < 25 mm	not < 1.0 in.	
Displacement (A)			
Finger activation	3–6 mm	0.12–0.25 in.	
Palm or thumb activated	3–38 mm	0.12–1.50in.	
Resistance			
Finger activation	3–11 N	10–40 oz	
If control tip is small	3–23 N	10–80 oz	

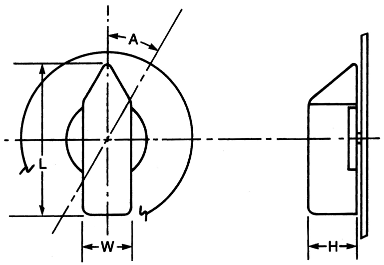
(2) Push Buttons *(Sources: U.S. Department of Defense 1998; Murrell 1965; Moore 1975)*

Frequently used to enter information into a piece of equipment where each button represents a separate response, e.g., selecting a beverage from a vending machine. Push buttons must be accompanied with a display for feedback of the activation, e.g., legend switches that light up.

Sequentially operated push buttons used by alternate fingers should be designed according to keyboard guidelines (see later). Large push buttons may be operated by the heel of the hand or the hip in assembly and packaging operations. However, to avoid soft tissue damage, a foot pedal or finger-operated control should be considered first. Automatic counting devices employing photocells or weight checks are preferable to hand-or foot-operated controls in many of these operations.

(table continues on p. 308)

TABLE 4.9 (Continued)



Parameter	Recommended Design Values (Minimum—Maximum)		Comments
Dimensions			Minimum widths (W) are not given (NA, not available) since this value will vary with the characteristics of the material used to fabricate the switch. The marks at either end of the displacement path represent stops.
Length (L)	25–100 mm	1.0–4.0 in.	
Width (W)	NA–25 mm	NA–1.0 in.	
Depth (H)	16–75 mm	0.6–3.0 in.	
Displacement (A)			
Closely grouped controls	15°–40°		
Widely separated controls	30°–90°		
Resistance	0.110–0.675 N·m	1–6 lbf·in.	

(3) Rotary Selector Switches *(Source: U.S. Department of Defense 1998)*

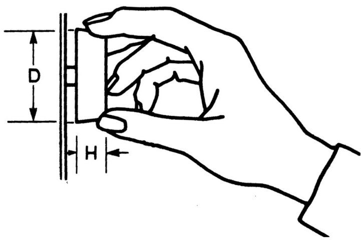
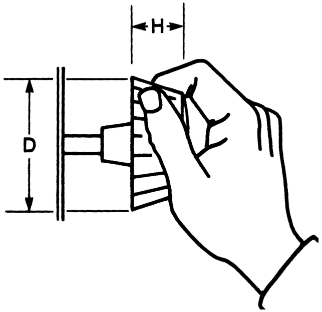
Useful for applications where from 3–24 values must be selected and where accuracy is needed. Because there is a preset detent for each value, the selections can be made accurately and quickly. These switches require more space for operation than toggle switches do, since room must be made for the fingers. The selector may be either a bar or a round knob, the former being preferred on panel boards with a large number of similar controls so that the values are easily seen. The illustration below shows some rotary selector switches.

To reduce potential for error in using rotary switches:

- Avoid selections that are 180° apart. Use only as much of the control's 360° rotation as is needed to accommodate the number of values required.
- Fit stops at the beginning and end of the range of values. The stops allow the operator to count off the appropriate number of detents if visual control of the selection is not possible.

(4) Knobs *(Sources: U.S. Department of Defense 1998; Chapanis and Kinkade 1972; Kellerman, van Wely, and Willems 1963; Woodson, Tillman, and Tillman 1992)*

Knobs extend the range of rotary selector switches since they can be rotated through more than 360° and can be moved through a continuous, rather than discrete, series of settings. They should be designed so that the fingers do not obscure the scale, and they should be mounted on the control panel with adequate clearance to allow proper grasping. Adequate clearance is particularly necessary for knobs where forces to activate them are near the maximum values. Maximum values for each type of knob operation are given below after fingertip and palm grasp operation information.

	Parameter	Recommended Design Values (Minimum—Maximum)		Comments
Fingertip Operation (precision grip) 	Diameter (D)	10–100 mm	0.4–4.0 in.	For precise movement
	Diameter minimum, for very low torque	6 mm	0.2 in.	
	Depth (H)	12–25 mm	0.5–1.0 in.	
Palm Grasp Operation (power grip) 	Diameter (D)	35–75 mm	1.5–3.0 in.	For high torque (or large forces) control such as knobs operating valves Use a star pattern or knurled knob
	Depth (H), minimum	15 mm	0.6 in.	

(table continues on p. 310)

TABLE 4.9 (Continued)

Maximum Torques of Round Knobs *(Source: Woodson, Tillman, and Tillman 1992, adjusted for gender and age)*

Maximum torques that can be applied to a round knob as a function of knob diameter and depth.

The maximum forces (torques), in newton-meters (N·m) and pound-force inches (lbf·in.), that can be generated by most people in turning round knobs of different diameters (column 1) and depths (across the top) are presented. For precision control, both very small (< 25 mm, or 1 in.) and large (76 mm, or 3 in.) knob diameters put the hand at a biomechanical disadvantage, so less force can be developed than at intermediate values. For power grip control, the larger knob results in more palmar support and more force development. Too little depth, however, can limit grip stability and reduce the amount of force that can be developed or maintained.

This table shows that a knob of 5 cm (2 in.) diameter is preferable to a smaller or larger one for fingertip control, and that setting the knob out 2.5 cm (1 in.) from the panel surface improves the ability to exert force on it.

The values given below are not recommended values but maximum torques that can be applied by most people. For frequent operation of a control, the tabulated values should be cut in half for the appropriate design limits.

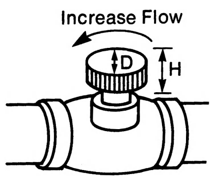
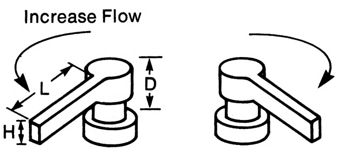
	Knob Depth, Precision Grip		Knob Depth, Power Grip	
Knob Diameter	12 mm (0.5 in.) Maximum Torques	25 mm (1.0 in.) Maximum Torques	12 mm (0.5 in.) Maximum Torques	25 mm (1.0 in.) Maximum Torques
12 mm (0.50 in.)	0.43 N·m (3.8 lbf·m)	0.51 N·m (4.5 lbf·in.)	0.90 N·m (8 lbf·in.)	1.36 N·m (12 lbf·in.)
19 mm (0.75 in.)	0.51 N·m (4.5 lbf·in.)	0.68 N·m (6.0 lbf·in.)	1.70 N·m (15 lbf·in.)	2.49 N·m (22 lbf·in.)
25 mm (1.00 in.)	0.68 N·m (6.0 lbf·in.)	0.85 N·m (7.5 lbf·in.)	5.08 N·m (45 lbf·in.)	6.10 N·m (54 lbf·in.)
38 mm (1.50 in.)	1.11 N·m (9.8 lbf·in.)	1.27 N·m (11.2 lbf·in.)	7.12 N·m (63 lbf·in.)	10.17 N·m (90 lbf·in.)
51 mm (2.00 in.)	1.70 N·m (15.0 lbf·in.)	2.03 N·m (18.0 lbf·in.)	11.19 N·m (99 lbf·in.)	13.22 N·m (117 lbf·in.)
76 mm (3.00 in.)	0.51 N·m (4.5 lbf·in.)	0.51 N·m (4.5 lbf·in.)	14.24 N·m (126 lbf·in.)	16.27 N·m (144 lbf·in.)

(5) Valves *(Sources: Woodson, Tillman, and Tillman 1992; Imrhan and Farahmand 1999)*

There is very little information in the literature on the design of valve handles for controlling liquid flow. Guidelines for the circular valve handle have been adapted from the study of tool handles by Imrhan and Farahmand (1999), as the valve would be activated with the whole hand over the knob in a similar way to the postures of the study. The guidelines for the lever-type handle have been developed from field observations and data on hand anthropometrics and strengths. Most valves have torques in the range of 0.56–4.52 N·m (5–40 lbf·in.) when first installed (Rodgers and Jones 1981; Eastman Kodak 1983).

Additional guidelines for the selection and installation of valves:

- Consistency in the direction of operation of two- and three-way valves is very important in order to minimize human error. Specification of rotation direction should be given whenever ordering valves.
- Labeling of the valve ports on multiple-way valves is recommended, but chemicals may obscure the labels if there is frequent use of the valves. Thus consistency in the assignment of valve ports to specific functions is desirable across a chemical production system.
- The way a valve is mounted (e.g., stem handle up, down, or to one side) will influence how an operator grasps it for turning. Method of grasping, in turn, will determine how much force can be applied to it to break open a corroded, or frozen, valve. Maximum muscle strength for valve activation is available at 51–114 cm (20–45 in.) above the floor and within 38 cm (15 in.) of the front of the operator's abdomen. When locating valves on equipment, the designer should specify clearances so that the operator can easily access these and other controls.

	Parameter	Recommended Design Values (Minimum-Maximum)		Comments
Circular Valve Handle 	Diameter (D) minimum	35 mm	1.5 in.	The circular handle, D, represents the knob diameter, and H represents the distance form the top of the knob to the valve body. The handle should be knurled to aid grasp.
	Depth (H) of handle, minimum	25 mm	1.0 in.	
	Activation force, maximum,			
	For 35-mm (1.5-in.) handle, Dry gloves	7.12 N·m	63 lbf·in.	
	Greasy gloves (should be avoided)	3.44 N·m	30 lbf·in.	
Lever-type Valve Handle 	Length (L) minimum	35 mm	1.5 in.	In the lever-type valve, L represents the lever length, D represents the handle-to-valve body depth, and H represents the vertical height of the valve handle.
	Height (H) of lever, minimum	16 mm	0.6 in.	
	Depth (D) of handle, minimum	25 mm	1.0 in.	
	Activation force, maximum, for 35-mm (1.5-in.) handle diameter or length	7.12 N·m	63 lbf·in.	

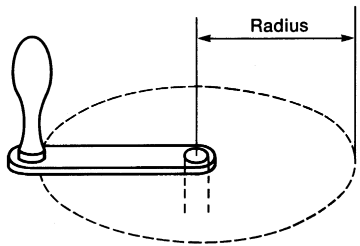
(table continues on p. 312)

TABLE 4.9 (Continued)

(6) Cranks *(Sources: Ely, Thomson, and Orlansky 1963a, 1963b; Murrell 1965; Chapanis and Kinkade 1972)*

Cranks take up a large amount of space, but they have the advantage of providing either fine or coarse adjustment over a wide range. For fine adjustment the crank grip should not rotate. However, for grosser adjustments the grip should rotate so that the wrist and hand can be kept in optimal alignment throughout the rotation.

The recommendations below are for cranks with radii between 3.8 and 19 cm (1.5 and 7.5 in.). For larger cranks (12–20 cm, or 5–8 in. radii), the maximum torques will increase, the values being most affected by the height of the crank above the floor, the speed of operation, and the forward reach required at its furthest travel from the operator. If rapid turning is required, peripheral forces should be kept below 45 N (10 lbf), so that most people's strength capacities will not be exceeded.



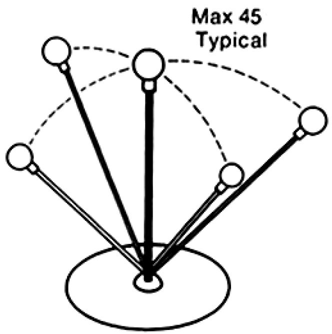
Parameter		Recommended Design Values		Comments
Minimum crank radius at specified handle orientation to apply torques in four ranges				Torque (force) is expressed in Newton-meters and pound-force-inches. Crank radii should not be less than the values given for each torque range, but larger cranks may be used. At radii greater than 25 cm (10 in.), vertical cranks mounted on the side of a piece of equipment may require excessive reaches for operation.
Torque Range		Horizontal or Vertical on Side		
N·m	lbf·in.	91 cm (36 in.) above floor		
0–2.3	0–20	3.8 cm (1.5 in.)		
> 2.3–4.5	>20–40	11.4 cm (4.5 in.)		
> 4.5–10.2	>40–90	19.0 cm (7.5 in.)		
> 10.2	>90	19.0 cm (7.5 in.)		
Torque Range		Vertical and Facing the Operator		
N·m	lmf·m.	91 cm (36 in.) above floor	122–142 cm (48–56 in.) above floor	
0–2.3	0–20	3.8 cm (1.5 in.)	6.4 cm (2.5 in.)	
> 2.3–4.5	>20–40	6.4 cm (2.5 in.)	6.4 cm (2.5 in.)	
> 4.5–10.2	>40–90	11.4 cm (4.5 in.)	11.4 cm (4.5 in.)	
> 10.2	>90	11.4 cm (4.5 in.)	19.0 cm (7.5 in.)	

(7) Levers *(Sources: Kellerman, van Wely, and Willems 1963; Murrell 1965; Chapanis and Kinkade 1972)*

Levers are useful in providing accurate adjustment over a small range, and they are useful in situations where simultaneous operation of controls is needed. Knobs or locking devices can be mounted on a lever to permit an operator to manipulate two controls with one hand.

The selection of lever length depends on the task to be done. Long levers require relatively less force in operation than short ones and permit more linear arm motion. For small lever displacements (less than 30°), a straight stick is suitable. For larger displacements, a ball grip or T-handle should be used.

Levers necessitating considerable force should be activated at shoulder level for standing work, at elbow level for seated work, and preferably somewhat to one side, not directly in front, of the operator. The lever should move toward the axis of the body so that the body is subjected to as little torsion as possible. Location of the lever at all positions should be within the arm reach envelopes given in the section on "General Workplace Layout & Dimensions" (Chapter 3).



Parameter	Recommended Design Values (Minimum-Maximum)		Comments
Operating angle, maximum in each direction from neutral	45°		A minimum force of 10 N (2.2 lbf) is recommended to reduce the opportunity for accidental activation of a lever that is activated with a palmar grasp. A finger grasp is used for precision, and a palm grasp is a power grasp. The displacements, operating angles, and range of handle diameters are for a floor-mounted lever, such as a gearshift.
Displacement, maximum			
From front to back	35 cm	14 in.	
From side to side	95 cm	37 in.	
Diameter of handle, minimum to maximum			
For finger grasp	12–75 mm	0.5–3.0 in.	
For palm grasp	38–75 mm	1.5–3.0 in.	

(table continues on p. 314)

TABLE 4.9 (Continued)

Parameter	Recommended Design Values (Minimum-Maximum)		Comments
Height of lever handle above floor			
Seated operation	75 cm	30 in.	
Standing operation	125 cm	49 in.	
Distance range in front of body, lever in neutral (assumes optimal height for lever and that person can lean forward if necessary)	50–65 cm	20–26 in.	
Recommended maximum forces (one-handed operation, seated position)			
Front to back, palm grasp	130 N	29.0 lbf	
Front to back, finger grasp	9 N	2.0 lbf	
Side to side, palm grasp	90 N	20.0 lbf	
Side to side, finger grasp	3 N	0.8 lbf	

(8) Handwheels *(Sources: U.S. Department of Defense 1998; Kellerman, van Wely, and Willems 1963; Ely, Thomson, and Orlansky 1963a, 1963b; Murrell 1965; McMulkin and Woldstad 1993; Bullinger, Kern, and Braun 1997; Attwood et al. 1999)*

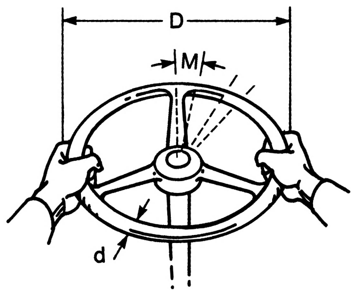
Handwheels are used when considerable forces have to be exerted and two hands are available to exert them; in all other cases knobs or cranks are preferable. Handwheels are slow to activate through multiple revolutions unless equipped with a flywheel. Check readings are not possible because rotations greater than 360° are used. Accuracy can be achieved, but grosser adjustments are usually made.

Recesses in the rim of a handwheel, by permitting a better grip, may permit more force to be applied to it than would otherwise be the case. However, these recesses should not force a small or large hand to take an abnormal position (see the section "Tool Design" later in this chapter). Larger wheels should be able to be grasped with the whole hand and should offer a means of support. If there is any risk of uncontrolled movement of the wheel, it should be cast in one mold without multiple spokes.

There may be some benefit to alternative wheel designs, such as a zigzag, that allow better grip and leverage than a standard wheel, or even a rim surface that is knurled.

Vertically displayed handwheels should be placed between 95 and 120 cm (37 and 47 in.) above the floor for standing workplaces. Horizontally displayed handwheels should be located from 125 to 140 cm (49 to 55 in.) above the floor. Equipment or other structures in the production system should not block access to the handwheels.

Too tight a packing of the pressure seals and poor maintenance have been attributed to large increases in forces to open wheel valves.



Parameter	Recommended Design Values (Minimum-Maximum)		Comments
Handwheel diameter (D)	18–53 cm	7–21 in.	Design values are given for handwheel and rim diameters and displacement, for handwheels operated by two hands.
Rim diameter (d)	20–50 mm	0.8–2.0 in.	
Displacement (M), from neutral	60°		
Resistance at rim (tangential force)			
One-hand operation	20–130 N	4–29 lbf	
Two-hand operation	20–220 N	4–49 lbf	

(table continues on p. 316)

TABLE 4.9 (Continued)

(9) Foot Pedals *(Sources: U.S. Department of Defense 1998; Kellerman, van Wely, and Willems 1963; Ely, Thomson, and Orlansky 1963a; Murrell 1965; Mortimer 1974)*

Foot-operated pedals leave the hands free to do other work. They are frequently used to keep count in assembly operations (switching pedals) or to operate equipment during packing or assembly tasks when both hands are occupied (operating pedals). In a switching pedal, the pedal stroke is usually accomplished with the front of the foot, and small forces and strokes are used. In an operating pedal, the whole foot applies the force, and the amount that can be exerted is dependent on the holding time and frequency of operation. Very precise force development is best relegated to the hands, not the feet.

Foot pedals are not recommended for standing work, except for very infrequent use. It is unwise to use more than two foot pedals in a seated workplace. Operations that require movement of the feet between controls, such as in playing an organ, are very tiring.

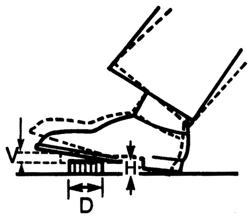
	Parameter	Recommended Design Values (Minimum-Maximum)		Comments
Switching Pedal or Push Button 	Diameter (D)			Minimum forces or counterpressures will increase to 40 N (9.8 lbf) if the foot rests on the pedal. Maximum forces depend on which muscles can be used to activate the pedal; the large muscles of the leg are able to deliver more force than the smaller muscles controlling ankle motion.
	minimum	12 mm	0.5 in.	
	preferred	50–80 mm	2–3 in.	
	Displacement range(V)			
	for ankle flexion	12–65 mm	0.5–2.5 in.	
	for whole leg movement	25–180 mm	1–7 in.	
	Maximum height of pedal above heel rest (H), lower leg vertical	8 cm	3 in.	

TABLE 4.9 (Continued)

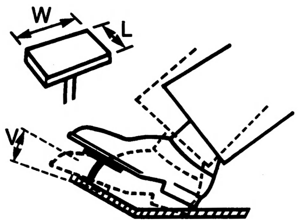
	Parameter	Recommended Design Values (Minimum-Maximum)		Comments
Operating Pedal 	Angle of ankle from neutral position recommended minimum-maximum range, operator seated	20° up, 30° down		Pedals that are in constant use should be provided with an adjustable return spring to allow for differences in operator strength and variations in the nature of the work. Pedals that result in overstretching of the ankle joint (more than 25° around the resting position of the foot) are not recommended. The more frequently a foot pedal is operated, the nearer it should be to its minimum force limit. If the operation of a foot pedal requires very high counterpressures, the pedal should be placed to allow the leg muscles, not just the ankle, to exert the force. Counterpressures greater than 400 N (90 lbf) should not be required on a frequent basis even when the leg is involved, as in operating a brake.
	Counterpressures, recommended minimum-maximum	15–75 N	3.3–16.5 lbf	
	Minimum length (L)			
	occasional use	8 cm	3 in.	
	constant use	25 cm	10 in.	
	Minimum width (W)	9 cm	3.5 in.	
	Displacement range(V)			
	for ankle flexion	12–65 mm	0.5–2.5 in.	
	for whole leg movement	25–180 mm	1–7 in.	
	Angle of ankle from neutral position recommended minimum-maximum range, operator seated	20° up, 30° down		
	Counterpressures, recommended minimum-maximum	15–90 N	3.3–19.8 lbf	

TABLE 4.10
Summary of types of uses for different input devices (Bullinger, Kern, and Braun 1997; Wickens, Gordon, and Liu 1997)

Device	Uses	Recommended Use and Characteristics
Alphanumeric keyboard	Select entering of texts and numbers	General-purpose entry device; slower for pointing functions than mouse, etc.
Numeric keyboard	Entering numbers	Fast entry of massed numbers; calculations; no text entry on pad
Cursor control keys	Discrete cursor movement	Tasks with short, basic cursor movements
Mouse	Point; drag; move cursor	Tasks requiring little keyboard use; accurate
Trackball	Track; select; move cursor	Integrating graphics with keyboard entries; flexible
Joystick	Track; select; move cursor	Task with intensive cursor positioning; flexible
Graphic tablet	Draw; trace; move cursor	Drafting or digitizing hard copy; accurate and fast
Touch screen	Select	Coarse pointing; fast and discrete functions

called for the first few letters of the top left-hand row of alpha keys. Usually the number pads are fixed within the keyboard and to the right of the letters. A cursor control set is often between the letters and number pad.

Fixed-function keyboards are specialized with function keys that are often arranged by importance, frequency of use, and sequence of use, and are highly application-specific. This type of keyboard is effective when (Bullinger, Kern, and Braun 1997):

- Functions must be executed quickly
- One set of functions is frequently used during a task
- The correct selection of functions is critical

Variable-function keyboards refer to the standard keyboard that has functions in several layers: by using the shift key; labeled overlays that sit over the keys; and software control of functions that would assign a different function to the key that is pressed. The software is easily modified and there is less visual search, as fewer keys are needed. Some disadvantages are the number of keys that sometimes have to be held, along with the shift key, to input a command. Overlays are effective only if the operator remembers to use them. These features are effective when:

- The subsets of functions are often used
- The pacing of entry is not forced

- Relatively sophisticated prompting and feedback is available
- Frequent modification of the functions is needed

Chording-type keyboards are less common. There are only a few keys, usually one under each digit, so that the operator's hands barely move. The fingers press combinations of at least two keys to input information in the form of a code. Chorded keyboards have been found to be 50 percent faster than a typewriter (Ivergard 1999), and ternary keyboards have been found to be as quick to learn as conventional typing (Kroemer 1992). However, chorded keyboards remain minimally used except by stenographers and for some mail-sorting machines.

Alternative keyboards are sequential keyboards that do not have the keys straight across the board. Instead the keys are separated into two groups for the left and right hands. Cursor keys are often placed in the middle and a number pad to the right of the alpha keys. A separate numeric pad is sometimes required. The keys are angled in frontal, horizontal, and vertical planes that allow an operator to assume more natural hand positions and hence improved comfort while typing.

CHARACTERISTICS OF STANDARD KEYBOARDS The keyboard is an important part of an overall VDT system. Therefore, it is important that the keyboard is separate from the monitor to provide flexibility for workstation setup (see "Computer Workstations" in Chapter 3). The following are some guidelines on keyboard design (Bullinger, Kern, and Braun 1997; ISO 9241-4 1998; Ivergard 1999).

- The QWERTY layout is not the most efficient, but it has become the standard format (except for linguistic variations).
- The base of the keyboard should prevent it slipping on the desk.
- Keyboards should be as thin as possible, less than 30–35 mm (1.2–1.4 in.), measured at the home (middle) row.
- Keyboard angle should range from 0 to 15 degrees up at the back. Adjustability is desirable so that the keyboard can be flat if it has to be used occasionally from a standing position (as is typical in production) without the overall table height raised. Ivergard (1999) suggests 30º of adjustability raising the front of the keyboard as well, just for this purpose.

There is continued investigation into the concept of a flat to "negative" sloping keyboard (that is, the back of the keyboard slopes downward). Wrist extension has been shown to be less with a flat to negative slope, and also if the wrists are slightly higher than the elbows (Hedge et al. 1999; Simoneau and Marklin 2001). However, other studies find that the cumulative tendon travel in the wrist and fingers is of importance, and this is reduced by a combination of the wrist and finger positions that are optimized when there is a positive pitch (Nelson, Treaster, and Marras 2000; Treaster and Marras 2000).

- Keyboard rows can be stepped, sloped, or dished, as there is no evidence of relative advantages.
- The key top should be slightly concave to assist placement.
- Ensure there is feedback when keying, either tactual, auditory, or visual. Tactual is the primary medium, but often all three methods are used together. Tactual feedback is recommended in the form of a rapid buildup force as the key is pressed, with a reduction in required force in the region of activation, after which a second increase of force follows.
- Keys should be matte, well marked with characters of minimum height of 25 mm (0.1 in.) and with a contrast ratio of 1:3.
- The key response time should be long enough to avoid "bounce," where more than one activation occurs when only one was intended. However, too long a response time will interfere with fast typing. For occasional use the response time should be about 0.08 second (Stevens 1977). System response time, such as the time needed for the computer to initiate another prompt, should not exceed 2 seconds and preferably be much less (Hinsley and Hanes 1977).

Size and force parameters of the keyboard are shown in Figure 4.16.

NUMERIC PAD Preferably the numeric pad should be independent of the keyboard, as this allows much greater flexibility in workstation setup (see "Computer Workstations" in Chapter 3). The current convention for the computer numeric pad and adding machines is for the numbers 789 across the top row. Telephone pads are generally 123 across the top row, and soon all phones will conform to that convention. Bullinger, Kern, and Braun (1997) state it would be likely that all numeric pads will be made to conform to 123 across the top. There is no performance difference between the two layouts, but where the zero is placed does make a difference (Marteniuk, Ivens, and Brown 1996). The zero should be positioned at the bottom of the number pad to give the

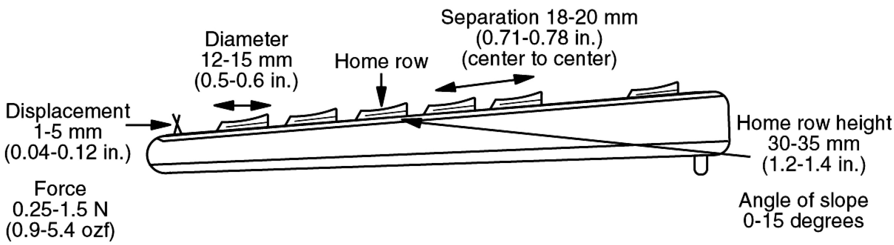


FIGURE 4.16 Recommended size and force characteristics of a keyboard (Bullinger, Kern, and Braun 1997; ISO 9241-4 1998; Ivergard 1999)

fastest performance. Key dimensions should be similar to those of a keyboard, as shown in Figure 4.16.

ALTERNATIVE KEYBOARDS There are many factors to consider with an alternative keyboard, and there appears to be tradeoffs to be made among some of those factors. For example, a sharply laterally inclined keyboard (or roll) may have the greatest reduction in wrist pronation, but not for radial deviation and extension, whereas an alternative keyboard with less lateral inclination was overall better for posture with moderate pronation, but otherwise neutral wrist. Although no one has determined a definitive design, there appears to be growing empirical support for the benefit of alternative keyboards that have some tilt (pitch), split (yaw), and lateral inclination (roll). Some preliminary generalities follow about alternative keyboards compared to conventional keyboards, although not all the points made below were found with all alternative keyboards. Some keyboards appear to have more effect than others. Alternative keyboards (Cakir 1995; Swanson et al. 1997; Nelson, Treaster, and Marras 2000; Strasser, Fleischer, and Keller 2000; Tittiranonda et al. 2000; Treaster and Marras 2000; Zecevic et al. 2000):

- Allow a more neutral forearm and wrist posture
- Produce less tendon travel through the wrist
- Reduce muscle activity in upper arm and shoulder, and forearm and hand
- Reduce pressure in the carpal tunnel
- Improve subjective postural comfort
- After several weeks of use, can decrease pain severity in users who are symptomatic of musculoskeletal disorders (initially, there was a general placebo effect for all keyboards; this is possibly why a few studies have found no difference with an alternative keyboard)

Some studies have found:

- Considerable training time may be needed to grow accustomed to the keyboard, with skilled typists adjusting more slowly.
- Initially, productivity can drop and or significant errors made, especially with a lateral roll of about 30° or greater. This has been hypothesized to be one reason for slow acceptance of alternative keyboards.

When installing such devices at a workstation, consider the increased footprint that an alternative keyboard can have. In addition, attached number pads are often further off to the right than with standard keyboards and therefore even more awkward to use.

There are still no clear design guidelines for alternative keyboards, as there are many interactions between the characteristics and tradeoffs that are still

FIGURE 4.17 A left-hander using an alternative keyboard with an integrated wrist rest

being studied. At present, the characteristics that appear to bring benefit, combined with acceptance, are a split (yaw) of 12–15°, lateral inclination (roll) of 10–30°, and an angle (pitch) of about 12°. However, the presence of a wrist rest with the keyboard can affect the outcome of the characteristics on hand posture, so much so that in one study only a positive pitch was of significance. Figure 4.17 shows an example of an alternative keyboard.

NOTEBOOK KEYBOARDS Keyboards on notebooks vary in key size. Some have full-size keys, while others have keys that are smaller than on conventional keyboards. The preference depends on the frequency of use and an individual's finger size. The use of notebook computers as the primary computer appears to be on the rise, but there are alternatives that can be considered if the computer is used for a significant amount of time. The approach depends if the notebook is being used during travel or at a workstation

- Choose a notebook with full-size keys.
- Use a travel keyboard that attaches externally but folds for packing.
- Attach a full-size keyboard (the monitor of the notebook would probably need to be raised as well).
- Dock the notebook and use a desktop monitor and keyboard.

Mouse

The mouse is a small, palm-size unit with sensors underneath, which conveys the position of the mouse to the computer. There is at least one press button, often three, that allows the user to send commands to the computer. Typically, a mouse is not the sole input device but rather works in conjunction with a keyboard. As shown in Table 4.10, the mouse is good for pointing, moving the cursor, and dragging objects. It does not work as well for drawing.

There are mechanical and radio frequency (RF) mice. The cordless RF mouse conveys its position through radio contact with the computer. Batteries are needed to operate the mouse, which makes it a little heavier than a traditional mouse. There are many shapes of mice that follow anatomical features of the hand and fingers, as the mouse can be used in the palm or with the fingertips. There are also left-handed mice, although the 10 percent of the population that is left-handed appears not to be disadvantaged by using right-hand mice (Hoffmann, Chang, and Yim 1997). However, placing the mouse on the left of most keyboards would bring it closer to the user than where the mouse is on the right-hand side, beyond the number pad. The physical demand of using a mouse on the right-hand side is reduced if the number pad is removed, bringing the mouse closer (Cook and Kothiyal 1998). Control features of mice can be modified through the software so that the user can tailor the control-display gain (degree of movement sensitivity and screen responsiveness). This is an important feature that can be forgotten by the user and can be a method to help reduce the amount of "skating" required, that is, picking up and brushing the mouse on the pad to make large moves of the cursor. Dragging tasks have been found especially to increase carpal tunnel pressure (Keir, Bach, and Rempel 1999).

Some disadvantages of a mouse are:

- It requires space and a flat area.
- It has to be picked up to operate.
- Mechanical roller balls can become dirty (which increases the force required to use the mouse).
- A mouse is not too compatible with notebook computers.

Studies of vertical computer mice indicate they may be a viable alternative to traditional computer mice, as they appear to bring some improved comfort for the user. However, they are less easy to use and performance is slower (Straker et al. 2000).

There are few specific criteria for mouse design. Although MIL-STD-1472F (U.S. Department of Defense 1998) provides some general dimensions for a mouse, many mice on the market differ from the recommendations because they are designed for use with the fingers rather than with the whole hand. The ISO 9241-9 standard (2000) has a few specific recommendations:

- Buttons should have displacement force of 0.5–1.5 N (1.8–5.4 ozf) until actuation.
- Button displacement should be a minimum of 0.5 mm (0.02 in.).
- A hardware or software lock should be provided for buttons that need to be continuously depressed for the duration of a task, such as dragging or tracing.

See "Computer Workstations" in Chapter 3" for further discussion on positioning the mouse and the keyboard.

Trackball

A trackball or roll ball is a mouse alternative where the fingers move a ball that is housed in a unit. Therefore, the user does not have to pick up the unit to move the sensor balls as they do with a mouse. Because the ball can be relatively easily moved with the fingers, the trackball is especially effective for rapid cursor movement with high accuracy (Bullinger, Kern, and Braun 1997). There are both mechanical and optical trackballs, although the former is the most common. The control-display gain can be set so that slow-velocity movements of the ball will allow sensitive control of the cursor and fast movements will allow the ball to move more easily for rapid and large cursor movements. There are several advantages of trackballs (Bullinger, Kern, and Braun 1997):

- Flexibility: accurate positioning and rapid movements can be set.
- Comfort: trackballs can be used for extended periods, as the forearm can be well supported.
- Feedback: direct tactile feedback is given by the ball's rotation.
- Space: only a small fixed space is needed, so it can sit close to the keyboard or even be integrated into the keyboard.

The main disadvantage of trackballs is that they are not suitable for tracing or hand drawing.

Trackball designs are highly variable. Some designs incorporate a small ball for use by the thumb, or a small centrally mounted ball for use by a single digit. The most common design is a large ball for several fingers to control, with control buttons on either side or above the ball. The ISO 9241-9 (2000) standard has a few specific recommendations:

- The rolling force should be 0.2–1.5 N (0.7–5.4 ozf).
- Starting resistance should be 0.2–0.4 N (0.7–1.4 ozf).
- For a main trackball the diameter should be 50–150 mm (2–6 in.) and the exposed arc between 100 and 140°.

MOUSE VERSUS TRACKBALL There is no definitive advantage of one device over the other. Karlqvist and colleagues (1999) report that different techniques are used with the two devices and so there are different biomechanical demands. Trackball tasks entailed lower shoulder elevation and less neck/shoulder muscle activity but more wrist extension than tasks with the mouse. Use of trackballs mounted centrally in a keyboard has been found less demanding on neck/shoulder musculature than using a mouse to the right of a keyboard (Harvey and Peper 1997).

Joystick and Touchpad

Another alternative to the mouse is a small joystick that is incorporated into the center of the keyboard, usually on some notebook computers. A finger controls the multidirectional lever. Use of a joystick has been found to decrease shoulder muscular load but increase the forearm load compared to the mouse (Fernstrom and Ericson 1997).

Touch pads appear to have replaced joysticks in many keyboard and notebook designs. The pads are usually small areas that are brushed or tapped by the fingertips to control the cursor and give input to the computer. A control button resides below the pad. Performance with a touchpad is better than with a joystick but not as good as a mouse (Sommerich 2000).

Graphic Tablet

The graphic tablet is a specialized input for graphic artists or computer-aided design (CAD) users. Input to the flat panel of the tablet is by stylus, puck (graphic mouse device), or finger. Graphic tablets are almost the only input device for drafting or hard-copy data entry by tracing or digitizing. Digitizing tablets work with a special stylus or puck that is attached to the tablet, while touch tablets are touch-sensitive and can be used with any stylus. The size of the tablets can vary from keyboard size to the size of a large table. These tablets have higher resolution than touch pads and so can be leaned against without spurious input.

The tablet layouts vary by task. Some have surfaces that are divided into a drawing area, alphanumeric input area, and other function-designated areas, while others may be less subdivided. Likewise, the overall size of a tablet is task-dependent. At times there may be advantages to having a large tablet; however, if the tablet is used for long periods of time, then the smaller the tablet the better, as the task and software allow. Large tablets provoke prolonged forward stretched postures to reach the back of the tablet, which leads to upper back and shoulder/neck discomfort, even though the arms may be resting on the table. A tablet of 420 mm (16.5 in.) in width and 300 mm (11.8 in.) in depth is recommended (Bullinger, Kern, and Braun 1997).

Touch Screen

Touch-screen displays can be considered both a display and input method combined. Touch screens are becoming common not only in point-of-sale (POS) devices at checkouts, but also in machine operations, where touch screens are simple controls for operations that are growing more complex.

There appears to be a cost-saving engineering trend of reducing mechanical switches, lights, and input devices and going toward using touch screens (Merritt 2001). Touch screens are usually operated by a finger as an alternative to a cursor movement and do not involve digitizing. They are well suited for approximate positioning tasks and menu selection activities. They are also useful in reducing workload when the types of inputs are limited and well defined (Bullinger, Kern, and Braun 1997).

Operating controls have to allow the operator to enter data, select options, choose processing sequences, adjust settings, and perform many other functions for which traditional hardware is less suited. Touch screens are also more practical for use with gloves and in environments where input devices would be soiled. Interface design should be built using the user-centered approach discussed and illustrated in "Computer Interface Controls" in this chapter.

Touch screens using LCD technology appear to be replacing the technology of light pens on CRTs. There are small touch screens, such as personal digital assistants (PDAs), that use a stylus and larger touch screens used with a finger.

For large touch screens that are used frequently, the height and angle of the display should be adjustable for different users. Touch-screen use entails a particular user tradeoff between visual distance, angle of view, and comfortable reach. There should be opportunity for height adjustability of the device or work surface, which will depend on whether the touch screen is to be used while seated or standing or both (see Chapter 3), and there should be considerable angle adjustability to allow for perpendicular viewing. The angle adjustability depends upon how the touch screen is being used, that is, whether it is mounted on the side of a machine or on a work surface with customer interaction. For use in a point-of-sale (POS) device at a fixed work surface height, one study found that at a height of 91.4 cm (36 in.) an angle range of 30–55° off the horizontal was anthropometrically (worldwide range) appropriate, although users employed a wider range of adjustment (Schultz, Batten, and Sluchak 1998). Manual touch-screen actuation guidelines are shown in Fig. 4.18.

The small screen size issue is especially challenging, as there is an increase of complex information. Some traditional interaction methods can be used, such as zooming, scrolling, panning, and hyperlinks. Nontraditional methods are being researched, such as dynamic magnification, in which important information is presented at a larger size than less important information; translucency, which is overlapping transparent layers of information; and dynamic labeling, which is adjusting text information to maintain a useful size font (Good et al. 2001). Also of current study is the size of text and methods of text presentation, such as rapid serial speed presentation (RSSP) and the Times Square method (Rahman and Muter 1999).

Small touch screens have some unique design issues: using and designing recognizable special function keys; when writing with a stylus, the letter has to be drawn distinctively and with a certain style requiring fine motor skill; and there is limited feedback while tapping. These drawbacks may be exacerbated by the effects of age (Wright et al. 2000).

Voice

The information in this section is generally based on Wickens, Gordon, and Liu 1998 and McMillan, Eggleston, and Anderson 1997.

Automatic speech generation and recognition are becoming more wide-

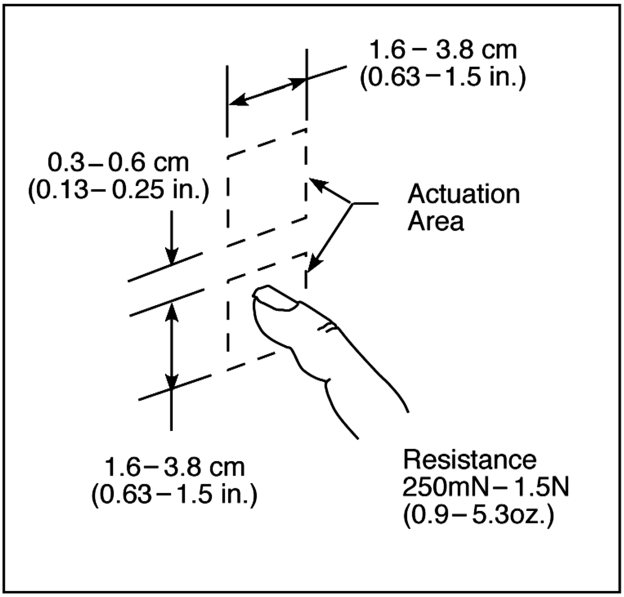


FIGURE 4.18 Touch screen control recommendations (adapted from Woodson, Tillman, and Tillman 1992)

spread, and they are being used in environments such as airplane cockpits. Speech generation is more advanced than automatic speech recognition (ASR) systems. Computers are also being designed to provide speech reminders or warnings to users, such as notification of a printing problem. The telecommunications industry has used voice recognition for telephone menu selection for some time.

ASR systems are used in a variety of ways. ASR systems that are speaker-dependent and continuous-speech are usually used in offices as an alternative input device to the computer. The disadvantage is that there is a time investment, as each user has to "train" the computer to recognize his or her own accent. This is partly why ASR is used as an accommodation for a disability. The advantage is that a full vocabulary can be developed, which allows letters and memos to be dictated. There are reports of considerable accuracy for some systems once they have been set up for the user. Isolated-word or connected-word systems (command and control by voice options) can also be used in the office with some benefit, depending on the computer task (Schwartz 1995).

In other production environments, ASR speaker-independent, isolated-word systems are used successfully where there would be many users and fewer words (so there would be less confusion from accents). For example, the technology has been adopted to sort parcels, record inventory checks, and acknowledge selecting an order in distribution centers or stocking warehouses. However, in some circumstances an ASR system may not be any more productive when other aspects of the process are slower, such as the need to do visual checks. The cost of a mistaken recognition also has to be considered when weighing the effectiveness of voice recognition systems.

The speech recognition technology is improving rapidly. However, there are some current limitations that make it suitable to only specific tasks and environments. Some of those limitations are (Wickens, Gordon, and Liu 1998):

- Confusion and limited vocabulary size
- Constraints on speed (rate of speech)
- Acoustic quality and noise and stress (degrade the quality of the voice)
- Compatibility (limited at controlling continuous movement).

Computer Interface Controls

More and more machines are being designed with computer interfaces. Computer interfaces are used not only in sophisticated industries such as nuclear power and chemical processing plants, but also with specific machines, such as an automatic palletizer or inventory management when picking orders from a distribution center. Progressive automation brings increased complexity of the human interface so the operator can oversee the system.

There are many issues to address concerning the human interaction with automation. These can be categorized as the use, misuse, disuse, and abuse of the automated system (Parasuraman and Riley 1997). *Use* refers to how humans use the system, such as their trust, mental workload, and risk taking. *Misuse* of the system refers to overreliance on automation that, in turn, is influenced by design factors affecting monitoring, such as automation reliability and saliency of status indicators. *Disuse,* which is the human neglect or underutilization of automation, is commonly caused by false alarms and lack of design in the trade-off of false alarms and omissions. Finally, *abuse* is when automation is designed without due regard for human performance, which can lead to human misuse and disuse of the automation.

The advantages of easy human-machine interface (HMI) development in lower costs and shorter time to market do not negate the importance of the ergonomics of the interface, the controls and displays or Web design. User-centered design is essential for good control design, and that means delineating the tasks, display content, and display form based on considerable research into how people think and behave and their capabilities and limitations (Kontogiannis and Embrey 1997; Pedersen and Lind 1999).

Until the last several years, the high cost and limited speed of computer systems dictated a design trade-off that favored the capabilities and limitations of the computer rather than those of the human user. This sometimes had the effect of making the operator appear to be the weakest link in the chain of the complex system. As a result of the rapid advances in computer technology and the subsequent cost reductions in computer hardware, designers can finally give the human aspect of a control system the attention it deserves.

However, even with the best intentions, designers need to be constantly on guard against the major design pitfall: creating controls that fit themselves rather than the end user. Understanding the user is the key to good control design.

Understanding the User

It is important to think of the user at all times as an integral part of the system, not as someone who is external to the system. The user is within the system and must be considered in the design of every display and control. This is particularly critical when dealing with computer-based controls, which often have no perceived link to what is being controlled. Designing for the user implies regard for (1) the user's mental model of the overall system (which includes expectations and the use of design metaphors), (2) the limits of human memory and attention, and (3) the limitations of human perceptual systems.

Within a user-centered design methodology, user characteristics such as knowledge, skills, abilities, and system expectations are gathered early in the design process. This stage is often referred to as a user profile or user definition. This process usually identifies a representative end user group, defines the distinct roles among those groups (e.g., doctors, nurses, administrative staff), and identifies the characteristics specific to each of those roles or user groups.

Controls should be designed to relate to the way operators think about the system. For example, a mental model of a system that would apply to a home user of software will be different from the model held by a programmer or that held by a systems analyst. Each of these three models is correct, but they are all different. It is unrealistic to expect the home or business user to have the designer's model of the system. It is incumbent upon the designer to make sure that the controls match the model that is expected of the intended user. It is, therefore, necessary for the design team first to determine what an effective system model should be for an operator and then to design to that model. For example, the user's model of a system will be influenced by the control system he or she currently uses, or by an analogous or metaphorical system (the physical desktop as it relates to the computer "desktop").

As a follow-up to the user profiling described earlier, there is also a need to understand user tasks and user requirements. By understanding how users currently complete a task and how they would expect to complete it in the future, the designer can take steps to make sure that the system reflects those expectation in the interface.

Understanding the Control System

TECHNOLOGY CONSTRAINTS In an ideal world, the hardware and software to be used in a control system would be selected after the controls had been designed. In this way, control would not be compromised by limitations imposed by the technology. In the real world, however, the design process is frequently constrained by the technology. For this reason, the first step in designing controls is for the design team to become familiar with the capabilities and limitations of the control hardware and software they will be working with. Some of the features to be addressed are the following:

- Type of operating system
- Speed requirements
- Control devices

TOTAL SYSTEM STRUCTURE The design of individual controls should be preceded by some decisions about the grouping of controls. Many control systems operate as part of a larger system. For example, controls for a large interactive database must consider not only the system and its users, but also the interaction of all the other users and systems. The following are examples of how controls can be conceptualized by the user as being related to each other as part of a system.

Spatially. For certain situations, a set of controls can be organized according to the spatial relationships of the items they control or manipulate. Or a set of controls might be laid out to match the mental model that the operator has about that system. A mapping structure enables the user to move from one control to another just as though the controls were parts of a map.

Multiple Views. The multiple-views approach to control structure recognizes that a control may be viewed in a number of different ways. A throttle for an engine, for example, can be regarded as controlling the physical process of converting energy, as an economic process, and so on. Each of these views can be thought of as a different level of the control set structure.

Other Structures. A number of other types of control organizations can be used, each having certain advantages and limitations. For example, a circle network is desirable when it is necessary to move directly from one control to

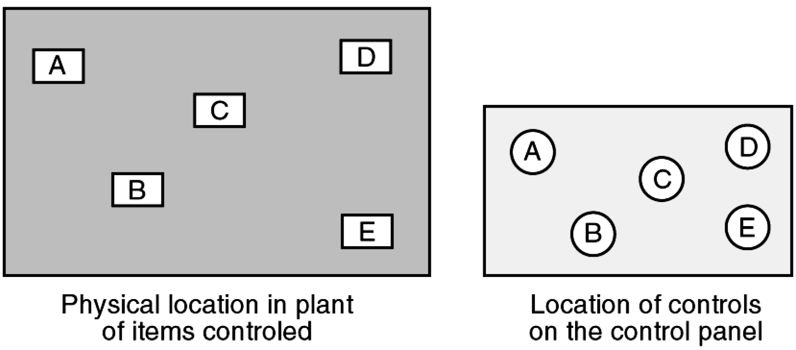


FIGURE 4.19 Example of spatial structure of controls

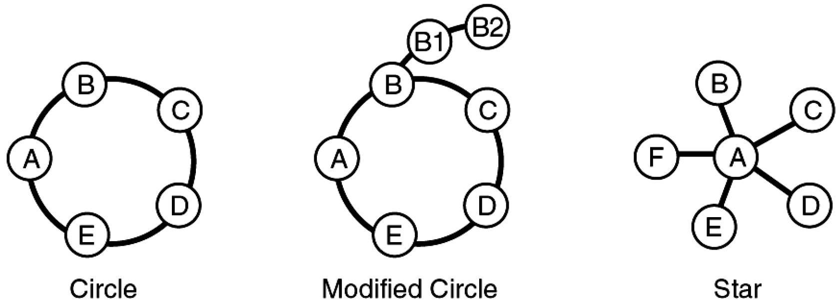


FIGURE 4.20 Additional system structures for Computer Controls

another without going through a series of menus. The modified circle allows direct access to some controls and indirect access to others. The star network allows access from one control to another only through the center node.

DESIGNING CONTROLS The design of a control begins with a definition of its exact purpose. This statement of purpose is essential for several reasons:

- It provides the standard against which the control can be evaluated.
- It ensures that the design team understands and agrees on the purpose of the control.
- It keeps the designer on track. Once one becomes involved with the nuts and bolts of design, it is all too easy to forget the purpose of the control.

A well-written objective should indicate clear and unambiguous answers to the following questions:

- What is the control to do?
- Who will use the control?
- When will the control be used?

Matching the User's Expectations

Controls that match the user's expectations (i.e., the user's model) of the system can be achieved by adhering to the following six principles:

- Limit precision of the controls to what the user needs.
- Match order of control with objective.
- Make the control system consistent.
- Make the control system flexible.

- Control relevant data.
- Keep the false alarm rate low.

LIMIT PRECISION TO WHAT THE USER NEEDS The level of precision should be determined by what the user needs to meet the objective and not by the level of precision possible from the machine. For example, if the user does not deal with units less than whole dollars, that should be the level of precision used by the system—even if it could deal with inputs of a hundredth of a cent. More precision only increases the workload of the users.

MATCH ORDER OF CONTROL WITH OBJECTIVE The order of control refers to the directness of the relationship between a control and the object it controls. A zero-order-of-control item directly controls a given system component (e.g., a cursor on a computer display) or a directly measurable variable (e.g., fuel flow). A higher-order control is much more complex (e.g., the control of the rate of change of acceleration) and can involve a very complex interaction of system components (e.g., nuclear fission). Controls that will be used for higher orders of control need careful attention, as human performance degrades geometrically with increases in task control order.

MAKE THE SYSTEM CONSISTENT Consistency in control systems permits the user to develop a conceptual model of the operation of the controls. To ensure consistency, it may be necessary at times to require unnecessary operations that appear to decrease control system throughput in one task in order to ensure that it is similar to other procedures that always require those actions.

MAKE THE SYSTEM FLEXIBLE Individual differences among users necessitate a system flexibility to ensure optimum performance by all users. Fortunately, this flexibility can be achieved by capitalizing on the capabilities of the computer. Unfortunately, in many instances a decision is made not to permit flexibility but only to accommodate either the expert or the average individual.

Flexibility can also be built into the control system by allowing for different styles of work. Whereas the environment in which operators work can be very unpredictable, they should be allowed to overcome system inadequacies in order to meet unexpected events or failures. A control system should make it possible for controllers to work around the system to deal with unforeseen events. The control system, in other words, should put a floor, not a ceiling, on operator performance.

CONTROL RELEVANT DATA Data should be provided that may directly support the operator's control task. For example, a system notice that describes the symptom of a problem is generally less useful than data telling the operator of the problem's cause. In turn, data that inform the operator how to manipulate the controls to restore normal function tend to be even more useful.

KEEP THE FALSE ALARM RATE LOW In systems with high false alarm rates, alarms are often either ignored or simply turned off because the operator has developed a model in which the alarm system is inconsequential. To counteract such a model, control systems must be designed to reduce the number of times they provoke unnecessary actions on the part of the user.

Make Use of Memory-Aid Principles

For humans to effectively control any complex system, they need to make effective use of their cognitive capabilities, particularly their memory and information processing capabilities. To make the best use of both short- and long-term memory, construct controls and their supporting information according to the principles listed below. These principles use computer and control capabilities to serve as memory aids in a variety of situations where the operator traditionally has been required to recall data.

MAKE EACH CONTROL SELF-EXPLANATORY Controls should be able to be used without instructions. This can be accomplished by following standard human factors guidelines (e.g., to increase a value with a slide switch, one should move it up). However, more complex control tasks will require more complex input, which can usually be determined only by experimentation. The test is that if the control needs special instructions or labels, it is in violation of this principle.

MINIMIZE THE NEED FOR THE USER TO TRANSLATE, TRANSPOSE, INTERPRET, OR REFER TO DOCUMENTATION This can be achieved by adhering to the following principles:

- System output should be compatible with the control tasks to be performed.
- Both the user input and the system output should be consistent across the controls, the task, and the system.
- The choice of control terminology, format, and action should be consistent and familiar.
- The control input required of the user should not be ambiguous, and the feedback should be clear and useful.
- To minimize the information processing requirements of the user, command and feedback information should be presented in a directly usable form for control.
- If a controlled object moves, the direction of movement should be the same as the direction of user input—e.g., both movements up, both down, both left to right.

KEEP INPUT AND OUTPUT MESSAGES BRIEF TO MINIMIZE THE PROBABILITY OF ERROR Theories of human memory suggest the existence of some upper limit of information that can be held active within a given period of time. In computer-based control, this would suggest that both the input required of the user and the output from the system should be brief enough to work within the capabilities of the operator, while still providing sufficient information. The requirements of the task that is being performed should dictate the length of a given message. Testing of the system with representative users early in the design process will help determine if messages sufficiently support the task.

USE CHUNKING FOR LENGTHY INPUT AND OUTPUT To increase the amount of information that can be included in one input or output sequence, meaningful units of information should be grouped together to form chunks.

PROVIDE COMPUTER PROMPTS For a control that requires the entry of critical data, the computer should prompt the user. The user should not be forced to remember the exact control sequence.

PROVIDE IMMEDIATE FEEDBACK A control system should be a closed-loop system, providing feedback to the users about the quality of their performance and the condition of the system. This feedback should be immediate and easy to understand. In computer-based control systems, users should at all times be aware of where they are, what they have done, and whether it was successful. The users should also be given every opportunity to correct control errors.

AVOID PERCEPTUAL SATURATION People can pay attention to only one task at a time, but in the operation of a complex system, many events often occur at the same time. The control system must therefore be designed to assist the operator by allowing multitasking to be dealt with sequentially.

AID SEQUENTIAL AND TIMED CONTROL TASKS Tasks that must be performed in a given sequence or only at certain times place a significant load on memory. Controls should be designed to reduce or eliminate this load by including the sequence and timing data so that the user does not have to remember it.

AID SELDOM-PERFORMED CONTROL TASKS Control performance will deteriorate with lack of practice. Controls for tasks that are seldom performed, such as emergency tasks, should therefore contain special assistance.

Group Controls

Controls should be arranged in such a way that users *immediately* perceive how/why they have been grouped. The user should be able to discern the groupings *before* reading any of the labels.

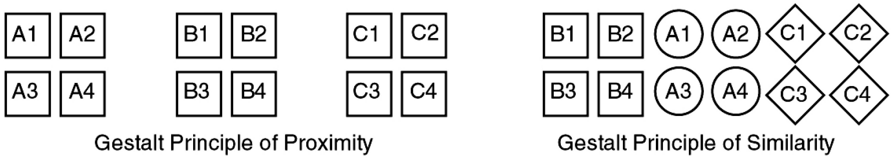


FIGURE 4.21 Examples of Gestalt Principles and Grouping

This perception of grouping depends primarily on spacing but may also involve placement of labels, use of color, or variations in type size. Avoid using lines to mark groupings in crowded spaces. This can produce clutter. Instead, try to reduce the size of the groupings so that the space between them is increased. The principles of gestalt psychology provide excellent guidelines on grouping.

CONSISTENCY IN GROUPING The principle of grouping need not be the same for all controls, but it should be the same for all controls of a certain type.

Grouping Options. Grouping should follow a logical principle. Possibilities include the following:

- Importance
- Frequency of use
- Sequence of use
- Function (controls that support one function should be grouped)
- Location (in a spatially organized system, controlled items that are physically close to each other would have related controls close to each other)
- Alphabetically or chronologically (when all else fails)

Label Controls

To promote quick reading and to avoid reliance on the user's memory, every control should be labeled. Labels should be short, unique, and distinctive. It is a good idea to keep an alphabetical listing of labels as you proceed so that they can be reviewed for length, duplication, and consistency before final adoption.

Avoid overreliance on abbreviations. Given that the user must decipher each abbreviation, the abbreviations selected must be consistent and distinctive. Abbreviations that look or sound similar create the possibility of error.

LABEL CODING Effective coding can enhance labels for controls. The enhancement involves using such characteristics as size, color, or shape to carry meaning. Once users understand, for example, what a red knob means, they will respond appropriately whenever they see a control with that code. Coding can be a very efficient way of conveying a message to the user throughout the system. Remember, however, that control coding could easily be overdone.

Just because a code exists does not mean that it should necessarily be used unless it supports the objective of the control.

CODE SELECTION Certain basic coding principles should be followed in the selection of codes:

- Use natural coding dimensions. Most features that can serve as codes have natural aspects, which can be used to advantage (blue for cold, red for hot). To violate natural expectations can lead to errors.
- Use learned associations. Every user has already learned certain codes. These codes can, therefore, be used to advantage in coding.
- Use intuitive rather than arbitrary codes. An arbitrary code taxes the user's memory. For example, as a code for "print," *2* is harder to remember than *PR*.
- Keep coding consistent across the control set. Codes should not change from one control to another. Once a code has been established, it should remain consistent across the system.
- Avoid overuse of codes. The use of excessive coding will increase the probability of error.

Color Codes. Using color to convey meaning depends on the operator's ability to identify a particular color each time he or she sees it. Generally, people can identify no more than nine different colors with any precision.

Color is probably the most abused type of coding. If not applied correctly, color can actually impede the operator's use of the display. To avoid abuse, it is best to design controls first without any color codes. Color should be added only to enhance the coding. All color coding should be redundant. It should not serve as basic coding but should enhance some other coding technique. Do not design color coding in a way that keeps people with color vision deficiency from safely using the control.

Shape Codes. Geometric shapes for controls can be used effectively as codes, especially for identification of components and their operational status.

Feedback

Feedback is essential in any type of control process. Without feedback, it is impossible for the operator to know whether the system has received the command. Therefore, every control input by the operator should have an obvious and natural response that should leave no doubt in the operator's mind that the system has received the command.

NEGATIVE RESPONSE Lack of response does not constitute acceptable feedback. Such feedback can also mean that the system has crashed, is not listening to inputs, or is overloaded.

RESPONSE TIME Basic feedback—for example, a response to common control inputs—should appear to be instantaneous (0.1 sec). It should happen simultaneously as the input. A time lapse of more than 2 seconds between input and response of some kind is unacceptable when the operator must remember data or is involved in problem solving with the computer.

Error Messages and Error Handling

High-quality error messages may have a very positive effect on system control. Effective error messages can allow the operator to recover quickly from an input error. Good error messages can improve productivity, reducing errors and minimizing the negative effects of errors.

Control Integration

When operators look at a set of controls (particularly on a CRT), they should be able not only to understand what each control does, but to know immediately how that control fits into the remainder of the control system. If operators need to move quickly and without error from one control to another (particularly if located on different CRT pages), they must have a good grasp of the overall continuity by which the controls have been arranged. The following principles provide relevant guidance. They describe integration techniques that assist an operator to quickly and correctly move from one control to the next independent of their physical or virtual location. These principles are based on the techniques used by motion picture editors to provide transition from one scene to the next.

WIDE ANGLE This integration principle gives the operator an overview of all the stations and their relative location. A wide-angle display of controls might serve as a high-level menu, but it must be more than merely a list of all the controls or types of controls. It must show the interrelationship of the controls so that it gives the operator a clear picture of where controls are and how the operator can get to where he or she wants to be in the control set.

LANDMARKS A landmark is a feature of an individual display that links the individual controls on that display with others in the set. In a film, a landmark is something in the background, such as a building or a mountain, that establishes the location of a scene for the viewer.

Landmarks in a control system can be any detail of the system that the operator will immediately recognize. It might be a building or a key piece of equipment. Once the operator recognizes a landmark, he or she can easily determine where to look next or where to find the appropriate control.

A landmark need not be directly on the control. It may be a peripheral item. For example, a menu that varies as a function of the control can serve as a good landmark.

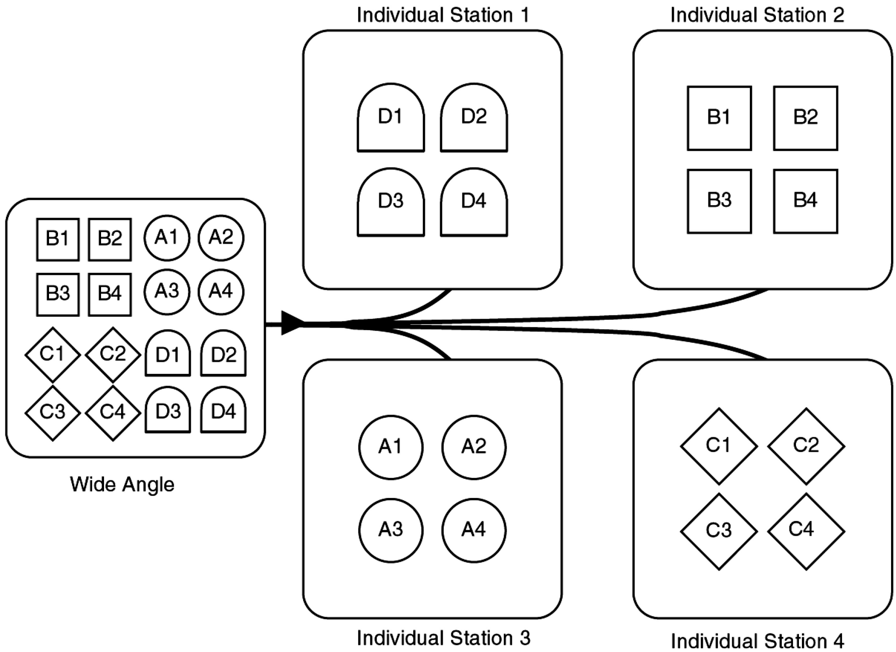
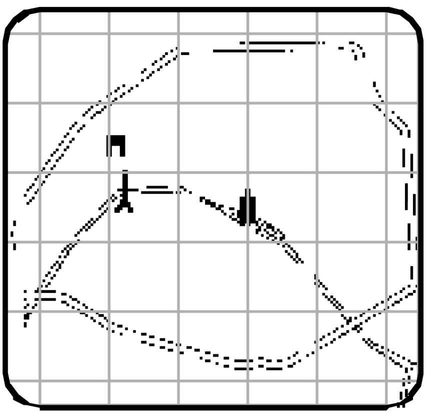


FIGURE 4.22 Use of Wide Angle



Controls grid for Paris traffic lights

FIGURE4.23 Use of Landmarks for traffic light controls

OVERLAP Another method of integrating a control set is to provide some overlap from associated controls. For instance, in controls for the air-conditioning of a particular section of a building, the inclusion of relevant data from neighboring sections may help the user understand not only how that section fits into the overall system but perhaps also how parts of the system interact.

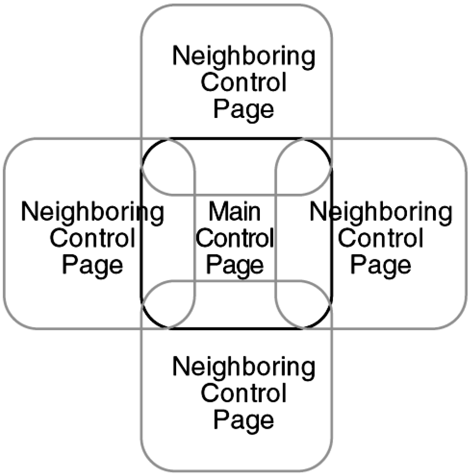


FIGURE 4.24 Example of Control Page Overlap

Control overlap should be thought of in terms of control relationships as well as spatial overlap. When a middle-level control, for example, includes key data from the next higher level control, this data overlap indicates where the user is in the control set, as well as the type of commands the user could find on/in neighboring controls.

Overlap can be used, for example, when a control set is organized functionally. If the relationships among functions are clearly understood by both designer and user, it will be easy to include function overlap on a control.

Evaluation

The evaluation process is made up of a number of tests that involve actual users. Evaluation is currently often called usability testing. By presenting representative end users with tasks that are similar to those that will be performed on the finished system, potential errors can be identified and corrected early in the development process.

REITERATION The key to successful evaluation is the recognition that both the design and evaluation phases are iterative. That is, as a control moves through the evaluation process, it will often be kicked back into the design phase several times before it continues through the evaluation successfully.

This happens because any change induced by the evaluation process can precipitate other, unanticipated changes. Anytime a significant change is made in a control, it is necessary to repeat the evaluation of several controls: not just the changed control, starting from the beginning of the evaluation process, but other controls that are related to the changed control, as a change in one control may necessitate a change in others.

Date: _______________
Scenario: ____
Task: ____

Task Criticality:	No Effect	1	2	3	4	5	Loss of Life
Task Difficulty	Easy	1	2	3	4	5	Difficult

What type of control is needed ____

What types of controls are used? ____

	Yes	No
Are all required controls available?	___	___
Are extraneous controls omitted?	___	___
Are controls organized appropriately?	___	___
Are controls compatible with displays?	___	___
Are controls compatible with system structure?	___	___
Are controls coded/labeled effectively?	___	___
Do controls meet user's precision needs	___	___
Do controls meet order-of-control needs?	___	___
Is control operation consistent?	___	___
Is control grouping consistent?	___	___
Is each control operation self-explanatory?	___	___
Is appropriate feedback given?	___	___
Are error messages clear?	___	___

Comments:

FIGURE 4.25. Example of a task-based evaluation form

TASK-BASED EVALUATION Following use of a general checklist (see Figure 4.25 for an example), it is recommended that the control system be analyzed using a task-by-task approach. This involves stepping through the task sequences identified during the task analysis, one task at a time. For each task, the appropriate controls are evaluated according to the needs of that task. Some controls will need to be evaluated several times, each time for a different task.

The system should be tested to identify the impact that nonperformance (or incorrect performance of a control) would have on the outcome of the function. If the function cannot be completed without proper performance of the task, it is a critical task. If nonperformance or improper performance would have no effect, the task is rated as not critical.

The system should also be evaluated to identify how hard or easy the control task is to complete properly. The more difficult or critical a task, the more important it is for the supporting controls to have optimal design.

TALK-THROUGH The talk-through method of evaluation involves having an experienced operator step through a task sequence using the control set designed for that purpose. The controls may be shown on paper (early in design), a CRT screen, or actual control hardware. For each task, the operator reviews the appropriate controls and comments on their ability to meet the needs in the described situation.

Because time and cost constraints normally make it impossible to evaluate every potential situation, the key to success in talk-through evaluations lies in the selection of the task sequences to be evaluated. The sequences selected should be those that will provide the most well-rounded test of the control system, not necessarily those that are most difficult for the operator. The sequences should test how well the controls assist the types of work activity that are relevant to the objectives of the control system.

MOCKUP PROCEDURE One method that can be extremely effective in early talk-through evaluation is to build a cardboard or foam-core mockup of the entire workstation. The proposed controls can be presented by means of paper drawings mounted with clips in the appropriate locations. In this way, the operator can select the appropriate control drawing for each task.

The advantage of the workstation mockup is that it permits the identification and evaluation of the interactions that take place between the controls and the other system components, such as telephones and paper-based procedures.

USABILITY TESTING Usability testing should be conducted on new software to evaluate user performance and acceptance of products and systems. On developing systems the testing can be conducted iteratively on prototypes. An Industry Usability Reporting (IUSR) project is a current initiative to promote and format usability test data from suppliers that the consumer can use to help make better software purchase decisions (Wichansky 2000).

The following general design guidelines are valid regardless of complexity and can be used for either designing or assessing a computer interface (based on Liu 1997; Cakir 1999).

- Clearly specify the system task.
- Use a task-oriented design approach (user-centered) versus interface design (product-centered).
- Design for all the people involved with the computer interface, such as operators and maintenance personnel.

- Design for the skills and capabilities of the users.
- Enable users to be in control of the system; provide some autonomy for the users in deciding priority, pace, and procedure.
- Provide meaningful feedback.
- Allow easy reversal of actions.
- Offer simple error-handling mechanisms.
- Organize sequences of actions into groups.
- Reduce short-term memory load.
- Allow for development of skills and new skills with the task (and for knowledgeable, frequent users to take shortcuts).
- Design for users to control the application efficiently.

TOOL DESIGN

Hand tools are used in most jobs to perform tasks that require more precision or more force than a person's hand can safely sustain. They can be powered (e.g., air guns, chain saws, grinders) or manually powered (e.g., screwdrivers, pliers, wrenches, clamps), and they may be used occasionally (to open a valve) or all of the time in an assembly operation, such as grinding burrs off metal parts. A hand tool is rarely sized to fit different operators' hand characteristics; more often, the handle size is based on the torque generated by a power tool, or the span of a two-handled tool is designed to match the size of the fasteners used. See the section "For Whom Do We Design?" in Chapter 1 for a discussion of how people of many different hand sizes can be accommodated using ergonomic design guidelines.

Factors of concern in the use of tools include:

- Tool design can affect the user because the interface of the user with the tool will determine what the upper extremity and neck posture will be. Tools that create a need to abduct the elbow or shoulder to do a task will contribute to static muscle fatigue (see Chapter 6) and limit the time the task can be sustained.
- The hand-tool interface is also important in ensuring that the operator can stabilize the tool during work and that the hand and forearm can work in postures that enable the strongest muscles to do the work.
- Noise and vibration from power tools can contribute to stress through interference with communication and by increasing the risk for vibration-induced white finger to occur. When prolonged work is done with a vibrating tool (e.g., grinders), higher forces are often being used to control the tool because the sensory feedback from the fingers is reduced.
- Two-handled tools are also of concern if it is possible to pinch a finger or the hand between them during work. Tools with sharp edges or knives should be designed to reduce exposure to these surfaces during use.

Postural Stress and Muscle Fatigue During Tool Use

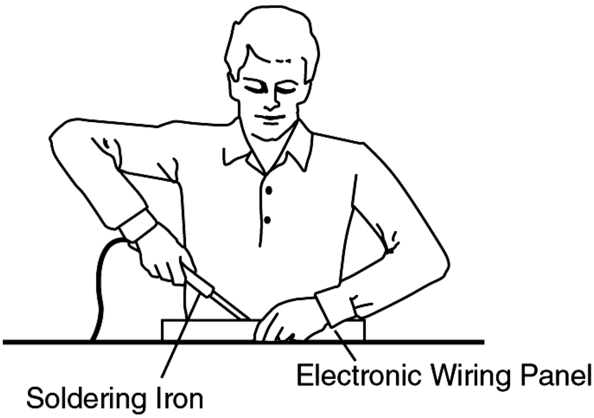
The use of hand tools influences body posture if it requires the tool to be oriented in a specific way to do a task. The arms, wrists, elbows, shoulders, neck, and back may each play a role in orienting the tool and doing the work required. The fingers and hand need to support and manipulate the tool and may hold it for many minutes before the task is done. The longer the tool has to be used with postures that are non-neutral and fatiguing, the more difficult it will be for the operator to stay on the task and perform it with high quality (see "Designing to Minimize Fatigue" in Chapter 6).

A common posture seen with tool use is abduction of the elbow, or raising it, to get above the part being worked on. This may be the outcome of using an in-line tool on a horizontal work surface instead of a tool with a right-angle tip or a handle with a 19-degree bend. Figure 4.26 illustrates an operator's upper extremity and neck postures when using a straight soldering iron (a) and when the tip of the soldering iron has been modified to let the operator work with his elbows closer to his side (b). The reduction in static loading of the worker's shoulder, arm, and neck when the tool was bent at the tip reduced the muscle fatigue and allowed the operator to work for a greater length of time without significant discomfort. Similar reorientation of the tips of pliers, surgical clamps, and air guns can be made to reduce arm and shoulder static stress in other occupations.

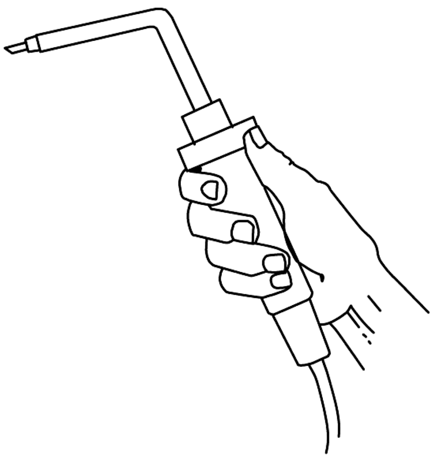
When an operator holds a tool continuously, hand and arm muscles have to do work (even if the tool is light) and cannot fully relax between line items. This can lead to static loading and muscle fatigue of the hand and arm. Some suggestions to reduce this static loading are:

- For jobs where there is time to release the tool between line items, and where the work is conveyed to a specific workplace, use tool balancers or tension reels to keep the tool easily accessible while giving the operator's upper extremity a rest.
- For workplaces where the assembler or repairer walks the line while working, provision of a tool holster that stores the tool between uses has also been found helpful, and a hose reel ensures that trip hazards from air lines are avoided.
- For tools used intermittently but fairly often (e.g., cutting first-pass rubber on a mill or taking film or paper samples in a winding operation), attach a small tool holder to the front of the machine where the work is done so that the tool can be procured quickly when needed but is not carried in a holster on the body.

If a finger is being used to help open up the tool between actions, as with a pair of scissors, it may be appropriate to put a spring at the juncture to automatically open the blades after each cut. This would be similar to the mecha-



(a) A soldering iron with a straight tip has to be held at an angle to the piece being soldered. As a result, the operator's elbow has to be moved away from the body, placing a load on the shoulders.

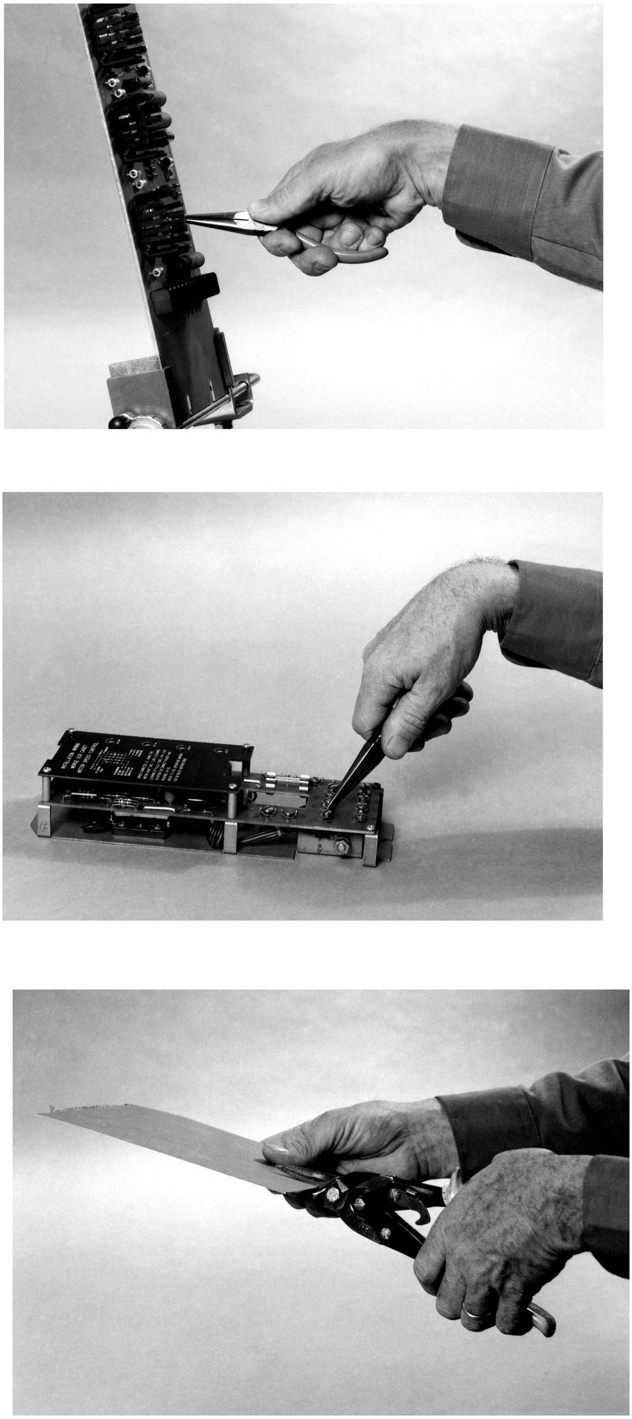


(b) A soldering iron with an extended and bent tip allows the operator to work on the piece without moving the elbow away from the body.

FIGURE 4.26 Working with a Soldering Iron

nism that is used on many garden shears. Eliminating the task of opening the tool helps reduce the work done by the operator.

Examples of wrist angles seen during tool use are shown in Figure 4.27. The orientation of the work and the choice of the tool determine what wrist and elbow angles the operator needs to use during the assembly or repair task. Because strong wrist angles reduce grip strength capacity for both the part-supporting and tool-use hands, they make the work more difficult to perform



(a)

(b)

(c)

FIGURE 4.27 Wrist angles during tool use

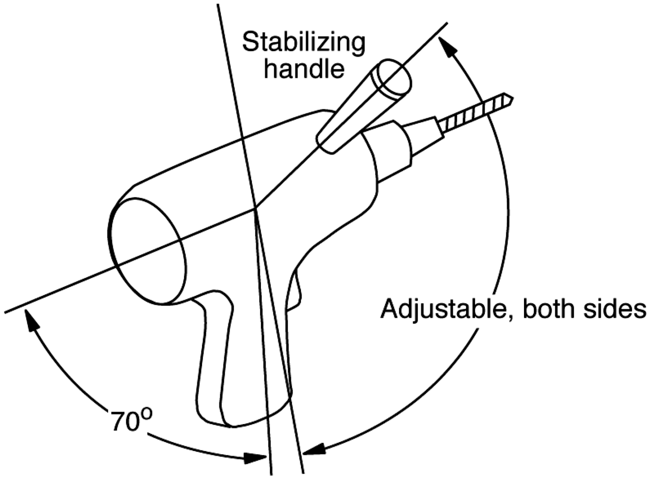


FIGURE 4.28 Electric Drill with stabilizing handle (adapted from Greenberg and Chaffin 1977)
Note that stabilizing handles should be adjustable to accommodate both left- and right-handed users. The optimum position for the primary handle is 70° to the drill.

and more fatiguing if it is done repetitively. For more discussion of the effects of wrist angle on grip strength, see "Biomechanics of Gripping" in Chapter 2.

One way to reduce some of the stress on the hand when using a tool is to give the operator the opportunity to use the other hand to stabilize it. This is frequently done with industrial air tools, such as heavy grinders. Figure 4.28 illustrates the use of a second handle to stabilize an electric drill (Greenberg and Chaffin 1977). The secondary handle is at approximately 70° to the main handle of this pistol-grip tool. People who work with these tools caution others to be sure that the hand is not on the stabilizing handle or near the back of the tool if one decides to reverse the drill's direction of motion (e.g., back out a screw). The drill can whip around and break the operator's wrist if the handle catches it on the rotation.

One of the most effective ways to reduce wrist angles during hand tool assembly tasks is to use a rotating fixture that clamps the part and moves it into the best orientation for the task. The fixtures reduce static holding and orient the task for the tool, thereby improving the wrist angles and making it easier to see the parts.

Pressure Points on the Hand

The material in this section is based on Greenberg and Chaffin 1977 and Rehnlund 1973.

High forces per unit area (>22 psi or 150 kPa) on the skin and underlying joints of the finger or hand increases the user's discomfort when using hand

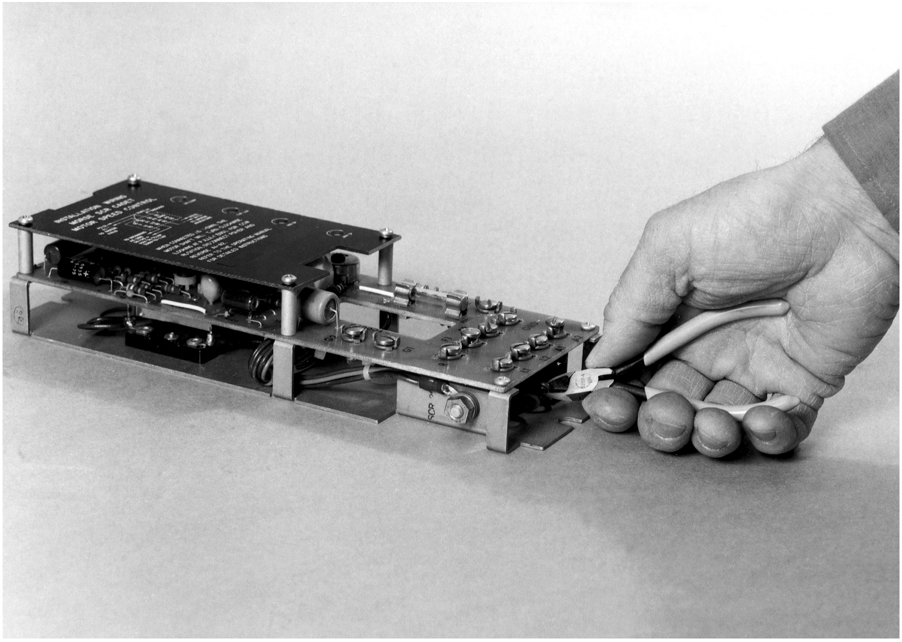


FIGURE 4.29 Pressure Point in palm

tools. Too short a handle results in pressure in the palm of the hand near the base of the thumb, where the blood vessels and nerves that serve the fingers pass through the wrist (Fig. 4.29). High pressure in this area can disturb the blood flow and put a pressure block on the nerve, increasing the opportunity for swelling and the development of symptoms such as numbness, tingling, and some pain.

Undesirable pressure points are created when there are deep ridges or mold edges on plastic handles that the fingers will have to work on when using a tool, especially when the tool is rotated while exerting force (e.g., using a screwdriver). Although low-height knurling effectively reduces the opportunity for the hand to slip when using a screwdriver (Bahco 1995), an elevated ridge traveling perpendicular to the direction of rotation reduces the acceptable torque values because of the concentration of force on the ridges.

Safety Aspects of Hand Tool Design

Two-handled tools come in a large range of handle lengths and are used in different ways depending on the task, the amount of clearance for the hand and tool, and the size of the fasteners or parts being worked on. Pinch points at the junction of the two handles may be reduced by adding stops (Fig. 4.30) (Tichauer 1966).

FIGURE 4.30 Stops on two handled tools to reduce pinches

Utility knives, box cutters, and knives can all represent safety hazards if they are not properly guarded or well designed. The use of a finger stop near the top of the blade to prevent the fingers from coming into contact with the sharp blade can prevent cuts if the hand slips during a cutting task. Ergonomic utility knives provide a more stable grip by including a thumb stop in the curved handle (a 19° angle down from the horizontal position) and being designed so they sit comfortably in the palm of the hand when being used (AliMed 2002).

Very smooth metal surfaces are potentially hazardous on hand tools because of the reduced coefficient of friction between the operator's hand and the tool. The likelihood of there being oil in the area where tools are used is high. It is not uncommon to see a tool slip out of a operator's hand when the user is exerting a force with it. It can contribute to a cut or laceration, a contusion, a finger or forearm fracture, or a strain or sprain of an upper-extremity muscle. With air tools, the slippery surface may be cold, and the grip may be too wide for the operator to have a stable hold on it. Tool handle wraps with vibration-damping materials have been used to improve grip and reduce vibration exposure at the same time. See "Vibration" in Chapter 8 for more discussion on segmental vibration from power tool use.

Design and Selection Recommendations for Hand Tools

Handle Design

The material in this section is based on material from Greenberg and Chaffin 1977 and Little 1977.

- Recommended length for a handle is 13 cm (5 in.)
- The handle should not be less than 10 cm (4 in.) long to avoid pressure on the palm.
- When gloves are worn, add 1.5 cm (0.5 in.) to the handle length to accommodate them.
- For two-handled tools, the desired grip span at the point where pressure is being applied is from 6.5 to 9.0 cm (2.5 to 3.5 in.). Grip spans that exceed 10 cm (4 in.) will be difficult for people with small hands or short fingers to use with one hand or hold with a stable grip. Pop riveters, for example, are often designed with 12.5- to 15.5- cm (5- to 6-in.) spans and are suitable for use by only about 10 percent of the workforce.
- For Cylindrical Handles, the Best Power Grip is at 4 cm (1.5 in.), with a Range of 3 to 5 cm (1.25 to 2 in.)
- When precision grips are used on tools (pencil grinders, engraving tools), a diameter of 12 mm (0.45 in.) is recommended, with a range of 8 to 16 mm (0.3 to 0.6 in.).
- For a cutout handle (e.g., in a saw), the hole should be angled up about 15° from the vertical to keep the wrist position closer to neutral. The length of the hole should be no less than 12 cm (5 in.) and the width should be at least 6 cm or 2.5 in. (Figure 4.31).
- If the tool generates heat or becomes cold because of airflow, the surface in contact with the hand should be insulated to reduce this exposure. Air tools should have their air exhaust directed toward the front of the gun instead of back toward the operator's wrist. Oil mists should be captured as they exit the tool to avoid making the tool more slippery or exposing the operator to mists in the breathing zone.

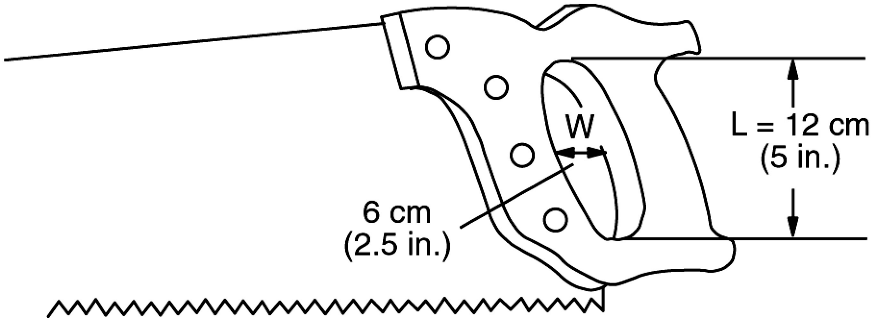


FIGURE 4.31 Saw Handle Dimensions

- Tool handles should be hard enough to resist particles from being embedded in them but soft enough to prevent putting high force per unit area on the fingers as they are used. They should also be impervious to solvents and oils typically present in the workplaces or sites where they are used.

Switches and Stops

- It is preferable to have a strip trigger instead of a single-finger trigger on power tools, such as air guns, nut runners, and disc grinders, because it provides more options for the operator.
- Thumb triggers should be used sparingly because the thumb is the primary grip stabilizer. Using it to trigger a tool reduces the stability of the tool and can result in quality problems or injuries from loss of control of its motion.
- Push-to-start tools do not require constant holding of a trigger, but they tend to be hard to use in some operations because the pressure has to be applied exactly perpendicular to the part or fastener. A good application for them is in a line where screwdrivers are mounted above the line and the parts come in below it. The screwdriver has a hilt, or stop, on it that allows the operator to draw it down to the assembly point and exert enough pressure to trigger the tool to drive the screw. Push-to-start screwdrivers are less satisfactory for operations when the assemblies are in the horizontal or a diagonal plane.
- The reverse button on a power screwdriver or air wrench should be close enough to the thumb to be activated if a fastener has to be loosened (e.g. because of cross threading). But it should not be so easy to access that it might be triggered accidentally by a less experienced user.
- Stops or guards should be placed on hand tools that are used to cut or to exert high forces, such as utility knives. Figure 4.32 illustrates a thumb stop on a set of needle-nose pliers.

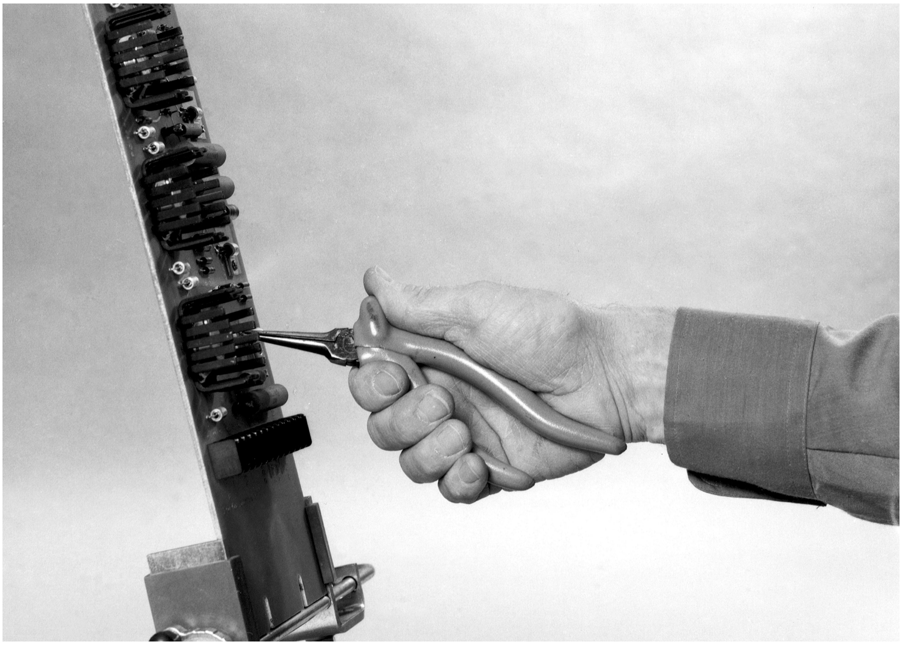


FIGURE 4.32 Thumb stops on a set of needle-nose pliers

- Power tool trigger forces should be high enough to avoid accidental activation, but not so high that they fatigue the fingers used to hold them down during tool use. Activation forces of 2.4 lbf. or approximately 1 kgf (10 newtons) are the recommended values for hand tool triggers; however, there are many tools that require forces two to five times more than that (Table 4.11). Those are the tools that are most often associated with musculoskeletal disorders and which many workers cannot use for extended work periods.

Other Tool Characteristics

- The weight of a hand tool should be less than 2.3 kg (5 lb.) if it will be used away from the body or above shoulder height. If it weighs more than 2.3 kg (5 lb.), it should be supported with a counterbalance or tool balancer, especially for overhead work.
- Precision tools should not weigh more than 0.4 kg (1 lb.) for the user to be able to control them well. If they weigh more than 0.4 kg (1 lb.), they should be supported in a counterbalanced arm so they can be manipulated by the operator who is freed from supporting the extra weight.
- Vibration-absorbing material should be placed on the handles or on the sides of power tools to reduce the operator's exposure to tool vibration.

TABLE 4.11
Power Tool Weights and Trigger Activation Forces (adapted from Little 1981)

	Weight				Average Force to Activate Trigger	
Tool Type	kg	lb.	Trigger Type	Grip	N	ozf
¼-in. electric hand drill	2.3	5	Index finger trigger	Pistol	17–22	62–80
⅜-in. electric hand drill	4.3	9.5	Index finger trigger	Pistol	30	108
½-in. electric hand drill	4.5	10	Index finger trigger	Pistol	52	189
7-in. grinder	7	16	Thumb bar	Straight	33–36	120–130
Air hammer	7	16	Thumb bar	Straight	10	37
Chopper hammer	8	17	Thumb bar	Straight	32	115
Air saw	3	7	Thumb bar	Straight	16	56
Air saw	3	7	Index finger trigger	Pistol	10	37
Air angle drill	3	7	Thumb bar	Straight	9	34

Some tools can be more easily damped than others, and vibration characteristics should be evaluated along with the effectiveness of the tool. There are materials that reduce direct vibration transmission to the hands (Sorbothane and Viscolas, for example) and there are gloves with these materials sewn into them that can also effectively reduce hand vibration exposure for power tool users.

- Heavy tools, such as chipping hammers, pavement breakers, heavy nut runners, and high-torque air wrenches, can fatigue the arms, shoulders, and backs of their users quite rapidly. Supporting these tools on brackets on the bumpers of trucks or carts or on articulating arms inside a plant makes them less difficult to operate and also reduces vibration exposure for the operator.

Special-Purpose Tools

Our use of hand tools is what distinguished us from other primates up until a few decades ago, when it became clear that apes also made hand tools. If one traces the history of many of our hand tools today, one finds that they have stood the test of time well (Sloane 1990). That they have not changed a great deal in several centuries, except in the area of power tools, suggests that a major characteristic that we look for in a tool is versatility. Screwdrivers and wrenches vary in size and thickness to accommodate different torque requirements for the fasteners used in assemblies of a large variety of products. Shovels vary in length, pan size, pan shape, and handle type to accommodate the types of materials transferred and the locations of the starting and ending points. In an assembly workplace, most workers prefer to use three or four tools for their work, not ten to twelve, so they tend to use one tool for several functions, whether that was intended or not. The availability of too many tools is inefficient because choices have to be made, tools have to be found, and the number of extra movements needed to get the task done puts extra pressure on the workers to meet their production goals. Even maintenance mechanics tend to choose six or seven tools to carry to a work site with them instead of bringing their entire tool cart into the area.

With these observations in mind, the concept of having specialized tools for many tasks in order to improve the wrist and upper-extremity postures may be too theoretical. They are probably appropriate for use in jobs where people do the same task repeatedly and use only a few tools. Some of the tools used in chicken processing plants have been very successful at reducing upper-extremity stress by letting the tool take the awkward postures, not the worker (Armstrong et al. 1982).

They have also been useful to make specific operations more ergonomic, such as the example mentioned earlier in the soldering operation (see "Postural Stress and Muscle Fatigue" in this chapter). As illustrated in Figure 4.33, a

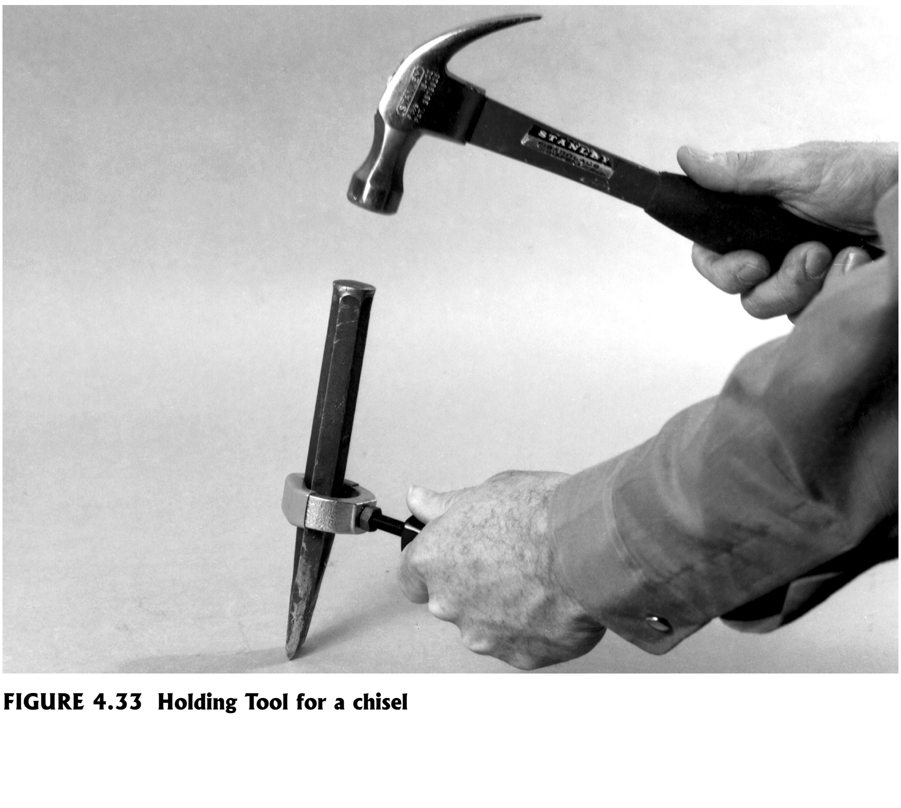


FIGURE 4.33 Holding Tool for a chisel

chisel-set tool may be used only occasionally, but it clearly reduces the hazard of hammering one's thumb by moving the thumb back from the strike path.

Another example is the design of a holder (Fig. 4.34) to pick up large, heavy parts that contain no inbuilt handles or grips.

Pipettes

Several studies on manual-plunger pipetting have found an increased risk of hand, wrist, thumb, and shoulder complaints (Björkstén, Almby, and Jansson 1994; Fredriksson 1995; David and Buckle 1997; Moomey et al. 1997). Discomfort from pipetting tasks can be due to a variety of factors, including time on the task, sustained postures that lead to fatigue, aspects of the workstation and materials that provoke the person to adopt an awkward posture, and the design of the pipette itself. Workstation issues have been addressed above in "General Principles of Laboratory Bench Design" and "Microscope Workstations" in Chapter 3.

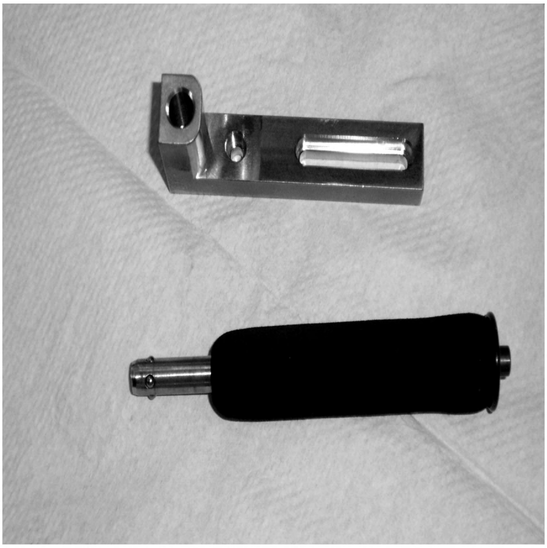
The following is a summary of recommendations on the design of a pipette from research on pipette use (Björkstén, Almby, and Jansson 1994; Fredriksson 1995; David and Buckle 1997; Lee and Jiang 1999):

DESIGN TO REDUCE REPETITION Whenever possible, minimize use of a top-plunger manual pipette (Fig. 4.35). Consider alternatives such as:

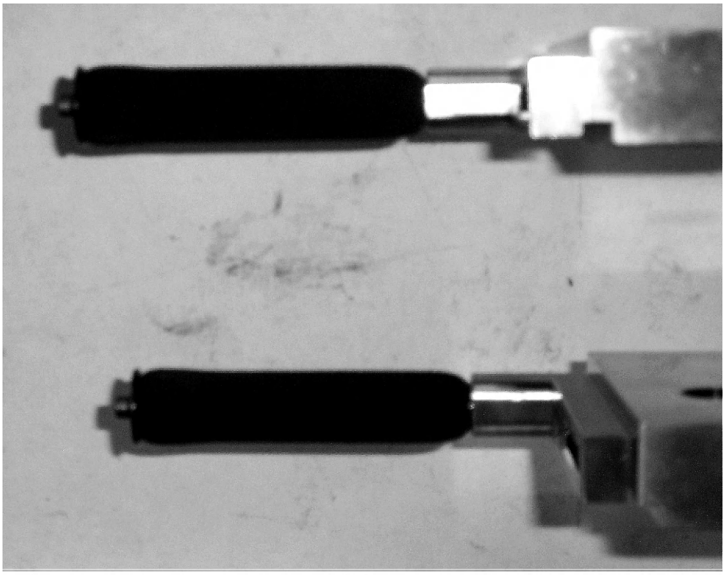
- An electronic (or motorized) pipette (which almost eliminates activation force and issues with volume setting)
- A repeater pipette (Fig. 4.36)
- A multichannel pipette (but only if it has easy activation) (Fig. 4.37).
- Autopipetting

DESIGN TO REDUCE FORCES, ESPECIALLY ON THE THUMB Consider the following plunger pipette features that help to reduce forces exerted by the hand. Many of these features are also pertinent for alternative pipettes, listed above

- Choose pipette handles with diameters of 3–5 cm (1.25–2 in.) so the worker's grip strength capacity is maximized.
- Use pipettes with an activation button or trigger used by the fingers while in a grasp position versus thumb activation, especially a top-plunger, thumb-activated pipette. This is a more comfortable design that can also reduce errors, shorten task completion time, and reduce deviant arm, wrist and, hand postures (Lee and Jiang 1999).
- Consider a hook to support the pipette on a finger, or profiling on the handle, to reduce constant gripping.
- Ensure minimal activation forces and a short trigger travel distance.
- Choose easy-to-adjust volume controls.



(a)



(b)

FIGURE 4.34 Holding tool for large high-precision bars with no handles
The photographs show a spring-loaded holder used to transport metal bars that can be up to 70″ long and weigh up to 70 lbs. The holder is in two parts: a base that attaches to the metal bar and a spring-loaded padded cylinder as shown in (a). The base has a screw hold and a slot to enable it to fit various sizes of bars. The base is screwed into the end of the bar and the spring-loaded cylinder is inserted when the operator needs to lift it, as shown in (b). The cylinder is released through the button at the end.

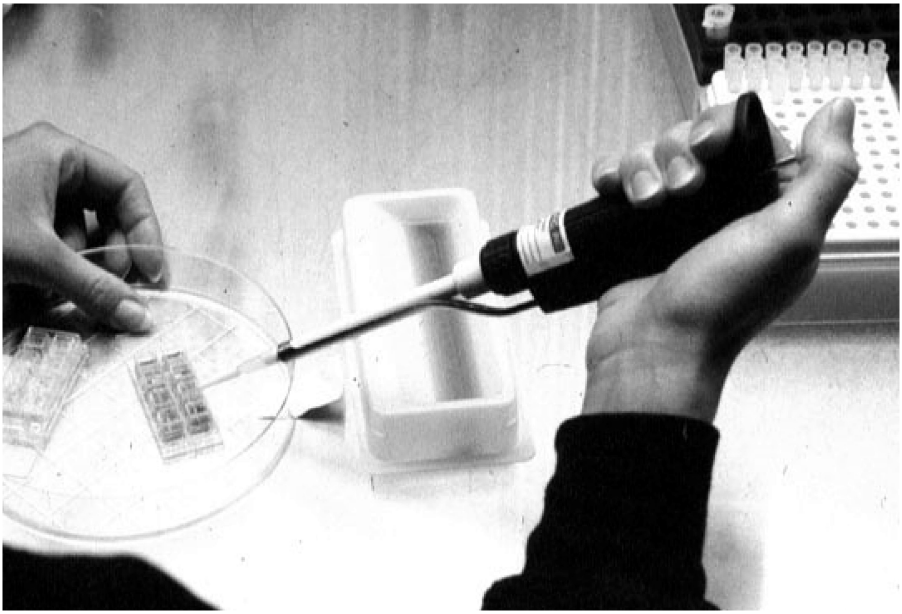


FIGURE 4.35 Plunger Pipette

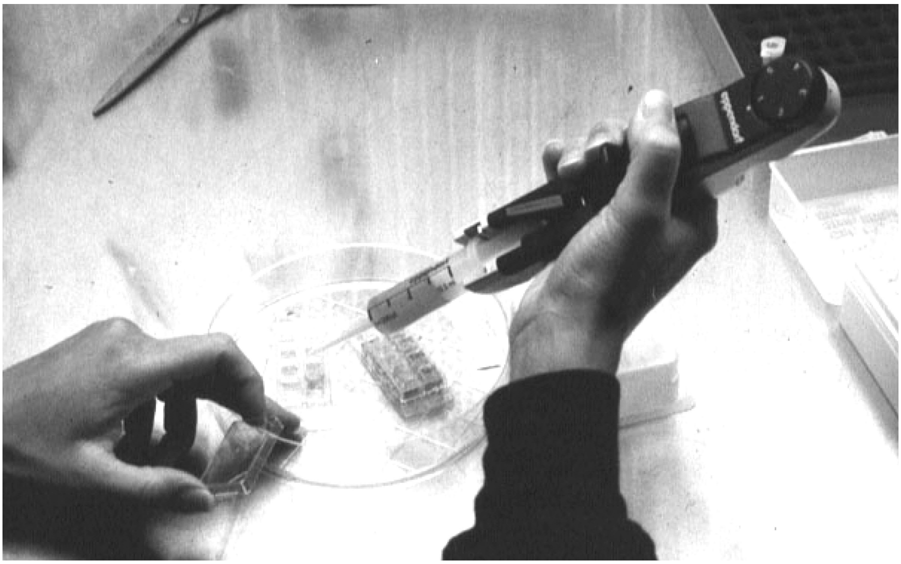


FIGURE 4.36 Repeater Pipette

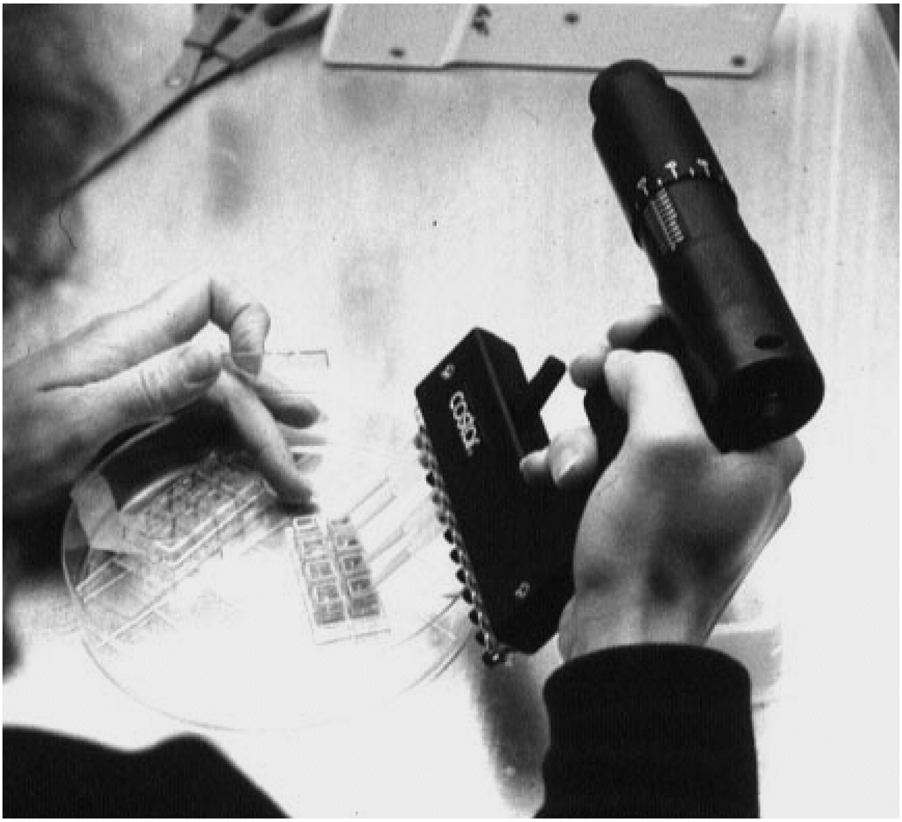


FIGURE 4.37 Multichannel Pipette

- Use pipettes that are as light as possible in weight, with the center of gravity in the hand. If the center of gravity is not in the hand or the pipette is heavy (especially with multichannel pipettes), consider using a balancer.
- Ensure that the pipette is easy to maintain and is well maintained, so that the controls retain a low operational force.
- Use good-fitting tips to reduce the pounding or shaking needed to place or remove tips that often occurs with bad tips. Some manufacturers suggest that only tips specified by the manufacturer should be used, to ensure good fit as well as accurate performance.

LAY OUT THE WORKSTATION TO ADOPT A NEUTRAL, RELAXED POSTURE Often the task requires a postural compromise of the neck, visual distance, and height of the arm. The arm height influences the angle of the wrist. Consider the following:

- Set work at the height that provides the best compromise in body position. This might entail placing the work on a raised platform so that the neck is less flexed. However, caution should be used if the pipette is long.
- Angle the work if feasible.
- Support the arms during extended pipetting sessions. Consider freely moving, articulating arm supports.
- Avoid having the user hold trays in the non-pipetting hand—use a support instead.

Specialized tools have their place, but widespread development of new tools will probably not find acceptance in the workforce if any of the following situations are present:

- If the tool is used infrequently and is only one of several tools needed to do a multitasked job, so that tools have to be set down and picked up often during the shift
- If it takes longer to use the specialized tool than it does to improvise with a more commonly used tool
- If the operation is not a continuous one and occurs infrequently during the shift
- If there is limited space for tools in the workplace and no place to store them between uses
- If the operators have not been trained how to use the specialized tool.

A key to good tool design is that the tool is easy to use and understand, and that a new operator needs only a minimal amount of time to learn to use it properly. It should be versatile and be able to be used in the horizontal and vertical planes and on the diagonal, as well as by left- and right-handed operators. Many specialized tools have been developed by workers and mechanics, and these should be evaluated first and dignified by a more formal design if they are working well.

Evaluation and Selection of Equipment

Whether shortcomings are identified in a workplace design or there are plans to provide new tools, an evaluation of candidate interventions or tools will help make the decision more rational. The ideal approach to selecting an intervention or tool is to (1) develop a long list of possibilities, (2) make a short list of reasonable possibilities through some experience and professional judgment, (3) evaluate each approach on the short list, and (4) select one or a group. More often, the short list of interventions is created directly. For instance, a decision is made to purchase chairs for an office; what chair should it be?

This section describes a generic approach to evaluating the short list. The method described here is designed to provide the analyst with more structure than merely asking potential users which intervention is preferred. The steps in this process are:

- Compile a list of criteria.
- Develop the evaluation scales and weighting factors.
- Evaluate the short list against each measure.
- Score each evaluation scale.
- Collapse the scores into overall rankings

Regardless of how the short list was developed and evaluated, it is important to field-test an intervention or tool before final implementation is started.

List of Criteria

When considering various interventions and tools, there will be multiple features that address the shortcomings of existing options and what is desired in the new intervention or tool. The criteria should be developed prior to the creation of the short list of interventions or tools to be evaluated. Analytical tools, such as those used for job analysis as well as some that are more common to controlled laboratory evaluations, can be employed for an objective assessment of the intervention or tool. The objective measures may include a biomechanical analysis, evaluation of strength requirements, EMG assessments, and potential for fatigue. Oftentimes, there are subjective and use features that are less amenable to objective analysis. Psychometric methods are best employed to make these kinds of evaluations. The list of factors to be considered in the evaluation should map over the aspects of the job demands that are to be addressed by the interventions.

To illustrate the process, suppose a clean-room coverall is to be selected from among different fabrics. The current construction of the coverall is considered acceptable and all the candidate fabrics have acceptable barrier characteristics for the clean room. The evaluation issues center around fabric properties as they affect employee comfort and acceptability. Fabric bench tests that are commonly associated with comfort are insulation and moisture vapor transfer rate (MVTR). These represent objective criteria that are related directly to the fabric. In addition, there are a number of "touch" scales used to judge subjective observations of fabrics—touch, stiffness, and scratchiness are examples. Other subjective judgments of comfort are used in fabric evaluation, such as thermal and moisture sensation.

Evaluation Scales and Scale Weighting

Objective measures may have a quantitative feature associated with them, and that can be the scale for evaluation. If the method does not, some thought must be given to how a rational (or at least an ordinal) number can be assigned to the results. For the clean-room clothing example, clothing insulation is reported as degrees Celsius per watt per sq meter of body surface area (m^2°C/W) and moisture vapor transport rate is grams of water per meter squared per hour (gm/m^2/hr).

For subjective or psychophysical assessment, the selection or construction of scales should be appropriate to the factor being examined. When constructing subjective assessment tools to evaluate an intervention, the question or statement should not contain any bias, the scale should assess only one dimension and one feature of the intervention, and the statement should be clear and understood by the participants. The advice of someone familiar with psychophysical scales or measurement is valuable. It is essential to pilot-test the scales.

If perceived exertion for a typically high-force application is sought, a validated scale such as the Borg scale would be appropriate. Other subjective factors such as comfort and desirability may be solicited through a question and a indicated response along a visual scale. Using comfort as an example, it is possible that the intervention may be viewed as extremely uncomfortable at one end to very comfortable at the other end, with a neutral point at the middle of the scale. Other subjective scales, such as desirability, may not have a neutral point; the characteristic is absent at one end of the scale and fully present at the other end. A visual analog scale is often used with the two anchor points, and the individual is asked to place a mark along a 10-cm (2.5-in.) line between the anchors. The scale value is the number of centimeters from the left. Alternatively, five, seven, nine or eleven hash marks can be placed along the scale, including the anchors, with or without some intermediate descriptors at some or all of the intermediate marks. Another subjective judgment method is the Likert scale, for which a statement is made and the person is asked to what extent the statement reflects his or her position (i.e., strongly disagree to strongly agree along a five- or seven-point scale). Figure 4.38 illustrates a data collection form for the clean-room clothing that includes five psychophysical scales.

Often, evaluation measures and scales contain some similar information, or the evaluation scheme has more evaluation scales for some features than for others. If all the scales are treated equally, then there is the potential to bias the results toward those interventions or tools that do well in terms of features represented by a greater number of evaluation scales. To help remove some of that potential bias, the scales can be weighted with a factor ranging from 0 to 1.0. For instance, if the decision is made that the objective data, the thermal data, and the "touch" data will have equal contributions to the overall ranking, then the scale weights within each of these groups must add up to 1. Letting the components in each group have equal weight, the weights for the objective measures and thermal responses are both 0.5, while the weight for the "touch" factors is 0.33.

Evaluation Step

Evaluate each intervention and tool along with the current situation. Some of the evaluation criteria will be based on a semiquantitative or quantitative

Name:______________________________ Date: _____ /_____ /_____
Location:___________________________ Time:___________________
Code:_______________________________ Coverall ID:_____________

Please describe the properties of the clean-room clothing that you just wore. You must provide a response to each question by checking the appropriate box.

1. How would you describe the thermal sensation of this garment?

Very Cool	Cool	Slightly Cool	Neither Cool nor Warm	Slightly Warm	Warm	Very Warm
❑	❑	❑	❑	❑	❑	❑

2. How would you describe the moisture sensation of this garment on your skin?

Very Damp	Damp	Slightly Damp	Neither Damp nor Dry	Slightly Dry	Dry	Very Dry
❑	❑	❑	❑	❑	❑	❑

3. How would you describe the touch of this garment?

Very Harsh	Harsh	Slightly Harsh	Neither Harsh nor Soft	Slightly Soft	Soft	Very Soft
❑	❑	❑	❑	❑	❑	❑

4. How would you describe the stiffness of this garment?

No Sensation	Slightly Stiff	Somewhat Stiff	Very Stiff	Extremely Stiff
❑	❑	❑	❑	❑

5. How would you describe the scratchiness of this garment on your skin?

No Sensation	Slightly Scratchy	Somewhat Scratchy	Very Scratchy	Extremely Scratchy
❑	❑	❑	❑	❑

FIGURE 4.38. Subjective evaluation of clean-room clothing

analysis, with the resulting determination representing the job, intervention, or tool. Other criteria will require input from a range of potential users. To obtain a good representation of the intervention, involve as many potential users as practical. Ten is a good minimum number, and there is a statistical point of diminishing returns above thirty.

Scoring

For each criterion in the list and its scaling method, normalizing the scoring on an eleven-point scale (0 to 10) is helpful. The scores are set such that the worst (most undesirable) end of the scale is 0 and the best (most desirable) end is 10. This process is usually more intuitive for subjective scales but requires care for some objective measures. Before some examples are given, the following are two generalized functions to assign scale values. For the case where the lowest value (LOW) in the range is the least desirable and the highest value (HIGH) is best (e.g., acceptable percentage or comfort),

$$\text{Score Value} = 10 \times \text{Scale Value} / (\text{HIGH} - \text{LOW})$$

For the opposite condition, LOW represents the best condition (e.g., back compressive force):

$$\text{Score Value} = 10 \times [1.0 - \text{Scale Value} / (\text{HIGH} - \text{LOW})]$$

The score value can be treated as a continuous variable or rounded to the nearest tenth. Carrying values beyond one decimal place has little meaning.

For objective measures, a reasonable range should be selected. For instance, the estimated back compressive force might range from 0 (LOW) to 2,000 (HIGH) lb. In this case, the second relationship would be used. Continuing with an example, suppose one intervention resulted in an estimated back compressive force of 450 lb. while the current job is 1,150 lb. For the intervention, the score value is computed as follows

$$\text{Score Value for Intervention} = 10 \times [1.0 - 450 / (2000 - 0)] = 7.8$$

For the current job,

$$\text{Score Value for Current Job} = 10 \times [1.0 - 1{,}150 / 2{,}000] = 4.3$$

The intervention has a higher score value, indicative of an improvement. In a similar example using the first relationship, suppose the acceptable percentage for a lifting task is determined from the Liberty Mutual tables. The current job has an acceptable percentage of 25 for women and the intervention is 90. The scale values have a range of 0 percent (LOW) to 100 percent (HIGH) acceptable. For the current job,

$$\text{Score Value for Current Job} = 10 \times 25 / (100 - 0) = 2.5$$

And for the intervention,

$$\text{Score Value for Intervention} = 10 \times 90 / (100 - 0) = 9.0$$

Again, the higher scale value represents an improvement. If an occasional objective measure is out of range, the closest scale anchor is assigned; if out of range occurs often, it may be necessary to adjust the range.

The same method is used for the subjective scales. For instance, the visual analog scale can be readily converted because it already spans values from 0 to 10, but remember to maintain the desired relationship of 0 at the less desirable end of the score. For Likert scales and other discrete scales with specific marks, each possibility is assigned a sequential integer number (e.g., 1 to 5, 0 to 4, -3 to +3). The low and high values can be used as described above to score the scale for evaluation purposes. A special case occurs when the center of the scale is the HIGH or LOW point. In this case the distance from the center in either direction is the important value.

When there is only one score to represent an intervention, tool, or current situation because it is evaluated directly using objective (semiquantitative or quantitative) assessments, then that is the scored value. Other objective measures may be based on individuals, such as the level of sustained effort from an EMG analysis. In this case, the average of those participating in the evaluation should be taken to represent the intervention or product. In similar fashion, the subjective scales are scored and averaged over all the evaluation participants. Again, when the scales are scored, higher values must represent an improvement.

Table 4.12 illustrates the scoring method of the objective and subjective measures for the example of clean-room clothing. Beside each measure is the range of expected values along with the HIGH and LOW values used in the denominator of the scoring ratio. Finally, notes about the most favorable scale value, special notes about computation, and the basic computation of scores are provided

Overall Ranking

For the simple scoring of an intervention, add the intervention level scores for each factor being considered. It is reasonable to weight some factors more than others, and this is accomplished by multiplying the score by the weighting factor. The interventions as well as the current situation can be rank-ordered based on the total scores, with the highest being best.

TABLE 4.12
Scoring Methods for the Clean Room Coverall Evaluation

	Scale Values (SV)			
Measure	**Range**	**High**	**Low**	**Computation of Score**
Insulation [m^2°C/W]	0 to 0.20	0.20	0	Lower is better Score = 10 (1.0 − SV/0.20)
Moisture vapor transfer rate [$gm/m^2/hr$]	0 to 40	40	0	Higher is better Score = 10 × SV/40
Thermal sensation	−3 to +3	3	0	0 is best SV is an absolute value Score = 10 (1.0 − |SV|/3)
Moisture sensation	−3 to +3	3	0	0 is best SV is an absolute value Score = 10 (1.0 − |SV|/3)
Touch	−3 to +3	3	0	0 is best SV is an absolute value Score = 10 (1.0 − |SV|/3)
Stiffness	0 to 4	4	0	0 is best Score = 10 (1.0 − SV/4)
Scratchiness	0 to 4	4	0	0 is best Score = 10 (1.0 − SV/4)

TABLE 4.13
Evaluation Criteria and Evaluation Results for the Example of Clean Room Clothing

	Average Scale Value				
Fabric Criteria	A	B	C	D	E
Objective—Measured Value					
Insulation	0.15	0.07	0.19	0.12	0.05
MVTR	10.2	25.0	15.8	30.0	37.2
Subjective—Average Responses					
Thermal sensation	−0.08	−0.50	−1.00	−0.69	−0.65
Moisture sensation	1.20	1.12	0.85	0.69	1.15
Touch	−0.40	1.00	0.77	1.65	1.23
Stiffness	1.52	0.65	0.77	0.35	0.54
Scratchiness	1.04	0.50	0.62	0.19	0.50

	Score						Weighted Average Score				
Fabric Criteria	A	B	C	D	E	Wt	A	B	C	D	E
Objective—Measured Value											
Insulation	2.5	6.5	0.5	4.0	7.5	0.5	1.3	3.3	0.3	2.0	3.8
MVTR	2.6	6.3	4.0	7.5	9.3	0.5	1.3	3.1	2.0	3.8	4.7
Subjective—Average Responses											
Thermal sensation	9.7	8.3	6.7	7.7	7.8	0.5	4.9	4.2	3.3	3.9	3.9
Moisture sensation	6.0	6.3	7.2	7.7	6.2	0.5	3.0	3.1	3.6	3.9	3.1
Touch	8.7	6.7	7.4	4.5	5.9	0.33	2.9	2.2	2.5	1.5	1.9
Stiffness	6.2	8.4	8.1	9.1	8.7	0.33	2.0	2.8	2.7	3.0	2.9
Scratchiness	7.4	8.8	8.5	9.5	8.8	0.33	2.4	2.9	2.8	3.1	2.9
Sum							17.7	21.5	17.0	21.1	23.1

Table 4.13 provides the evaluation results for the clothing example. The top part of the table reports average scale values found from the bench tests and subjective evaluations. The bottom part reports the assigned score for the average scale value on the left. The right half reports the weighted scores. The sum of weighted scores for each fabric is provided at the bottom. Fabric E appears to come to the top, followed by fabrics B and D, with fabrics A and C at the bottom.

Often, there is a clustering of interventions, and the cluster with the highest scores should be considered more closely. It is also appropriate to do a reality check in case an unexpected result emerges.

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5 Human Reliability and Information Transfer

The two primary focus points for ergonomics are the reduction of stress and the reduction of error. Chapters 1–4 have focused primarily on the reduction of physical stress associated with work. Errors can lead to system failure, and this could be potentially hazardous, as in the cases of the Three Mile Island nuclear reactor and the Bhopal chemical plant incidents. A well-designed system should take into account not only the equipment but also the human element when analyzing for the risk of failure. Like every other component in a system, the human element is not perfectly reliable, and human error could cause the system to fail. In this chapter, ways to assess the potential for human error (human reliability) as well as methods to minimize a common source of error (information transfer) are discussed.

HUMAN RELIABILITY

Reliability analysis began in the 1950s and included only equipment reliability assessments. Hence, estimates of system performance were overly optimistic because they excluded the human element in system operations (Meister 1985; Sanders and McCormick 1993). Human reliability assessments evolved because of catastrophic disasters in the nuclear power industry, on which most HRA work has been focused. Events such as Three Mile Island, Bhopal, the *Challenger* explosion, the Zeebrugge ferry disaster, the nuclear plant catastrophe at Chernobyl, and the King's Cross Underground fire have emphasized the need for human reliability analysis. All these accidents were a compilation of maintenance, design, management, operational, and training failures (Reason 1990; Kirwan 1990).

Human reliability analysis provides methods of quantitatively predicting and evaluating human performance in man-machine systems (MMS) (Meister 1985). By definition, "Human reliability as an activity is the analysis, prediction and evaluation of work-oriented (MMS) human performance in quantitative terms, for example, such indices as error likelihood, probability of task accomplishment, and response time" (Meister 1985, p. 146).

Human reliability assessments can be performed on any task or activity that possess a specific goal, a set of procedures (more or less fixed) in which to accomplish the goal, and a measurable output or consequence that is used to determine the success or failure of the goal (Meister 1985). Human reliability assessments can be considered either a methodology, meaning a formal procedure to quantitatively analyze and predict human performance on a specific task or activity, a theoretical concept, in that it addresses how human error is produced and the effects on the system, or a measure, in that the output is a quantitative numerical value of human performance on a task in which the probability of error can be assessed (Meister 1985; Sanders and McCormick 1993).

The goals of HRAs are to identify potential areas of high risk, quantify the overall risk, and indicate where and how improvements should be made to the system. HRAs can also compare alternative designs and evaluate their tradeoffs or potential side effects (Meister 1985). Human reliability assessments can also predict human performance outcomes related to specific task/activities, isolate factors in the system that are most likely to induce human error, and identify factors that may produce undesired outcomes (Meister 1985). Hence, HRAs can indicate ways to minimize the costs of and/or reduce human failures in potentially hazardous, high-risk environments while simultaneously providing a better understanding of the interactions between humans (designer, operator, maintainer, etc.) and overall system performance (Reason 1990; Humphreys 1988).

Clearly, HRA can be of considerable value not only to human factors specialists and systems engineers, but to design engineers as well, especially in the preliminary stages of system design. By utilizing HRA techniques, tasks or activities that have a high probability of human error can be quickly identified and evaluated, especially those with catastrophic outcomes. This may allow engineers to either redesign that aspect of the system or take other error-reducing measures to circumvent undesired outcomes and accidents.

Cited below are a few additional definitions provided by Dhillon (1986), which may be helpful in better understanding human reliability:

Reliability: the probability that any item will perform a specified function for a given time under specific conditions

Human reliability: the probability of successful human performance on a job or task in any stage of system operation(s) under a given time parameter

Human performance reliability: the probability that the human will fulfill a given task under specified conditions

Human Reliability Analysis (HRA) Techniques

There are numerous techniques used in predicting performance of the human element in the human-machine system. Current techniques use either historical data or computer simulation of behavioral processes to predict error probabilities (Park 1997). These techniques are useful in quantifying human error probability (HEP) (Kirwan 1990). HEPs are defined as the number of actual errors divided by the number of opportunities for errors to occur (Kirwan

1990). Several HRA techniques include Absolute Probability Judgment (APJ), Paired Comparisons (PC), TESEO (an Italian acronym for *tecnica empirica stima errori operatori,* "empirical technique to estimate operators' errors"), Technique for Human Error Rate Prediction (THERP), Human Error Assessment and Reduction Technique (HEART), Influence Diagram Approach (IDA), Success Likelihood Index Method (SLIM), and Human Cognitive Reliability Model (HCR) (Reason 1990; Kirwan 1990).

The APJ, PC, IDA, and SLIM use a group of expert judges to evaluate HEPs, while TESEO, THERP, and HEART use a database of HEPs or provide a procedure for developing a database of HEPs. The HCR model, also referred to as the Time Reliability Correlation Approach or just simply Time Reliability Technique, uses a combination of judgments and simulator data.

The THERP is the most common and widely used predictive technique. However, the SLIM and HEART are most valuable to ergonomists. In addition, it was found in a comparative study performed by Kirwan (1988) that THERP and APJ were the most accurate techniques in terms of precision, consistency, convergence, and predictive validity. Furthermore, both were found to provide the most useful qualitative results. Hence, only these particular techniques will be discussed in detail.

Techniques for Human Error Rate Prediction (THERP)

THERP is the widely used and accepted predictive technique for human error prediction (HEP) in probabilistic risk assessment (PRA) studies (Reason 1990; Park 1997; Humphreys 1988). It is also one of the oldest techniques, originating in the 1960s by developer Alan Swain (Swain and Guttman 1980; Reason 1990). It is the most well developed and most accessible current methodology (Sanders and McCormick 1993; Reason 1990). It uses a logical approach with an emphasis on error recovery (Kirwan 1988).

THERP analyzes success or failure of an operator's action(s) in the same respect as it would a system component. Hence, the reliability of the human component is assessed in the same manner as system equipment, with the human activities broken down into task elements, which would be comparable to equipment outputs. The THERP technique involves four steps (Reason 1990; Meister 1985; Dhillon 1986):

- Identify system goals and functions of the system that may be affected by human error.
- Perform a function/task analysis. This involves identifying and analyzing jobs and tasks performed by human operators.
- Estimate the probability of human error on each task as well as the probability that the error may be undetected. This step involves using either existing data banks or expert judgment.
- Evaluate and estimate the consequences of the human error(s), including success or failure as well as errors that may be undetected or uncor-

rected. This step also involves using existing databanks and/or expert judgment.

- An additional iterative step (Step 5) may be added in the design process, which involves making amendments to the system and repeating the process in order to recalculate error probabilities.

These steps are repeated until system degradation and vulnerabilities are at an acceptable level (Dhillon 1986).

The basic analytical device of the THERP model, specifically used in the task analysis stage, is the event tree, also referred to as the probability tree diagram. The events are depicted as a sequence of binary decision branches or limbs in which the correct and incorrect actions are the only available outputs (Reason 1990; Park 1997; Dhillon 1986). Each limb represents factors, referred to as performance-shaping factors (PSFs), that affect human performance and human error probabilities (HEPs) within the work environment (Reason 1990). PSFs may include factors such as stress, motivation, skill level, experience, and expectations of the operator. THERP contains twenty-seven tables of nominal HEPs, which assign generic values to the probability an error will occur given a specific operator task. Modification to the basic HEP database, referred to as a conditional HEP, can accommodate diagnostic errors and errors related to high-level cognitive processing (Reason 1990; Park 1997).

Beginning with a specific point of interest in the system, typically an initiating event, the event tree chronologically progresses forward in time, including all human operator tasks and activities, which are conditional probabilities and illustrated by each limb (Reason 1990). In using the event tree, the probability of each outcome through the tree can be predicted. Figure 5.1 is an example of an event tree for a (dust) explosion (Rausand 1999). After the initiating event (the explosion), a fire may or may not occur. Assuming that a sprinkler system and alarm system have been installed, they may or may not be operating appropriately, and so on, until quantitative outcomes in frequency of occurrence have been assessed.

Success Likelihood Index Methodology (SLIM)

The SLIM (Kirwan 1990; Reason 1990) uses experts aided by software products to develop models that link human error probabilities characteristic of a specific situation to performance-shaping factors (PSFs) (called performance-influencing factors or PIFs in SLIM). PIFs are less based on behavioral factors than the PSFs in THERP. For example, PIFs may include quality of training, time pressure, procedures, and feedback. The success likelihood is derived from evaluation of PIFs or PSFs, which can be given a numerical value (based on expert judgment) in relation to their effect on the integrity of the system. Possible human error characteristics of a specific situation are weighted and rated, and these two values are multiplied together for each PIF or PSF. The

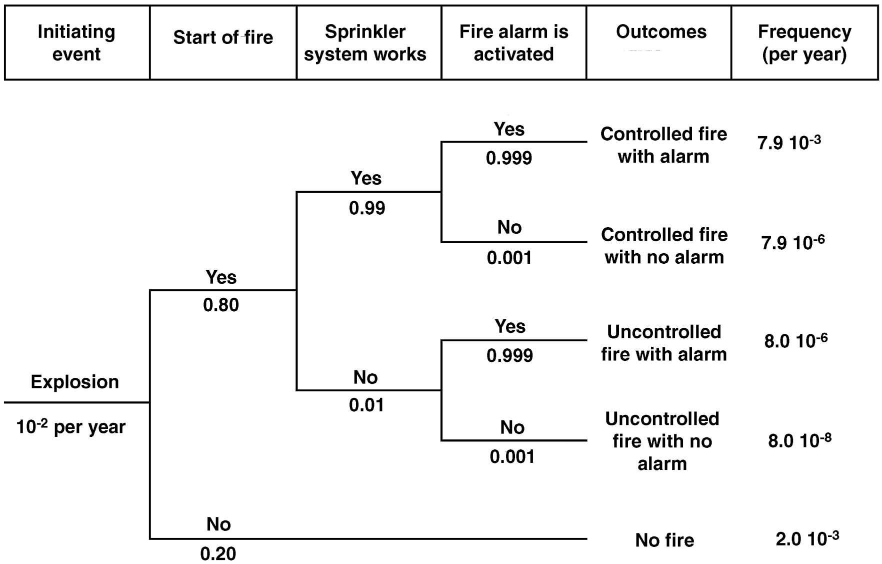


FIGURE 5.1 Event Tree for a Dust Explosion

TABLE 5.1
PSFs Ratings for Three Human Errors Under Analysis

Errors	Training	Procedures	Feedback	Perceived Risk	Time
Valve open	6	5	2	9	6
Alarm misset	5	3	2	7	4
Alarm ignored	4	5	7	7	2

These specific ratings of the PSFs in this example have been derived by a panel of experts. SLIM is a technique that uses experts in the field to establish ratings and evaluate HEPs.

following example (taken directly and entirely from Kirwan 1990, p. 729), applies SLIM to the evaluation of an "operator decoupling a filling hose from a chemical road tanker. The operator may forget to close a valve upstream of the filling hose, which could lead to undesirable consequences, particularly for the operator." The human error being analyzed: "The failure to close V0602 prior to decoupling filling hose." Table 5.1 shows PSF ratings for three human errors under analysis, and Table 5.2 shows the weightings for different PSFs

The products of all PIFs/PSFs pertaining to the given situation are summed to produce the success likelihood index (SLI) of that situation:

Weightings (W) x Ratings (R) = SLI (WR)

See Table 5.3 for an example.

TABLE 5.2
PSF Weightings

PSFs	Weighted Value
Perceived Risk	0.30
Feedback	0.30
Training	0.15
Procedures	0.15
Time	0.10
	1.00

TABLE 5.3
Success Likelihood Index for Decoupling a Chemical Hose from a Tanker (Kirwan 1990, p. 730)

Weighting	PSF	Open	Alarm Misset	Alarm Ignored
0.30	Feedback	0.3(2) = **0.6**	0.3(2) = **0.6**	0.3(7) = **2.1**
0.30	Perceived Risk	0.3(9) = **2.7**	0.3(7) = **2.1**	0.3(7) = **2.1**
0.15	Training	0.15(6) = **0.9**	0.15(5) = **0.75**	0.15(4) = **0.6**
0.15	Procedures	0.15(5) = **0.75**	0.15(3) = **0.45**	0.15(5) = **0.75**
0.10	Time	0.10(6) = **0.60**	0.10(4) = **0.40**	0.10(2) = **0.2**
	SLI (Total)	**5.55**	**4.30**	**5.75**

SLIs are not probabilities but indications of the likelihood of different errors. To transform SLIs into HEPs, which will produce an absolute probability value, the SLIs must be calibrated using this equation (Reason 1990; Kirwan 1990):

$$\text{Log (HEP)} = a\ (\text{SLI}) + b$$

where a and b are two other calibration tasks whose error probabilities are given or already known.

For example, if the two other tasks, a and b, have HEPs of 0.5 and 10^{-4} and SLIs of 4.0 and 6.0, the equation would be as follows:

$$\text{Log (HEP)} = 1.85\ \text{SLI} + 7.1$$

Hence the HEPs for the example would be:

Valve open = 0.0007

Alarm misset = 0.14

Alarm ignored = 0.003

In order to eliminate biases induced by expert opinions, a computerized version, the SLIM-MAUD (SLIM Using Multi-Attribute Utility Decomposition), is used. The explicit mathematical requirements of the software produce unbiased and different values than those attained by using the hand-calculated SLIM (Kirwan 1990).

Acceptable levels, or cutoff levels, of HEPs are dependent upon the situation, the task, and the environment, as well as the risks associated with the error. In other words, there is no set cutoff level for HEPs. However, when risks extend to massive internal and/or external damage and high costs, and/or human life is threatened, logically only low probabilities are acceptable.

Human Error Assessment and Reduction Technique (HEART)

This technique (Kirwan 1998, 1990) is based on human performance literature and is simple and quick to use, as well as easy to understand. HEART analyzes ergonomic factors that have a significant, derogatory effect on human performance. This is an important and valuable asset, because it allows human factors specialists to establish a quantitative value for their design recommendation(s), which will, in turn, establish a level of importance in design criteria for the engineers. In short, this technique can bridge the gap between human factors specialists' concerns and recommendations and those of the engineers designing the system.

The HEART assessment begins by taking a specific task/activity of interest performed by the operator and assigning it a nominal human error probability by classifying under a predefined generic task. Examples of generic tasks used for classification may be (Kirwan 1990, p. 732):

1. Very unfamiliar, performed at a rate with no real idea of likely consequences.
2. Complex task requiring high level of comprehension.
3. Restore or shift a system to original or new state following procedures, with some checking.

Next, error-producing conditions (EPCs), such as no feedback, lack of experience, and so on, are specified for a given situation. For example, the following is an assessment, using HEART, of an operator's likelihood at failing to "isolate a plant bypass route following strict procedures" (Kirwan 1990, pp. 732–735). The given scenario is that of

> a fairly inexperienced operator applying an opposite technique to that which he normally uses to carry out isolations and involves a piece of plant, the inherent major hazards of which he is only dimly aware. It is assumed that the man could be in the seventh hour of his shift, that there is talk of the plant's imminent closure, that his work may be checked and that the local manage-

> ment of the company is desperately trying to keep the plant operational despite the real need for maintenance because of its fear that partial shutdown could quickly lead to total permanent shutdown. (Kirwan 1990, p. 732)

The generic task #3 would be used because it best classifies the operator's task. This generic task has a given proposed nominal human unreliability of 0.003, and 5th to 95th percentile bounds of 0.0008–0.007. In addition, the error-producing conditions and their nominal unreliability values (the values of which are given in a chart in human reliability charts) would be: inexperience (x 3), opposite technique (x 6), risk misperception (x 4), conflict of objectives (x 2.5) and low morale (x 1.2). The HEART assessment for this situation is shown in Table 5.4:

The HEP of 0.27 is a high predicted error of probability and in most, if not all, cases would be unacceptable (Kirwan 1990).

Absolute Probability Judgment (APJ)

APJ (Reason 1990) uses expert(s), whether an individual or a group, to create the human error probabilities (HEPs). These expert judgments are structured in way that provides an analytic evaluation of probabilities given a specific situation/event at a given time. In short, outputs are derived from probabilities assessed given situation/event A, B, C, etc. at times t_1, t_2, t_3, etc. For this reason, the APJ may also be referred to as the confusion matrix.

APJ is advantageous in that it can identify situations or events, specifically

TABLE 5.4
HEART Assessment for Isolating a Plant Bypass Route

Error-Producing Conditions Factors	Total HEART Effect	Engineers' Assessed Proportion of Affect (0–10)	Assessed Effect
Inexperience	× 3	0.4	(3 − 1) × 0.4 + 1 = 1.8
Opposite technique	× 6	1.0	(6 − 1) × 1.0 + 1 = 6.0
Misperception of risk	× 4	0.8	(4 − 1) × 0.8 + 1 = 3.4
Conflict of objectives	× 2.5	0.8	(2.5 − 1) × 0.8 + 1 = 2.2
Low morale	× 1.2	0.6	(1.2 − 1) × 0.6 + 1 = 1.12

Nominal human reliability: 0.003

Assessed nominal likelihood of failure: 0.003 × 1.8 × 6.0 × 3.4 × 2.2 × 1.12 = **0.27**

The predicted 5th to 95th percentile bounds: 0.07 − 0.58 (total of probability of failure cannot exceed 1.0). The percentage of contribution made by each error-producing condition is as follows:

Opposite technique:	41%
Misperception of risk:	24%
Conflict of objectives:	15%
Inexperience:	12%
Low morale:	8%

rare or abnormal ones, that cannot be assessed by other HRA methods. In addition, it is also more valuable in providing qualitative assessments. However, its disadvantage is the fact that the data are subjective and may be a source of controversy and dispute among the experts.

Cautions When Using HRAs

There are several problems with human reliability assessments.

(1) The techniques do not account for common-mode failures, specifically involving human interactions, throughout all aspects of system operation and involvement, including installation, management, maintenance, operation, etc. (Reason 1990).

(2) Furthermore, when quantifying events or activities, data on types of faults or human error may not exist and hence may have to be estimated.

(3) These estimations may be provided by expert judgments, which may be subject to biases and are subjective in nature.

(4) Estimations may also be derived using data related to another, different component or system failure or error, which may not be transferable to the activity/event being analyzed (Reason 1990).

However, HR specialists argue that although the estimates may not be completely accurate, they are good approximations and hence may be useful and viable in predicting and identifying task or activities that are most vulnerable to human error (Sanders and McCormick 1993).

There are also concerns around the consistency and predictability of human behavior in system operations. The primary goals of HRA methods are to predict, and in turn reduce, human error. However, human behavior is unpredictable, and hence human error is inevitable. For this reason, critics argue, the best way to protect the system is to make it more error-tolerant. However, this entails identifying areas where human errors are most likely to occur, particularly those that pose the greatest risks; this is where HRA can be valuable. In order to make the system error-tolerant, safety measures should be employed in the specified areas (Reason 1990). Such safety techniques include the "30-minute rule," which allow the human operator time to think after initiating an action before an automated system takes over in order to restore and ensure the overall safety of the system (Reason 1990). Backup systems or redundancies within the system are another technique used to make the system more error-tolerant (Reason 1990). Other error-preventing techniques, such as manipulation of the work environment or personnel, can be integrated into the system in order to further ensure the safety of the system (Park 1997).

Although the criticisms contain valid arguments, human reliability assessments remain valuable tools in identifying tasks where human error is highly probable. This information is essential in determining what operations require safety measures or preventative techniques in order to make the system error-tolerant. In addition, by analyzing areas where human error is highly probable, engineers can better identify when, where, and possibly why breakdowns in human-machine interactions are likely to occur. This may be critical in determining what safety measures to integrate into the system operations, or whether redesign would be the best way to ensure safety.

INFORMATION TRANSFER

One source of error (and hence failure) in a system is the transfer of information, either from equipment to the operator or between people via written instructions, warnings, codes, forms, or surveys. A common understanding has to exist between the sender and receiver of the information to minimize such failure. By identifying where errors may occur, one can utilize human factors principles to reduce their likelihood. Common errors include:

- Not complying with a warning
- Misinterpretation of instructions
- Information overload from too many codes
- Entering information in the wrong location on a form
- Misinterpreting a survey question, thus providing inaccurate data

Over time, an individual becomes familiar with a task and its environment, reducing the reliance on such information while increasing his or her comprehension of the information. However, when designing for the general population, the novice or infrequent user should be the target audience. In addition, because emergency situations often result in reflex reactions rather than analytical troubleshooting, well-designed written information is needed for people with experience in the workplace as well. This section focuses on design guidelines aimed at improving the transfer of information between people and reducing the potential for human error.

Warnings

Designing warnings is a complicated task. Described herein is an overview of the issues that should be taken into consideration. The information presented here is not all-inclusive, nor should the concepts presented be regarded as guaranteeing proper warning design. Further, an individual familiar with the latest developments and legal standards should also review the proposed warnings in order to ensure that they are compatible with current legal standards.

The effectiveness of any warning relies on a key limiting factor—whether the warning is capable of influencing an individual's behavior. Sanders and McCormick (1993) offer a hierarchy of hazard control where they describe two methods preferable to reliance on warnings.

- Design the hazard out
- Guard
- Warn

Designing the hazard out of the system and guarding, or establishing a barrier between the user and the hazard, are preferable because they remove or greatly reduce the effect of the hazard. Relying exclusively on warnings to influence an individual's behavior is rarely totally successful.

Regretfully, there are situations and products where it is neither feasible nor desirable to remove the hazard or completely guard against the hazard. A chain saw is one example of a product where the utility of the device is the very aspect that is dangerous, thus making a redesigned product infeasible. Similarly, while advances in safety features (e.g., multiple-location chain brakes located on the grip) have been made in recent years, a robust guard that does not substantially impede the utility of the tool has yet to be developed. Consequently, these and other similar devices rely heavily on the usage of warnings.

Specifically, where the risk of serious injury or death is involved, warnings should be rigorously tested within environments closely resembling the actual environment of use and should employ a representative population closely resembling the end user population.

There are four general reasons for issuing a warning:

- To inform individuals of a dangerous or potentially dangerous situation.
- To provide individuals with information regarding the likelihood and severity of injury that could possibly occur through use, or reasonably foreseeable misuse, of an object.
- To provide information as to how the likelihood or severity of an injury may be reduced.
- To remind users/operators when and where the danger is most likely to be encountered.

The successful warning will be detected (most likely seen or heard), correctly interpreted, and abided by. Each of the three steps—detection, interpretation, and abidance—can be influenced positively though the application of human factors principles.

Relative to *detection,* the warning message or signal must be clearly conveyed so that it is obviously identifiable and distinguishable from the background noise. For visual warnings, size, shape, contrast, and color are attributes that may aid in improving detection. For auditory warnings, temporal patterns, sound level, and sound spectrum are a few attributes that need to be considered when trying to improve detection.

Accurate *interpretation* and understanding of the message by the user population is essential for the properly designed warning. Whether visual or auditory in nature, warnings must be tested in order to ensure that the end user population accurately comprehends their meaning. Several principles to consider when developing warnings are:

- Avoid vague, ambiguous, or ill-defined terms (words or icons), highly technical terms or phrases, double negatives, complex grammar, and long sentences (more than twelve words).
- Consult industry standards (e.g., ANSI, OSHA, ISO).
- Know the target population. Consider language, local custom, and the possibility that visitors may be present. Design for the low end of your user population. Confirm results with the general population (to ensure that no intrapopulation differences exist).
- Know the target environment. Environmental considerations (e.g., noise, lighting, primary task) may impact the design and presentation of the warning. Consider other alarms or warnings currently in place to ensure accurate discrimination.
- Match severity of the warning with perceived severity of the alarm. For example, all other things being equal, the alarm for the condition with the most severe consequence should sound the most urgent to the user.
- Test and experimentally validate any warning system under realistic conditions with the appropriate user population.

After the warning has been detected and interpreted, people must heed the warning (*abidance*). They must know and be able to complete the action required of them. Further, issues related to additional cost to the individual must be considered. These costs can be measured relative to the cost in time, inconvenience, or discomfort that will be incurred through complying with the warning. Finally, the individual's perception of risk will impact compliance with a warning.

Visual Warnings

A properly designed warning should include the following fundamental elements:

- Signal word—indication of risk severity (*danger, warning, caution*)
- Hazard—identification or brief description of the hazard
- Consequences—the associated cost or likely impact of not abiding by the warning
- Instructions—a description of behavior that will reduce or eliminate the hazard

Three signal words are commonly recognized. They are differentiated in their ability to warn and convey the severity of the situation.

Danger: immediate hazard that, if encountered, will result in personal injury or death (preferred visual presentation: red print on a white background or vice versa).

Warning: hazards or unsafe practices that, if encountered, could result in injury or death (preferred visual presentation: black print on an orange background).

Caution: hazards or unsafe practices that, if encountered, could result in minor personal injury, product damage, or property damage (preferred visual presentation: black print on a yellow background.

Describing the minimum requirements for a warning, Wogalter, Desaulniers, and Godfrey (1985) offer the following as the minimum requirements for an acceptable (albeit hypothetical) warning:

Danger (signal word), *high-voltage wires* (hazard), *can kill* (consequences), *stay away* (instructions).

The following considerations are important for a warning sign: size, shape, color, graphical (iconic) depiction, contrast, placement, and durability. A more comprehensive list of variables affecting the effectiveness of warnings is presented by Rogers, Lamson, and Rousseau (2000).

Size: Within reasonable limitations, the larger a warning is depicted relative to surrounding information, the easier it will be detected.

Shape: Similar to graphical depiction, shapes have the ability to draw an individual's attention to a warning message (e.g., an arrow). Shape coding for warning signs is predominately used in the area transportation where an approximate meaning of some signs can be derived from their shape alone (e.g., octagonal stop sign, rectangular information sign).

Graphical (iconic) depiction: Similar to shape coding, icons have the ability to attract an individual's attention to a warning by representing the consequences that could occur.

Color and contrast: High contrast between text and background on the warning sign itself (dark text on a light background, or light text on a dark background) will aid in detection. Similar contrast between the background and the warning sign itself will similarly aid in detection (e.g., a colorized warning on an otherwise black and white printed page). Generally, black, white, orange, red, and yellow are the recommended colors for warning labels or signs. Table 5.5 shows the legibility of different color combinations.

Location: Western culture text reads left to right and top to bottom; therefore, warnings should be presented toward the top or left, depending on the design of the display. Whenever possible, it is desirable to place the warning label near the location of the hazard. Separation of the warning from other information such as a sign or label may also aid in detection (Godfrey et al. 1991).

TABLE 5.5
Legibility of Color Combination in White Light (adapted from Woodson and Conover 1964)

	Color Combination	
Legibility	**Characters**	**Background**
Very Good	Black	White
	Black	Yellow
Good	Yellow	Black
	White	Black
	Dark Blue	White
	Green	White
Fair	Red	White
	Red	Yellow
Poor	Green	Red
	Red	Green
	Orange	Black
	Orange	White
Very Poor	Black	Blue
	Yellow	White

Auditory Warnings

Auditory warnings can be categorized as either intentional or incidental (Wilkins and Martin 1987). Intentional warnings are engineered sounds specifically designed to warn. Incidental warnings are intrinsic sounds from the system but are not especially useful in situations necessitating advance warning and thus will not be addressed here. Auditory displays conveying intentional warnings include both speech and nonspeech signals. Alarms or warning signals should be detectable, recognizable, intelligible, and conspicuous.

SPEECH SIGNALS Research indicates an operator preference for auditory warning systems that make use of speech signals (Kemmerling et al. 1969). Voiced or speech warning signals are technologically feasible and beginning to be more prevalent, especially as research has found greater compliance with voiced warnings than the same warnings in print (Barzegar and Wogalter 2000). In addition to being highly redundant, a major attribute of speech is its tremendous transmission rate, up to 250 words per minute (wpm) in environments where a high signal-to-noise (S/N) ratio prevails (Deatherage 1972).

Speech displays are often considered a viable alternative to visual displays as a means to reduce visual workload (Sorkin 1987). Verbal warnings are a form of presentation that falls between the general advantages of visual or auditory presentations shown in Table 4.2 ("Modes of Display" in Chapter 4). That is, a verbal warning can convey more than a nonverbal warning but not as much detail as a visual presentation.

Speech-based warning signals have been found to be especially favorable under high workload conditions because they afford the operator flexibility to evaluate the situation prior to responding. Furthermore, speech-based warnings are easily learned and remembered.

Vocal alarms can accommodate the increase in anomalies of complex systems, allow directives with the notification, and describe problems with greater specificity and clarity.

The perceived urgency of a spoken warning depends on pitch, intensity, and duration. The following features of a voiced warning of words such as *danger, caution, warning* or of short voiced warning statements will enhance the perception of the urgency of a warning (Barzegar and Wogalter 2000; Hellier et al. 2000; Hollander and Wogalter 2000)

- Female voice
- Short word or phrase duration
- Fast sound rate
- Emotional voice style rather than monotone

Speech displays, while very effective in some situations, are not suitable in all environments or situations. There should be caution when choosing the mode of warning or alarm, as verbal warnings may not be responded to as effectively as nonverbal alarms at times of high workload (Bliss and Kirkpatrick 2000). For example, if a warning system uses multiple speech signals, individual warnings may be confused with one another. Speech signals also take a relatively long time to present a simple message or warning. As a result, Patterson (1982) recommends that speech signals be used to augment nonspeech signals, especially in urgent or imminent situations.

NONSPEECH SIGNALS A well-designed set of auditory displays should be both discernible and discriminable, enabling the use of multiple simultaneous alarms (Patterson 1982; Sorkin 1987). There are simple and complex nonverbal signals. Simple sounds are usually used for attention-getting signals. An emergency vehicle's siren is one of the most common auditory warning devices and uses nonspeech audio and the conventional "brute force" or "better safe than sorry" approach to warnings (Edworthy, Loxley, and Dennis 1991; Patterson 1990).

While signals of this nature are certain to attract attention, the consequences of such alarms, if used excessively, include startled operators and hampered communications at crucial times (Patterson 1990). These factors may lead to high operator annoyance, causing many operators to disable or turn off alarms (Edworthy, Loxley, and Dennis 1991; King and Corso 1993).

TABLE 5.6
Parameters Affecting Perceived Urgency of Auditory Warning Signals (adapted from Edworthy, Loxley, and Dennis 1991; Haas 1993)

Parameter	Effect on Perceived Urgency
Fundamental frequency	The change in fundamental frequency is the significant factor, since the salient feature of a pitch change is the direction of change rather than the magnitude of change. Higher frequencies elicit a higher perceived urgency.
Amplitude envelope	Shorter onset and offset times are perceived as being more urgent than longer ones.
Harmonic series	Irregularity and unpredictability contribute to urgency in the resulting pulse.
Speed	Faster warning signals increase perceived urgency.
Rhythm	A regular rhythm is perceived to be more urgent than an irregular, syncopated rhythm.
Number of times a burst is played	Increasing the number of times a burst is played results increases the perceived urgency of an auditory signal.
Pitch range	A large pitch range is perceived to be more urgent than a small pitch range.
Musical structure	A burst with an atonal melodic structure increases perceived urgency.
Pulse level	The higher the pulse level, the greater the perceived urgency.
Time between pulses	The shorter the interval between pulses, the greater the perceived urgency.

TABLE 5.7
Guidelines for Improving the Design of Auditory Warnings (adapted from Patterson 1982)

Determine the necessary signal sound pressure (SPL) level for the pulse.
Develop a pulse lasting from 100 to 300 milliseconds.
Include the fundamental frequency and several harmonics in the pulse.
In order to reduce operator startle, the sound pulse should be contained within an amplitude envelope making use of a relatively short onset and offset times.
Develop a burst by repeating the pulse several times, each time at a different pitch, amplitude, and with varying time periods between each pulse.

Much of the recent research into auditory signals suggests that the "brute force" or "better safe than sorry" approach is often unsatisfactory, especially in environments employing multiple auditory warnings (Ballas 1994).

A summary of the parameters found to have an effect on perceived urgency is shown in Tables 5.6 and 5.7 (Patterson 1982; Edworthy, Loxley, and Dennis 1991; Haas 1993). ISO 7731 (International Standards Organization 1986) offers guidelines for setting appropriate signal level relative to background noise.

When multiple alarms are necessary, using warning signals with distinctive spectral and temporal patterns can reduce operator confusion. Incorporating several different spectral components from throughout the auditory spectrum creates a distinctive sound less prone to operator confusion (Patterson 1982). Complex ones are composed of sounds of different amplitudes, frequency, and temporal patterns, such as warbling or wailing. These dynamic, complex sounds communicate different levels of hazard, but the listener needs to know what the code means. Hellier and Edworthy (1999) list five characteristics in order of greatest effect on perceived urgency: speed of the sound; repetition, or number of repeating units; length, or total duration of the stimulus; pitch, or fundamental frequency; and inharmonicity. There are several common signal devices that can be used as either simple or dynamic signals. These are, in order of penetration characteristics from least to most penetrating: buzzers, chimes, bells, horns, and sirens.

The following are general principles for nonverbal auditory presentation of warning signals (based on Sanders and McCormick 1993):

- Signals should be audible, that is, discriminable from the ambient noise level and about 10 dB above it (see “Noise” in Chapter 8).
- Signals should be discriminable from each other (between one and two octaves, or two to four times the frequency) and should not mask each other.
- Signal frequency should be compatible with the midrange of the ear’s response for both pitch and loudness, where response reliability is greatest.
- Low frequencies, below 1,000 Hz, should be used when signals have to travel further than 350 m (1000 ft.).
- Very low frequencies, below 500 Hz, should be used if the signals have to go around or through major obstacles or partitions.
- The characteristics of the signal’s sound should be attention-getting without producing traumatic sensory overload (see “Noise” in Chapter 8).
- Signals should be standardized within a facility. There should be caution in designating a signal for two different functions even if in different areas of a plant.
- Common conventions where certain types of signals are recognized and associated with particular activities should be followed—for example, sirens for police, firefighters, and ambulances.
- Dual presentation of auditory and visual warnings, or a shifting frequency signal, should be used in noisy environments that are difficult to penetrate.
- Audio warning systems should be provided with means of testing the audio signal at any time, and a reset function should be provided.

While operators have the ability to learn large sets of warning signals, it is often impractical to do so because of the time spent acquiring and maintaining knowledge of the system; current guidelines suggest that a maximum of five or six signals be used (Patterson and Milroy 1980).

EVACUATION ALARMS Evacuation alarms notify people in a work area of a situation requiring them to leave the building. The design of these alarms should take into account the ambient noise level, and they should be distinct enough to be immediately recognized. A spoken message is often desirable to reassure people and to let them know what to do. The following guidelines apply to the design of emergency alarms and public address systems (Eastman Kodak Company 1983; Fidell, Pearsons, and Bennett 1974; Corliss and Jones 1976; Fidell 1978)

- The evacuation tone should precede any verbal evacuation messages announced over the public address system.
- The evacuation alarm tone should have a minimum duration of 10 seconds. Coded alarms should be repeated until the building is evacuated.
- An evacuation alarm tone with a swept frequency of one octave somewhere between 500 and 2,000 Hz is recommended (the range where the ear is most sensitive).
- The evacuation tone should be about 10–12 dB higher than the highest one-third octave band of the ambient noise; that is, the uppermost of the three bands encompassing the tone frequencies.
- Speech should be 14 dB or more above the ambient noise level. If the resulting noise level is 70 dB or more (based on the four-band PSIL), the address system should incorporate 12-dB speech peak clipping and reamplification.
- Visual alarms, such as blinking lights, should also be included in the emergency evacuation alarm installation to alert those with hearing loss.

Innovative evacuation alarm designs are being developed that act as directional beacons by being located over exit doors and emitting rapidly pulsing broadband noise, contrary to the narrow frequency range of most exit alarms. In addition, near stairs, the noise includes a sweeping up or down melodic complex according to whether the exit stairs are going up or down. The pulse rate increases at the beacons located closer to the final exit (Withington 2000).

ALARMS AND EAR PROTECTION Operators wear ear protection to reduce noise to acceptable levels (see "Noise" in Chapter 8). There are two generic types of ear protection: earplugs that fit into the ear, and earmuffs that cover the ears. Commercial ear protection products are usually certified with a noise reduction ratio (NRR), expressed in dB. Wearing ear protection does not necessarily preclude hearing alarms, although there will be many who are disadvantaged by the use of ear protection. The extent of hearing auditory warnings while wearing protection depends on (Coleman 1998):

- The listener's frequency resolution and absolute hearing ability
- The frequency response of the protectors
- The nature of the noise spectrum
- The frequency components of the warning signal
- How well the protector has been fitted

Depending on the spectral characteristics of the noise and signal and on the noise-reduction function, the signal-to-noise ratio may be enhanced even if both noise and signal intensity are reduced (see "Noise" in Chapter 8). However, it is known that ear protection does disturb detection of the location of sounds, creating front-back confusion as well as horizontal and vertical location error, although there is the possibility that adaptation can occur (Bolia et al. 2001).

Some newer ear protection devices are being developed to overcome the issue of some hearing-protection devices attenuating all noise too much, so speech and displays are inaudible. These augmented hearing-protection devices work by selectively attenuating characteristics such as frequency or amplitude or by electronically incorporating an equal amplitude 180 degrees out of phase so that the noise is canceled. Other devices may incorporate a dedicated speech communication system at the earmuffs. To date, the potential of these augmented hearing-protection devices has not been fully realized (Robinson and Casali 2000).

AUDITORY ICONS Both speech and nonspeech auditory warnings have shortcomings. While speech is capable of conveying information about the nature of a problem in addition to alerting the user of its occurrence, speech warnings are generally longer in duration than nonspeech warnings and have limited effectiveness in environments with a low S/N ratio. Nonspeech displays, on the other hand, are capable of functioning in environments with low S/N ratios and are generally shorter in duration than speech displays. Nonspeech displays are also capable of providing limited additional information to the operator through coding. Coding enables additional information to be embedded in nonspeech audio signals. Perceived urgency is one such example, where in addition to the presence of the alarm, the alarm conveys the seriousness of the impending situation. Coding, however, relies heavily on specialized training to inform the operator of a signal's meaning and is frequently incomprehensible to untrained individuals.

A relatively new type of auditory warning called "earcons" or "natural warning sounds" or "auditory icons" have recently been proposed (Gaver 1986, 1989). These are sounds that relate to the situation (naturally occurring sounds) and differ from traditional nonspeech auditory displays in which various sound attributes are manipulated. For example, the sound of a coin falling into a slot would be used to convey that an automated toll payment is completed (Blattner 2000; Ulfvengren 2000).

Such cues can be used to convey information about a system's status, and because auditory icons build upon everyday sounds, they will be more easily learned and less likely to be forgotten than traditional nonspeech auditory displays (Buxton 1989). Preliminary studies have found that auditory icons or representational sounds may be more effective than conventional warnings (Belz, Robinson, and Casali 1999). It has been suggested that auditory icons (Gaver 1986, 1989) could reduce the learning effects of coding while significantly reducing an operator's reaction time. Conventional nonspeech warning signals rely on an operator's interpretation of the psychophysical properties of the sound, whereas with auditory icons, what an operator believes produced the sound is of primary importance.

Many of these new approaches are being investigated for their potential in complex, specialized environments, such as for medical equipment in hospitals, where many devices are used simultaneously and there are too many alarms (Weinger 2000). Overall, there is a paucity of research in the areas of widespread everyday sound identification and implementation of auditory icons as warning devices. However, preliminary results are promising (Ballas 1993; Belz, Robinson, and Casali 1999; Belz et al. 2000; Graham, Hirst, and Carter 1995; Haas and Schmidt 1995), although generalizability may be low since warnings are both task- and environment-dependent. Belz and colleagues (2000) provide a summary of the most salient factors for recognition. Some international standards for alarms of medical devices have been developed, and others are currently being worked on (Hedley-Whyte 2000). Computer-controlled environments are also being considered for creative presentation of warning signals, such as nuclear power plants (see "Computer Interface Controls" in Chapter 4).

Instructions

When providing instructional information to users, both the words and the accompanying graphics need to include human factors input. Written communication can be enhanced by proper attention to the components of the process (see Table 5.8).

The most important concern when creating instructions for complex systems is the user of the system. At the outset, the most effective format for the instructional information needs to be determined, using the following guidelines:

- Short sentences, flow diagrams, algorithms, lists, and tables are superior to paragraphs (Miller 1975).
- Inexperienced users react best to instructions that contain integrated diagrams and text, whereas experienced users react best to diagrams (Kalyuga, Chandler, and Sweller 1998).

TABLE 5.8
Factors Affecting the Written Communication Process (adapted from Caplan 1975)

Design of Message	Factors Affecting Message Transmission	Elements Influencing Receipt of the Message
Comprehensibility	Environment	Discrimination
Purpose	Viewing distance	Visual abilities
User knowledge	Viewing angle	Interpretation
Brevity	Illumination	Language skills
Accuracy	Deterioration	Situation knowledge
Clarity	Competing displays	Recall
Legibility	Timing pressure	Time delay
Font style		Interference
Font size		
Colors		
Readability		
Borders		
Layout		
Abbreviations		
Spacing		
Case		

- The choice between formats is situation-dependent and should be validated with users before final implementation.
- If the system's users are a specific target population, particular nomenclature, such as acronyms and abbreviations, may be utilized.
- If a general population will use the system, words that are easily understood should be used. Simple sentences made up of short and commonly used words will improve the comprehensibility of the instructions. *The American Heritage Word Frequency Book* (Carroll, Davies, and Richman 1971) can be consulted to find out how often certain words are used; those used more frequently are best.
- A document targeting the general population should aim for a reading level of grade 7 or 8. To assess the reading level of written instructions, the Fleish-Kincaid formula is recommended (U.S. Department of Defense 1978):

1. Calculate the average sentence length:

$$L = \text{Number of words} \div \text{Number of sentences}$$

2. Calculate the average number of syllables per word:

$$N = \text{Number of syllables} \div \text{Number of words}$$

3. Determine grade level:

$$\text{Reading level} = (L \times 0.39) + (N \times 11.8) - 15.59$$

- Instruction sets should be simple, concise, and clear while giving enough information to allow the operator to make judgments about specific problems that may not be addressed directly in the instructions.
- Too much information can overwhelm an individual's working memory, the part of memory that processes information, resulting in a degradation of the instructions (Kalyuga, Chandler, and Sweller 1998).
- If providing a numerical code to represent a part or service, include a short description so that the user needn't memorize the numeric code.

Instruction text should be organized in a sequence parallel to the sequence of actions that is performed with the system. However, if there are actions that need to be performed concurrently, the instructions should display the instructions for the actions in parallel, so that the user understands that they must be done together. The relative importance of each instruction should also be considered, with order priority given to those that pertain to tasks with potentially serious consequences. This vital information may be presented redundantly throughout the instruction set, to give several opportunities for it to be read and comprehended by its users.

Place the main topic of the instructions at the beginning of the sentence (Broadbent 1977). The sentence should be positive and active, to ease the user's comprehension and understanding (Sanders and McCormick 1993).

Positive and active sentence: The blue handle opens the door.

Passive sentence: The door is opened by the blue handle.

Negative sentence: The green latch does not open the door.

Instructions should be integrated into the equipment or the production work sheet rather than set aside on a separate sheet (Szlichcinski 1979). Ensure that the user will see the instructions before a mistake or an unsafe action occurs. Warnings contained within a set of instruction can be effective, because often those individuals who read instructions are unsure of the task's procedures or their own ability to complete the task (Sanders and McCormick 1993). Yet there are those individuals who do not read instructions, or if they do, their retention of the content may degrade over time. It is suggested that you put the warning up front in the instructions, to increase compliance with it (Wogalter et al. 1987).

If warnings are included within instructions, they should be distinct—by either color, graphic, or organization—so that they are obvious at first glance.

Within the warning, indicate the potential consequences of not following the instructions.

Coding

Systems may utilize information coding, wherein the original information is converted to a new form (Sanders and McCormick 1993). Once a coding system has been designed and implemented, it is difficult to change it, and this often becomes a deterrent to utilizing a coding system. However, with the increased usage of video display units and handheld devices, space is reduced, necessitating some degree of information coding. Coding may occur along various dimensions, such as alphanumeric, color, and shape. However, poorly designed coding may be misinterpreted. Thus coding conventions should be designed to minimize errors and to make sure that any errors that do occur are quickly detectable. When creating a coding convention for a system, the following heuristics should be followed (from Sanders and McCormick 1993):

1. *Codes need to be detectable*. Can a user distinguish a code element from extraneous elements that are not codes? When measuring detectability, the threshold, the point at which a positive detection is made, needs to be determined (typically about 50 percent of the time).
2. *Codes need to be discriminable from one another*. Can a user discriminate the meaning of one code from another? If there are too many codes, then the likelihood of this is low. The just noticeable difference (JND), also known as the difference threshold—the size of the difference between two stimuli that are just noticeably different—needs to be established.
3. *Codes need to be meaningful*. The designer should use codes that fit the common mental stereotypes that users have, such as a triangle for a warning or green to represent go.
4. *Standardization of codes*. If codes are standardized, it is important to use them across identical situations. This increases users' learning and understanding.
5. *Multidimensional codes*. If there is a need for a large number of codes, using multidimensional codes will increase the number of available codes and their discriminability.

Even when all the above principles are followed, the designed coding convention should be evaluated by users before it is finalized.

Alphanumeric Coding

The following review of coding dimensions was taken from Caplan, Lucas, and Murphy 1983.

The basic types of errors are omission, addition, substitution, and transposition of characters. The guidelines listed below are general and affect more than one type of error.

- An all-digit code should be used where possible and should not exceed four to five digits in length.
- Where longer codes are necessary, the digits should be grouped in threes and fours and separated by a space or a hyphen.
- If a numerical code system contains several digit sequences that occur frequently, they should comprise the first or last section of the code.
- In tabular listings when a digit sequence occurs repeatedly at the start of a many-digit number, only the last digits for subsequent entries should be printed. For example:

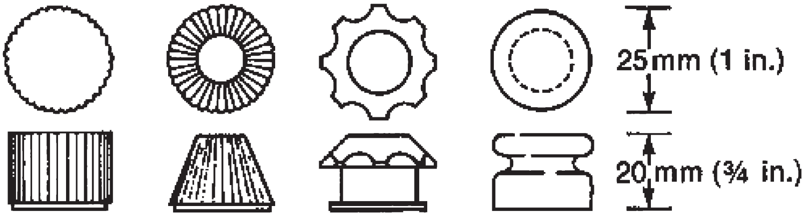
758017		7580170
7581010	should be	1010
7582030		2030
7591000		7591000

- Alphanumeric codes should have the letters grouped together rather than interspersed throughout the code.
- The letters B, D, I, O, Q, and Z and the numbers 0, 1, and 8 should be avoided in alphanumeric codes (McArthur 1965).
- For long alphanumeric codes, digits should be used in the last few positions.
- Simple fonts with clearly distinguishable characters should be used for the codes.
- Bold printing and high contrast should be used for all codes on labels or displays. Faded characters on a card or sheet should be avoided, especially if they need to be read under low-light conditions. Use color combinations that make codes easy to read (Table 5.5).

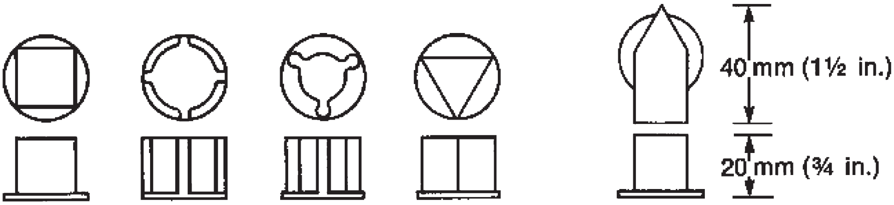
Shape Coding

The material in this section was developed from information in Bradley 1969, Hunt 1953, and Jenkins 1947.

In addition to alphanumeric coding, the designer of production equipment systems may also use shapes to transmit information efficiently. Shape coding is a useful technique to employ when visual control is limited. It has also been employed effectively in controls used under low-light conditions (Figure 5.2) and on signs for traffic control. The shapes chosen should follow accepted standards, where they exist, or should bear some resemblance to the function or component they mark.



(a) Knobs for multiple rotations



(b) Knobs for fractional rotations.

FIGURE 5.2 Shape Coding of Control

It is not advisable to use more than one size of a shape code in order to increase the number of items coded (usually five is the limit), particularly if the shape code has to be viewed from a distance or if discrimination between the two components similarly shape-coded is critical.

If two components occur either separately or together, the shapes should be compatible so that they can be displayed together without losing the distinguishing shape of either. For instance, a circle and a triangle can be displayed together if the circle is open in the center and the triangle is small enough to fit in the open area. In some chemical work areas, an open circle has been used to designate the location of a safety shower and a triangle used to indicate where an eye bath is. For cleansing stations where both shower and eye bath are present, the triangle and circle symbols can be superimposed.

Guidelines for choosing shapes for visual displays are developed from studies of people's ability to discriminate shapes or symbols (Sleight 1952). Some examples follow:

- Under normal viewing conditions (such as white light and daylight), people use area and jaggedness most frequently to describe shapes (Mavrides 1973).
- Under poor viewing conditions (such as subdued light, glare, or fading), area and the largest dimension are used to distinguish different shapes (Casperson 1950).
- As measured by the time required to search out and sort one shape out

TABLE 5.9
Symbols Ranked by Discriminability

1. Swastika	5. Cross	9. Diamond
2. Circle	6. Star	10. Triangle
3. Crescent	7. Ellipse	11. Square
4. Airplane	8. Rectangle	

of twenty-one, the eleven most discriminable symbols can be ranked as shown in Table 5.9 (Sleight 1952).

Based on these findings and excluding shapes having additional meanings (such as the swastika, cross, crescent, and airplane), a discriminable set of shapes is the following: circle, star, ellipse, square.

Color Coding

The material in this section was developed from information in Brown and Hull 1971, Christ 1975, and Smith and Thomas 1964.

Color coding is used more often than shape coding, and permits the designer a wider range of applications . There are from eight to fifteen colors that can be absolutely discriminated at least 90 percent of the time (Jones 1962). It is possible to increase the number of options by varying a color's brightness and saturation (Feallock et al. 1966). The following guidelines should be used in the design of color codes:

- Two levels of luminance (brightness) are probably the maximum that can be identified absolutely if error-free performance is required.
- Luminance is not a reliable cue in color perception because dark hues are difficult to recognize; use it sparingly.
- The accepted colors should be used for detection by people with color-defective vision (Munsell Color Company 1959).
- When there is a choice, colored lights are preferred over painted coloration.
- When codes are used for sizes, red should be used for the largest size. There is a strong association between color and size; however, a rainbow or light spectrum order from red to white (red, orange, yellow, green, blue, indigo, violet, white) could be an easily learned code for large to small (Poulton 1975).

Forms and Surveys

When collecting information in the workplace, because of time and resource constraints, often design of the data collection device is overlooked. There are two main types of data collection devices used in industry: surveys/questionnaires and forms. A survey is when a set of questions is presented and the individual provides either a written, oral, or data-input response (Cronbach 1970). Surveys in industry are typically used to evaluate a potential employee for selection purposes, or to gather attitudes toward the work environment or job responsibilities. A form is a method of recording information about a current situation or procedure for future use, such as temperature monitoring. Both surveys and forms may be paper-and-pencil-based or computer-based; surveys may also be administered orally. Surveys and forms should be tested in a pilot study before being employed. This pilot test will determine if there are problems with unclear wording, layout, or the interpretation of questions. Before creating a survey or a form, a basic set of questions should be answered:

- What is the budget allotted for this?
- Who are the users/respondents?
- Is the survey/form needed? Does a similar one already exist?
- Are there past surveys/forms that can be used in the creation of a new one?
- Is every question/item needed? Is it repeated elsewhere?
- How many copies are needed?
- When will the collected information be used?
- How will the collected information be used?
- Who will be using the collected information?

In addition, the following design guidelines should be utilized when creating forms for collecting information in the workplace (adapted from Caplan, Lucas, and Murphy 1973):

Sequence

- Sequence the items on the form in a logical and easy-to-follow way. Follow standardized item locations where they exist.
- Make the sequence of items on the form follow the sequence of the source document or the production process.
- Consider clerical routines when determining the order of items on the forms.

Readability and Comprehensibility

- Provide clear instructions for filling out the form.
- Make sure all captions are easy to understand and are legible under all conditions of use.
- Use color coding or other highlighting techniques to facilitate handling, checking, routing, or dispatching of the forms.
- Make the margins and filing data correspond to the characteristics of the

filing equipment or binders that the forms are stored in. For computer terminals, try to keep the forms to one page (full screen).

Space and Content

- Keep the amount of writing or typing to a minimum.
- Provide sufficient space for each answer.
- Provide for overflow or continuation pages if the designated space may be inadequate.
- Design the answer space to take advantage of computer, typewriter, or printer characteristics.

Question Design

When creating a survey, the same principles for the physical layout of a form pertain to the physical layout of the questions on a survey. There are two types of test items that can be used on a survey: open-ended questions (those questions that do not provide possible answers and require the respondent to provide their own response) and closed-ended questions (those questions that require a respondent to choose from a limited set of responses). Scoring a survey that has open-ended questions can be difficult because of variations in the scorers' interpretations. The utilization of closed-ended questions eliminates this problem, and it also has the advantage of allowing for rapid hand or machine scoring (Cronbach 1970).

A closed-ended question typically uses a scale for measuring attitudes or opinions. A sample survey question containing a measurement scale would be: *Using a 1 to 5 scale, where 1 means "not at all satisfied" and 5 means "extremely satisfied," please rate the level of your satisfaction with your work schedule.*

When creating a scale, its *reliability*, the scale's ability to consistently measure the same attitude, and *validity*, the scale's ability to measure what it is designed to measure, need to be ensured. In addition, when creating a survey with closed-ended questions, several general guidelines are:

- Design the questions so that they are appropriate for the target population's reading level and experience level. Use words that would be familiar to the respondents and define terms, abbreviations, and acronyms that may be unknown.
- Use short, active, affirmative sentences. Lead with a verb whenever possible (Wright and Barnard 1975).
- The word descriptions for the scale items are independent of one another, so there is no overlap or confusion in their meaning.
- There should be an odd number of scale items, with an equal number of items on either side of a neutral point.
- Provide an option of "Don't know," "Don't remember," or "No opinion" (Selltiz et al. 1959).

In the United States, we have a multicultural society with 27 million functionally illiterate adults and 6 million children under the age of 6 (Oldenburg 1993). Using icons in the construction of measurement scales is beneficial when trying to gather information from this population. Herbert and Tepas (1995) found that an Item Response Icon Scale (IRIS) consisting of faces is parallel to a Likert-type scale. The IRIS was developed using the symbols found in Wingdings, a standard font included in many computer word processing programs (as shown in Table 5.10 with the actual point size and the Likert-type scale that it is parallel to).

The IRIS may be a valuable design tool for collecting survey data from worker groups with diverse reading skills and/or from different cultural backgrounds.

Survey Design

The material in this section was developed from information in Douglas and Anderson 1974 and Goode and Hatt 1952.

- Provide brief and clear instructions in boldface type on the first page.
- Group items coherently and logically. Move from simple questions to complex ones.
- Design the survey for easy data analysis. The answers should line up, preferably along the right margin; a consistent method of responding (circling, checking, or underlining) should be used throughout.
- Collect basic demographic information about the respondent at the start or end of the survey (job classification, years of experience on the job, gender, age, height and weight, etc.).
- The survey should take no longer than 30 minutes to complete; preferably a respondent should be able to complete it within 15 minutes.

Data Analysis

In analyzing the data from the survey, some general guidelines are:

- Evaluate the demographic data to characterize the sample. Include this information in the results report.

TABLE 5.10
IRIS and the Parallel Likert-Type Scale

☺	☺	😐	☹	☹	Pleased Satisfied Mixed
29	21	15	21	29	Dissatisfied
points font size					Unhappy

- Report the percentage of the original sample that did not respond to the questionnaire, and, if possible, determine why they did not.
- Use statistical analysis techniques appropriate for the questions and types of scale employed. Choose a multivariate technique (one that is able to recognize multiple variables affecting a result). Multivariate analyses are often superior to univariate (frequency counts) analyses of data; attitude is rarely determined by a single factor.
- Report when the statistical analysis yields statistically significant results.

Labels and Signs

Labels and signs are short messages used to transfer information about policies or equipment use between people. There are three factors in message design for labels and signs that enhance communication: comprehensibility, legibility, and readability.

Comprehensibility

Comprehensibility is a measure of how reliably the receiver interprets a message. Among other things, it depends on the person's prior knowledge of a situation and his or her language skills. See "Instructions" earlier in this chapter for more information on comprehensibility.

Legibility

Legibility affects the user's ability to discriminate among or recognize letters or numbers. It is affected by the character's shape, size, contrast, color, and quality of reproduction. Use of the following guidelines (based on information in Berger 1944, Cornog and Rose 1967, and McCormick and Sanders 1982) should help improve the legibility of messages on labels and signs, as well as in other written communication such as forms:

- Keep the fonts simple; avoid curlicues and flourishes.
- Under normal lighting conditions:
  - Stroke width should be 1/6 of the height of black letters on a white background (see Figure 5.3).
  - Letter width should be 3/5 of the letter height, except for *I*, which should be one stroke width, and *M* and *W*, which should be 4/5 of the height.
  - Number width should also be 3/5 of the number height, with the exception of *1*, which should be one stroke width
  - Letter and number height will depend on viewing distances and the criticalness of the information. For situations where illumination is adequate (greater than 108 lux or 10 foot-candles), Table 5.8 can be used to determine the appropriate letter or number height.

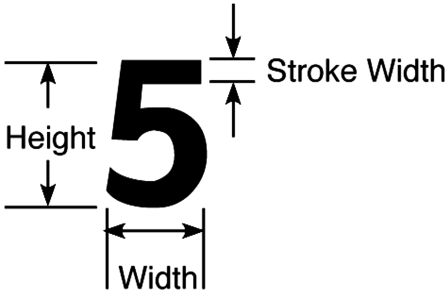


FIGURE 5.3 Definitions of font characteristics
Height is measured from the top to the bottom of the character, and width across its widest part. Stroke width is the thickness of the line used to generate the letter or number.

TABLE 5.11
Letter or Number Height Versus Viewing Distance for Labels (adapted from Peters and Adams 1959; Smith 1979; Woodson and Conover 1964)

Viewing Distance	Critical Labels	Routine Labels
0.7 m (28 in.)	2–5 mm (0.1–0.2 in.)	1–4 mm (0.04–0.2 in.)
0.9 m (3 ft.)	3–7 mm (0.1–0.3 in.)	2–5 mm (0.1–0.2 in.)
1.8 m (6 ft.)	7–13 mm (0.3–0.5 in.)	3–10 mm (0.1–0.4 in.)
6.1 m (20 ft.)	22–43 mm (0.9–1.7 in.)	11–33 mm (0.4–1.3 in.)

- Characteristic openings or breaks in a letter or number should be readily apparent.
- In darkrooms or other reduced-light locations, white letters on a black background tend to be more visible. In this case, the stroke width should be 1/8 of the height. The characters should be about 50 percent larger than the values shown in Table 5.11.
- If the sign or label is more than 200 cm (79 in.) above the floor, the character dimensions should be altered for better legibility. For instance, if a label or sign is placed substantially above head height and must be read by people working at ground level, character height should be increased in relation to width.
- Avoid the use of colored print. However, if colored letters or numbers must be used in order to take advantage of color coding, note that legibility may be reduced. Table 5.5 illustrates different combinations of colors and their legibility in normal lighting conditions. Use of color in reduced-light areas is less satisfactory. If colored light is used, color combinations should be tested in that condition to assess their legibility.

- Tailor the materials and methods used for constructing labels and signs to the environmental conditions. For instance, engraved labels should not be used in an area where dirt is likely to fill in the indentations. Paper labels should be given protective coatings if used in areas where corrosive chemicals are present.
- Place labels and signs on the equipment in the workplace so that glare, reflections, and shading do not make them difficult to read. If a sign or a label is placed outdoors, pay attention to the changing direction of the sun when locating it in order to improve its visibility. Matte surface paints may also be used to reduce reflections.
- Size and place labels or signs for curved surfaces (pipes or drums) so that the lettering remains readable from one viewing location.

Readability

Readability refers to the ease of reading words or numbers, assuming that the individual characters are legible. It is affected by the use of uppercase and lowercase, spacing, borders, and layout. The following guidelines show ways to improve readability of labels and signs:

- Use capital letters for headings or messages of a few words only. Use lowercase letters for longer messages. Do not use italics except when they are needed to emphasize specific words or short phrases. Underlining is an alternative method for adding emphasis.
- Avoid abbreviations. Use standard ones if they must be used. If no standard abbreviation exists, test the newly developed ones on inexperienced subjects in order to determine their appropriateness.
- Leave a minimum of one stroke between characters.
- Use a border to improve readability of a single block of numbers or letters (see Figure 5.4).
- If several labels or messages are clustered in the same area, put distinctive borders around the critical ones only. Keep the embellishments to a

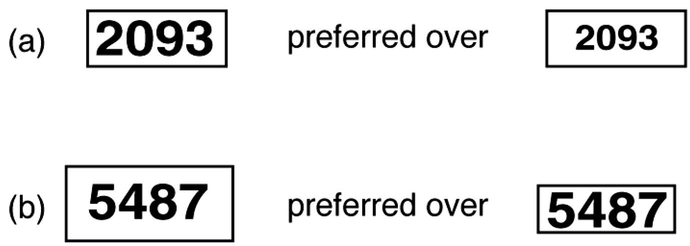


FIGURE 5.4 Spacing and Borders that Improve Readability
If space is limited and the character size is critical (a), it is preferable to fill most of the space within the border. If space is not critical (b), a larger surrounding border contributes to even better readability.

minimum, because each one reduces the effectiveness of display of the others.

- Place labels and signs in locations where they will not be damaged by painting or routine maintenance procedures
- Make the signs and labels accessible and easy to change if new procedures or equipment are likely to be added to the system. Permanently attached fixtures into which current labels and signs can be inserted are preferable to labels attached directly to the equipment or surrounding workplace.

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6 Work Design

ORGANIZATIONAL FACTORS IN WORK DESIGN

The Importance of Organizational Factors in Work Design

The design of good jobs must include not just ergonomically designed workplaces and equipment and temperate environments but also the organizational factors that affect the way the work is done and how much control the workers have over their work patterns and performance. In recent years, the term *macroergonomics* has been used to describe the more global approach to ergonomic design in the workplace (Hendrick 1986). Previous to that, sociotechnical systems and organizational development programs were evaluating the impact of social and psychological factors on job satisfaction and performance (Quick et al 1984).

With the leaner workforce and increased job demands of recent years, psychosocial factors in the job have become increasingly important. There were more ways to get around nonoptimal job designs in the past because there was some excess capacity in terms of personnel to assist or time to rework a process or product. Without those backup conditions, workers have fewer options to overcome excessive demands and to maintain quality performance when some tasks increase in difficulty or complexity for a short time. The factors outlined in this section are ones that should be considered when designing jobs and systems in a business.

One of the outcomes of designing with the organizational factors in mind should be a reduction in occupational stress, which is correlated to increased absenteeism, health problems, behavioral problems, and high turnover (Cooper and Payne 1988). In this context, stress is defined as the third, or exhaustion, phase of the general adaptation syndrome (GAS) (Selye 1975). The first stage of the GAS is the alarm reaction, where the body has a strong physiological reaction to the presence of a stressor. The second stage is the resistance stage, where the body and its systems adapt to the presence of the stressor by containing it, removing it, or living with it. When the stressor continues to be present for an extended period, the adaptation response energy may become depleted and the resistance is lost, subjecting the body to a higher risk of injury and illness. By building the factors listed below into the design of jobs, there will be less opportunity for fatigue and injury/illness, and the workers should be able to do quality work with less effort.

Organizational Factors Influencing Job Demands

The organizational factors in jobs can be seen through the eyes of the workers, the stress management professionals, or of the ergonomists. All three approaches are included in this section, with the emphasis on the workers' perspective. There is increasing interest in the quantification of these factors in order to better understand why some people appear to be more susceptible to occupational illnesses and injuries, such as musculoskeletal disorders, than others on the same job.

Many of the factors listed below have emerged from research on job stressors, and others have emerged from root-cause problem-solving sessions during team training sessions inside manufacturing companies. There is a strong interconnection between management policies, these psychosocial factors, and the extent to which they influence the workers' ability to work well and without excessive stress. For this reason, it may be useful to use a low/moderate/high rating for each one to indicate the degree of influence a factor appears to have on job stress.

Organizational Demands and Stressors and Their Management

The factors affecting workers' performance are described by four categories grouped by twos: the task and physical demands of the job, and the role and interpersonal demands (Quick et al. 1997). This suggests that the task and physical demands can be addressed by the following management approaches:

- Job and task redesign
- Participative management
- Flexible work schedules
- Career development
- Design of physical settings

The role and interpersonal demands can be improved by:

- Role analysis
- Goal setting
- Social support
- Team building
- Diversity programs

There are also prescriptions for the workers to manage their perceptions and responses to stress in order to prevent it from becoming excessive. Of the factors shown, ergonomists have focused on the design of physical settings and job and task design.

Workplace Stressors Associated with Occupational Illnesses

Another conceptual summary of factors associated with occupational illnesses (Cooper and Payne 1988) suggests that the following intrinsic factors may contribute to cardiovascular disease, immune disorders, and mental health problems:

- Work conditions (noise, chemicals, radiation, etc.)
- Technology (pacing, cycle time, etc.)
- Workload
- Responsibility
- Underutilization
- Lack of autonomy
- Role factors (conflict, ambiguity)
- Support from boss, colleagues, subordinates
- Organizational climate/structure
- Career factors
- Job mobility

Stressors in a Computer-Based Workplace

Another model has been developed to look at occupational stressors in computer workplaces (Cooper and Payne 1988). It divides the principal sources of stress into four categories: human factors/ergonomics constraints, work demands, organizational decisions, and personal characteristics. The factors within the first three categories are similar to ones discussed earlier. The personal characteristics factors relate to how the individual worker copes with the stress.

Human Factors/Ergonomics Constraints

- Workstation layout
- VDU and keyboard design
- Hardware characteristics
- Interface design

Work Demands

- Changes in work pattern
- Increased cognitive load
- Temporal and structural changes
- Constraints on planning and work strategies
- Opportunities for control and discretion

Organizational Decisions

- Introduction strategies
- Implementation and job impact
- Training and user support
- Long-term strategies
- Constraints on communication and social interaction

Personal Characteristics

- Stress tolerance
- Cognitive skills

Macroergonomics

Organizational design from a macroergonomics perspective (Hendrick 1991) includes consideration of the human-machine interface, the human-environment interface, the user-system interface, and the organizational-machine interface. This is preferable to a technological human-machine interface design without the inclusion of the social and organizational factors that determine how well the human can perform the tasks. In the presence of increased amounts of automation and technology that place high demands on human information-handling capabilities, the best designs will be ones that are human-centered and include ergonomics thinking from the conceptual stage. Designing subcomponents of a system ergonomically is much less effective because the human-environment interface may be suboptimal, preventing the humans from being able to use their capabilities.

Organizational designs can be evaluated by many measures. The over-all effectiveness of the system can be measured as productivity, efficiency, profitability, and quality, along with the health and safety, absenteeism, and turnover record. Employee morale, job control, motivation, participation in decisions related to their work, flexibility and adaptation to changing job demands, and job satisfaction should be considered when choosing technologies or equipment and when setting up materials flow patterns. Management skills, communication flow, and respect for the employees all influence how well the work can be done.

Designing a system with horizontal and vertical integration of the subcomponents and attention to the distribution of necessary functions and the amount of information needed to perform them allows one to achieve a more optimal and effective design than does designing each of the subcomponents ergonomically and toggling them together at the end.

Organizational Factors Contributing to Occupational Stress from the Workers' Perspective

The following organizational risk factors have been compiled from root-cause-analysis problem solving and accident-analysis training sessions in manufacturing plants (Rodgers and Williams 1987; Rodgers 2000). They bear a close resemblance to the lists above but have more detail on some of the specific factors that the workers consider stressful.

The first list divides the organizational risk factors into three major categories: job requirements, job control, and communications. These were generated by identifying the risk factors for injury or illness first, such as leaning forward, handling a heavy object on stairs, and so on, and then asking why until a root cause for the risk factor being present was reached. The purpose of reviewing this list is to identify risk factors in the "surround" of the task that people consider stressful so that the job can be improved even if the most stressful activity is difficult to change. For example, handling a patient in a chronic care facility is physically difficult and often requires the availability of specialized equipment and/or another nurse or assistant. If the equipment or another person is hard to find, and if time is important, one person may try to make a transfer and incur an injury. Planning the transfer by scheduling the task and ensuring that the extra person and/or the special equipment is available at the scheduled time will reduce the risk for injury. This is done by reducing the organizational problems that make it difficult for the patient handler to do the task safely.

Job Requirements

- Awkward postures
- Inadequate recovery time
- Heavy effort
- Complex tasks
- Environmental factors (heat, lighting, noise, vibration)

Job Control

- External pacing/automation
- Lack of flexibility—coping
- Tight standards
- Skill level
- Quality of parts
- Perceived job importance
- Inability to use skills

Communications

- Feedback and feed-forward
- Peer pressure
- Respect and sensitivity from supervision
- Coordination of return-to-work process
- Instructions/training
- Management policies
- Timeliness of response to concerns
- Understanding of overexertion injuries

Organizational factors are part of the picture in any accident investigation. The checklist below is part of one developed for an ergonomic approach to accident investigation in manufacturing and service plants (Rodgers 2000). The other three parts of the checklist are individual factors, job factors, and environmental factors.

Hours of Work

- Night shift worked/end of shift
- Extended overtime schedule
- End of year or before shutdown

Production Schedule Pressure

- Emergency situation—unusual
- Inadequate staffing for task
- Development task—deadline
- Quality problem
- Vacation coverage inadequate
- Seasonal demand
- Vendor or purchasing failure
- Communication failure

Training

- Inadequate initial training
- Inadequate follow-on training
- Inadequate health-and-safety and ergonomics training for job
- Standard operating procedures (SOPs) not clear
- Worker introduction to tools and equipment not adequate

- ◆ Worker returned after several weeks off of the job (vacation, illness or other assignment)

Policies/Style, Management Issues

- ◆ Preventive maintenance is not scheduled regularly
- ◆ Parts quality inadequate for task
- ◆ Inadequate tools or equipment
- ◆ Expense budget too small
- ◆ Investment budget too small
- ◆ Too many responsibilities to perform all needed tasks
- ◆ Inadequate communications between departments/cells
- ◆ Too little time to institute new processes, products, etc.
- ◆ Delays in communicating changes or projects to the production floor

Experience with this part of the checklist shows that it is used for more than the specific accident being investigated. Many of the items shown are more universal, and the workers need to bring them to management's attention. Rather than being a negative outcome, though, the list allows some of these issues to reach the attention of the people who can remedy them. Although this checklist was developed more for machine shop and metal fabrication jobs, it can be modified to fit other occupational groups. Its strength is in making people look for the multiple factors that contribute to accidents and in not affixing blame in one area, often on the worker who has been injured. By identifying more than one contributor to an accident/injury case, one can almost always improve something to reduce the risk of the same thing happening again.

Guidelines to Improve the Organizational Factors in Job Design

General Guidelines

It is generally recognized that organizational factors are important in any occupational setting, and that they contribute to the ability of the worker to perform well and to avoid excessive stress that could lead to injury, illness, and mental or behavioral problems. Following are some generic design guidelines that build on the concepts presented above. They have been developed mostly for engineering training courses in manufacturing plants. They have been tested in the field and found to be effective ways for the layout and process designers to think of the larger picture when doing their work (Rodgers and

Williams 1987; Rodgers 1986; Sauter and Murphy 1995; Cooper and Payne 1988).

- Design the system so that communications are enhanced. For example, if people are working in sequence on a manufacturing line, be sure they share information with the people before and after them about defects or other problems.
- Minimize manual handling of materials or product and other non-value-added activities. Design the materials flow to minimize the travel distances across the manufacturing system.
- Provide ways to have timely feedback on quality issues to the people making the products. Feedback that does not come until after a shift is done will not influence quality performance as much as feedback within 2 hours, for instance.
- Provide easy-to-use processes to allow feedback to supervisors on the job demands and workers' needs for equipment, tools, supplies, and so on. Participatory ergonomics processes are effective, but there needs to be some formalization of the feedback process so that things do not get lost.
- Provide a mechanism for the workers to be involved in the design process for their areas. For example, have the designer present his or her design concept to the ergonomics team. When possible, set up a test station on the floor that can be evaluated and critiqued by the workers and have them submit suggestions for improvement to the design team.
- Develop a process for involving the ergonomics team in evaluations of major equipment and tools prior to purchasing them.
- Identify potential human factors and ergonomics issues on equipment designs by reading the training manuals. Wherever there is a strong statement of caution to avoid doing something, that is usually a situation in which human error is likely to occur, and it should be addressed with an ergonomics or human factors design improvement. For example, if a machine operator is told never to turn on switch A if switch B is off, the switches should be cascaded to prevent that event.
- Formulate guidelines for how to handle emergency demands, quality problems, machine failures, labor shortages, and high numbers of short orders so that they do not result in putting excessive demands on the workers. These guidelines should be formulated by the workers and their supervision with the involvement of production planners, health and safety and human resources people, union representatives, and support staff, including maintenance mechanics and engineers. Options for addressing the overloads can include temporary adjustments to line speed, shifting of workers or supervision to the area until the problem is alleviated, rotating workers through the jobs so that they are not exposed to the extra work for extended periods, and so on.

- Provide workers with control over their pattern of work , giving them enough latitude to vary the muscle groups used and to work a little ahead and a little behind the line rate or production standards. For example, provide enough space to inventory 15 minutes of work at the workplace in high-volume operations. Power-and-free conveyor systems on continuous high-volume manufacturing lines are one way to give the worker some control over work pace.
- Develop a process for what the worker should do if poor-quality parts get into the manufacturing process. This might include guidelines for when to set up a subassembly operation to repair them if no others are available, or it might be a go/no-go decision point.

Two general philosophies for ergonomic system design are: (1) to be sure that the designer asks good questions of the workers who are familiar with the manufacturing process, work activity, equipment, tools, and working environment; and (2) to always ask what the person will have to do when technologies are placed in the system. One important question is to anticipate what the workers will have to do if the automation fails.

Design of Work in a Job Shop Production Department

CHARACTERISTICS OF JOB SHOP WORK The move toward reducing production costs by keeping inventories low that started in the early 1970s in many manufacturing plants (just-in-time production, JIT-squared, and design flow technology, for instance) has had impacts on the stress level of the workforce. Although the fundamental principles are sound from an economic standpoint, the decision to build to the order, rather than accumulate an inventory of low-volume products or parts, can have profound effects on the workload.

Most job shop work is characterized by having many runs of different products scheduled in a shift. This means that the production machine or system has to be adjusted and setups have to be done several times a shift. In a machine shop that services a manufacturing area, the priority for doing the work will be set by the impact the problem has on production demands. The hottest problem gets attention first. In a production department, the time when an order arrives and the promise made to the customer about delivery time will determine the priority for handling it. For a frequently ordered item, satisfying the delivery time promise is usually not difficult. But for rarer items, machine setup time becomes a significant part of the production time, and the department's work is often less efficient.

Many job shop schedules are set for just 24, 48, or 72 hours at a time rather than planned over a week or two. As a result, there may be a large number of orders for one or two items at a time. With a weekly schedule there will be more chances to run three or four at a time, improving efficiency and reducing waste from thread-ups, edge trims, orientation checks, or sample checks.

THE IMPACT OF JOB SHOP SCHEDULING ON WORKERS The primary justification for the trend to turn production departments into job shops has been to reduce in-house product inventories so their costs can be reduced. The role of the production planner becomes more critical when a product is not made until an order is received and when the customer is promised a 48-hour turnaround on the order. When the products are a series of color or size variations on the same basic materials (e.g., paper, paint, screws, etc.), the scheduling that permits the longest runs between changeovers is preferable.

Job shop production has a few positive aspects for the workers. Because long production runs are infrequent, it is unlikely that the workers will use the same muscles the same way for a majority of the shift. Changeovers to a new product require a different type of work, and usually delays occur between runs that allow tired muscles to get recovery time before the next run begins. Another advantage of job shop production work is that it requires more mental work by the operators as they try to plan the most efficient use of the equipment for their shift.

Some negative effects of running production on an as-needed basis are:

- The need to spend more time on machine setups and teardowns between product types
- The increased waste that can be generated at each product change (e.g., the thread-up product that will be lost each time one starts making a new product, such as a roll of sensitized paper)
- The difficulty of establishing a work rhythm when each cycle is only a few minutes between changeovers
- The reduced efficiency of manually handling different products on carts, trucks, or pallets and trying to keep them separate for the shipping department
- The increased potential for errors when very similar products are handled on the same assist devices (carts, bins, etc.) and held in temporary storage sites until they are shipped
- The loss of opportunities for using semiautomation to assist in the moving of products around the plant because the volume of any one product is low and often does not make up a pallet load
- A need for more training time for new workers in the area because of the probability that they will have to know the assemblies on many products from the beginning of their work time instead of working their way from simpler to more complex assemblies
- A need to inventory more parts on the floor or in adjoining "white zones" to be prepared for the product mix that shift;
- A reduced flexibility for substituting people into the line when the principal operator is ill, on vacation, or being trained for another job
- More stress on the quality assurance specialists to try to keep tabs on the quality of product arriving in small batches

DESIGN GUIDELINES TO REDUCE THE STRESS OF JOB SHOP WORK ON WORKERS

- Plan production schedules over a week instead of over 24-to-48-hour periods so that similar products can be clustered and fewer changeovers are needed. This provides for a more efficient use of time and better production control.
- Evaluate the appropriateness of using a job shop schedule for each production area. If the reduced inventory costs are not greater than the additional costs of more nonproductive machine setup time, more waste, and more quality problems, then the build-to-order process is not recommended.
- Review the flow of the product and materials in and out of the production area to be sure that the variety of parts and products can be segregated and shipped to the customers with little opportunity for error.
- Improve the machine setup or changeover procedures and streamline them in order to minimize the production down-time when products are changed. For example, simple fasteners and adjustment scales are ways to improve these operations.
- Decrease the need for heavy efforts and awkward postures during machine changeovers to reduce the opportunities for worker muscle fatigue.
- Increase communications between the sales and production workforces so that unreasonable deadlines to fill orders are not created.
- Allow the workers to work with the production planners and to have some freedom to alter the production schedule if necessary to improve efficiency. For example, if two different products can be made from the same master roll of paper, it is more efficient to run them sequentially than to run them with other products from different master rolls interspersed between them.
- When a new line is being designed, the information about product flow and type and available temporary storage space should be known before the system is started and the ergonomics considerations should be included in the conceptual stage.

HOURS OF WORK: SHIFT WORK AND OVERTIME

Introduction and Regulations

Although shift work and hours of work have been studied in the last half century, changes in social and cultural settings, individual and business economics, utilization of capital resources including machinery and plant facilities, and regulations have been implemented and have increased the efforts to study shift work in the United States and internationally (Jeppesen, Boggild, and

Larsen 1997; Kogi 1993; Smith, Macdonald, et al. 1998; Spurgeon, Harrington, and Cooper 1997) since the 1970s. Studies of shift work have included the effect of changing from 8- to 12-hour schedule systems (Duchon, Keran, and Smith 1994; Jaffe, Smolensky, and Wun 1996; Mitchell and Williamson 2000; Smith, Folkard, et al. 1998b; Tucker, Barton, and Folkard 1996), and the safety and health effects of working shift work and extended working hours (Frank 2000; Monk, Folkard, and Wedderburn 1996; Spurgeon, Harrington, and Cooper 1997).

The year 1985 saw the expiration of the Walsh-Healy Act, which had limited the number of hours that an employee (working for a company that did work funded by the U.S. government) could work in a 24-hour period before being paid an overtime differential. As a result, companies began to explore opportunities to work longer shifts and compressed workweeks. The European Community Directive on Working Time (ECD 93/104/EC), introduced in November 1993, addresses the organization of working time and requirements related to working hours. It was implemented by the member states in November 1996. In June 2000 the directive was amended to include traveling or flying transport services for passengers or goods by road, air, or inland waterway; "offshore work," or work performed mainly on or from offshore installations, to be implemented by January 2003; and for doctors in training, to be implemented by August 2004. This directive has generated many studies looking at the various aspects of working hours, including shift work systems.

Shift Work and Employee Health and Safety

Employees working shift work are exposed to health and safety issues related to social factors, psychological factors, behavioral factors, and physiological factors, such as sleep deprivation.

Coronary Heart Disease (CHD)

The relative risk for coronary heart disease (CHD) for shift workers has been shown to gradually increase given the number of adverse lifestyle factors in their work, such as stress associated with social and psychological problems; shift-work-related behavioral patterns such as smoking (Knutsson and Nilsson 1997) and unhealthy nutrition habits (Stewart and Wahlqvist 1985); and sleep deprivation caused by disturbed circadian rhythms (Brugere et al. 1997; Knutsson and Boggild 2000).

Psychosocial Factors

Shift work has been shown to affect social/domestic factors, and psychological well- being may be affected by stress and sleep deprivation. Shift workers as a group suffered no more depressive symptoms than traditional workers. However, while both sexes had similar mean scores on depression among the shift workers, however, the women were significantly more depressed than the men among traditional workers (Goodrich and Weaver 1998). Exposure to shift work has been shown to be associated with an unexpectedly high prevalence of identified major depressive disorder occurring during or after shift work, with a higher rate for women than for men (Scott, Monk, and Brink 1997).

Sleep

Night shift workers show decrements in performance that are expected of people suffering from chronic sleep deprivation, and this may relate to productivity problems, safety issues, or health concerns. Sleep disorders may be an additional problem facing night shift workers. They report difficulty falling asleep or staying asleep at rates higher than workers who do not work nights, and many times they practice poor sleep habits as well as sleep longer to recover from the accumulated fatigue of working night shifts (Folkard et al. 1985; Garbarino et al. 1999; Knutsson and Nilsson 1997; Tepas and Carvalhais 1990).

Given the issues directly or indirectly associated with shift work, an active prevention program should be instituted to promote more positive sleep and nap strategies, exercise, nutrition, and other health-related behaviors to shift workers (Atkinson and Reilly 1996; Miyazaki et al. 2001; Rosa et al. 1990; Stewart and Wahlqvist 1985; Tenkanen, Sjoblom, and Harma 1998; Tepas and Carvalhais 1990).

8-Hour Shifts Versus 12-Hour Shifts

As more experience is gained and research performed, the effects of shift work and, in particular, extended or 12-hour shift systems will be better understood, specifically the long-term effects. Smith, Macdonald, and colleagues (1998) performed a review of the literature studying the differences between 8- and 12-hour shift systems. The evidence suggests that few differences exist between 8- and 12-hour shift systems in the way they affect people. There may even be advantages to 12-hour shift systems in terms of lower stress levels, better physical and psychological well being, improved duration and quality of off-duty sleep, and improvements in family relations. One such schedule change showed improvements in health, particularly in psychological health, and in reduced feelings of tiredness throughout the work period (Williamson, Gower, and Clarke 1994).

On the negative side, the main concerns are fatigue and safety (Smith, Macdonald, et al. 1998). Reducing the aerobic requirements by 5 percent from acceptable 8-hour shift limits can eliminate possible fatigue derived from performing aerobic work over a 12-hour shift (Rodgers 1997). Work requirements should be measured and analyzed with the goal of reducing the effect of nonaerobic accumulated muscular fatigue as well (Rodgers 1987, 1988, 1992). Because physical and mental fatigue can be related to possible sleep issues, the long-term effects might be more critical. Smith, Macdonald, and colleagues (1998) noted that the effects of longer-term exposure to extended workdays have been relatively uncharted in any systematic way.

It would appear that if there is a need to change shift schedules and 12-hour systems are an option, changing to a 12-hour system could be beneficial. However, fatigue and sleep issues need to be addressed when one adds 4 hours as "overtime" simultaneously reducing the recovery time between shifts by 4 hours. The number of consecutive shifts worked must also be considered.

Overtime Considerations

Overtime is often used to manage peak schedules and/or head count. The hours worked during overtime can approach the same hours worked during a 12-hour system. However, overtime is typically applied with little regard to the number of consecutive shifts worked. Aging and understaffing have been shown to interact with schedule by necessitating overtime and reducing the actual number of rest days. These, in turn, affect fatigue and reliability (Bourdouxhe et al. 1999).

Rodgers (1997) noted that if overtime or 12-hour shift systems are worked, especially more than three days in a row, the fatigue and acceptable workload of the employee should be considered. Reducing the limit for aerobic work for an 8-hour shift by 5 percent would be an appropriate limit for routine overtime situations as well. Recovery time between workdays would be reduced, so increased accumulated fatigue and increased muscle soreness can occur in the soft tissues, including muscle-tendon and tendon-bone junctures (Garrett 1990).

Aging Considerations

More experience and research are needed to understand the long-term impact of shift work and, in particular, extended or 12-hour shift systems on aging issues. Some aging-related issues that are important to consider in the design of shift work systems include the following:

- Older, more experienced operators may practice energy-reducing methods and effectiveness enhancements, allowing them to work with less fatigue during shift work (Volkoff 2000).
- There may be a selection effect, in that the employee who isn't capable of adapting to shift work stops working shift work between the ages of 42 and 52 (Marquie, Foret, and Queinnec 1999).
- With recent legislative changes in the United States encouraging a delay of the retirement age by five years, the effects of shift work on older

operators may be observed to a greater degree in the next five to ten years as well (Bourdouxhe et al. 1999).

- A time-delayed response for shift workers before experiencing any psychological and health problems has been associated with an increased lifetime risk for major depressive disorders when exposed to shift work for up to twenty years (Scott, Monk, and Brink 1997).
- There is a cumulative effect for age and shift work, with an increasing risk of crossing a threshold beyond which a schedule is no longer tolerated (Brugere et al. 1997).

As companies change the workforce levels to meet demand, they may hire fewer people, which means there will be fewer employees to place in shift work and limitations on reassignment of the current older workers to nonshift work (Bourdouxhe et al. 1999). These findings further support the observation that the redesign or design of shift work systems needs to account for fatigue, as much as possible, to become more in line with the shift worker's needs.

Shift Work Characteristics

If extended work shifts (10- and 12-hour) are to be implemented, care must be taken to consider the characteristics of the shift work through proactive shift system design and its timely modification. The characteristics of shift work that are known to be effective and to meet the psychological, social, and physiological needs of shift workers practices are presented in Table 6.1.

The characteristics given in Table 6.1 must also be considered within the work system, including operational, compensation, and work environment requirements.

Shift Work Design and Redesign Process

Spurgeon, Harrington, and Cooper (1997) state that there are a range of modifying factors that influence the level and nature of health and performance including the attitudes and motivation of the people concerned, job requirements, and other aspects of the organizational and cultural climate related to shift work. This suggests that a systematic approach include sociotechnical systems to be used in the redesign or design of shift work systems using the previously-mentioned shift work characteristics. A sociotechnical approach applied to work systems is also known as macroergonomics (Hendrick 2001). Organizational factors affecting job design are discussed earlier in this chapter.

A participatory process, which is a specific sociotechnical tool, is very important in generating a compromise between the employer's goals, the wishes of the employees, and ergonomic recommendations for the design and implementation of a new shift system (Knauth 1997).

Table 6.1
Guidelines for Designing or Selecting Alternative Work Systems

1. Specific night shift issues:
   - Straight night shifts should be assessed very carefully to minimize negative effects and provide strategies to accommodate the specific night shift issues.
   - Keep consecutive nights to less than four in a row. when possible.
   - Provide adequate rest periods of at least 24 hours after each night shift period. More rest time should be given when more consecutive nights are worked before the next rotation occurs.
2. Overtime considerations:
   - For extended shift systems, avoid overtime solutions that further extend the shift time to avoid further decreasing the hours of recovery between shifts. For example, if a 12-hour shift system is employed, avoid overtime that would extend the shift to 16 hours.
   - If extended periods of non-seasonal overtime work occur on 8-hour shifts and, as a result, shift time is extended or consecutive shifts are required for more than 3 months, institute some form of alternative work schedule (AWS).
3. Shift design issues:
   - Consider forward-rotating schedules unless, through employee feedback, having a long weekend (on 8-hour systems, four-plus days) once a month is seen as being a better benefit.
   - Continuous shift systems should have rest days fall on all or part of the weekend, when possible.
   - Special considerations, screening, or instituting some form of AWS for the time period needed should be applied if the number of consecutive shifts exceeds eight.
   - Short-cycle rotations on continuous shift work systems are generally preferable to long cycle rotations, such as a monthly rotating system. The physiological advantages of longer rotations are usually overridden by the psychosocial disadvantages.
   - Time off between shifts should be maximized as well as time off between blocks of consecutive shifts (fewer than four for 12-hour systems).
   - Travel time should be considered, especially for extended systems, because of shortened recovery time.
   - Shift start times should not be scheduled to start too early in the morning, as that reduces the workers' sleep duration, since family/social pressures tend to keep bedtime constant (around 10 pm).
4. Type of work:
   - Review the type of work and any limitations required considering the characteristics of the shift schedule and the nature of the task.
   - Physically, mentally, or perceptually demanding work may not be well-suited for extended shift hours.

Table 6.1 (Continued)

- ◆ Work that is acceptable for day shifts may be excessive for night shifts.
- ◆ Exposure to chemicals or physical agents should also be considered when selecting a shift system.

5. Psychosocial characteristics:
   - ◆ Spread the positive and negative aspects of any shift schedule as equitably as possible across the crews.
   - ◆ Allow flexibility between employees and across shifts either by design of the shift system or through an informal system.
   - ◆ Allow more than one type of shift schedule, if possible, to create flexibility for the employees and more options for coverage of increased work demands.
   - ◆ Avoid complex schedules, or frequent changes in shift schedules, which make it difficult for the worker, family, and friends to know which are workdays and which are days off. Keep the schedule as regular as possible.

These guidelines are adapted from Eastman Kodak Company Ergonomics Group 1986 and Tepas, Paley and Pokin 1997.

Work is a series of systems driven by business requirements and needs given specific sociotechnical and environmental parameters. Shift work is a result of business needs within a large sector of companies and businesses. If shift work is considered a required aspect of certain work systems, then a work system approach should be taken to address shift work issues and possible changes. A limitation in studying shift work and applying shift schedule system changes is the number of variables, including individual, type of work, type of shift being worked, sociotechnical systems, outside environmental issues, labor agreements, and psychosocial and cultural issues in the region that may be directly or indirectly influencing the outcomes of the effort. This further supports a sociotechnical approach using a participatory model to address shift work systems. The following case study presents such a model.

Case Study: Shift Schedule Redesign Project

History

A plant had been operational for about 13 years. One portion of the plant had been operating on a 5-day continuous operation with three weekly backward-rotating 8-hour shifts. Initially, the weekends were shut down because of ramp-up and low demand. Maintenance and cleaning operations were performed on the weekends. This was consistent with the culture of the region (rural), since there were few manufacturing operations, let alone continuous 7-day operations. After about 11 years of operation demand was higher, more hours were being worked, and overtime became common and even expected.

The operations were made continuous and another crew was added, for a four-crew weekly backward-rotating 8-hour shift. See Table 6.2.Operations had been working this schedule for about 2.5 years. There was growing employee dissatisfaction with the current schedule, including fatigue, health and safety, and social issues; there was also increasing concern with performance issues. This coincided with the results of a study that compared an 8-hour weekly backward-rotating shift to other shifts. The 8-hour backward-rotating shift work group fared worst when compared to other shift work systems, in sleep quality, physical well-being, and time for family and personal pursuits. The differences between the groups were believed to reflect the stress of the respective work shift schedules (Jaffe, Smolensky, and Wun 1996).

Alternative Work Scheduling (AWS) Process Outline

This effort was coordinated plant wide by a doctor who was both plant Medical Director and a production organization Assistant Director (Amoroso 1986). The plant General Manager and leadership team were fully supportive of this effort. The ergonomics group coordinated organizational and departmental AWS efforts.

Planning entailed designing and developing a process to analyze issues associated with shift work employees and the associated health, safety and work system parameters. The information would help determine strategies for adapting to shift work, organizational design change needs, workplace environment solutions, and a possible redesign of the current shift schedule. The AWS process was integrated into a program based on quality, continuous improvement and optimized work environment. The following steps made up this AWS process:

1. An outside consultant was retained for the AWS process (Krieger 1986).
2. An AWS steering committee (AWS SC) was established. This group included representatives from leadership, medical, industrial relations, operations, payroll/compensation, training, and ergonomics.
3. Payroll/compensation and operations design teams representative of critical functional areas were established to define critical boundaries and needs for their respective functional areas.
   - The payroll/compensation design team (PDT) addressed pay practices and policies to make the work schedule change possible.
   - The operational design team (ODT) identified and considered operational needs, including manning, unplanned absenteeism, and training.
4. The workplace environment design team (WEDT), comprising medical, industrial hygiene, safety, and ergonomics representatives, implemented a workplace AWS assessment model for collecting, analyzing, and defining alternative strategies and solutions as well as follow-up. Specifically, they considered tasks that might be within normal limits

TABLE 6.2
Schedule for Pre-AWS Study (Four-Crew, 8-Hour, Backward-Rotating)

	Week 1							Week 2							Week 3							Week 4						
Crew	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S	M	T	W	T	F	S	S
1	R	B	B	B	B	B	B	B	R	R	A	A	A	A	A	A	A	R	R	C	C	C	C	C	C	C	R	R
2	B	R	R	A	A	A	A	A	A	A	R	R	C	C	C	C	C	C	C	R	R	R	B	B	B	B	B	B
3	A	A	A	R	R	C	C	C	C	C	C	C	R	R	R	B	B	B	B	B	B	B	R	R	A	A	A	A
4	C	C	C	C	C	R	R	R	B	B	B	B	B	B	B	R	R	A	A	A	A	A	A	A	R	R	C	C

A = 7 A.M.–3 P.M. (day), B = 3 P.M.–11 P.M. (evening), C = 11 P.M.–7 A.M. (night), R = rest

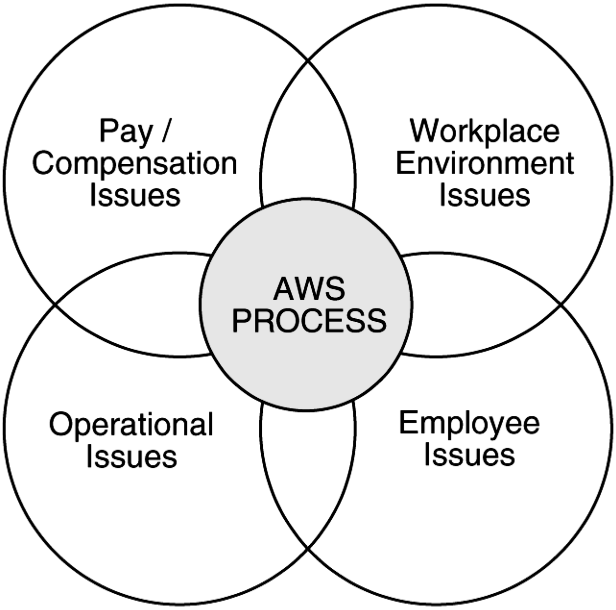

Figure 6.1 Alternative Work Schedule Process Components

for an 8-hour working shift but would be of concern when performed in a 12-hour shift. Whether or not these recommendations could be adopted would determine if extended work hours could be considered in the AWS process. Employee input was gathered during interviews, observations, and actual ergonomics/industrial hygiene/safety problem-solving techniques. See Figure 1.5 in Chapter 1.

5. To develop in-house expertise, the outside consultant provided a "train-the-trainer" course for internal shift work change facilitators, who would deliver employee training sessions conducted in groups of ten to fifteen.
6. Formalized leadership boundaries and guidelines developed from the work of the three Design Teams were used to focus on the overall AWS process, help define the limits of schedule design for individual operational departments, and to allow the project to proceed to smaller groups of department employees.
7. An AWS employee survey was designed by a team consisting of the company's health care specialist / trainer, the outside consultant, the plant AWS coordinator, and the ergonomics specialist. This survey was designed to collect information from the participating organization/ department employees, including pertinent demographic profiles, health beliefs and practices, and individual shift preferences (Howell

1986). This survey was administered at the end of the employee education session. Six-month and 1-year follow-up surveys were administered and reported to AWS committees as well as at organizational/department employee meetings.

8. Employee education and information-gathering sessions were instituted. The initial AWS study population consisted of 284 employees working shift work. All affected employees were trained in small groups of ten to fifteen. An introductory presentation (60 minutes) was given outlining the basic physiological, medical, and psychosocial aspects of shift work. These sessions were provided around the clock during the employees' working shifts. The AWS survey was completed by each employee. A second session was scheduled a week later to elicit feedback about the schedule preference as well as about specific issues raised by the AWS survey.
9. After the employee education group sessions, members from each AWS design team and organization/department leadership participated in a debriefing session to formulate a consensus of worker preferences and desires.
10. Combined design team boundaries that considered all parameters and limitations of the schedule redesign were outlined and summarized.
11. In the schedule design process, first payroll/compensation, operational, and work environment issues were identified and analyzed, and strategies were developed to reduce or eliminate the issues. After these strategies were implemented, shift worker schedule preferences were considered. Members of the design teams and the outside consultant drafted potential versions of schedules that met all requirements. These were presented to the AWS SC for review and analysis.
12. The employee groups met and reviewed the possible alternative schedules. These sessions covered payroll, operations and medical implications of the schedule(s). A specific schedule was identified as the most optimal considering all issues studied, particularly the employee's preferences and AWS survey outcomes. Although each organization/department could select from thirteen different schedules, one schedule became the consistent selection. See Table 6.3.
13. A date was established for schedule implementation. Spouse/roommate sessions were also scheduled. The spouse/roommate sessions had few attendees.
14. As part of the process of follow-up evaluation, it was determined that the new shift schedule would remain in place for at least 6 months, and ideally 1 year. However, if major issues arose during that time, changes could be made earlier. It was specifically agreed to adhere to the AWS process as the AWS SC and design teams had outlined it. A 6-month and 1-year survey was administered to determine the longer-term (seasonal) effects of a new work schedule. The monitoring and

TABLE 6.3
Schedule Selected After AWS Process [Four-Crew, 12-Hour, Rotating Schedule, Every Other Weekend Off)

	Week 1		Week 2		Week 3		Week 4	
Crew	MTWTF	SS	MTWTF	SS	MTWTF	SS	MTWTF	SS
1	DRRNN	RR	RDDRR	NN	NRRDD	RR	RNNRR	DD
2	RDDRR	NN	NRRDD	RR	RNNRR	DD	DRRNN	RR
3	NRRDD	RR	RNNRR	DD	DRRNN	RR	RDDRR	NN
4	RNNRR	DD	DRRNN	RR	RDDRR	NN	NRRDD	RR

D = 7 A.M.–7 P.M. (day), N = 7 P.M.–7 A.M. (night), R = rest

feedback process was achieved through small groups and through regular plant/organization/department communication channels.

Outcomes

Because of the internal changes occurring in production and quality and work system efforts, the results could not be attributed solely to the shift work schedule change studied during the AWS Process. At no time was any variable or issue considered to be a "showstopper," causing the organization to revert to its original 7-day, 8-hour schedule.

The following outcomes of the shift schedule redesign, one year later, comparing the 7-day, 8-hour backward-rotating schedule to the new 12-hour schedule, were significant:

- The population studied did not change significantly over the year. This was a relatively young population (49 percent under 35 years, 29 percent between 36 and 45 years, and 18 percent over 45 years), and about 47 percent had worked 11 years or more with the company. This may depict relatively limited experience with shift work systems. About 15 percent of the study population was female.
- Fewer workers (n = 214) completed this survey compared to the original one (n = 284); specifically, one department didn't because they didn't want to take part in any more surveys and liked this schedule.
- About 11 percent of employees found the 12-hour schedule to be less of a problem for obtaining childcare compared to the 8-hour schedule ($p = 0.02$).
- Overall, 7.5 percent more employees had more sleep on a typical 12-hour shift compared to the typical 8-hour shift ($p = 0.001$).
- Approximately 9 percent fewer employees fell asleep or nodded off while working a 12-hour night shift compared to an 8-hour night shift ($p = 0.001$).

- Approximately 17 percent more employees felt that their work had a better effect on their health when working the 12-hour shift compared to the 8-hour shift (p = 0.0001).
- Comparing the 12-hour shift to the 8-hour shift schedule, employees listed their degree of satisfaction considering each of following items:
  - Health - approximately 30 percent were more satisfied (p = 0.0001).
  - Sleep - approximately 56 percent were more satisfied (p = 0.0001).
  - Time with family - approximately 61 percent were more satisfied (p = 0.0001).
  - A full social life - approximately 38 percent were more satisfied (p = 0.0001).
  - Freedom in the daytime - approximately 28 percent were more satisfied (p = 0.0001).
  - Weekends - approximately 61 percent were more satisfied (p = 0.0001).
  - Communication with daytime leadership - approximately 29 percent were more satisfied (p = 0.0001).
  - Access to employee services (credit union, safety shoes) - approximately 27 percent were more satisfied (p = 0.0001)
- Approximately 29 percent more employees liked shift work while working the 12-hour shift schedule compared to the 8-hour shift schedule (p = 0.0001).
- Only 7.5 percent of employees were dissatisfied with the 12-hour shift schedule, which is significant considering that typically 20 percent of employees working shift schedules are dissatisfied with any shift schedule worked.

Conclusions

This AWS process was used to implement schedule redesign for approximately 1,000 additional employees working 7-day and 5-day backward-rotating schedules during the period 1986–1988. Any current schedule change considerations use this AWS Process. The organization presented in this case study is continuing to work this same schedule today, 14 years later.

Some general observations showed that these special considerations must be made in the AWS process:

- It is more difficult to implement 12-hour schedules in smaller departments because of increased coverage difficulties and issues related to training. Vocal minorities also appeared to have greater influence in smaller departments.
- Shift work may exacerbate underlying health or psychosocial issues for individual employees. This appears to be true when working an extended-hours shift work schedule as well. Each case must be seen in terms of its individual merits.

- There must be a certain adaptation or transitional phase, from a psychosocial as well as a physical perspective, for workers working extended shift work schedules. For example, when working 12-hour shifts, some employees might feel more fatigued in their feet and legs because they are exposed to 4 additional hours of walking and standing. These issues should be analyzed specifically for that job, and solutions should be developed that would lower the accumulated effect or treat the individual specific issue.
- Care must be taken in selecting AWS alternatives, most notably the schedule that has larger blocks of days off in a row. In order to gain the longer blocks of time off, more consecutive shifts must be worked. This was not desirable from the standpoint of production, health and safety concerns, and comments from several employees working very different jobs also indicated that they experienced fatigue from working three consecutive 12-hour day or night shifts.
- Changing shift schedules from 5-day, 8-hour shift schedules, with weekends off, to combination 12- and 8-hour schedules (to allow for more time off) are more difficult for AWS consideration. Primarily, this relates to having known time off that generally coincides with that of the traditional 5-day workweek.
- Changing shift schedules from a 5-day, 40-hour week, with weekends off, to a 7-day schedule must be carefully planned from a work system perspective, be closely monitored, and incorporate a great deal of awareness, adaptation strategies, and flexibility for the employees.
- Some shift workers felt that the 12-hour shift was long and the third consecutive shift more fatiguing than the initial two. But, considering the overall shift schedule normally worked on a 7-day schedule (rotating or straight shifts), most employees felt that the specific 12-hour schedule selected was a much better alternative.
- Other considerations include:
  - Selection of AWS alternatives (hidden agendas, pitfalls)
  - The need to address overtime issues and call back systems
  - Dealing with management, supervision, and power brokers

A formalized, structured approach of using participatory methods to develop prevention strategies for shift work problems will clarify responsibilities and communication needs (Day 1998; Jeppesen, Boggild, and Larsen 1997). Such a systematic, formalized approach is supported in recent international regulations that have focused on guidelines for enterprise-level consultations on shift schedules, promotion of health and safety measures, and participatory strategies for locally adjusted shift work arrangements and social support (Kogi 1998). Shift work interventions should also include a program that periodically monitors workers' tolerance for shift work and provides information and recommendations for employees to effectively manage a lifestyle that incorporates nighttime work schedules (Duchon, Keran, and Smith 1994; Siebenaler and McGovern 1991) See Chapter 1 for further information on ergonomics programs.

ERGONOMIC WORK DESIGN

Goals in the Design of Jobs

From an ergonomics perspective, a well-defined job is one that most of the potential workforce can perform well without excessive stress. Some of the characteristics are:

- Physical dimensions are such that reaches, clearances, and work heights accommodate the capabilities and characteristics of at least 90 percent of the workforce.
- Peak loads are within the strengths or endurance capacities of at least 90 percent of the workforce.
- Environmental factors do not place unacceptable risk or performance limits on most healthy workers.
- Perceptual, cognitive, and visual demands are within the capacities of most workers, including the older ones.
- Job repetition rates and pacing are not excessive, and the workers have control over their work patterns.

The ultimate goal for the employee and the employer is to make it easy for quality work to be done without unnecessary risk of injury or illness because of biomechanical, physiological, or psychological overload.

The Measurement of Work Capacities

To design work within the capacities of most people, one has to be able to define those capacities. Whole-body aerobic capacities are used as the basis for most total workload guidelines, and upper-body aerobic capacities are used for work where much of the effort is made by the upper extremity muscles. The work capacity of the arms and upper body is roughly 70 percent of whole-body capacity. Information on the recommended data to be used for determining how to design for most people can be found in "For Whom Do We Design?" in Chapter 1.).

Some of the relevant work capacities used to determine acceptable physical workloads are:

- Aerobic work capacity—whole body
- Aerobic work capacity—upper body or large muscle groups

- Aerobic work capacity—lifting tasks specified by weight, frequency, and locations of lifts
- Aerobic capacity in the heat—whole body, different heat/humidity levels
- Muscle strengths—3-to-4-second efforts in a posture specific to the job demands, varying with the location of force application. This is often a static measure, but dynamic lifting capacity is probably a more accurate simulation of occupational lifting tasks.
- Muscle endurance—continuous effort at a specified level (usually the force required by a task) to fatigue. Time to fatigue is the measure of interest since it helps to predict the percent of strength used
- Muscle strength for gripping—pinch and narrow- and wide-span grips, as well as effects of wrist angles on those strengths
- Maximum voluntary lift weight, which is specific to grasp and container design.

There are many other tests for flexibility, spurt work, reaction time, high repetition muscle activity, and balance that may be relevant in studying a particular job, too. These and psychological testing methods to determine work capacities are covered at length in the writings of Fleishman (1964, 1982).

Designing to Minimize Fatigue

When they are on the job for 8 to 12 hours a shift, what most people monitor in themselves is fatigue (Rodgers 1972). This could be physiological fatigue, sensory or perceptual fatigue, or a fatigue more associated with social interactions or organizational factors on the job. Physiological fatigue can be viewed as a whole-body sensation of exhaustion or a localized sensation referenced to one or more muscle groups. Factors that contribute to sensory and perceptual fatigue are discussed in Chapters 3, 4, and 5. See also "Organizational Factors in Work Design" earlier in this chapter.

Signs of Fatigue

There are some basic similarities between all types of fatigue. When measuring work performance on a task within the individual's skill set, decrements in performance over time may be an indication of physical or mental/perceptual fatigue. A more sensitive measure of fatigue includes an evaluation of the physiological cost of performing the task at the required level. The physiological cost is often a cardiovascular measure, such as heart rate, blood pressure, or arteriolar peripheral resistance affecting flow in the small blood vessels of the hands or earlobe (Sternbach 1966). At the beginning of the shift, the work is being done well within the person's capacity and with low cardiovascular stress. By the end of the shift, the performance might be similar but the cardiovascular stress may be substantially elevated.

For psychological fatigue, a secondary task, such as mental arithmetic or detection of a random signal, may be used to explore how alert the person is at different parts of the shift (Kalsbeek 1971). The secondary tasks have to be long enough to show the true status of the mental or perceptual work processing systems because short tasks (less than 2 minutes) can be overcome by the worker's motivation to perform well on the primary task (Singleton 1962). These are indirect measures of the person's "reserve capacity."

It is not uncommon in manufacturing to see people working at higher production rates at the beginning of the shift and at much lower rates near the end of the shift to compensate for fatigue. Other factors also determine how individuals arrange their work over the shift, but few people pace themselves evenly over the 8 to 12 hours unless they are tied to a machine. (Workers' ability to change their pace is a positive aspect of an ergonomically designed job, but fatigue should not be used as the mechanism for achieving that goal.)

Serious fatigue can be seen clearly if a person goes to exhaustion. The cardiovascular and musculoskeletal system can be pushed by the worker's motivation to perform very well. As a result, he or she may effectively "collapse" when the driving stress is removed at the end of the activity. It takes much longer to recover from sustained heavy work than it does from intermittent heavy work where the continuous effort is less than 15 minutes at a time. In industrial tasks it is unwise to have people working for extended periods at high percentages of their work capacities. Short, heavy work activities (15 minutes continuously) that are within the peak capacities (strength, endurance) of a large majority of the potential workforce become risky if they are sustained for 30 or 45 minutes continuously. Recovery time is needed to re-establish the muscles in the rested condition and to wash out the lactic acid accumulating in them from the high efforts.

In this section, the emphasis will be on physiological fatigue. Whole-body fatigue is usually driven by cardiopulmonary strain as reflected in metabolic energy expenditure. Environment, especially heat stress, further contributes to cardiovascular strain with lesser contributions from vibration, noise and psychological factors. Specific muscle groups may fatigue due to an overall pattern of static efforts resulting in insufficient perfusion of blood.

Workload and Fatigue

Static work is characterized by sustained muscle contractions. Generally, static work leads to localized muscle fatigue and is not associated with high metabolic demands. Dynamic work is characterized by rhythmic muscle contractions and the obvious movement of arms and legs. Dynamic work is associated with the performance of external work (exerting a force through a distance) and elevated metabolic demands; and it leads to whole-body fatigue.

A simple model with which to frame physiological fatigue is the buildup of lactic acid. Lactic acid is a metabolic product that accumulates in a muscle group when there is insufficient oxygen to support the metabolic demands.

Within this framework, the potential for fatigue is a composite of relative effort level, effort time, and recovery time. The quantitative means to assess work demands with respect to fatigue are provided in Chapter 2. The principles are repeated here only to the extent that a qualitative sense of how fatigue may develop can be presented and design goals highlighted.

The relative effort level is the feature most sensitive to individual capacity for effort because it is the effort as a fraction or percentage of the individual capacity. From a design point of view, the design capacity is that of the least strong and least fit worker who might be on that job.

In the broadest sense, the likelihood of causing fatigue, and the time it takes to recover from it, depends on:

- The distribution of tasks in the job
- The degree of control the worker has over the work pattern and the order in which the tasks are done
- The recreational or domestic activities done outside of work
- The number of hours the worker rests between shifts

The first feature is most readily controlled by the job designer. Local muscle fatigue works in a time framework of minutes while whole-body fatigue might be viewed within a framework of minutes to hours. The second (individual control) is a mix of job design and operating philosophy. For local muscle fatigue, again the framework for consideration is minutes while it can be an hour or more for dynamic work. The last two have much more to do with dynamic work than with local muscle fatigue. They are outside of workplace control but are points to raise during training of employees.

Static Muscle Work

MECHANISMS OF STATIC MUSCLE FATIGUE Work that requires sustained muscle contractions has a strong potential for local muscle fatigue. The first factor in the consideration of static work fatigue is relative effort. When two people are asked to hold a heavy weight, they can do it for a short period of time but will eventually stop, and the stopping time is likely to be different for each. The stopping time is influenced in major ways by individual strength and motivation. In a well-motivated person, the muscle group will cause considerable discomfort to the individual before it becomes exhausted (endurance time). Asking participants in tightly controlled studies to hold until exhaustion is an accepted means of getting reliable data, but this is less helpful for direct job design. That is, it should not be viewed as a design goal. When a more subjective limit is sought, such as the time to change hands, the time can be shorter, again depending on the motivation of the individual, and the data are much more variable.

A major influence on endurance or acceptable holding time is strength, also called the maximum voluntary contraction, which is the greatest force that a person is willing to exert for a brief period of time (typically 6 seconds). Endurance time is related to the holding effort and individual strength through relative effort expressed as a percentage of the maximum voluntary contraction (%MVC). This relationship is shown in Figure 2.10 in Chapter 2. Following the simple model of lactic acid accumulation, there is a low but not zero risk with relative efforts below 15 %MVC, and the rate of accumulation increases with increasing relative effort. As the relative effort increases, the endurance time drops as a power function, where the greatest drops occur at the lower effort levels.

Besides strength, relative and absolute effort depend on posture and biomechanical considerations. There is an optimum posture for each muscle group at which the greatest strength is exhibited. For instance, the greatest elbow flexion strength will be seen when the included angle between the forearm and upper arm is about 90°. With elbow angles that are different, strength will decrease. Across most joints, this is due to lengthening or shortening the muscle group outside of its optimal range with some biomechanical disadvantages added for good measure.

Above and beyond holding an object, some muscles may be under static contraction to maintain a posture. For instance, bending forward causes a static contraction of the back muscles and raising the elbow places a demand on the shoulder muscles. While a little more difficult to assess, strength can be viewed as the maximum moment that can be developed around the joint in the posture of interest, and the effort by the moment created by the body parts maintained in that posture. (See "Biomechanics" in Chapter 2 for more details on the computation of moments.) Basically, the body parts have weight, this weight must be supported, and the effort for supporting it comes from muscle contractions.

A second important factor in inducing local muscle fatigue is the contraction time. The concept is simple: the longer the muscle remains under contraction, the more time lactic acid has to build up. Because the rate of buildup depends on the relative effort, the total accumulation depends on relative effort and contraction time. As the accumulated level increases, the sensation of discomfort will increase. Finally the muscle will reach a stage of exhaustion, where no further effort is possible. In practice, it is not often that the muscle will be exhausted with just one effort. What is likely is that the debt associated with the build up is not paid off in full during a period of relaxation and thus accumulates.

The third factor in fatigue is recovery time. It is reasonable to assume that there is no overall reduction in the accumulated lactic acid (debt) until the muscle relaxes. At this point, oxygen and glucose are brought into the muscle via the increased blood flow and the accumulated lactic acid is moved to the liver for rebuilding glycogen supplies. The amount of time required to bring the muscle back to a resting state depends on the accumulated lactic acid and, therefore, on the combination of relative effort and contraction time.

Because there are three inter-related factors in local muscle fatigue, the designer of the work can manipulate two of these factors somewhat independently, but the third factor then becomes fixed. The combinations of design factors are given below.

- Relative effort for the weakest person and contraction time are set, which means a minimum recovery time must be allowed.
- Contraction time and recovery time are set (as might be the case for machine-paced work), which means that the acceptable relative effort for the weakest person must be the limiting effort.
- Relative effort for the weakest person and recovery time are set, which means a maximum contraction time must be considered.

Figure 6.2 shows a family of curves relating minimum recovery time to contraction time for a range of relative effort (%MVC). It is clear that recovery time increases greatly with contraction time and that there is an efficiency gained from keeping contraction times short. Also, reducing the relative effort reduces the recovery time needed.

Scherrer and Monod (1960), Rohmert (1960a, 1960b, 1973a, 1973b), and many recent European investigators have tried to quantify and describe the local muscle fatigue determinants. A more detailed description of their findings can be found in Rodgers 1997.

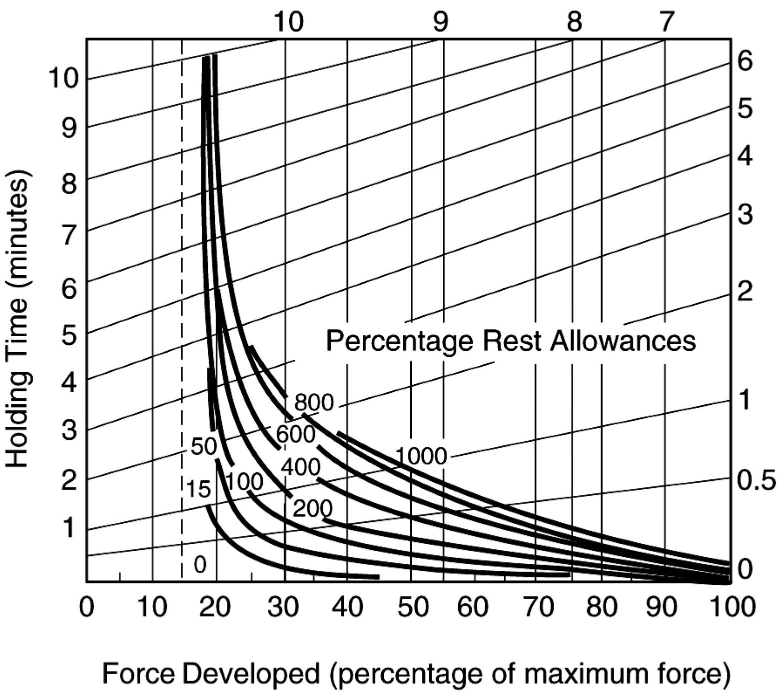

Figure 6.2 Rest Allowances for Static Effort Activities (adapted from Rohmert 1973a)

RECOGNIZING STATIC WORK Local muscle fatigue is easily observed through worker behaviors. Remembering that considerable discomfort is associated with the advanced stages of local muscle fatigue, looking for compensatory behaviors is the key. During the course of the day, workers will change postures, such as changing hands or raising the elbow, usually with increasing frequency; they will step away from the job as much as possible; and they will complain of the discomfort. The likelihood of these behaviors in a person is inversely related to the individual strengths of the active muscle groups.

Looking at the job itself, postural fatigue is usually associated with awkward positioning of the worker when trying to access work or when performing a maintenance task. Some tasks require heavy effort to maintain the posture during the task, and fatigue accumulates rapidly in just a minute or two of work. Other postural fatigue may accumulate slowly in even light-effort tasks because of static loading of the support muscles. With continuous effort over many minutes or hours, the muscle may not be perfused with enough blood to satisfy its need for oxygen, and some anaerobic muscle metabolism is present. The longer the muscle is statically loaded, the more the lactic acid accumulates.

Besides posture, job demands that require more than momentary efforts are candidates for static work considerations. For static efforts, the greater the external effort and the greater the biomechanical disadvantage, the greater the risk of local muscle fatigue.

Very high frequency tasks may have a static muscle component because there is not enough time to have full relaxation of the muscle between contractions. A discussion of this situation is included later in this chapter in "Special Considerations: Design of Ultra-Short-Cycle Tasks."

WORK DESIGN TO REDUCE STATIC WORK It is the relative strength (%MVC) that the effort requires of the worker that determines the level of stress. Small alterations in postures of the upper extremities bring in additional muscle groups, either to help generate the needed forces or to change the biomechanical force translation in a way that effectively reduces the work capacity of the hands and forearms. One of the goals of good job design is to allow the work to be done using the strongest postures and largest muscle groups, so that the worker can do sustained work at a lower percentage of his or her capacity.

The ergonomic approach is to design the workplace and equipment so that awkward postures and static muscle loading are minimized. When it is difficult to eliminate these problems, another approach is to select the tasks on a job setup to provide a muscle recovery period from another, more difficult, one. For example, if a shipping worker handles heavy items frequently when unloading boxes from conveyors to pallets, between handling tasks he or she might also process the shipping manifests while seated at a computer.

In the design of jobs, reducing the static component of any task can prevent local muscle fatigue from limiting productivity. The following guidelines for workplace and job design have the goal of reducing static effort:

- Avoid reaches or lifts above 127 cm (50 in.).
- Avoid forward reaches of more than 50 cm (20 in.) in front of the body when standing and 38 cm (15 in.) in front when sitting.
- Design standing workplaces to avoid stretching or stooping.
- Provide seating or supports for leaning for people who must work on their feet much of the day.
- Provide adequate foot support at seated workstations.
- Ensure minimal force requirements on controls that might be operated rapidly (>10 times per minute) or held for periods in excess of 30 seconds.
- Design foot pedals to reduce or eliminate the need for sustained pressure.
- Provide rest breaks within highly repetitive jobs.
- Provide aids such as carrier bags or carts for carrying tasks taking more than 1 minute with objects weighing more than 7 kg (15 lb.).
- Use jigs and fixtures to reduce holding times in assembly tasks.
- Provide handles or handholds on objects to be lifted or carried.

Most industrial tasks involve both static and dynamic work. Since static work more likely limits productivity, it is a good general practice to reduce the static component of work whenever possible. An example of how job stress can be reduced in this way is a skimming operation in a chemical plant (Brouha 1973). The operators were skimming tanks at shoulder level. By installing a work platform to raise them above the tank, the static load on the shoulder muscles was reduced. Similar features can be seen in materials handling tasks. As the weight of the object increases, a greater percentage of strength is needed to handle it. At weights greater than 18 kg (40 lb.), the static component becomes a limiting factor for many people in the work force. This problem is made worse by inadequate handholds.

Dynamic Work

MECHANISMS OF DYNAMIC WORK FATIGUE Work that has very clear movement of the whole body or any of its parts is dynamic work. While both static and dynamic work must have muscle contractions, the key point is movement. To distinguish it from static effort, which has little or no movement associated with the muscle contraction, dynamic work has noticeable movement and is linked to exerting a force over a distance. At the very least, the force exerted is the weight of the body part moving against gravity. More often, it is moving the whole body or materials against gravity or a resistive force. Metabolically, the person requires the expenditure of energy for several broad categories. The first is the base metabolic rate required to support basic life functions. This is the resting metabolic rate. There is an additional cost to maintain a posture. On top of these are the metabolic costs of doing work and moving the whole body. In most physically-demanding work, it is the latter two categories that provide the greatest contributions to overall metabolic rate or rate of energy expenditure. As the energy expenditure (or metabolic rate) increases, the cardiopulmonary adjustments needed to support those demands also increase. If the adjustments are not sufficient to supply all the oxygen that is necessary to support the metabolic demands of the working muscles, lactic acid can buildup in the body as a whole. This buildup is different from static contractions of local muscle groups because the buildup is not localized.

For static work, the measure of capacity is strength. For dynamic work it is maximum aerobic capacity (MAC) also known as maximum oxygen consumption (V_{O2max}). Although the measurement of people's aerobic work capacities on a treadmill or bicycle ergometer test is done quite regularly for medical and physiological evaluations, it is more relevant to measure work capacity in the same posture in which the job is performed. For instance, much work is done with the upper extremities and trunk and with little involvement of the lower torso. The work capacity of the arms and upper body is roughly 70 percent of whole-body capacity. The metabolic demand of the work may be relatively small when comparing it to a person's aerobic capacity measured on a walking or pedaling task, but it may be a high percentage of the worker's capacity for upper-body work. Information on the recommended data to be used for determining how to design for most people can be found in "For Whom Do We Design?" in Chapter 1. In practice, population distributions of maximum aerobic capacity with reasonable adjustments for task-specific capacities are used.

The level of effort for dynamic work is the metabolic rate. Characterization of the metabolic demands of jobs is best done by defining the tasks performed and the portion of shift time that each typically takes. The demands of the tasks can then be measured directly or estimated using comparison tables (see Table 1.21, Chapter 1), observational methods (ISO 1990; Bernard and Joseph 1994), or prediction equations (Garg, Chaffin, and Herrin 1978). While direct measurement provides more accuracy, estimation methods are usually sufficient. There are several ways to report the metabolic demands as energy expenditure or oxygen consumption, including watts, kcal/hr, kcal/min, l_{O2}/min, and ml_{O2}/min. Also, oxygen consumption can be normalized by body weight and is usually reported as ml_{O2}/kg/min. The time-weighted average for the metabolic demands of tasks within the job is used to characterize the effort assigned to a job. The average metabolic demands include the rest breaks. This analysis of workload is treated more extensively in Chapter 2, in the section "Estimation of metabolic rate."

The relative effort for dynamic work is the ratio of the time-weighted average metabolic rate divided by the maximum aerobic capacity (in the same units). Endurance time as a function of percentage of maximum aerobic capacity (%MAC) is illustrated in Figure 6.3. The greater the relative effort, the faster lactic acid can build up and the less the endurance time is. As with static

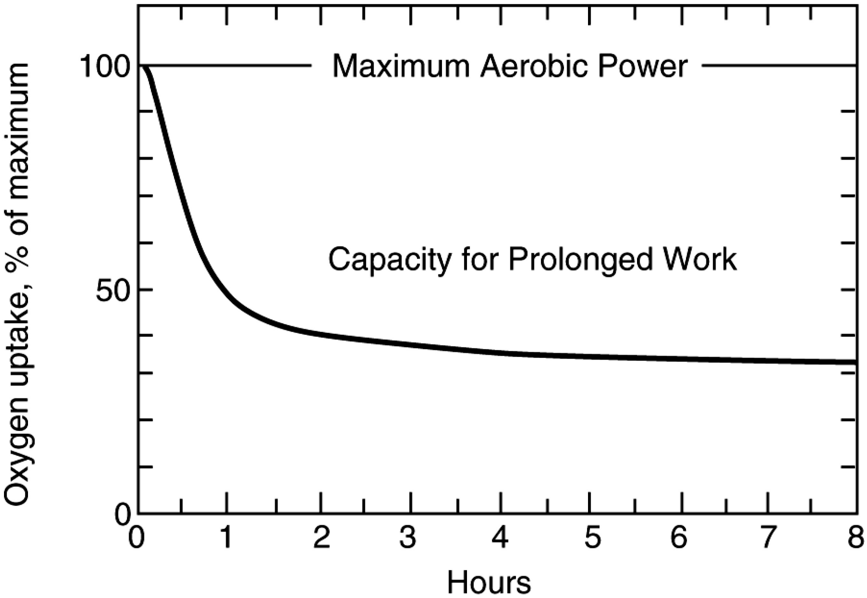

Figure 6.3 Effect of Duration on Percentage of Maximum Aerobic Capacity That Can Be Used (adapted from Astrand and Rodahl 1970)

work, the effort time and recovery time must also be considered to understand the potential for whole-body fatigue. The interrelationships are shown in Figure 6.4, assuming an 8-hour workday.

The relationships among relative effort (%MAC), work time, and recovery time are linear and based on the premise that 33%MAC can be supported for 8 hours (and 30 and 25%MAC for 10- and 12-hour days respectively). The design level aerobic capacity is 27 ml_{O2}/kg/min. As with static work, once any two of the three factors (i.e., relative effort as %MAC, effort time, and recovery time) are set in the design, the other cannot be manipulated.

If simple scenarios of work and rest exist using the design-level aerobic capacity to determine relative effort, the questions are: Does the time for any period of work approach the endurance limit? With the recovery time averaged in, does the %MAC exceed 33 (or the base for other shift lengths)? If the answer to either question is no, then there is little chance for whole-body fatigue.

RECOGNIZING DYNAMIC WORK Overall, or whole-body, fatigue is not seen as often as local muscle fatigue because workers pace themselves and adjust their work patterns to avoid metabolic overloads. When they are being driven or paced by outside factors, such as line speed, an ill-considered deadline, or a poorly balanced system, you may see fatigue attributed to too heavy a physical workload. When the work patterns cannot be adequately adjusted, workers

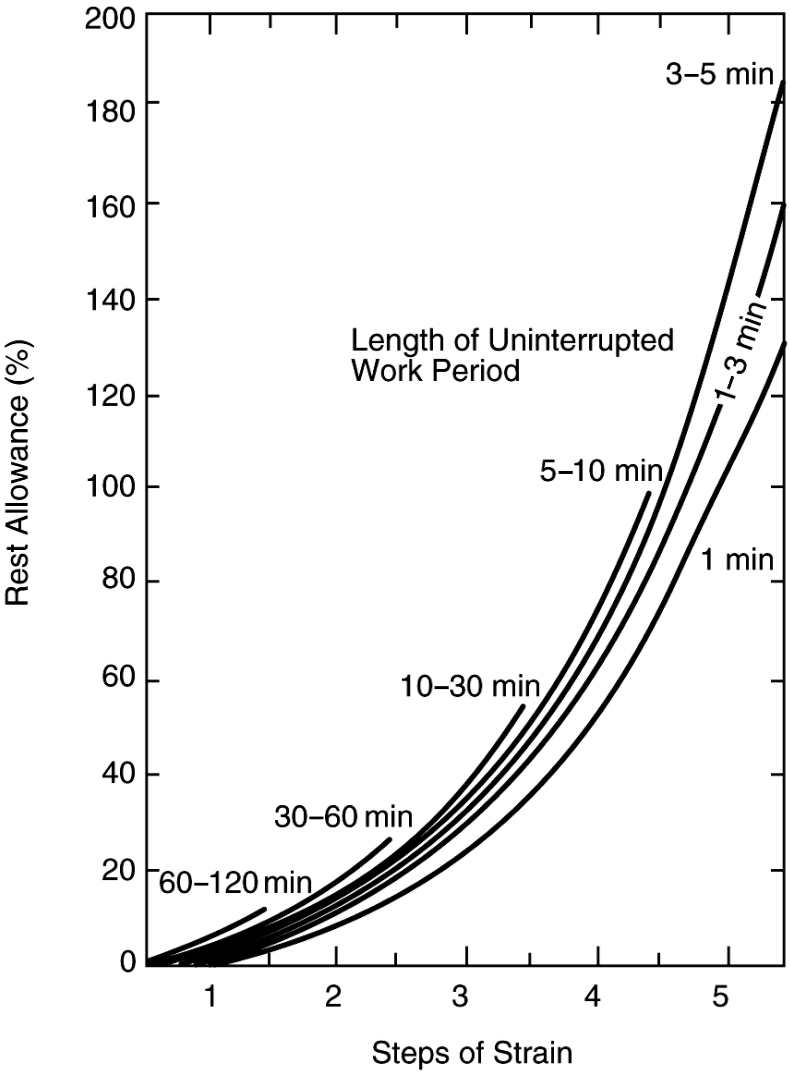

Figure 6.4 Rest Allowances for Dynamic Work (adapted from Rohmert 1973a, 1973 b)

will report being very tired and needing more sleep; they may take breaks in which an elevated breathing rate or more labored breathing is noticed during the first minutes of the break, and there will be elevated heart rates. Methods to assess heart rates are described in Chapter 2 ("Dynamic Work: Heart Rate Analysis").

Because metabolic rate is driven by external work (an external force moved through a distance), the observable job factors follow. Activities that increase the metabolic rate are:

- *Involving more parts of the body.* Progressive increases would be expected moving from hand work to hand and arm work to work requiring motions of the trunk to those involving the whole body.
- *Walking.* The greater the distances traveled in a fixed period of time (i.e., the average speed) to perform the job, the greater the metabolic costs.
- *Manual materials handling.* The metabolic cost increases as more mass is raised vertically or there are higher resistances to pushing or pulling.
- *Climbing.* Anytime the body is moved vertically, there is potential for a high metabolic cost. The rate of rise is most important, and there is less dependence on whether it is a ramp, stairs, or ladder.

Jobs that are acceptable to most people in temperate conditions where environmental and psychosocial stressors are minimal may become too fatiguing if they have to be done under conditions of heat stress. Blood flow that would usually be available to the working muscles will be shunted off to the skin to help control the rising body temperature, thereby making the same physical work load a higher percentage of the available aerobic capacity (Brouha, 1973).

Shift schedules and hours of work can also affect the amount of fatigue that is associated with performing a job. For example, there is a general feeling among firefighters that they work much harder doing the same treadmill exercise protocol when they are on the early morning shift compared to the day or afternoon shift. Yet, their heart rates on the test and predicted work capacities do not appear to be different at these times of day. The subjective feeling that the work is harder should not be ignored, but it does not declare itself in the measurements usually taken to define the intensity of the effort.

WORK DESIGN TO REDUCE DYNAMIC WORK DEMANDS The overall goal is to bring the combination of relative work (both effort and time) and recovery for the design level aerobic capacity below the time-weighted limit of 33 % MAC for an 8-hour shift, or other appropriate limit for other shift lengths. While doing this, it is also important to avoid sustained demands that may cause exhaustion. Some design considerations follow.

- Appreciating that the dynamic work demands depend on external effort that is translated through a distance, work design is guided toward methods that would reduce the external work—that is, opportunities to provide powered assists or sharing of the effort.
- Work that is generally viewed as very demanding (e.g., shoveling) should be performed for very short periods of time and with as much self-pacing as is reasonable.
- Providing short recovery periods during intense efforts reduces the risk of fatigue.
- Varying the active muscle groups and providing undemanding tasks promotes recovery of the muscle groups that are not currently active.

Job/Task Control

Besides improvements made to use the strongest muscles in the best postures through the ergonomic design of workplaces, equipment, and tools, there are other strategies to reduce fatigue, many of them psychosocial in nature. As has been discussed in "Organizational Factors in Work Design" in this chapter, anything that decreases workers' control over the way they do the job will increase their stress and contribute to mental and physical fatigue. Since the person doing the job is the only one who is able to feel when he or she may have overdone the effort or is feeling very tired, the worker is the one who should have the discretion to modify the tasks enough to get some relief. The window within which workers can alter the way they do the work should be wide enough to allow them to respond to typical emergencies on the job without sacrificing productivity, quality, or safety. In another way of looking at it, the job should be designed so that the worker has enough reserve capacity to be able to work around problems when they occur.

Physical Fitness of the Workforce

A worker's general well-being and fitness can reduce the amount of fatigue experienced on the job. A person with good muscle tone and strong muscles will be working at a lower percentage of strength or work capacity because the capacities are increased. Therefore, the person can work for a longer time before needing a recovery break and does not accumulate lactic acid as rapidly as a person who is less fit. The level of fitness does not have to be that of an Olympic athlete. A steady, moderate exercise program of about 30 minutes a day that includes walking at a comfortable speed and using light weights for upper-body muscle toning should be sufficient for most jobs. The walking exercise also provides an opportunity to clear the mind and reduce some of the less specific feelings of fatigue.

Stretching exercises are another way to reduce some of the feelings of fatigue on a job. These are important to do at the start of the shift and after the midshift meal break in order to warm up the muscles before a heavy load or intensive task is undertaken. This prepares the muscle for the increased load by bringing the blood to the active muscles even before it is needed, thereby reducing the initial mismatch between blood flow and oxygen demand when a new task is begun. Intermittent, short (less than 2 minutes) stretch breaks at other times in the shift provide a chance to change the worker's posture, which may be contributing to accumulative lactic acid buildup. They also provide a break from intensive monitoring tasks, in which perceptual or cognitive demands are high. It is not necessary to have scheduled stretch breaks during the shift, but the workers should be encouraged to take them, rather than discouraged from interrupting their work.

They are more likely to increase productivity and quality than to reduce them.

Job Rotation

Job rotation has been suggested as an administrative strategy to reduce fatigue and overexertion of the job (OSHA 1990, 1999). However, implementation of this has been uneven, resulting in its having excellent results in one situation and terrible ones in another. The following observations may help in determining when to use job rotation and when to use another strategy:

- If a task is already one that large parts of the population have difficulty performing for even 15 minutes without the risk of injury, it is not a good candidate for rotation. By rotating it, more people are exposed to that risk and more injuries are likely to occur.
- A job or task that is shown to be highly fatiguing for a given muscle group should not be rotated with another job or task that is fatiguing for the same muscle group, even if it seems less fatiguing than the first task.
- The best candidates for rotations are tasks where moderate fatigue may occur after 2 hours of continuous work. A switch to a less fatiguing task for the next hour or two permits the accumulating fatigue to be paid back within the shift.
- Providing extra rest periods ("fatigue allowances," Konz 2001) on heavy jobs after 2 hours of continuous work may not be sufficient. The amount of lactic acid that has accumulated may be too great to remove from the muscle even with an additional 15 to 20 minutes away from the job. The preferred work pattern allows the worker to break up the intensive work into smaller units so that recovery times are shorter. The best recovery environment for fatigued muscles is being able to do light, dynamic work that stimulates blood flow to the affected muscles and washes out the lactic acid faster than keeping the muscle at rest would.
- If the fatiguing activity is associated with an environmental stress that is difficult to control (e.g., outside work in July and August), job rotation to a task with a lighter workload or in a cooler environment would be advantageous.
- If the rotation is needed to reduce the total workload for workers who are working overtime or extended shifts, it is recommended that a check be made to be sure that the extended hours are appropriate based on the job demands. It may be better to design a shift schedule that ensures that the work can be done in an 8-hour shift or to add labor as needed rather than going to a longer shift. See "Hours of Work: Shift Work and Overtime" in this chapter for more information on this approach.
- One advantage of job rotation is that the workforce becomes multiskilled. A multiskilled workforce is a strong advantage when a person

usually assigned to that job has an extended illness, is on vacation, or is being trained for another job, as there is more flexibility in the way the work can be covered.

- Rotating a job every week between members of the same team has little impact on the prevention of some musculoskeletal injuries and illnesses. The primary benefit of this type of rotation is to give an injured muscle or joint time to repair itself. It is preferable to prevent the degree of injury that such a schedule implies by reducing the damage during the shift through good task and job pattern design. Rotations every day are not much more satisfactory. The best rotations occur when the workers establish reasonable times to stay on the harder tasks and then develop a schedule that is feasible based on the types of tasks done and the natural cycle times of the job. Rotations within a 2-hour period usually suggest that the task should be modified.

THE DESIGN OF REPETITIVE WORK

In many production and construction workplaces, the time to complete a specific unit or cycle of work is less than a few minutes. If the cycle is repeated continuously for 2 or more hours, the work is considered repetitive. Although the energy demands are usually low, the repetitive use of small muscle groups may cause muscle fatigue, and the repeated application of tension in the muscle tendon group and the repeated motion around a joint may cause soreness and inflammation. When ignored, other disorders may emerge, such as nerve impingement. When the musculoskeletal disorder (MSD) is associated with the job, it is called a work-related MSD (WRMSD). MSDs account for large portions of occupationally-reported illness and injury as well as worker compensation costs. Based on average incidence rates, the chances of a WRMSD run from 2 to 10 percent of workers in manufacturing and food processing industries (OSHA 1999).

Job Risk Factors

WRMSDs are not new. Rammazini observed 300 years ago that violent and irregular motions and unnatural postures among miners resulted in disease (Rammazini, 1713). The literature on MSDs and risk factors has been growing with the increased interest in the subject over the past 30 years. To help establish the case, five critical reviews were published recently that evaluated the literature for evidence of a relationship between job risk factors and the development of work-related musculoskeletal disorders. Bernard (1997) at the National Institute for Occupational Safety and Health (NIOSH) published a critical review of over 600 epidemiological studies to determine if existing literature supported a causal relationship between workplace MSDs and job risk factors. The National Academy of Sciences (NAS) (1998) published a review of the evidence for work-related MSDs. It examined laboratory-based, epidemiological, and intervention studies. While it drew from the NIOSH review, it did not provide the same level of detail. A similar review was published by the Faculty of Occupational Medicine (of the Royal College of Physicians), using a rating system to define the level of evidence linking low back pain to occupational risk factors (Carter and Birrell 2000). Keyserling published two reviews, one for the low back (2000a) and another for the distal upper extremity (2000b) to document the current state of the art for laboratory-based research. The Occupational Safety and Health Administration published a proposed ergonomics standard (OSHA 1999) that incorporated much of this work and also evaluated the success of intervention programs in reducing the number and severity of workplace MSDs. The studies come to similar conclusions, that MSDs are associated with certain physical job risk factors, but they are also associated with psychosocial risk factors. Causation is not strongly established between the risk factors and the injuries and illnesses to specific body parts. In this regard, the recommended treatment is active, not passive, rehabilitation and early symptom reporting.

Table 6.4 is a summary of commonly -recognized job risk factors for work-related MSDs and the strength of the evidence for each factor by body region.

TABLE 6.4
Primary Job Risk Factors Considered in Major Reviews

Risk Factor	Low Back	Distal Upper Extremities*	Neck and Shoulders
Force	Strong	Strong	Strong
Awkward Posture	Strong	Strong	Strong
Static Posture	Good	Good	Good
Repetition	Good	Strong	Strong
Dynamic Factors	Good	Weak	Weak
Compression	Good	Weak	Weak
Vibration	Strong†	Strong‡	Weak
Combined	Good	Strong	Good

* Hands, wrists, and elbows; † Whole-body vibration; ‡ Hand-arm vibration

Other job and workplace risk factors including:

Machine pacing
High-speed work
Large number of movements, both regular and overtime work
Incentive pay system
Off-specification assembly parts
Direction of force application, requiring extra force to accomplish task
Poor tool design
Cold or wet work environment for hands
Poorly fitting gloves for hands, reducing grip strength

The compelling job risk factors for the low back are force, poor posture, and repetition along with combined factors and whole-body vibration. For the distal upper extremity, the most important risk factors are force, poor posture, repetition, and combined factors. Segmental vibration was also important. The major job risk factors for the shoulders and neck are awkward posture, force, and repetition; exposure to a combination of risk factors is moderately important.

There is sufficient evidence that other job and workplace factors should be considered in the design of jobs as well. For instance, workplace design will influence body postures during the job, especially the amount of static muscle effort required to support the arm during an assembly or packing task. Work surfaces that are too high and make the worker abduct the elbows and shoulders, extended reaches that statically load the shoulder muscles, and orientation of the work piece so that large wrist deviations are required in the task all contribute to the risk for overexertion of hand, arm, and shoulder muscles and joints (Tichauer 1978). Static work and deviations of the wrist also play a role. Visual task requirements may put additional stresses on the neck and shoulders.

Machine pacing and/or incentive pay can lead to work rates on repetitive tasks that do not allow appropriate recovery periods for heavily loaded local muscle groups. Slaughterhouse workers in forced-pace jobs paid on a piece-rate basis, for example, were found to have a significantly higher number of shoulder, elbow, wrist, hand, back, and neck complaints than workers in jobs that were paced less rapidly or paid at an hourly rate (Hansen 1982).

The speed of work will influence the forces developed on the tendons of the hand and arm muscles, and this also appears to be associated with increased risk for MSDs. At higher speeds, larger peak forces are generated, and repeated work at these levels may aggravate symptoms in susceptible people (Welch, 1972).

The larger the force required, or the more wrist deviation or pinch grip used, the higher the percentage of work capacity of the active muscles required to do the task, and the more opportunity there is for fatigue and inflammation to occur in the muscles and joints (Armstrong 1983). With overtime work or extended work weeks, there may be inadequate time for repair of the traumatized joints and muscles, and muscle and joint soreness may progress to more severe MSDs, such as tendonitis, carpal tunnel syndrome, or “frozen” shoulder (Bjelle, Hagberg, and Michaelsson 1979)

Poorly designed, machined, or molded parts and components that do not assemble easily and require excessive forces from the hand and arm in order to be used, are associated with increased complaints of MSDs (Welch 1972). Repetitive trauma from banging on a tool with the palm of the hand to dislodge a part or to clean it will increase the risk for tendonitis and carpal tunnel disorders (Tichauer 1978). Some guidelines for tool design are summarized in Chapter 4.

The use of vibrating tools is recognized as a factor that can lead to spasm of the small blood vessels of the hand, wrist, and arm. The impaired circulation has a direct effect on the function of these muscles, and continued work with them can lead to MSDs (Bernard 1997; Armstrong 1983). In a study of the physical stresses associated with the use of pneumatic screwdrivers, researchers found that a grip force of 110 newtons (25lbf) was used to control the tool. This force, in conjunction with the vibration, increases the risk. See Chapter 8 for more information about vibration illness and guidelines to reduce the risk for it.

Hand function, which is an important factor in the risk of MSDs of the hand and wrist, is also influenced by other workplace factors. Hands that are continually cold or wet may have impaired function due to reduced blood flow and altered neuromuscular function. The meat-cutting and fishing industries experience this problem, and both report a high incidence of MSDs. The use of gloves to protect hands can have undesirable effects if the gloves fit poorly or are the wrong type. The observed loss in grip strength when gloves are worn can range from 20 to 40 percent (see Table 1.14, Chapter 1). Wearing gloves may be an additional factor contributing to MSDs in people using their hands to do repetitive work requiring large force exertions.

Table 6.5 provides examples of how risk factors may be present in jobs. It describes risk factors in generic terms, details how they may be present in a job, and gives examples of jobs that have been observed with these risk factors.

There is increasing evidence that psychosocial factors affect the development of MSDs, although the reasons are poorly understood. However, it is generally accepted that psychosocial factors primarily influence the reporting of MSDs, and their role is less significant than that of physical job risk factors (National Academy of Sciences 1998). The psychosocial factors typically evaluated include job dissatisfaction, intensified workload, monotonous work, job control, job clarity, and social support (Bernard 1997; Burdorf et al. 1997).

Individual Risk Factors

Individual risk factors normally include age, gender, smoking, physical activity, strength, and anthropometric measurements. Following is a list of reasonable individual risk factors for MSDs. As noted below, these do not predict who will develop a MSD, but rather who may be more susceptible to the work demands:

- Preexisting arthritis, bursitis or other joint pain
- Peripheral circulatory disorders
- Preexisting neuropathy
- History of smoking
- Reduced estrogen levels
- Excessive weight
- Small hand/wrist size
- New to the job or inexperienced
- Aggressive work methods

TABLE 6.5
Tasks and Occupations That May Aggravate Repetitive Motion Disorders

This table is not all-inclusive; rather, it is meant for use in identifying job characteristics that may predispose a susceptible person to repetitive-motion disorders. (Adapted from Feldman, Goldman, and Keyserling 1983.)

Aggravating Actions and Motions	Job Requirements	Some of the Occupations Affected
A. Hand and Wrist		
Repeated forceful pronation of the hand in conjunction with forceful finger flexion.	Writing; manipulating controls and levers; scraping with a putty knife; using paint brush or roller; applying labels; sealing cartons.	Electronic wiring technician Assembly worker Painter Paint scraper Sheetrock installer Manual packaging worker Telecommunication repair worker
Repeated flexion-extension of the wrist; stress increased when accompanied by pinching and gripping; stress may be related to extent of flexion and extension wringing action.	Pulling cloth; repeated handling of objects on conveyor belt or work table with a flexed wrist; use of ratchets and screwdrivers in awkward positions; use of paint roller and brushes; closing bags, wrappers, envelopes; placing brick stonework.	Chassis assembly worker Sewing machine operator Painter Cabinetmaker Fishing industry employee Manual packaging worker Musician (violinist) Mason
Repeated deviation of the wrist; stress increased with forceful grasp.	Hammering; shoveling; sweeping; using tin snips, side cutters, pliers, and cross-action tools.	Carpenter Cabinetmaker Janitor Electronic assembly worker
Repetitive pinching.	Grasping and pulling of fabrics, paper, or other materials; using of tweezers, forceps; inserting small parts with fingers.	Sewing machine operator Upholsterer Small-parts assembly worker Manual box maker
Repetitive pressure, pounding and compression into the palm.	Pressing tools into the palm; using the palm to apply pounding forces; using scrapers and wood gouges; shoveling.	Sailmaker Carpenter Cabinetmaker Painter Leatherworker Digging, earthmoving worker

TABLE 6.5 (Continued)

Aggravating Actions and Motions	Job Requirements	Some of the Occupations Affected
B. Arm and Shoulder		
Repeated forceful supination-pronation of the arm; forceful extension of the elbow; repetitive abduction and abduction movement of shoulder and arm.	Hammering with a straight elbow; lifting with extended arms; heavy packaging operations. Carrying heavy loads on shoulder; working overhead; signaling.	Carpenter Mason Handler, shipping dock worker Storeroom worker Carpenter Pipe filter Sheetrock installer Electrician Traffic controller
C. Leg and Foot		
Repetitive crouching, squatting, kneeling.	Repair and maintenance; large-product assembly work; mining and floor scrubbing.	Equipment mechanic Janitor Equipment assembly worker Mining industries employee
Repetitive flexion and extension of foot	Operating foot pedal; ladder climbing	Heavy equipment operator Tractor driver Assembly worker Process control operator Press operator

- Inefficient work methods requiring excess force application
- High personal stress level

Workers with preexisting medical problems are at a higher risk of developing symptoms than healthy workers. Disorders such as arthritis, peripheral neuropathies, and circulatory disorders can be aggravated by the performance of repetitive tasks (Wells, 1961). Alteration in female ovarian hormone levels, related either to surgery or to the use of oral contraceptives, has also been suggested as a factor that may increase the risk of MSDs (Cannon, Bernacki, and Walter 1981). Small wrist or hand size has been suggested as a risk factor, particularly for the development of carpal tunnel syndrome. The force per unit of surface area on the median nerve during wrist deviations is higher for small wrists and hands (Armstrong and Chaffin 1979b). The significance of wrist size for predicting who may be predisposed to carpal tunnel syndrome has not been proved, however (Armstrong and Chaffin 1979a). Symptoms of muscle, joint, and tendon soreness may be noticed by a new employee in the first several weeks on a new job. The new or inexperienced worker may be at greater risk for development of MSDs, either because of a higher individual susceptibility for these disorders, or because the untrained worker is less highly skilled at the tasks being performed. During the learning period, inefficient applications of force and overly aggressive work methods may be responsible for increased symptoms (Welch 1972). New workers may be under additional stress due to their efforts to perform up to department standards, and this tension may contribute to their susceptibility for symptoms of MSDs. As the worker's muscles become accustomed to the work and as his or her skills are developed, the risk for MSDs appears to become less.

Although plausible mechanisms of action for each factor have been proposed, their associations with the development of MSDs are both varied and mixed in studies reported in the literature. Among otherwise healthy people, the most consistent associations appear to be smoking with low back pain and obesity with carpal tunnel syndrome. In general, many factors unique to individual workers have been identified as MSD risk factors in that they are present more often in people who develop disorders. The ability to predict the occurrence of MSDs in a specific worker based on the presence of risk factors, however, is not even remotely possible. The recommended approach is to advise these individuals of increased risk and to monitor them more closely.

Guidelines for the Design of Repetitive Work

There are many workplace factors that have been associated with the risk of developing MSDs. Ergonomic interventions in the workplace begin with recognition of the contributions of the workplace, work methods and work tools to the development of these problems. While there is no evidence that following the guidelines presented here will eliminate the development of MSDs symptoms in susceptible people, there are indications that the probability of their occurrence will be reduced. General and specific guidelines are given for the prevention and management of MSDs in the workplace.

General Guidelines

- ◆ Engineer products to allow machinery to do highly repetitive tasks; leave more variable tasks to human operators.
- ◆ Spread the load over as many muscle groups as possible to avoid overloading a single muscle group, especially smaller ones.
- ◆ Design tasks to permit grasping with the fingers and palm instead of pinching.

- Avoid extreme flexion or extension of the wrist.
- Design work surface heights, orientations, and reach length to permit the joints to remain as close as possible to their neutral positions.
- Keep forces low during rotation or flexion of the joint. Use power assists if forces are high.
- Avoid repetitive gripping actions.
- Provide fixtures to hold parts during assembly so that awkward holding postures can be minimized.
- Provide a variety of tasks over a work shift, if possible.
- Minimize time or pace pressures.
- Give people time to adapt to a new repetitive task.

Specific Design Guidelines

- Keep the work surface height low enough to permit the operator to work with elbows to the side and wrists near their neutral position. Avoid sharp edges on workplace parts bins that may irritate the wrists when the parts are procured (Armstrong 1983).
- Keep reaches within 50 cm (20 in.) of the front of the work surface so that the elbow is not fully extended when the forces are applied (Armstrong 1983).
- Keep motions within 20 to 30° of the wrist's neutral point (Tichauer 1978; Welch 1972).
- Avoid operations that require more than 90° of rotation around the wrist (Tichauer 1978).
- Avoid gripping requirements in repetitive operations that spread the fingers and thumb apart more than 6.25 cm (2.5 in.) (Hertzberg, 1955). Cylindrical grips should not exceed 5 cm (2 in.) in diameter (Pheasant and O'Neill 1975), with 3.75 cm (1.5 in.) as the preferable size (Ayoub and LoPresti 1971). Hand tools that produce vibrations, require wide grip spans, or repetitively abrade the wrist area during use are of particular concern (Greenberg and Chaffin 1977).
- For repetitive operations that require finger pinches, keep the forces below 10 newtons (2.2 lbf). For gripping actions, keep the required forces to 21 newtons (4.8lbf). These represent 20 percent of the isometric strength of the average woman.
- For continuous, highly repetitive operations, design a 5-minute break for another activity into each hour.
- Select a glove with the least interference for gripping if hand protection is needed for a repetitive task. Provide a range of glove sizes to permit people to get the best fit.

The guidelines in this section have been addressed more to the wrist and hands because many jobs require repetitive motions of the fingers and hands.

The general guidelines also apply to other joints and muscles. Using less than 20 percent of maximum isometric muscle strength of the weaker worker as a guideline provides a reasonable limit for forces in repetitive work over a full shift. For very high repetition rates, this value will drop below 10 percent (Rodgers 1997).

Hand Tool Design for Repetitive Tasks

Many repetitive tasks require the use of hand tools. Careful consideration for the design and selection of these tools can help reduce the potential for MSDs. See also "Design and Selection Recommendations for Hand Tools" in Chapter 4.

- Design handles that make use of the maximum strength capability of the hand by featuring a power or oblique grip involving the palm. Make handle diameters as close as possible to 3.75cm (1.5 in.) and the span on double-handed tools from 5 to 6.25cm (2 to 2.5 in.)
- Make handles long enough (about 10 cm or 4 in.) to avoid applying repeated pressure to the base of the thumb, as when using a putty knife or a paint scraper.
- Orient the tool handle so that it does not have to be used with the wrist deviated markedly in either the ulnar or radial direction.
- Design tools to reduce the need to exert a sustained force on a cold and hard surface. Properly textured handles increase the feeling of control on a powered tool; handle material with low thermal conductivity may also be desired.
- Reduce the vibration from a powered hand tool as far as practicable.

Management of MSDs in the Workplace

Some people will still experience symptoms of MSDs on their jobs even if many of the preceding recommendations are implemented. Careful management of their workload and of their pattern of work on repetitive tasks requiring heavy force exertions may ensure that even these workers will lose little time from work because of their disorders. Some management approaches are:

- First and foremost, train workers to recognize early symptoms of MSDs and to report them immediately so that workers can receive conservative treatment. It is possible at this point to reassign workers to a less stressful job until the symptoms subside. Early detection can reduce the risk for more severe problems and decrease the time lost from work
- Rotate workers among jobs having different force requirements so no one person has to spend a full shift on the heaviest tasks. If the job has a high level of fatigue associated with it, however, fix the job instead of rotating it between more people. See "Analysis Methods" in Chapter 2

for methods to determine the risk of specific types of jobs. If rotation between jobs or tasks is not feasible, intersperse the primary task with several lighter tasks that provide a break for the muscles and joints most involved in the task.

- Identify the best ways to accomplish the more difficult repetitive tasks so that joint, tendon, and muscle strain are minimized. Teach these techniques to all new workers, and reinforce the training in the more experienced workers on a regular basis
- When people are starting a highly repetitive job with forceful exertions or are returning to work after more than two weeks' absence, rotate them among several activities until their muscles, tendons and joints are accustomed to the work. A maximum of 2 hours of continuous work, for a total of 4 hours per shift, is recommended for the first few days on a highly repetitive job if musculoskeletal symptoms have been seen.

Special Considerations: Design of Ultra-Short-Cycle Tasks

Definitions and Concerns

There are many jobs in manufacturing, agriculture, food processing, service shops, and offices where repetitive tasks are done for much of the shift. The repetition rate on the tasks can range from 1 per minute to 60 per minute, and they usually involve the upper extremities, especially the forearms, wrists, hands, and fingers.

The ergonomics concern about these tasks is the probability that fatigue will accumulate in the active muscle groups during each work period. The fatigue that accumulates is directly related to the pattern of work and the effort level exerted in the posture required by the equipment and workplace design. In self-paced operations, the worker can vary the task and intersperse it with other activities that may allow the muscles to recover between bouts of the heavier work. On a paced assembly line or in a situation where there is a tight standard or a pay incentive to work fast, the worker may have to keep up with the external pacer, and this can lead to inadequate recovery times for the efforts exerted.

Accumulating fatigue in the active muscle groups will eventually decrease the worker's capacity for the muscle effort. This is because the accumulation of lactic acid in the muscles changes the environment in which the enzymes work to break down blood sugar or muscle glycogen to carbon dioxide and water and thereby generate the energy needed to support muscle contraction. The heavier the effort and the greater the difference between the required recovery time and the time available between contractions, the faster the fatigue will accumulate and the longer it will take to repay the debt.

Repetition rates greater than 30 per minute for the same muscles are of particular concern because there is usually not a full relaxation of the muscles between activations. Most movement times will be 1 to 2 seconds, so a repetition rate of 30 per minute allows only 1 second of recovery time per effort. This is too little for all but very light efforts, yet even with light efforts, people will maintain their muscle tension between activations. At 60 per minute, the effort is more or less continuous, more like a static load than a dynamic one. Some relief will be needed after about 30 seconds, and often that is when the worker will start alternating hands on the task or find ways to reduce the frequency by picking up multiple items at a time.

ESTIMATING LOCAL MUSCLE FATIGUE ON SHORT CYCLE AND HIGHLY REPETITIVE TASKS The material in this section is based on Rohmert 1960a, 1960b, 1973a, and 1973b; Rodgers 1987, 1988, 1992, 1997, 1998; Scherrer and Monod, 1960.

The curves in Figure 6.5 describe the relationships between effort level and holding time as they affect the repetition rate (the reciprocal of time before repeating) for a muscular task. These are based on static muscle effort studies done by Scherrer and Monod (1960) and Rohmert (1960a, 1960b, 1973a, 1973b). Dynamic work has less strict repetition limits than does static work, but all work has combinations of static and dynamic work. The stricter standard of static work was chosen because, based on the analyses of several hundred jobs, it appears to better reflect the interaction of effort level and duration of effort in short cycle tasks with smaller muscle groups.

Table 6.6 shows the needed recovery times for each effort level for different holding times. Three levels of effort are shown in the curves: light (30 percent of maximum strength in that posture), moderate (60 percent), and heavy (85 percent). There is a continuum of curves for each percentage of maximum effort, but these three are used to categorize them into three levels. A psychophysical ten-point scale for estimating the intensity of effort is presented in "Psychophysical Scaling Methods" in Chapter 2 (Borg 1973). Light effort on that scale is from 0.5 to 3, moderate effort is from 4 to 6, and heavy effort is from 7 to the maximum of 10. This scale can be used to ask workers about task effort levels in order to classify them into the same three categories for the fatigue analysis. It is important to tell them to classify only the effort intensity, as if it were exerted for 3 to 4 seconds and less than once a minute. Otherwise, they will tend to integrate the effort duration and frequency with effort intensity.

The holding time or effort duration is measured as the time that the level of effort determined for the active muscle group is sustained before it goes to a lower level of effort (that is, the muscle relaxes). If the effort goes to moderate from heavy, there may not be a real recovery for the fatiguing muscle fibers, but the rate of accumulation of lactic acid should be slowed. This new task or part of the task can be evaluated to determine whether it too is fatiguing. In studying a task, usually by videotaping it and watching several people do it, one can measure the times of muscle effort and recovery over 100 or more

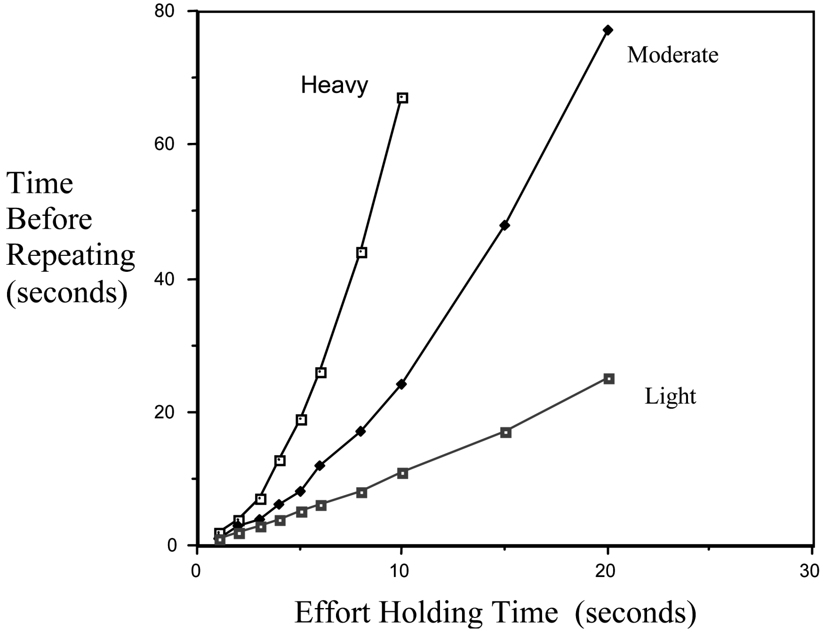

Figure 6.5 Work/Recovery Curves for Three Levels of Effort (derived from Rohmert 1973a, 1973b, Rodgers 1987)

cycles to get a frequency distribution of each. Figure 6.6 is an example of a data form for this data collection.

Figures 6.7 and 6.8 show such frequency distributions for an assembly task and an inspection task (Rodgers 1998). This will show you the predominant work pattern and will also identify "outliers" where longer work or recovery times are present. By reviewing the tapes to determine what contributed to those longer work times, it is often possible to identify production or training issues that will help the workers perform the task better. The three effort duration categories emerged from looking at the amount of fatigue that accumulates in 5 minutes of continuous work. Heavy effort begins to contribute to lactic acid accumulation when the effort duration is more than 6 seconds, and light effort is associated with increasing amounts of fatigue when it is held for more than 20 seconds, so the middle category is determined by those two end limits.

The frequency of repetition of the active muscle groups at the effort intensity determined from the first step will be determined by the pattern of use of the muscle groups. Each time the muscle is activated after a recovery period at a lower effort level, that is a new repetition. The frequency categories were chosen based on fatigue accumulations over 5 minutes of work. The first category has two patterns of work associated with it. Efforts with a frequency of less than one per minute could be either one short contraction that is not

TABLE 6.6
Recovery Time Needs for Three Levels of Effort for Different Effort Durations (Rodgers 1998)

Effort time plus recovery time is the time before repeating to avoid accumulating fatigue on a task.

Continuous Effort Time (seconds)	Recovery Time Needed for Nonfatiguing Work (seconds)		
	Heavy	Moderate	Light Effort
1	1	1	0
2	3	2	1
3	4	2	1
4	9	3	1
5	14	3	1
6	18	4	1
7	27	5	1
8	35	8	1
9	49	11	1
10	57	14	2
11	62	17	2
12	74	20	3
13	97	24	3
14	111	28	3
15	135	32	3
16	149	36	3
17	158	43	3
18	167	48	4
19	186	53	4
20	220	57	5
21		62	5
22		67	5
23		73	5
24		79	5
25		86	5
30			11
35			13
40			15
45			17
50			20
55			25
60			40

Subject/# on tape ______________________

Job description ______________________

Total running time (seconds) __________ **# of units/cycles** __________

Left hand **Type of grip** ______________________

Right hand **Type of grip** ______________________

Left Hand					Right Hand				
On (L) Clock	Off (L) Clock	Effort Time (Secs)	Recovery Time (Secs)	Effort Intensity (Left)	On (R) Clock	Off (R) Clock	Effort Time (Secs)	Recovery Time (Secs)	Effort Intensity (Right)

FIGURE 6.6 Fatigue Analysis Data Collection Form—Videotape Analysis (Rodgers 1998)

repeated until more than 1 minute has passed (for instance, a quick lift of a fairly heavy object that only takes place every hour, such as supplying parts to a line in a tray), a muscle effort that starts in one minute and is still going on after a minute has passed, or a static effort of a postural muscle or a carrying task. The second frequency category, 1 to 5 per minute, is a common one for many repetitive tasks where usual holding times are less than 15 seconds. The upper limit of 5 per minute was partially influenced by the observation that a lifting rate of 6 per minute becomes limited by metabolic demands and so reflects more than just local muscle fatigue. The third category, between >5 to 15 per minute, was based on accumulated fatigue over a 5-minute period and is limited at the top end by the observation that the fatigue is under-predicted when frequencies greater that 15 per minute are required.

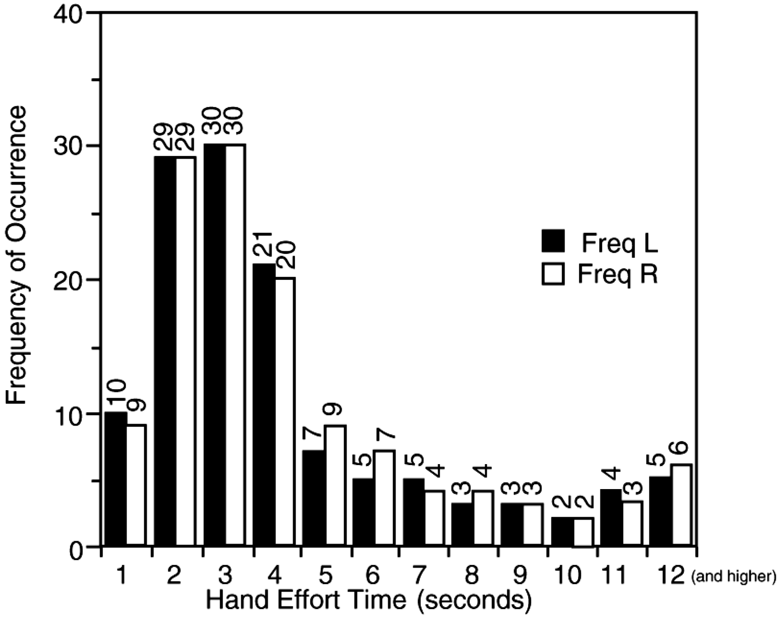

Figure 6.7 Effort Duration Frequencies for a Hand Assembly Task

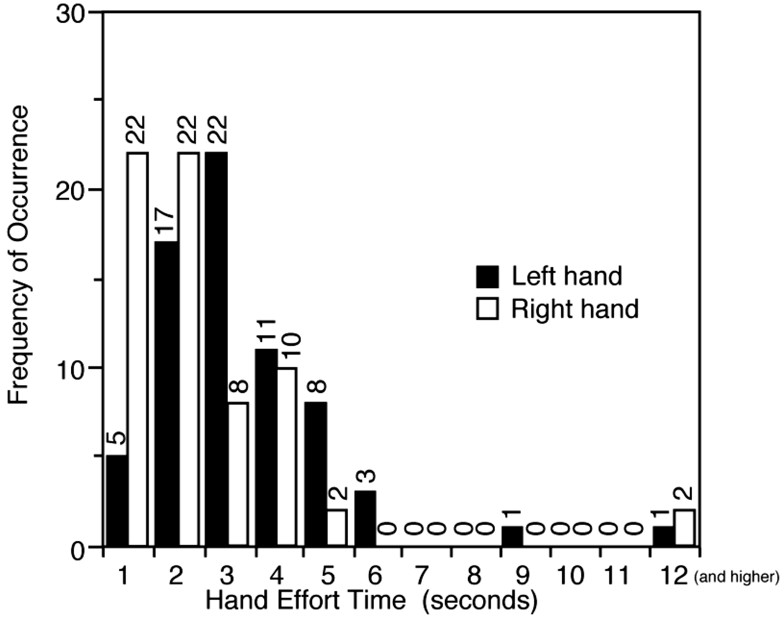

Figure 6.8 Frequency Distribution of Effort Duration in an Inspection Task

Units Made or Handled/Min	Seconds per Unit	Effort Level*	Recommended Max Time (secs)†	Observed Continuous Effort (secs)	Difference
1.0	60	L	45		
		M	17		
		H	9		
1.3	46	L	33		
		M	14.5		
		H	8		
2.0	30	L	25		
		M	11.5		
		H	6.5		
2.5	24	L	19.5		
		M	10		
		H	6		
3.5	17	L	14		
		M	8		
		H	4.5		
5.0	12	L	10		
		M	7		
		H	4		
10.0	6	L	5		
		M	3.5		
		H	2.5		

* Effort levels are L = light, M = moderate, and H = heavy

† For the given effort level to ensure no fatigue within one cycle. See Table 6.6.

FIGURE 6.9 Form for Predicting Fatiguing Tasks in Repetitive Tasks (Rodgers 1998)

PREDICTING ACCUMULATED FATIGUE Several methods for the analysis of repetitive tasks are shown in "Analysis Methods" in Chapter 2. Three of them now include fatigue as one of the important factors in determining the risk of musculoskeletal injury and illness on jobs. It should be noted that the fatigue analysis described above is based on just 5 minutes of continuous work. The longer the total work time before another, less demanding tasks is done, the more the fatigue accumulates, and the higher the risk becomes for muscle overexertion injuries. The form in Figure 6.9 can be used to predict what that accumulation may be for task times (e.g., units made) from 1 to 10 per minute at three levels of effort.

Steps for Use of the Form

1. Identify average cycles per minute from the production standards for the job.
2. Divide 60 seconds by the average cycles per minute to get the seconds available for each unit.
3. Observe the job and talk to the operator to determine the effort intensity and the most active muscles, or predict them from a task simulation.
4. Determine how many seconds of continuous effort there are in each cycle.
5. Identify the tabulated point closest to the task requirements and enter the seconds of continuous effort there under the appropriate effort level. If there is more than one level of effort, enter the continuous seconds for each effort intensity.
6. Subtract the actual seconds of effort from the maximum seconds value. If the result has a positive sign, the task should not be very fatiguing. If the result is negative, fatigue is accumulating in the active muscles, and additional recovery time will be needed. The greater the negative value, the more difficult the job is.
7. Establish a rating of the degree of difficulty of the task based on the muscle fatigue accumulating, the pace pressure, and other job factors. Use D = difficult, M = moderately difficult, and E = easy.
8. Alternation of tasks should be between the difficult and easy ones to control fatigue accumulation.

Lactic acid accumulations needing recovery times greater than 3 to 4 minutes can be detected by observing the way the worker starts changing the active muscle groups or doing the efforts faster to slow down the development of further fatigue. Faster efforts are also often heavier efforts, and that can contribute to additional overload on the muscle fibers. Another observation in the extended performance of fatiguing work is that the worker has to get away from the work more often in order to get adequate recovery time. The tasks that are used for these "breaks" can be called secondary work because they are legitimate ones, such as doing an extra quality check, talking to a supervisor or team leader, or attending to personal needs. The amount of time spent on secondary work tends to be higher when the primary task is fatiguing the muscles.

Responding to Short-Term, Highly Repetitive Task Demands

One reason why some people develop overuse musculoskeletal injuries and illnesses in a short exposure to very repetitive tasks is because they are asked to overcome a failure in automation or in a machine that has been used to increase the number of units produced per minute. In many instances, no provision was made in the system design to accommodate the worker when such a failure occurs (Rodgers 1998).

For example, bottling lines may handle from 60 to 120 bottles per minute in the filling, capping, and labeling operations. If a failure occurs in the final packing of the bottles at the end of the line, it is advantageous to keep the front part of the line running. There is not enough space between the front and the end to do that if the repair takes more than a few minutes. So the workers on the line may be asked to offload the bottles onto an adjacent table until the repair is completed.

Eventually they will have to load them back onto the line, too. The typical repair on the packing machine may take 15 to 20 minutes, so the people doing the bottle handling may lift up to 500 bottles in that period (assuming that several people are available to help out). A technique frequently used is to pick up two bottles in each hand and to lift at a rate of 6 to 10 per minute. The grip is fatiguing and the fast pace of the line contributes to them using fast and heavy efforts, so their risk of accumulating fatigue quickly is high.

This type of emergency activity, which is not a regular part of the job but is predictable, can probably be dealt with best by organizational improvements. Some examples of these are:

- Preventive maintenance on the line or machine so that breakdowns are less likely to occur.
- Determination of the points when the line should be slowed down or extra labor should be made available to reduce the risk of injury for the workers responding to the emergency. See the form in Figure 6.9.
- Determination of when it is most appropriate to shut down the line rather than continuing the emergency response work.
- Provision of automatic run-offs (and run-ons) for the product so that short emergencies can be accommodated. An evaluation of the types of emergencies and typical down times for them should be used to determine how much space is needed for these temporary storage units.

Other emergencies, such as bad parts, parts that are within specification but do not fit properly for assembly, a shortage of parts, and orders with short deadlines can usually be handled administratively providing that it is understood that additional labor or changed work patterns and recovery activities may be needed. For example, if bad parts or parts that don't fit get into the manufacturing system, the worker often is instructed to "make them work" because the just-in-time inventory system does not keep spare parts on hand. The time it would take to replace the good parts may only be 4 to 12 hours, but that would mean a significant loss of production. To avoid that, the worker may have to take more time to do the repetitive task, thus increasing the risk of more fatigue accumulation in the active muscles. One approach to prevent this is to fix the parts off the line in a separate operation. With a lean workforce, this may not always be an option, but having the workers injured from trying to use the bad parts or fix them under time pressure can create a problem.

Example: Predicting Muscle Fatigue in Short-Duration, High-Volume Tasks to Determine Labor Needs or Line Speed Changes

A. Determining the Demands of the Emergency Task

1. Measure the number of units per minute presented to the worker.
2. Determine how the units will be transferred (one or two hands, and how many per hand?)
3. For the same muscle group (e.g., right hand), calculate how many times per minute the effort will have to be made to keep up with the usual line rate.
4. Determine the usual holding time per effort, in seconds.
5. Determine the time for one cycle of the basic task, e.g., one transfer of a part or parts.
6. Subtract the holding time from the cycle time to get the actual recovery time within the cycle.
7. Compare the actual recovery time to the needed recovery time taken from Table 6.6 above.
8. If the needed recovery time is greater than the actual recovery time within a cycle, the muscles will be accumulating lactic acid (i.e., becoming fatigued).
9. To estimate the amount of fatigue that will accumulate in 15 minutes of work, multiply the excess recovery time needed per effort by the frequency of efforts per minute and then by 15 minutes. Divide the total seconds by 60 to get the minutes of fatigue accumulated during the 15-minute emergency situation.

B. Identifying Options for Reducing the Fatigue on an Emergency Task

1. Any task in which there is an accumulation of more than 3 minutes of fatigue in just 5 minutes of work can be considered highly fatiguing. Determine how many minutes a person could sustain the job

before 3 minutes of fatigue would accumulate. Calculate the fatigue rate per minute (see #9 above) and divide it into 180 seconds to get the minutes of work before the worker should be rotated off the emergency task.

2. Slowing down the line can reduce muscle fatigue by providing enough recovery time within the cycle to prevent lactic acid accumulation. If there is not another person available to assist on a short-term basis, a reduction in line speed to match the recovery time needs may be the best approach.
3. Reducing the effort level of the muscle work will substantially reduce the amount of recovery time needed. This may be done by using a tool or container so that the larger muscle groups can handle multiple units at a time, for instance. The numbers of efforts per minute may also be reduced if the items can be batched or clustered together.

C. Example of Off-loading Bottles on a High-Speed Filling/Packing Line

- Line rate = 60 bottles per minute.
- Removed from line using two hands, 2 bottles per hand.
- Transfer time = 4 second cycle, 3 seconds of effort, 1 second of recovery when hand returned to line.
- The load is shared equally between the hands, so each hand is doing 15 efforts per minute.
- The effort level (2 bottles per hand) is moderate.

Three seconds of moderate effort requires 2 seconds of recovery time to prevent accumulating fatigue.

One second is available within the cycle, so 1 second of fatigue can accumulate after each transfer (in each hand). At a frequency of 15 cycles per minute, that means 15 seconds of fatigue can accumulate per minute.

Continuous time on this task to an accumulation of 3 minutes of fatigue in each hand would be 12 minutes.

Slowing down the line by 20 percent would reduce the line rate to 48 per minute, with an effort frequency of 12 per minute. This would provide enough recovery time to prevent fatigue accumulation in the active muscles.

Adding a second person to assist with off-loading would reduce the stress on the hands further by effectively lowering the frequency of transfers for each person's hands to 8 per minute, providing more than enough flexibility for varying the rate and preventing fatigue accumulation. This is the better approach to take. Either the second person can work continuously with the original operator, or they can alternate doing the work in 5- to 10-minute slots. However, if the latter option is chosen, the work done between the off-loading work segments must not be hand-intensive.

Ergonomic Design Approaches to Reduce Local Muscle Fatigue

As a general guideline, it is important to keep the repetition rates to below 15 per minute for the same muscle groups where moderate or heavy efforts are used, when possible. This can be done by using hard or soft automation for the tasks done at that speed instead of asking a person to do it. If automation is not feasible, the task should be designed to minimize the effort time and maximize the recovery time so that fatigue does not accumulate. This could be done by:

- Providing parts and product within comfortable arm reaches.
- Delivering them to the assembly or handling station so that they are easily procured.
- Providing some space for in-line inventory so that workers can vary their pace and batch some of the work, if appropriate.
- Giving the worker some control over the pace of the operations so that it can be modified to match their subjective fatigue, either as a group or individually.
- Developing processes that will be activated in the event of machine failures, automation failures, bad parts delivered, emergency order responses, labor shortages, and so on.
- Providing a process for letting workers take short breaks without stopping production. This is an organizational way to deal with the accumulating muscle fatigue problem on production lines.
- Improving the assembly or shop process so rework is reduced (e.g., the worker can see well enough to do the task right the first time, and the proper tools are provided to do the job most efficiently).

THE DESIGN OF VISUAL INSPECTION TASKS

Much of the content of this section is from T.J. Murphy (1975).

For a large number of industrial manufacturing systems, visual scanning for defects is the primary inspection method. The product to be inspected may be moving on conveyors (dynamic inspection) or may be automatically fed to an inspection workplace, where it is held (static inspection). In some staged assembly routines, inspection is a subsidiary task: each person checks the previous work on the product while at the same time performing his or her own task. In some manufacturing tasks, different inspection responsibilities may be assigned to more than one person.

The more rapidly the product is manufactured, the more critical is the response time of the inspector. The process control inspector is under time pressure to identify and record defects so that quality problems can be rectified quickly. The batch release inspector assimilates information from many parts of the manufacturing and quality control stations and, from this information, decides whether a production run is ready to be passed on to the next operator. The product acceptance inspector is paced less by production equipment than by production goals. He or she still needs to respond in a timely manner if defects in appearance or function of a product are found at the end of the manufacturing cycle.

Measures of Inspection Performance

Feedback to a company on the success of their quality control process comes in the form of reviews of customer complaints, which will result in audits of previously inspected products, and job sample tests. Feedback to the inspector is critical to improve poor performance or maintain high performance. The following measures have been used to evaluate defect inspection performance:

- Percentage detected
- Percentage correctly rated
- Percentage incorrectly rated
- Percentage correctly named
- Material waste
- Time per inspection
- Units inspected per time period

Once these measures have been collected on a specific inspection task, it is easier to identify which of the four performance-influencing categories—individual, task, environmental, and organizational—need attention. Table 6.7 shows all factors that influence inspection performance.

It is important to use the results of the performance measurements to provide feedback to inspectors on their performance level. (For a review of inspection performance, see Czaja and Drury 1981; Drury 1992.) Performance feedback provides inspectors with information about search times, search error and detection errors while process feedback informs inspectors of the search process and strategies to help them better understand all the task characteristics (Nair et al. 2001).

Individual Factors

The individual factors that contribute to performance include visual system limitations, vigilance, cognitive processing, IQ, memory capacity, motivation, and personality factors. Task, environment, and organization factors should not disrupt these or make it difficult for the inspector to apply them at their optimal level.

Several studies have addressed the issue of whether certain tests can be used

TABLE 6.7
Factors That May influence Inspection Performance (adapted from Megaw 1979)

Individual Factors	Physical and Environmental Factors	Task Factors	Organizational Factors
Visual acuity Static* Dynamic Peripheral Color vision* Eye movement scanning strategies* Age* Experience* Personality Sex Intelligence Subjective probability of defect occurrence	Lighting General* Surround huminance Lighting for color Specialized* Aids Magnification* Overlays* Viewing screen* Closed-circuit TV Partitioning of display Automatic scanner Background noise Music while working* Workplace design	Inspection time Stationary* Conveyor-paced* Paced vs. unpaced Direction of movement Viewing area Shape of viewing area Density of items* Spatial distribution of items Defect probability* Defect mix Defect conspicuity* Product physical factors* Complexity 2- or 3- dimensional Specularity Hue Size Defect physical factors Shape Size Specularity Contrast	Number of inspectors* Briefing/instructions Feedback* Feed-forward* Training* Selection* Standards* Time on task* Rest pauses Shift* Sleep deprivation Social factors General* Isolation of inspectors* Working in pairs Effects on sampling scheme* Motivation* Incentives* Product price information Job rotation*

The ability of a person to perform an inspection task may be influenced by individual (column 1), environmental (column 2), task (column 3), or organizational (column 4) factors. Those factors that have been identified in industrial experiments are indicated by an asterisk (*); the other factors have been shown to influence inspection performance in laboratory tasks or military studies.

*Identified in industrial experiments.

to predict who will become a good inspector. Any test is difficult to validate to job requirements and, as Gallwey (1982) concludes, inspection tests should be task-specific to be of any value. Factors that seem more important in predicting inspection performance are training, motivation, and task design (Weiner 1975).

Visual capabilities that contribute to the ability to detect defects are:

- Static acuity (stationary targets)
- Dynamic acuity (dynamic targets)
- Contrast sensitivity
- Color vision
- Characteristics of prescription glasses worn
- Presence of visual defects such as cataracts, tunnel vision, yellowing of the lens, or clouding of the aqueous humor

Standardized vision tests of acuity in an eye clinic might not be the right ones to accurately predict inspection performance. For example, there are several ways to test visual acuity that relate to different aspects of seeing small details. Boff and Lincoln (1988) list the following measures:

- Minimum visibility: ability to see illuminated pinholes
- Minimum perceptibility: ability to see small objects against a background
- Minimum separability: ability to see objects that are very close but separate
- Minimum distinguishability: the ability to distinguish discontinuities or irregularities in object contours

Even though tests are available to measure these, Boff and Lincoln state that large differences in acuity measures result not only from individual characteristics but also from viewing conditions, training to perform the task, and instructions. If visual tests are used, they need to be designed to mimic the task demands as closely as possible. A vision test could help define why an individual might have trouble with specific types of tasks.

If the inspection task involves color vision, then a color vision test could identify congenital color deficiencies in an individual's eyes. About 8 percent of males and 1 percent of females have color deficiencies. The most common is a red-green deficiency. Color matching ability declines with age, especially for blue and yellow (Verriest 1963).

Chen, Gramopadhye, and Melloy (2000) have summarized tests that have been used to measure individual differences, along dimensions other than vision, in inspection performance. The tests that can best identify individual differences are shown in Table 6.8.

It is important to note that inspectors should not be selected based on any one of these tests. Chen et al (2000) hypothesized that the test could be used to measure effectiveness of feedback training. Environmental or organizational aids should be considered to overcome difficulties and assist in identification of defects.

TABLE 6.8
Individual Difference Tests, What They Measure, and Their Significance in Identifying Individual Differences in Inspection Performance (adapted from Chen et al. 2000)

Test	Measure	Significance	Reference
Vision			
Visual acuity	20/20	High	(Weiner 1975)
Aptitude			
Harris inspection test	Identifying unmatched objects	High for electronics	(Harris 1964)
Cognitive			
EFT	Identify embedded figures	High	(Gallwey 1982)
MFFT	Impulsives/reflexives	High	(Schwabish and Drury 1984)
Locus of control	Introversion/extroversion	High	(Eskew, Rhea, and Riche 1982; Sanders et al. 1976)

Physical and Environmental Factors

The lighting available for visual inspection tasks can influence performance and productivity significantly. Inadequate illumination, both qualitatively (shadows, glare) and quantitatively (too much, too little) can make the discrimination of a defect unnecessarily difficult. Table 6.9 shows special purpose lighting that can enhance the visibility of defects of many different types.
Workplace design can also influence inspection performance through its effect on musculoskeletal discomfort. An inspection job that requires constant awkward postures to enable the inspector to get a good view of the material can produce static muscle fatigue and can interfere with visibility. An inspector might have to lean over some obstacle to get close enough and could cast shadows on the surface being inspected. Muscle fatigue can become a distraction that interferes with the ability to devote full attention to the tasks. Yeow and Sen (2000) presented a project where ergonomic adjustments of the inspection workstation resulted in improved inspection performance that reduced returned products from 12.2 percent (± 4.1 percent) to 4.5 percent (±1.3 percent) and resulted in a 6 percent increase in productivity.

Depending on the types of defect to be detected, competition from other environmental factors can influence inspection performance. For instance:

- If a target is to be picked out from a large number of similar targets the density and complexity of the background should be kept to a minimum.

TABLE 6.9
Special-Purpose Lighting for Inspection Tasks (developed from information in Faulkner and Murphy 1973; Hopkinson and Colins 1970; Kaufman and Christensen 1972; T. J. Murphy 1981)

Column 1 describes fourteen improvement goals for inspection task performance. Aids that assist the inspection in detecting the defects are given in column 2; short explanations of how these aids work or descriptions of other actions that help the inspector are given in column 3. There is often more than one way to make a defect more visible; the nature of the material being inspected will help identify the most effective method. When more than one type of defect is being searched for a combination of aids at the workplace may be appropriate.

Desired Improvement in Inspection Tasks	Special-Purpose Lighting or Other Aids	Techniques
1. Enhance surface scratches	Edge lighting, for a glass or plastic plate at least 1.5 mm or 0.06 in. thick	Internal reflection of light in a transparent product; use a high-intensity fluorescent or tubular quartz lamp.
	Spotlight	Assumes linear scratches of known direction; provide adjustability so that they can be aligned to one side of the scratch direction; use louvers to reduce glare for the inspector.
	Dark-field illumination (e.g., microscopes)	Light is reflected off or projected through the product and focused to a point just beside the eye; scratches diffract light to one side.
2. Enhance surface projection or indentations	Surface grazing or shadowing	Collimated light source with an oval beam.
	Moiré patterns (to accentuate surface curvatures)	Project a bright collimated beam through parallel lines a short distance away from the surface; looking for interference patterns (Stengel 1979); either a flat surface or a known contour is needed.
	Spotlight	Adjust angle to optimize visualization of these defects.
	Polarized light	Reduces subsurface reflections when the transmission axis is parallel to the product surface.
	Brightness patterns	Reflection of a high-contrast symmetrical image on the surface of a specular product; pattern detail should be adjusted to product size, with more detail for a smaller surface.

3. Enhance internal stresses and strains	Cross-polarization	Place two sheets of linear polarizer at 90° to each other, one on each side of the transparent product to be inspected; detect changes in color or pattern with defects.
4. Enhance thickness changes	Cross-polarization	Use in combination with dichroic materials.
	Diffuse reflection	Reduce contrast of brightness patterns by reflecting a white diffuse surface on a flat specular product; produces an iridescent rainbow of colors that will be caused by defects in a thin transparent coating.
	Moiré patterns	See item 2 in this table.
5. Enhance nonspecular defects in a specular surface, such as a mar on a product	Polarized light	A specular nonmetallic surface acts, under certain conditions, like a horizontal polarizer and reflects light; nonspecular portions of the surface will depolarize it; project a horizontally polarized light at a 35° angle to the horizontal.
	Convergent light	Project the light at a spherical mirror, reflect it off the product, and focus it at the eye; requires very rigid posture for inspectors, however; mirror should be larger than the area being inspected.
6. Enhance opacity changes	Transillumination	For the transparent products, such as bottles, adjust lights to give uniform lighting to the entire surface; use opalized glass as a diffuser over fluorescent tubes for sheet inspection; double transmission transillumination can also be used.
7. Enhance color changes, as in color matching in the textile industry	Spectrum-balanced lights	Choose lighting type to match the spectrum of lighting conditions expected when the product is used; use 3000°K lights if the product is used indoors, 7000°K light if it is used outdoors.

TABLE 6.9 (Continued)

Desired Improvement in Inspection Tasks	Special-Purpose Lighting or Other Aids	Techniques
	Negative filters, as in inspecting layers of color film for defects	These filters transmit light mainly from the end of the spectrum opposite to that from which the product ordinarily transmits or reflects; this reversal makes the product surface appear dark except for blemishes of a different hue, which are brighter and more apparent.
8. Enhance unsteadiness, jitter	Parallel line patterns (Moiré)	Two sets of parallel lines, 3–5° offset; one set is mounted on the product and the other is stationary; this pattern can magnify the jitter 10–40 times.
9. Enhance repetitive defects, as in rotating shafts or drums	Stroboscopic lighting	Adjust strobe frequency to the expected frequency of the defect.
10. Enhance fluorescing defects	Black light	Use ultraviolet light to detect cutting oils and other impurities; may be used in clothing industry for pattern marking; fluorescing ink is invisible under white light but very visible under black light.
11. Enhance hairline breaks in castings	Coat with fluorescing oils	Use of ultraviolet light inspection will detect pools of oil in the cracks.
12. Reduce surface glow under white light that hides defects; the surface appears to fluoresce	Complementary filter or light source, similar to a negative filter	Use a filter or light source with low transmission on wavelengths reflected by the object's surface, and high transmission in other parts of the spectrum, so as to create a gray appearance.
13. Remove distracting reflections	Light shields	Place overhead or side shields on a workplace to eliminate reflections caused by room lighting.
	Light traps	For VDUs, mount a circular polarizer in front of the tube, set at a downward angle; the polarizer traps all incoming light from the room and allows only internally generated light back to the observer.

	Reposition workplace	Rather than have operators face a wall, with ceiling lights behind them reflecting off the 45°–90° surfaces of their work pieces, have them sit with their backs to the wall so that the work pieces reflect the low-luminance wall instead.
14. Reduce blurring of fast-moving products, as in the printing industry	Synchronized moving images	Projected or reflected images on flat, otherwise formless webs can provide fixation points and reduction of streaming.
	Stroboscopic lighting	Pulsed light above the fusion threshold, approximately 40-Hz, will make a random spot type of defect appear as a string of pearls, even if the formless web itself blurred (Taylor and Watson 1972).
	Elongate the observation area	Rule of thumb: 0.3 m (1 ft) of observation area per 18.3 m/min (60 ft/min) of object speed at close inspection distances of 0.6–1.2 m (2–4ft) allows proper fixation time, eye pursuit, and stopped images of the product (Murphy 1981).
	Group the product	For the same result, it is better to tighten the grouping and reduce the speed rather than to spread the product out and increase the speed.

- Simply increasing the contrast of the product relative to the background is not always appropriate, particularly if the background then tends to draw the eye away from the piece to be inspected.
- Luminescent, colorful paints on conveyor systems and line process equipment may brighten up the workplace and please the eye. But careful attention should be paid to how these colors affect the inspection task if they become part of the process control inspection station.
- The mistake is sometimes made of using a background that contrasts with the inspected piece. This design practice is incorrect. The goal is to reduce background contrast so that the contrast between the defect and the rest of the inspected area is at a maximum.

Task Factors

It is always easier to make relative judgments rather than absolute judgments in all modalities. Table 6.10 shows the number of discrimination levels that can be identified in several dimensions when making an absolute judgment.

Aids that permit an inspector to compare a product sample to a standard, instead of having to make an absolute judgment, are useful. Such aids are particularly effective for variations in color hue, brightness, and saturation, where many thousands of differences can be detected by using a comparator, but only eight to fifteen colors can be correctly identified on an absolute basis (Feallock et al. 1966).

Comparators can be as simple as photographs showing defect types and samples of the actual defects, or as complicated as stereomicroscopes that superimpose the standard and sample images. These approaches also permit classification of defect severity or identification of a defect in a complex field.

Harris and Chaney (1969) showed that the design of the comparator to be used is critical. In their study, people who were inspecting electronic chips were asked to assess the color of interference rings that indicated acceptability of the product for release. They were given three different aids: a verbal description of the color; a color scale; and a standard set of colored chips to use for color matching. The results are shown in Figure 6.10. The most effective comparator was the color-matching chips.

Thresh and Frerichs (1966, cited in Harris and Chaney 1969) did a comparator study illustrating that the comparator not only helped in identifying the defects, but also improved the consistency of judgments between inspectors by 100 percent. These inspectors looked at solder joints. They used color photographs of eight graded samples of unacceptable to acceptable solder joints. Their results are shown in Figure 6.11.

To summarize, task demands such as relative judgments, the use of a comparator, and time on task all contribute to the inspector's performance level. In addition, the following factors also affect performance:

TABLE 6.10
Amount of Information in Absolute Judgments of Various Stimulus Dimensions (adapted from McCormick and Sanders 1982)

Stimulus Dimension	Number of Levels That Can Be Discriminated on an Absolute Basis Under Optimum Conditions	Source
Color, Surfaces		
Hues	8–9	Halsey and Chapanis 1954; Jones 1962
Hue, saturation, and brightness	24 or more	Feallock et al. 1966
Color, lights	10 (3 referable)	Grether and Baker 1972
Geometric shapes	15 or more (5 preferable)	Jenkins 1947
Angle of inclination (indicating direction, angle, position on dial)	24 (12 preferable)	Muller et al. 1955
Size of forms (e.g., squares)	5–6 (3 preferable)	McCormick and Sanders 1982
Brightness of lights	3–4 (2 preferable)	Grether and Baker 1972
Flash rate of lights	2	McCormick and Sanders 1982
Sound		
Intensity (pure tones)	4–5	Deatherage 1972; Garner 1953
Frequency	4–7 (when intensity is at least 30 dB above threshold)	Pollack 1953
Intensity and frequency	8–9	Deatherage 1972
Duration	2	Pollack and Ficks 1954

The ability of people to distinguish among absolute levels of color, shape, position, size, brightness, and sound without comparisons is given in column 2. The number of discriminable levels increases markedly if these factors are combined and if comparisons are available. The third column indicates the literature from which the absolute judgment data are drawn.

- Complexity and variety of the product
- Distribution in space of the inspection area
- Whether the inspected material is moving or stationary
- Search time allowed
- How frequently defects occur

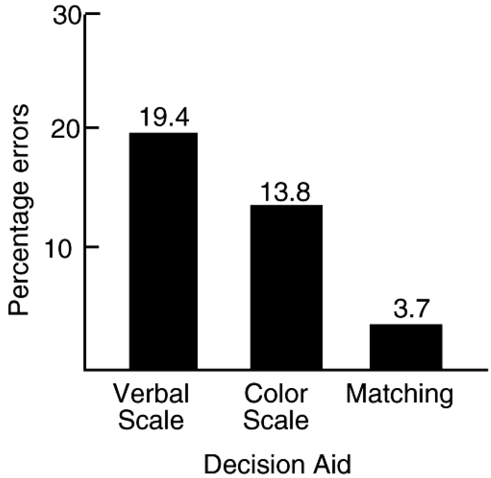

Figure 6.10 Percentage of Errors in Using Three Aids to Assist in Color Inspection of Electronic Chips (Harris and Chaney 1969)

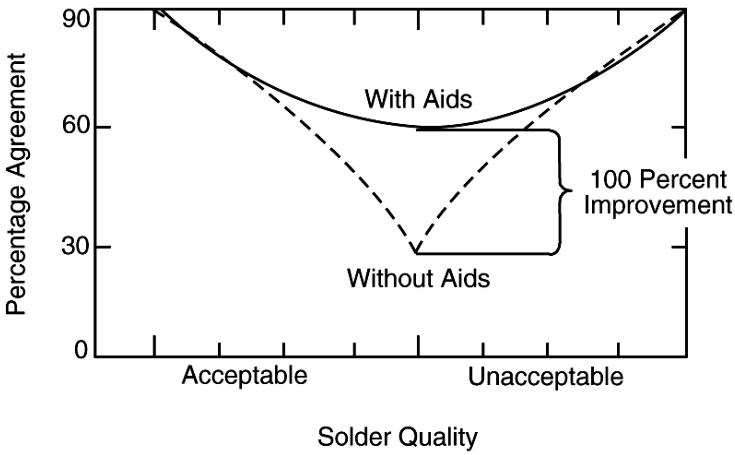

Figure 6.11 Increase in Agreement Among Inspectors Resulting from Use of Photographic Aids (adapted from Thresh and Frerichs 1966)

Machine-paced inspection, usually found in process control operations, is generally more difficult than self-paced inspection, especially when several type of defects are present.

Inspection tasks where defects are rare are difficult to perform since a lag in the inspector's attention can result in missed defects (Smith and Lucaccini 1977). As the defect rate falls below 5 percent, false reports increase rapidly. Defect rates below 1.5 percent result in reduced detection performance as well, as shown in Figure 6.12.

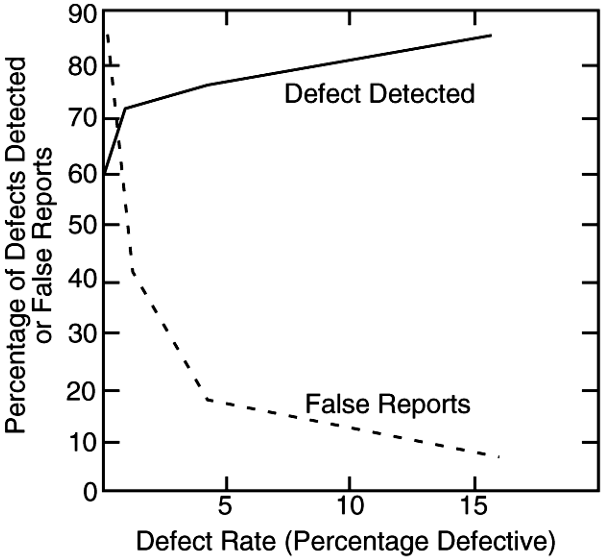

Figure 6.12 Defect Rate and Inspection Accuracy (adapted from Harris and Chaney 1969)

Rotating people between such inspection tasks and another, less visually demanding task every 30 minutes can improve overall performance. Inspection tasks require sustained attention that cannot be maintained for extended periods without resulting in a decrement in performance. Giambra and Quilter (1987) showed, in the laboratory, that performance declines rapidly over the first 30 minutes and then remains at a rather steady lower level over time.

Several studies have illustrated the effect of task factors in inspection performance. Table 6.11 presents the results of some of these studies that relate to industrial problems.

In general, the more time a person has to make an inspection, the better the performance (Drury 1973). As time shortens, fewer scanning options (sequential, rather than simultaneous, search for multiple defects, for example) are available, and there is less accommodation for individual inspector skill levels.

Organizational Factors

Training (including feedback on performance) work/rest cycles, shift schedules, and social factors can affect inspector performance. Routine audits of product passing or failing inspection are often used to assess individual training needs. This feedback is delayed, however. Rapid feedback on performance will maintain motivation, aid training, and maintain standards. Without feedback the inspector may not be aware of missing defects or may reject more

TABLE 6.11
Effects of Task Variables on Inspection and Performance (adapted from Murphy 1968, Purswell, Greenshaw, and Oats 1972)

Task Variable	Explanation of Inspection Task	Percent Errors	Conditions	Percent Detection
1. Complexity	Students identified defects in a series of geometric shapes on a 10 × 13 cm (4 × 5 in.) target. The shapes were 10 mm (3⁄8 in. high) on the 5 × 5 grid and 6 mm (1⁄4 in.) high on the 7 × 7 grid.	4.7 11.2	5 × 5 grid 7 × 7 grid	— —
	Process control inspectors on two inspection tasks searched for 50 or 200 defects on a product.	— —	50 defects 200 defects	81 42
2. Velocity	Students searched for defects or targets (geometric shapes) moving at 13 or 18 cm /sec (5 or 7 in./sec)	5.1 10.8	13 cm/sec (5 in./sec) 18 cm/sec (7 in./sec)	— —
3. Spacing	Students searched for defective shapes at 13 cm/sec (5 in./sec) with different spacing between the targets (25, 38, and 50 cm or 10, 15, and 20 in.)	10.1 4.5 2.4	25 cm (10 in.) spacing 38 cm (15 in.) 50 cm (20 in.)	— — —
4. Direction	Inspectors looked for defects on a moving web. Their position relative to the web's direction of movement was varied.	No significant difference	Left to right versus right to left	—
		—	Movement toward vs, away from inspector	Toward better than away from

product than necessary because of a desire not to make errors. In a study of a complex glass inspection where feedback was experimentally introduced, the number of defects missed was reduced by about 50 percent (Drury and Addison 1973). One technique to provide rapid feedback to inspectors is to perform random audits.

As technology has advanced another rapid feedback training method is computer based training off line that is used in aircraft inspection training (Czaja and Drury 1981; Gramopadhye et al. 2000)

Social factors tend to determine rejection rates in operations where people are doing similar inspection tasks in adjacent workplaces but with different defect rates. In one study, a group of inspectors was given product to inspect that had a known defect rate of 8 percent (Murphy, 1975). When they were working alone, these inspectors reported finding the 8 percent defects. They were then placed in an area near another group of inspectors who had product with a 16 percent defect rate. In a short time the 8 percent defect rate group was reporting 13.7 percent defects. This increase was attributed to their observation of the inspectors on the neighboring line with the higher rejection rate, which influenced them to change their criteria. If feedback is provided to inspectors these types of social influences can be minimized.

It may take one or two years to train an inspector to identify all defects on several products. These factors will increase the length of inspectors' education:

- How frequently a product is manufactured
- How often the product changes
- Changes in rejection criteria

Because inspection is often a highly repetitive activity and may be externally paced, attention should be paid to work/rest cycle needs, because of decrements of vigilance over time as well as development of visual and musculoskeletal fatigue. In a continuous paced web inspection task where five to six defects were being inspected at 76 m/min (250 ft./min), a 2 percent miss level in detection performance was noted in the first 10 minutes of the task. This rate increased to 3 percent by 30 minutes and 5 percent by 40 minutes (Murphy1975). Similar responses were shown in an experiment where inspection performance during a 60-minute session was compared with that in two 30-minute sessions separated by a 5-minute rest break (Colquhoun 1959). Without a rest break, the inspectors missed about 5 percent of the targets by the end of 50 minutes, compared with 1 percent when they had a rest break. (See also "Ergonomic Work Design" in this chapter.)

Shift work, particularly work on the midnight-to-early-morning shift, may influence inspection performance through its effect on subjective fatigue. The body is at a low point with respect to many of its 24-hour rhythms in the early morning hours, and alertness is reduced. Therefore, an inspector's ability to detect rare defects can be impaired.

A further social factor that may influence inspection performance is the diffusing of responsibility for quality inspection by providing several inspections for the same series of defects. An inspector early in the system who knows that someone else will also be inspecting the product may not be as thorough. The later inspector, who knows that the defect has already been looked for, may also not be as careful. Establishing specific responsibility for defect detection is a preferred alternative.

Guidelines to Improve Inspection Performance

- Make the viewing angle 15° and below to allow a natural downward gaze and head tilt.
- Evaluate the vision of inspectors who have to detect fine color differences or low-contrast defects. The color vision and acuity test should be as similar to the inspection task as possible and not be based just on standard tests performed in an eye clinic.
- Inspectors who wear bifocals, trifocals, or progressive lenses should be evaluated under the specific task requirements; try to make reasonable accommodations for them.
- For inspectors with single-correction glasses prescriptions, the normal viewing distance for clear vision is around 50 cm (20 in.).
- Encourage the visual inspector to find his or her resting position of the eyes (see "Visual Work Dimensions" in Chapter 3).
- Develop a standardized training program for inspectors; do not rely on one-on-one training by existing inspectors.
- Include procedures for continued training in a standardized program.
- Intersperse quality performance checks.
- Provide rapid performance feedback.
- Provide regular feedback to inspectors about errors or misses in detecting defects. Perform regular audits to help in this process and to identify training needs.
- Use different type of lighting to improve the detectability of different defects. Permit the inspector to adjust the lighting to fit his or her body size and visual requirements
- Provide defect samples.
- Provide photographic or standardized aids for comparative evaluations, especially at those inspection stations where multiple, and sometimes rare, defects are to be detected.
- If products are changed frequently, provide information (such as previous defect reviews) to the inspector to refresh his/her memory at each product change This review technique should decrease the warm-up period at product changes

- If the defect rate is low, provide environmental aids to assist the inspector in finding defects. Examples of such aids are special lighting or an alerting alarm. Sampling inspection may also be preferable to 100 percent inspection.
- Whenever possible, remove the process control inspector from direct machine pacing. Permit the operator to vary the time for inspection within a small range
- Minimize environmental distracters in inspection stations (Murphy, 1968)

A comprehensive review of methods for measuring vigilance, monitoring, and search performance, as well as observer, task, and signal characteristics, can be found in Boff and Lincoln (1988), Volume 2, Section 7.4.

ERGONOMICS IN THE CONSTRUCTION INDUSTRY

The Need for Ergonomics in the Construction Industry

Work in the construction industry is very different from other types of occupation in terms of the physical task requirements and the extent of the safety and health risks to workers. In the construction (or demolition) of buildings, houses, roads, bridges, and other structures, the majority of tasks require heavy physical labor and are often performed in extreme environmental conditions such as high heat and humidity or freezing conditions. The construction industry is consistently ranked among the most dangerous occupations (Center to Protect Workers' Rights 2001; Ringen et al. 1995) and accounts for a disproportionately large percentage of all occupationally-related illnesses, injuries, and deaths reported to the United States Bureau of Labor Statistics (Bureau of Labor Statistics 2002a, 2002b). Although the illness and injury rates for construction workers have decreased in the last 20 years, in 2001 the construction industry had its highest level of fatalities since the Bureau of Labor Statistics began conducting its fatality census, and the industry continues to have the largest number of fatal work injuries of any U.S. industry (Bureau of Labor Statistics 2002b). In 2000, 23.5 percent (1,220) of all occupationally related deaths occurred among construction workers (National Safety Council 2001). Approximately three construction workers died each day in 2000 from injuries sustained on the job. Although serious injuries in construction often result from acute trauma, many injuries develop over time from repeated physical stress and are broadly classified as musculoskeletal disorders (MSDs).

In the United States, as well as in many other countries, the construction industry accounts for some of the highest rates of occupationally related musculoskeletal injuries and illnesses (Holmström, Ulrich, and Engholm 1995; Schneider 2001). Musculoskeletal disorders are a major cause of work-related disabilities and lost-time illnesses and injuries in the construction trades. In the United States, the construction industry has the second highest incidence rate for reported injuries and illnesses as compared to other industries (Bureau of Labor Statistics 2002a). There is a large body of evidence indicating that illnesses, traumatic injuries, and deaths are more prevalent among workers in the construction industry than for most other occupational groups in all industrialized nations (Holmström, Ulrich, and Engholm 1995; Schneider and Susi 1994; Schneider, Griffin, and Chowdhury 1998). According to Holmström, Ulrich, and Engholm (1995), Swedish insurance companies determined that in the construction industry 72 percent of all sick leave greater than four weeks was related to MSDs. Musculoskeletal disorders can lead to absenteeism, lost productivity, personal financial burden, physical suffering, disability, and early retirement. Because of psychosocial, economic, and cultural factors specific to the construction industry, many construction workers do not report MSDs to their employer or seek early medical attention (Ringen et al. 1995; Schneider 2001; Rosecrance et al. 2002). Unlike workers in other occupational groups, construction workers may not seek medical attention until their disorder interferes with their ability to perform work tasks or activities of daily living. The consequences of occupational MSDs in the construction industry place a significant burden on the worker, the company, health care systems, and national economies.

In a comprehensive review of the data and literature related to MSDs and the construction industry, Schneider (2001) concludes that construction workers are at significant risk of musculoskeletal injury. Schneider points out that the MSDs are specifically related to the physically demanding job tasks performed in construction work. Additionally, the job factors that are physically demanding for men may be even more demanding for women in the construction trades. In a study of 1,000 construction apprentices, Merlino and associates (2003) indicated that women reported significantly more MSD symptoms in the neck, upper back, shoulder, elbow, wrist/hand, and hip/thigh than men. Female construction workers have suggested that tools, materials, and equipment should be available in sizes and designs appropriate for women (Goldenhar and Sweeney 1996). The application of ergonomic principles and methods is of primary importance for reducing the burden of occupationally related injuries and illnesses among construction workers.

Construction Job Factors and MSDs

The nature of construction work as well as the characteristics of the construction industry are highly variable and create greater obstacles to implementing an ergonomics process than in traditional fixed-site industries (Hecker, Gibbons, and Barsotti 2001). Some of the difficulties or challenges to ergonomic intervention in the construction industry include: a mobile workforce, workers with multiple work sites, workers with several employers, variable work tasks, the majority of work being performed at floor level or overhead, and extreme environmental conditions (hot, humid, or cold conditions). The variability inherent in construction work presents many challenges to the ergonomist. For example, it is more difficult to characterize and measure risk factor exposure among construction workers who often perform noncyclic work tasks at workstations that may change on a daily basis as compared to workers performing repetitive tasks in a fixed-site production facility. However, the basic elements of a job task that increase the risk of MSDs among construction workers are similar to those identified in other industries. Construction work is often associated with tasks involving forceful exertions that are excessive or prolonged, such as heavy lifting or prolonged grasping; awkward postures that are maintained for extended periods; pressure from hard surfaces or sharp edges on body tissues; vibration from tools and machinery; and environmental factors such as extreme temperatures and humidity.

A review of more than 13,000 job analyses performed by the United States Department of Labor demonstrated that occupations within the construction industry are more physically demanding than nonconstruction occupations, especially with regard to the physical strength requirements of the task (Schneider, Griffin, and Chowdhury 1998). More than 30 percent of construction jobs (various trades) were rated as heavy or very heavy as compared to 9 percent of nonconstruction jobs. Jobs rated as heavy or very heavy require lifting more than 45 kg (100 lb.) occasionally, 23-45 kg (50–100 lb.) occasionally or frequently, 11.5–23 kg (25–50 lb.) frequently, or over 4.5 kg (10 lb.) constantly (Schneider, Griffin, and Chowdhury 1998). The high physical demands of construction work are most likely related to the high rates of MSDs reported among construction workers. Several studies indicate that musculoskeletal disorders may start relatively early in a construction workers career (Merlino et al. 2003; Rosecrance et al. 2001).

An analysis of 1997–1999 illness and injury data from the Construction Safety Association of Ontario (2003) indicated that one-fourth of all work-related illnesses and injuries among construction workers were related to physical overexertion. This finding supports the high degree of manual effort still involved with most construction tasks. Over the three-year period low back pain was the most common injury (23.7 percent yearly average). Rates of injury to other body areas varied depending on the trade and the nature of work tasks. Lifting, carrying and moving materials accounted for nearly one-fourth of all injury-producing activities among construction workers. Sprains and strains were the most frequently cited types of injury overall, with a three year average incidence of 28.7 percent.

Using a self-administered symptom and job factors questionnaire, Cook, Rosecrance, and Zimmermann (1996a) assessed construction workers' perceptions of the physically stressful elements of their job. Questionnaires were completed by 2,929 construction workers (40 percent response rate) representing thirteen trades. The investigators asked construction workers to rate, on a 0–10 scale, fifteen specific job factors as to the degree to which each factor contributed to work-related injuries and illnesses. The three job factors that all trades rated as the most problematic in terms of contributing to injury and illness were (1) maintaining the same positions for prolonged periods, (2) bending and twisting the low back in an awkward way, and (3) working in awkward and cramped positions. Interestingly, the job factors rated as most problematic (9 and 10 on the scale) were dependent upon the specific trade. For example, the job factors rated as the most problematic among roofers were environmental conditions (hot, humid, cold) and bending or twisting the back. Laborers rated working while injured or hurt and bending or twisting the back as the most problematic (Cook, Rosecrance, and Zimmermann 1996a). Others have also reported that trade specific profiles or patterns of MSD symptoms and problematic job factors are specific to the type of construction work performed (Rosecrance, Cook, and Zimmermann 1996; Goldsheyder et al. 2002). Using a survey instrument similar to that employed by Cook and colleagues (1996a), Goldsheyder and colleagues (2002) assessed the magnitude and characteristics of MSDs among approximately 300 mason tenders and identified trade-specific work activities perceived by the workers as contributing to their MSDs. Their findings revealed that 82 percent of the mason tenders experienced at least one musculoskeletal symptom in the previous year and that low back pain was the most frequently reported symptom (65 percent of the sample). Due to low back pain, 12 percent of the laborers missed work, and 18 percent of them visited a physician. Bending or twisting the back, working in the same position or in pain, and heavy lifting were perceived as the most problematic work-related activities. Trade-specific profiles can be utilized to assist with efficient and targeted ergonomic intervention strategies for each of the construction trades.

In a review of the job factors associated with MSDs among construction workers, Holmström, Ulrich, and Engholm (1995) indicated that there were clear relationships between specific MSDs and specific construction tasks (e.g., work above shoulder level and shoulder problems, kneeling tasks and knee disorders, working in a bent-forward posture and low back pain). It is also likely that hand-intensive work that involves forceful exertions, vibration, frequent or repetitive use of hand tools, and/or awkward wrist postures is associated with hand disorders such as carpal tunnel syndrome (CTS). Although CTS has been portrayed as a disorder among computer users, construction workers are likely to have a higher exposure to the risk factors associated with CTS than computer operators. In an epidemiological study of MSDs among 1,100 construction workers from the sheet metal, electrical, plumbing, and operating engineering trades, Rosecrance and colleagues (2002) reported a CTS prevalence of 8.2 percent. The investigators utilized nerve conduction studies and symptoms in their case definition of CTS. The prevalence of CTS among construction workers is approximately three times that reported for the general population using similar epidemiological case definitions (Atroshi et al. 1999). Interestingly, when the operating engineers were separated into groups by work task, those performing mechanic-type work on the heavy equipment had a significantly higher association with CTS than the drivers of the equipment. This finding illustrates the relationship between specific MSDs and specific construction tasks.

Information regarding the influence of psychosocial factors on MSDs among construction workers is limited (Goldenhar et al. 1998; Holmström, Lindell, and Moritz 1992; Riihimäki et al. 1989). In an investigation of approximately 1,800 construction workers, 21 percent of the workers scored high on a stress index (Holmström, Lindell, and Moritz 1992). The stress index included four questions about "rushing even when you have plenty of time," "pushing oneself under pressure," "finding it difficult to relax," and "looking upon the job as a mental strain." There was a clear relationship between low back pain and high scores on the stress index, with a prevalence rate ratio of 3.1 (95 percent CI 2.3–4.0) for severe low back pain. Psychosocial stress was also associated with the 5-year prevalence of sciatic pain in concrete reinforcement workers and painters (Riihimäki et al., 1989). Nonoccupational factors have also been associated with MSDs among construction workers. Holmström, Ulrich, and Engholm (1995) referred to various studies that demonstrated relationships between MSDs among construction workers and their age, smoking habits, anthropometric factors (such as height, weight, and body mass index), poor physical fitness, and diminished muscle strength.

Responsibility for Ergonomics

There are a variety of stakeholders responsible for ergonomic decisions in the construction industry. Architects and designers, contractors and subcontractors, building owners, tool manufacturers, material suppliers, and individual construction workers are all involved in the decision-making process that affects ergonomics at the construction site. Architects, designers, and project owners make decisions that determine construction scheduling, project planning, materials delivery, and the methods and procedures that will be needed to complete the construction project. The choices they make often determine the physical access to building materials and the coordination of skilled trades competing for physical space. These decisions can ultimately influence the postures, repetitions, forces, and other risk factors that workers will be exposed to. Scheduling, planning, and sequencing of work have enormous implications for ergonomics on the construction worksite (Hecker, Gibbons, and Barsotti 2001). Many of the ergonomic risks associated with MSDs are influenced by decisions made during the planning and scheduling of construction jobs. Decisions related to planning and scheduling are beyond the control of the individual worker and often out of the control of general or sub-contractors (Hecker, Gibbons, and Barsotti 2001). Thus, those responsible for scheduling and project planning decisions must be brought into the ergonomics discussion process.

Construction contractors are usually responsible for the level of health and safety awareness at the construction site, and so their decisions have a major impact on the safety and "ergonomics culture" at the construction site. As with most ergonomic programs and processes in the manufacturing industry, management commitment is paramount to a successful ergonomics process at the construction site. Suppliers of construction materials make decisions that influence the design, packaging, and delivery of construction materials, tools, and machinery. Suppliers have influence on the weight of packaged materials, how materials are bundled, and the location of supplies and materials being delivered. Tool manufactures are also critical links in the ergonomics process. There is a great need for ergonomically designed hand tools for men and women in the construction trades. Poorly designed hand tools increase the amount of vibration transmitted to the hands, increase the forces required to operate the tool, and increase the awkward postures and positions taken when using them.

As in other industries, the individual worker is ultimately responsible for his or her health and safety and often makes decisions that influence the likelihood of future illness and injury. Ergonomics education for management and hourly workers is the foundation of most successful ergonomic processes in general industry. Thus it is reasonable to expect that construction workers with knowledge in ergonomic principles will make safer decisions related to the construction site and to their specific work methods. Ergonomics education should be integrated into apprenticeship and journey-level construction training programs. According to Hecker, Gibbons, and Barsotti (2001), contractor-by-contractor approaches to ergonomics education are beneficial but may be insufficient due to conflicting approaches and goals among contractors. Training programs jointly administered by labor and management organizations provide an ideal environment for delivering ergonomics education and for the dissemination of ergonomics education materials. Although ergonomics education is beneficial, worker education alone is not sufficient to ensure long-term ergonomic changes in the construction industry. Ergonomics education should be directed at all levels to all stakeholders. Additionally, training needs to be supported with other resources at the owner and contractors level to assist in the design and implementation of solutions in the field (Hecker, Gibbons, and Barsotti 2001). Smaller contractors may not have the resources to assist with ergonomics and will require additional support from trade associations and government health and safety agencies.

Controlling Risk Factor Exposure

There are three approaches to controlling or modifying the risk factors associated with job tasks in the construction industry. These include engineering controls, administrative controls, and the use of personal protective equipment.

Engineering controls are usually the best method for eliminating the risk factors present in specific construction tasks. Engineering controls consist of work methods and or tool designs that eliminate the risk factor altogether. Examples of engineering controls include modifications to tools that eliminate wrist deviations, the use of mechanical hoists to lift and move materials, and various worker-designed ergonomic modifications to tools and work process that make the job less fatiguing or less stressful. Engineering controls are usually the most effective long-term approach to reducing the risk factors associated with work-related MSDs.

Administrative controls are usually the responsibility of the contractor or owner. Administrative controls include modifications in work organization, education and training, decisions related to employee rest break and work schedules, and pay scales and incentives. Exercise programs that involve prework stretching and on-site instruction in lifting techniques have also be used as administrative controls for reducing MSDs in the construction industry (Hecker, Gibbons, and Barsotti 2001). See Chapter 7 for further discussion of exercise programs.

The least reliable approach to reducing risk factor exposure in the construction industry is the use of personal protective equipment. Personal protective equipment frequently used in the construction industry includes devices such as knee pads for workers who perform prolonged tasks at ground level, vibration-absorbing gloves for workers using vibrating tools, and back belts for tasks involving manual materials handling. There is still considerable debate as to the effectiveness of personal protective equipment used in the construction industry.

Ergonomics Interventions in Construction

The Participatory Process

Experience from general industry during the last 20 years has demonstrated that the most successful strategy for developing solutions and implementing effective ergonomic interventions is to use a team approach and to establish a process for identifying and solving poor work practices (Rosecrance and Cook 2000; see also Chapter 1 for further discussion of participatory ergonomics programs).

A common strategy employed to implement ergonomic changes within many industries involves a cyclical problem-solving process conducted by the stakeholders (workers and management) involved in the job tasks being investigated. This cyclical process includes five specific but overlapping steps: identification, analysis, solution development, implementation, and evaluation. This process is similar to other participatory problem solving techniques (Israel, Schurman, and Hugentobler 1992; Moore and Garg 1996; Schurman 1996) and to quality management programs (Deming 1986; Walton 1986). When this process is focused on ergonomic issues, it is often referred to as the "ergonomics process." The identification of work-related MSDs and their associated risk factors is the first step in the ergonomics process. Once MSDs are identified, specific work tasks and methods are analyzed to detect risk factors and develop potential solutions. Based on the findings from the analysis, priorities are established for solution development, and implementation is planned. The implemented solutions are then evaluated. In most instances, the initial solutions are imperfect, and therefore the situation is reanalyzed and the cycle repeated until a satisfactory result is obtained. This process must be continuous because of ongoing changes in designs, materials, tools, machinery, and work methods. These changes are especially prevalent in the construction industry, where a job site may change significantly during a relatively short period (Hecker, Gibbons, and Barsotti 2001; Schneider, Punnett, and Cook 1995).

Over the last five years, ergonomic committees (or teams) responsible for health and safety in the construction industry have utilized the ergonomics process more frequently. An ergonomics committee in construction should be primarily composed of the workers and contractors, with assistance from suppliers, manufacturers, owners, and others depending on the problem being addressed.

The ergonomics process can be adopted and followed to varying degrees when developing ergonomic solutions in the construction industry. The process may take several minutes for simple problems with obvious solutions or several months for difficult problems that require complex solutions. Ergonomic interventions that reduce the exposure to risk factors associated with MSDs range from very simple tool modifications to elaborate material handling devices. The costs and time required to design and implement ergonomic interventions vary significantly and are dependent to some degree on whether they are engineering or administrative controls. In general industry, Rosecrance and Cook (2000) reported the mean and median cost for individual ergonomic interventions that were considered engineering controls were $376 and $25, respectively. The examples of ergonomic solutions below will illustrate that the costs for specific solutions in the construction industry would be in a range similar to general industry.

Example of Ergonomic Interventions

BUILDING A PLANT Hecker, Gibbons, and Barsotti (2001) described several ergonomic interventions designed by a group of workers and contractors following ergonomics training at the building site of a large semiconductor manufacturing facility. After a period of approximately 6 months, two-thirds of the 110 workers who attended the ergonomic training indicated that they had made ergonomic changes to their workstations or work methods. The most frequently reported ergonomic changes included: modifications to lifting tasks (body position, getting help, using lifting equipment), changes in working position/posture, improving work height, the use of ergonomic tools, and preplanning of work. The following two examples are among many that the authors described.

Concrete core drilling: A team of four drillers, two above and two below, drilled 3,000 30 × 15 cm (12 × 6 in.) cores in a concrete deck. The two below positioned and secured steel boxes in place to catch the core and accompanying slurry from the drilling. They had to insert 1.2-cm (0.5-in.) all-thread bolts 41 cm (16 in.) long through a section of strut and thread on a nut to help secure the box. This was done 10–12 times per day by hand, by "rolling" the bolt between the palms. The result was repetitive hand and wrist motions and contact stress at the palms. Discussions among the ergonomist, the crew, and the general contractor's safety staff identified a slip-nut that can be slipped on the bolt at any point and twisted to tighten. Thus, the all-thread could simply be pushed through the strut rather than screwed for its whole 43 cm (16 in.) length.

Pipe cutting and reaming: Pipefitters needed to manually cut and ream about 5,000 pieces of 1-inch PVC pipe with a hand reamer. After attending the training, they recognized the repetition and non-neutral wrist posture involved in this operation. The crew attached to a drill a PVC connector sized to accept the 1-inch pipe. Then they mounted the hand reamer on a pipestand at waist height. They taped a vacuum hose to the back of the reamer to collect the pipe debris, a requirement in this microprocessor facility. To ream the pipe they inserted each length in the connector, pressed it against the mounted reamer, and avoided the repetitive motion of hand reaming.

DRYWALL INSTALLATION Workers who perform drywall (Sheetrock) installation have very high rates of back and shoulder injuries due to the physical demands of their trade (Schneider, Punnett, and Cook 1995). Drywall work includes three main tasks: manual handling of boards, cutting boards to size, and securing the boards to the wall and ceiling. Drywall boards are relatively heavy and because of their dimensions, awkward to carry. They weigh approximately 30 kg (66 lb) and are approximately 120 cm by 240 cm (4 feet by 8 feet) in size. To reduce the awkward handling of drywall boards, there are several commercially available drywall handles that facilitate improved handling while carrying it (see Chapter 7). The handle hooks under the board and allows the worker to carry it closer to the body with a more erect posture. Alternatively, two workers can each use a drywall handle to reduce the weight of the load. Drywall carts are also relatively inexpensive and excellent alternatives for transporting drywall boards around the construction site. Another ergonomic option that has been proposed in Scandinavia is to reduce the width of drywall board from 120 cm (4 feet) to 90 cm (3 feet) (Schneider, Punnett, and Cook 1995). The reduced width decreases the weight of the drywall board making it easier to lift, manipulate, and carry. Mechanical lifts are also available to raise and hold drywall overhead during ceiling installation. Although the worker is still required to perform overhead work while securing the drywall to the ceiling joists, the mechanical lift reduces the shoulder stress associated with holding the drywall in place.

BRICKLAYING The risk factors associated with bricklaying and laying masonry block involve the placement of the mortar mix, the placement of the brick/block supply, the weight and size of the bricks/blocks, the location of the work (e.g., height of the wall), the work rate, rest cycle, and duration of work. In a study of the working tasks of bricklayers, Luttmann, Jager, and Laurig (1991) measured muscle activity, time in awkward postures, brick holding time, and productivity relative to wall height. They determined that muscle activity and awkward postures were highest when the worker was in a bent-over position. Cook, Rosecrance, and Zimmermann (1996b) also reported that "bending or twisting your back in an awkward way" was the most problematic job factor for bricklayers, with nearly 40 percent of bricklayers indicating it was a major problem contributing to work-related injuries. Based on the studies related to bricklaying and a symptom and job factors survey of active bricklayers, Cook, Rosecrance, and Zimmermann (1996b) gave the following guidelines for ergonomic improvements in bricklaying tasks:

- The location of the worker should be (frequently) adjusted so that he or she can lay bricks as close as possible to waist height without extending the arms.
- The location of the bricks should be such that they can be grasped with minimal bending of the trunk and reaching with the arms. Very low and very high wall locations are clearly the most problem-producing.
- The location of the mortar pile should also be such that it can be reached with minimal bending and reaching.
- Brick weight should be limited.
- Brick design should allow for modest grip sizes.
- Attention must be paid to rate and duration of work (including overtime) and to the design of tools used by bricklayers.

OPERATING HEAVY EQUIPMENT Among the various construction trades, operating engineers are exposed to unique job-related musculoskeletal demands. While the typical construction worker is exposed to tasks requiring heavy lifting, carrying building materials, hand tool use, and forceful repeated motions, operating engineers are confronted with more subtle stressors (Zimmermann, Cook, and Rosecrance 1997a). The occupational stressors among operators of heavy earthmoving equipment tend to be more postural and sustained in nature as compared to workers in other construction trades. The most significant risk factors for operators are sustained awkward postures, the constant use of hand controls (especially in older equipment that requires more physical effort to operate) and vibrating environments (Zimmermann, Cook, and Rosecrance 1997b). Based on the studies related to operating engineers and the results of a symptom and job factors survey of operators of heavy equipment, Zimmermann, Cook, and Rosecrance (1997a) provided the following guidelines for ergonomic improvements in the operation of heavy equipment:

- Equipment should be designed to minimize the magnitude of frequency of vibration reaching the operator.
- Equipment controls should be located within the cab such that reach distance and trunk flexion and rotation are minimized.

- Cabs should be designed to provide the maximum operator visibility from an upright, supported, seated posture, thus decreasing the postural load associated with trunk and neck flexion.
- Equipment operators should be encouraged to take regular breaks during the workday to minimize the effects of sustained posture.

MANUAL MATERIALS HANDLING Manual materials handling is a significant aspect of most construction work and is a major risk factor for many MSDs especially those related to the low back. Thus, attention to manual materials handling tasks should be a priority at the construction site. Work organization is an important administrative control to reduce the frequency and quantity of manual materials handling. Management personnel, such as the job site superintendent or foreman, should ensure that materials are delivered to the job site in a manner than minimizes manual handling. Improved coordination of materials shipments and storage has been suggested as a method to reduce injury rates (Niskanen and Lauttalammi 1989). Materials should be stored as close as possible to where they will be used. Building materials should also be stored between knee and shoulder height for easier and efficient access. Additionally, lifting assists (cranes, hoists, lifts) should be made available and in good working order and easily accessible to the workers. If mechanical hoists are not available, there should be adequate personnel present to assist when moving heavy building materials around the job site.

Summary

Construction work is one of the most dangerous and physically demanding occupations throughout the world. The prevalence of work-related MSDs among construction workers is high, and the prevention of these injuries and illnesses presents many ergonomic challenges. Despite these challenges, strategies can be implemented to reduce the risk of illness and injury. Once effective ergonomic control measures are identified, implementation can be initiated through engineering, education, and/or regulation. The use of a participatory approach that involves the construction stakeholders can help facilitate the development, implementation, and acceptance of ergonomic interventions. Innovative work organization and materials planning schemes should be used to reduce the physical demands of materials handling tasks. Power-assisted lifting devices should be readily available and in working condition. The storage of construction materials should be near waist level. The use of alternative building materials, such as lightweight masonry blocks, and the development of ergonomically designed hand tools should be encouraged. Finally, effective and long-term ergonomic solutions in the construction industry will require a paradigm shift in the construction culture. All stakeholders will need to realize that disorders such as low back pain and premature osteoarthritis of the knee should not be accepted as "just part of the job" and that they can and should be prevented.

WORK DESIGN IN LABORATORY AND COMPUTER WORKPLACES

Discussions of two types of repetitive work that can be associated with musculoskeletal discomfort when performed for the majority of the shift are included in this section. They illustrate how a combination of work pattern, equipment design, and employee training can reduce the risk for injury and illness.

Laboratory Task Design

There are some common tasks performed in many laboratories that are known to be problematic when they are conducted repeatedly or over long periods of time. Liquid dispensing is discussed in Chapter 7 under "Carboy and Large Bottle Handling." Some recommendations to resolve issues pertaining to pipetting are discussed in Chapter 4 under "Tool Design." Those related to task and work design are discussed below.

Adopt a Neutral, Relaxed Posture

Often laboratory tasks will require a postural compromise of the neck, visual distance, and height of the arm. The arm height influences the angle of the wrist. Consider:

- Set work at the height that provides the best compromise in body position. This might entail placing the work on a raised platform so that the neck is less flexed. However, caution should be exercised if the tools used (e.g., pipettes) are long.
- Angle the work, if feasible.
- Support the arms during extended sessions spent working with the arms away from the body (e.g., pipetting). Consider very free-moving articulating arm supports.
- Avoid holding trays in the nonworking hand; use a support instead.

Control the Amount of Continuous Time on the Task

Björkstén, Almby, and Jansson (1994) found a significant increase in hand ailments with the use of plunger-operated pipettes (finger- and thumb-styled activation) when they were used for more than 300 hours per year (1–2 hours per day). David and Buckle (1997) found a significant increase of hand complaints after continuous pipette use of more than one hour. An alternative to controlling time on the tasks is to use electronic pipettes and other techniques that shorten manual pipetting time. There should be general caution against pipetting all day, even with electronic pipettes, due to other loads on the body, as discussed above, especially if plunger-type pipettes are used. Consider the following guidelines:

- Attempt to keep plunger-operated pipetting tasks to 1–2 hours daily. This may not always be easy if the laboratory run takes longer. Therefore, consider combining tasks between workers so that the load can be shared.
- Rotate tasks between workers to reduce overall exposure to pipetting.

Work Patterns in Computer Tasks

It is not difficult to spend extended hours on computer work when a task is interesting or extensive. This section describes why computer users should be educated to develop work patterns that minimize static fatigue and provide mental and perceptual breaks during their work shift. More discussion of these topics can be found in "Ergonomic Work Design" in this chapter.

Recovery Breaks

A recovery break is loosely defined here as any pause as short as a change in posture or as long as the time it takes to complete a non-computer-related task. Changing postures frequently is a critical work habit that all computer users need to develop. Several studies, both in the laboratory and in the field, have demonstrated that microbreaks have a positive effects both on computer users' well-being and on their performance. Seated work requires static loading of the muscles in the back, neck, shoulders, and upper arms. Exerting this type of muscle effort for an extended period of time can result in muscle fatigue. The blood flow is reduced, so the muscles do not receive enough oxygen and glucose at the same time as the waste products carbon dioxide and lactic acid are not all removed. Studies have demonstrated that intermittent pauses will reduce muscle fatigue and allow the muscles to recover.

In addition to frequent changes of posture, frequent, short breaks taken at the computer users' discretion also reduce muscle fatigue accumulation and improve task performance. These breaks have been found to be most effective if they also include some physical activity or exercise. Strictly scheduled breaks are not always recommended for a computer user, since they can be disruptive if they occur in the middle of a task and are often not introduced when recovery time is the most effective. The individual user can best tell when a short break is needed and should be encouraged to take them frequently during the work shift. In a non-computer-intensive environment, the recommendations for the degree of employee control over microbreaks, as well as their frequency and duration, may be different.

Training Programs for Office Ergonomics

Ergonomics training programs that help computer users adjust their workstations to satisfy their individual postural and visual needs are essential and have been found to improve not only working comfort but also performance. Examples of topics to include in such an office ergonomics awareness/training program are presented in Table 6-12.

Training for new employees is especially important since it can prevent the use of damaging work techniques and instill good work habits. Refresher ses-

TABLE 6.12
Examples of Topics to Include in Office Ergonomics Awareness Training (adapted from material developed by Inger M. Williams, 1994)

General Topics	Examples of Specific Issues to Address
Definition of ergonomics for the office	Special ergonomic issues in the office: Seated static work Visually demanding tasks Interruptions Deadlines
Musculoskeletal demands associated with office work	Sitting Standing Typing Mouse use Filing Mail sorting Phone use
Visual demands associated with visual display terminal work	Viewing distances Viewing angles Image quality Lighting environment
Workstation organization	Computer equipment Computer tasks Non-computer-related tasks Job characteristics
Workstation individualization	Strategies to introduce adjustability: Office layout Work surface organization Chair adjustability Assist devices Self-help strategies

sions are often needed, at least once yearly, as employees relocate, tasks change, and computer equipment is upgraded.

A team effort is often required to set up a computer workstation. Training should, therefore, benefit not only the computer user but also those responsible for purchasing computer equipment and office furniture; facilities and maintenance staff; information technology specialists; employees in medical, human resources, and health and safety departments; and managers and supervisors. For a team-building ergonomics training program to be successful, it must be designed to fit in a corporation's culture. See Chapter 1's section on ergonomics programs for a further discussion of this topic.

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URLs:

http://www.facoccmed.ac.uk/BackPain.htm

http://helping.apa.org/work/stress4.html

http://www.balanced living.com/cblstats.html

http://wwwunl.edu/stress/mgmt/#toc

7 Manual Handling in Occupational Tasks

BACKGROUND: MANUAL HANDLING AND MUSCULOSKELETAL INJURIES AND ILLNESSES

Injuries and illnesses associated with handling objects or exerting forces continue to be a large part of ergonomics-related problems in companies today (OSHA 2000). Low back pain and muscle strains may account for 25 to 60 percent of the incidents reported, the difference being accounted for by the types of work being done (Keyserling 2000; Nagira, Ohta, and Aoyama 1979; Rodgers 1980). About 24 percent of lost-work-time cases reported in 1994 were associated with manual materials handling or force exertion tasks (Keyserling 2000). In addition to occupational injuries and illnesses, heavy lifting tasks have made it difficult for people with non-occupational injuries to get back to their jobs. Absenteeism is usually higher in heavy jobs across many diagnoses (Rodgers 1980), because getting back to a heavy job is harder to do than returning to a well-designed job (Rowe 1983). Some of the types of injuries seen in people who handle objects as part of their job are summarized in this section.

Types of Musculoskeletal Overexertion Injuries Seen in Manual Handling Tasks

Muscle Overexertion Injuries

When the task to be done exceeds the strength of the active muscle groups, an overexertion injury can occur, such as a torn tendon, muscle, or ligament. If a task is designed without attention to the strengths of men and women in that posture, there may be a large part of the population for whom the task is not appropriate.

See "For Whom Do We Design?" in Chapter 1, particularly the muscle strength data, for guidelines for designing lifting and force exertion tasks. The best way to avoid overexertion injuries is to keep the muscle loads below the recommended maximum values. Another important approach is to ensure that static muscle loading does not fatigue the active muscles prior to a handling task.

Muscle Overuse Injuries

While muscle overexertion injuries can occur with a single lift or force exertion, overuse injuries are usually an accumulation of small fiber tears in the muscles and tendons and an accumulation of lactic acid that contributes to swelling of the muscles and joints. This "soreness" usually lasts for about 72 hours if it is not further aggravated by continued heavy work of the same muscle groups. It is frequently seen when an intense and unusual activity is done without preconditioning of the muscles and joints. It may also be seen when people first start a job if they are not allowed to break into the job in stages. An effective break-in pattern is to increase the hours per day from 1 to 8 over the first week or two.

Inflammatory Response to a Sustained or Repetitive Load

Whereas short-term overuse problems usually involve a task that is done occasionally, sustained or repetitive use of the muscles and joints with moderately heavy or heavy efforts can lead to more acute flare-ups of tendonitis or other inflammatory conditions. Some workers are more susceptible to these problems, perhaps because of personal risk factors, work patterns, or other psychosocial issues. Because there is no highly predictable way to identify the more susceptible people, the goal in ergonomics is designing for minimal exposure to musculoskeletal risk factors (see Chapter 6).

Work-Related Musculoskeletal Disorders

The musculoskeletal injuries and illnesses of most concern to industry are those that progress to the chronic stage. These are often nerve entrapment disorders, such as carpal tunnel syndrome in the wrist, rotator cuff syndrome in the shoulder, tennis elbow, and costaclavicular syndrome in the neck and shoulder. They may also involve inflamed bursae in the shoulder and knee or disc degeneration in the neck and back. They are work-related if there are sufficient risk factors present in the job or task requirements to contribute to joint stress, muscle fatigue, or muscle strain, or to aggravate a preexisting condition. Association between the identified risk factors and these injuries and illnesses is strong, although causation is still a matter of debate (Bernard and Bloswick 2003; Burdorf et al. 1997; Carter and Birrell 2000; Keyserling 2000; Marras 2000a, 2000b; National Research Council 1999; NIOSH 1997). Biomechanical, physiological, psychophysical, and epidemiological studies of musculoskeletal injuries and illnesses in the workplace have been joined recently by studies of job psychosocial factors. All appear to play a part in determining the risk of people for developing musculoskeletal problems at work (OSHA 1999; Sauter and Murphy 1995). See "Organizational Factors in Work Design" in Chapter 6 for more discussion of psychosocial factors.

Strategies to Reduce Manual Handling Risk Factors

Materials Flow Analysis

One of the best ways to reduce the risk of injuries on manual materials handling tasks is, wherever possible, to minimize the amount of manual handling. The philosophy of many manufacturing materials flow analysis systems is to remove non-value-added operations from the production line (SME 1998, 2000). Manual handling is a major non-value-added part of most production lines, in some instances making up 70 to 80 percent of the operations done in a product manufacturing sequence (Eastman Kodak Company 1986).

To design a system that minimizes the amount of manual handling, ergonomic considerations need to be to be included in the conceptual stage of the line's design, not added in after the design is mostly done. A systems design approach to the design of materials handling in a manufacturing plant includes using the following principles (after Beck 1978):

UNIT LOAD PRINCIPLE Increase the size, quantity, or weight of unit loads so they can be handled with powered equipment. For example, use pallet boxes or Super-Saks for powdered chemicals instead of paper sacks.

MECHANIZATION PRINCIPLE Move parts or products between workstations mechanically. Preferred methods are the use of overhead or horizontal conveyors. There should be a method to control the flow of materials on the conveyors to provide variability in the rate at which parts are presented to the next worker. Examples of this would be power and free conveyors, shunts, or speed controls with provision made to avoid line backups. It should be noted that some systems philosophies try to eliminate in-line inventory of the sort mentioned here (SME 2000). That has significant negative ergonomic consequences because it takes control away from the workers.

STANDARDIZATION PRINCIPLE Standardize handling equipment, types, and sizes of handling equipment. The equipment should be compatible across the system in order to avoid the need to move parts on and off other transfer devices. A corollary of this is to use the same system to store the product as is used to move it on the line or in the plant. For instance, this would be useful if the product has to wait a day or two before it is released because of stabilization issues like film blocking, the need for outgassing of foam products, or while waiting for the results from special final quality assurance testing.

ADAPTABILITY PRINCIPLE Use methods and equipment that can best perform a variety of tasks and applications. Few workplaces remain static for years, so any system should be flexible enough to accommodate more than one size of part, different conveyor rates, and the need for additional equipment in the same space. A corollary of this is to provide ways to manually work (comfortably) on those parts of the line that are automated so that the whole line won't have to be shut down each time there is a machine failure in one part of it. There are those who suggest that a good design should be fail-safe and that planning for failure is, philosophically, wrong. This is a noble sentiment that will be quickly modified by the reality of the workplace. Good ergonomic design provides ways to address failures in automation so that the risk of injuries for the workers who have to fill in until the automation is fixed is not increased. "Special Considerations: Design of Ultra-Short-Cycle Tasks" in Chapter 6 gives an example of this design need on a bottling line.

DEAD WEIGHT PRINCIPLE Reduce the ratio of the dead weight of the container or handling equipment to the load carried. The weights of trays, cans, bottles, cans, carboys, and barrels should be minimized, where possible, so that unnecessary weight does not have to be handled by either people or handling equipment. A similar situation exists for fixtures used on lathes, grinders, and other metalworking machines. Often, the weight of the fixture that holds the part on the machine is much greater than the weight of the part. It may contribute to injuries and illness of the operator's muscles, joints, and back as he or she tries to attach it to the table in the machine.

GRAVITY PRINCIPLE Use gravity to move material wherever practical. Examples of this are the use of gravity-feed conveyors, slides, and counterweighted tippers and handling devices. Sliding, rather than lifting, parts and products is ergonomically preferred because one can use gravity to assist with the movement. This assumes that the coefficient of friction of the object and the surface it is resting on is not too high. The availability of height-adjustable carts and trucks to help handlers slide items on and off shelves in a warehouse or storage room has considerably reduced the stress on their upper bodies and backs. Omnidirectional rollers with adjustable stops can be located at the beginning and end of conveyor lines to make it possible to slide cases or trays from the line without having to lift them. See the URLs at the end of this chapter for examples of sources for handling equipment.

AUTOMATION PRINCIPLE Provide automation to include production handling and storage functions, such as automated stacker/retriever systems. There is a tendency to treat the loading and unloading of parts and product on the line as separate from the assembly, inspection, packaging, and labeling parts of the line. Many automated systems do everything except load and unload themselves, a task that is easy to automate in many instances and, in terms of injury risk, much better for a machine to perform.

Using an automated retrieval and storage system will eliminate many non-value-added functions associated with transporting, retrieving, and storing product in other places. In machine shops and other nonmanufacturing jobs, storage and retrieval systems can be used for storing tools or parts so that they can be easily retrieved as needed and are always presented at waist height for comfortable handling.

Education of Handlers

TYPES OF TRAINING For many years, there has been a concerted effort in companies to teach people to lift well, especially people whose jobs require more than an occasional lift each shift. For specific jobs where tools are used and force applications may be very high, one-on-one training of new people in a workplace or area is used to pass on the skills for getting the job done without risking overexertion injuries.

While good training is essential so the workers can develop the correct skills for handling materials on the job, one cannot overcome poor handling task design by training alone. Lifts or forces that exceed the safe limits for most workers should be redesigned to fall inside those limits. If that is not feasible, then the people with the needed strengths and endurance have to be found using validated selection tests.

GUIDELINES FOR LIFTING TRAINING There are several types of lifting and force exertion training that are generic and that all workers should be aware of. They can be summed up under the following guidelines (Rodgers 1985):

- Plan the lift
- Determine the best lifting technique
- Get a secure grip and use an open stance for foot stability
- Keep the load or force exertion as close to the body as possible
- Use the legs to lift heavy objects
- Avoid twisting while lifting—use a step turn
- Alternate heavy lifting or force exertion tasks with light work tasks
- Use the larger muscle groups to exert forces and transfer loads

An Australian study that compared three different methods of lifting found that a semisquat stance was preferred and showed success in being safer and more effective in training because it allowed for more adaptability in the handling tasks (Sedgwick and Gormley 1998). With frequent lifting, the leg lifts increase the workload substantially for lifts from the floor and the semisquat can be done safely without adding the extra effort of lifting the whole body on each pick.

TWO-PERSON HANDLING TRAINING Some objects are difficult to handle unless a second person is available because of their weight, dimensions, or weight distribution. Examples of these include wallboard or other sheet materials, large packages with two or more dimensions exceeding 61 cm (24 in.), large bags of grain or pellets, pipes, lumber, stretchers, and furniture. The general guidelines for handling these objects with two people are the same as those for one-person handling with the addition of a need for close teamwork. The people should be closely matched in terms of strength, height, and endurance so that the loads are shared evenly most of the time.

In general, one has to expect that there will be times in a two-person handling task when one person will bear more of the load than the other, perhaps 60 percent to 40 percent. So, if the weight of the object is twice the weight recommended for one person, a two-person lift may still put either person at risk for an overexertion injury. To determine the safe lifting weight for a team, one should add the maximum acceptable weights of each person and then reduce the total by 12 to 15 percent (Lee and Lee 2001). A general design guideline would be to restrict the weight of loads handled by two people to 40 kg (85 lb) so most workers can make them safely. Two-person handling should not be considered an ergonomic way of addressing heavy lifting problems because there may not always be a second person available. It is best used to transfer bulky items that are not very heavy but are difficult for one person to hold close to the body.

When training people to do lifting together, the emphasis is on good communication between them so that they lift together and put the object down together. If one person begins to lose control of the load, it is important that he or she communicate the problem and that the pair resolve it as a team so that there are no sudden changes in the load. This is especially important when they are moving materials or a person up and down stairways, where the load is not evenly shared.

ONE-ON-ONE LIFTING AND FORCE EXERTION TRAINING A common way of training a new person on the job is to put the new employee with an experienced worker for the first week on the job. This approach is highly successful if the experienced worker is a natural teacher and can pass on techniques that are often better than the ones in the training manuals. However, not everyone is a teacher, and poor habits cam also be passed on in this way. In addition, unless the new worker and the experienced one have similar work capacities, techniques that work for one may not work for the other. For example, a person with a large hand may have no difficulty gripping a wide tool with one hand and using it to crimp a heavy wire or drive a rivet. If the inexperienced worker has a much smaller hand and less grip strength, he or she may find that task very difficult and may experience an overexertion injury when trying to learn how to do it.

One way to reduce the opportunities for new workers to get into trouble in the initial training phase of a handling job is to start them on the tasks that meet ergonomic guidelines before exposing them to the ones that are not yet fixed. Three training techniques are recommended:

- Make a videotape of the operations they will be doing using a skilled operator who is doing the job safely and who is explaining the steps as he/she does the work. The tape should be available for the new operator to look at a few days and again a few weeks after first starting the job. This will reinforce the proper methods and not require the new worker to rely on an incomplete memory of what was said before he or she really understood the operations.
- Provide a workplace on the floor where new workers can practice with the tools for the jobs (e.g., a crimper and a set of wires of different sizes) so that their skills can be developed without the production pressure. This could be placed in a break area and also used to discuss quality problems and how they could be avoided.
- Set up examples of the kinds of performance desired in the tasks where tools are used and where hand forces and coordination are involved. This reinforces the training in the initial hire period and allows the new worker to assess his or her progress on the tasks. Often it is a matter of choosing the right tool for the task, and such displays can reinforce the information needed to make the proper decision.

In workplaces or on jobs where there are large numbers of tools, gauges, or fixtures and where some may not be used more than once a year, there will need to be a short training segment available for the worker who gets that job. Placing instructions with the tools or fixtures that will be handled is preferable to expecting them to look up a protocol in a binder that has probably been stored in a desk and not updated for some time. Protocols that are available on a workplace or departmental computer are recommended because they should be easily retrievable and should be kept updated from a central source. In addition, they may be able to integrate a video of the process into the protocol as the technology progresses.

TRAINING HANDLERS IN THE USE OF HANDLING ASSIST DEVICES There are many devices available to assist workers in the transfer of raw materials, parts, and products in the workplace or between stations. Unfortunately, when one of these is recommended as a way of making a handling job more ergonomic, the workers on all shifts may not be given adequate training in how to use it, especially if the device is similar to one they are already familiar with. Some devices are more usable on some tasks than are others, so knowing the environment and task requirements is important when selecting a handling assist device (Mack, Haslegrave, and Gray 1995).

It is important to have at least one person on each shift properly trained by the vendor of the device. It is preferable to have all people who are going to work with or work on the device (maintenance mechanics, etc.) get the training and an opportunity to discuss it with the vendor's specialist. Any safety regulations that relate to use of the equipment (load-testing air hoists, for example) should also be included in this training.

Procedures and protocols for the use of handling devices should be available near the equipment, preferably on it in the form of decals or labels. A certification process may be required to permit workers to operate some of the equipment, and this should be made clear in the training sessions, too.

TRAINING IN THE USE OF BACK BELTS AND GLOVES Studies on the value of back belts in preventing injuries to the back have been inconclusive, but it is generally accepted that they are not protective equipment and should not be used in place of ergonomic interventions to improve lifting tasks (van Poppel et al. 1998). In warehouses, merchandise centers, and many agricultural companies, workers often wear back belts to remind them to lift properly. Although the evidence is not clear that flexible back belts protect the spine against degenerative changes, some companies have programs to provide flexible belts to employees who perform frequent lifting tasks. Most of them require that the employee using a back belt has to complete an orientation course to let him or her know what the belt can and cannot do.

Handlers in warehouses, on shipping and receiving docks, at the end of packaging lines, in agricultural work, and in many chemical manufacturing jobs wear work gloves to protect their hands. The gloves, if not of the proper size or style, can make the handling task more difficult because the hand has to work against the glove and effectively loses some of its gripping strength. This is discussed later in the chapter, in "Environmental Factors." Training the workers about their use of gloves—how to break them in, how to know which ones to use for their job, and when to get a new pair—should be one element in a good training course for manual handlers.

Selection

Selection of people to perform heavy lifting tasks has been offered to employers as a way to reduce musculoskeletal injuries on the job. For many years, there has been a form of natural selection going on in the heavier jobs because people without the capacities to do the heavy work have elected not to perform those tasks, usually voluntarily but sometimes because of an injury.

To use a selection task to screen people out of performing the heavier jobs in this age is considerably more challenging than it was thirty-five years ago. With the protections of equal employment and disabilities nondiscrimination legislation (Department of Labor 1990; Equal Employment Opportunity Commission et al. 1978), it is necessary to show that the test being used is not having a disparate effect on protected groups and that it has been validated—that is, people who pass the test can do the job safely, and people who don't pass the test cannot. In addition, people who are currently doing the job should continue to be able to pass the test year after year. With the heavier jobs, it is often difficult to meet the latter condition, because people's capacities decrease with age; they may still be capable of doing the job, but with more risk.

As a general philosophy that has been discussed in "For Whom Do We Design?" in Chapter 1, it is wiser in the long term to make jobs better for most people than to try to select from a small percentage of the population for heavier jobs. Even the selected workers take vacations, get ill, move on to other jobs, and have training assignments, all of which mean that the heavy job has to be staffed from the existing workforce temporarily. If only one out of twenty people has the capacity to do that job for a full shift, it may be hard to find a substitute. It is quite likely that the department will have to double people up on the job or take the chance that someone will be able to do it for short periods without getting hurt. Selection doesn't really solve the job problem; it works around it.

Some operations are difficult to improve ergonomically because the technology is not available yet or the job demands cannot be controlled. In these cases selection testing may be appropriate when staffing them. Some examples are firefighting, the assembly of large equipment (earthmovers, combines, etc.), and some agricultural jobs where the reaches and tools handled make the work difficult for many smaller and less strong people. The employer should take care to go to experts who are fully aware of the test validation requirements if the selection testing approach is sought.

Redesigning the Jobs and Workplaces

The redesign or design of the job and workplace to make handling tasks acceptable for most of the potential workforce reduces the risk of injuries and illnesses for all workers (Marras 2000b; Westgaard and Winkel 1997). It also gives the business much more flexibility in being able to staff operations when people are on vacation, on job training assignments, ill, or in classes. Well-designed jobs make it easier for people to get back to work after nonoccupational and occupational illnesses or injuries. In addition, they allow people to work better, with less fatigue, thus increasing their job satisfaction. These benefits have been discussed in "Organizational Factors in Work Design" in Chapter 6.

Some general guidelines that will bring manual handling tasks into the safe lifting zone for most people are:

- Keep the lifts above the knees and below the shoulders. This best zone is approximately 51 cm (20 in.) to 114 cm (45 in.) above the floor.
- Keep the load within 36 cm (14 in.) of the front of the body.
- Slide, instead of lift, items whenever possible. Lifting assists that are height-adjustable and provide low-resistance motion on their holding surface are effective in reducing handling injuries.
- Reduce twisting of the trunk and lower extremities in frequent lifting tasks by locating incoming and outgoing parts in containers or on conveyors that are perpendicular rather than parallel to each other.

- Use straps, tools, or assist devices to improve the grasp on the item to be handled. A steady and sturdy grasp is desirable to avoid being hurt if an object begins to move during a transfer.
- Minimize the numbers of transfers required to move the parts, supplies, or product down a production line or from one workstation to another.
- Follow the materials flow analysis guidelines when setting up a new line or workplace.

GUIDELINES FOR THE DESIGN OF MANUAL LIFTING TASKS

Lifting tasks are common in many jobs, and heavy lifting is still present where the number of lifts per shift is low. Very often, this lifting involves changing supply rolls, setting up supplies or equipment for production lines, doing maintenance tasks or construction work, handling materials in storerooms or warehouses, or loading and unloading machines in long-cycle metalworking operations such as lathe work. Frequent manual lifting of materials, products, and supplies is still seen in small companies or businesses, in agricultural jobs, and in other outside work where materials handling equipment is difficult to use or where the product runs are short and the products vary in size or types of packaging. In this section, guidelines are given for the design of lifting tasks that should accommodate the capacities of a large majority of the potential workforce. The material is based on the 1981 and 1991 NIOSH Guidelines for Manual Lifting documents (NIOSH 1981, 1994; Waters et al. 1993), on studies done in industry or universities, and on observations and measurements made in the field (Ciriello 2001; Ciriello and Snook 1983; Ciriello, Snook, and Hughes 1993; Eastman Kodak Company 1986; Mital, Nicholson, and Ayoub 1997; Rodgers 1976, 1997; Snook and Ciriello 1991). The Liberty Mutual tables on acceptable lifting and carrying weights and the NIOSH formula from the 1991 revision of the original 1981 Guidelines for Manual Lifting are found in "Quantitative Methods" in Chapter 2. The guidelines given in this section assuming certain conditions and ways of working that may not be present in every job. Consequently, it is important to evaluate the lifting task being done or to be designed to see if it meets these assumptions. They are (NIOSH 1994):

- Two-handed lifts in standing postures (not one-handed lifts or seated or kneeling postures)
- Eight hours or less per day (for repetitive lifting)
- Compact and stable loads
- Adequate workspace
- A temperate environment (70°F ± 10°)

- Lifting and lowering, not pushing, pulling, carrying, shoveling, or pushing a wheelbarrow
- Low or moderate speed of lifting, not : 30 in./sec
- Good floor coefficient of friction (? 0.4), not slippery

The 1991 guidelines are established to define safe lifting conditions for most workers. Lower back discomfort has been shown to correlate with lifting index values greater than 1 (Wang et al. 1998).

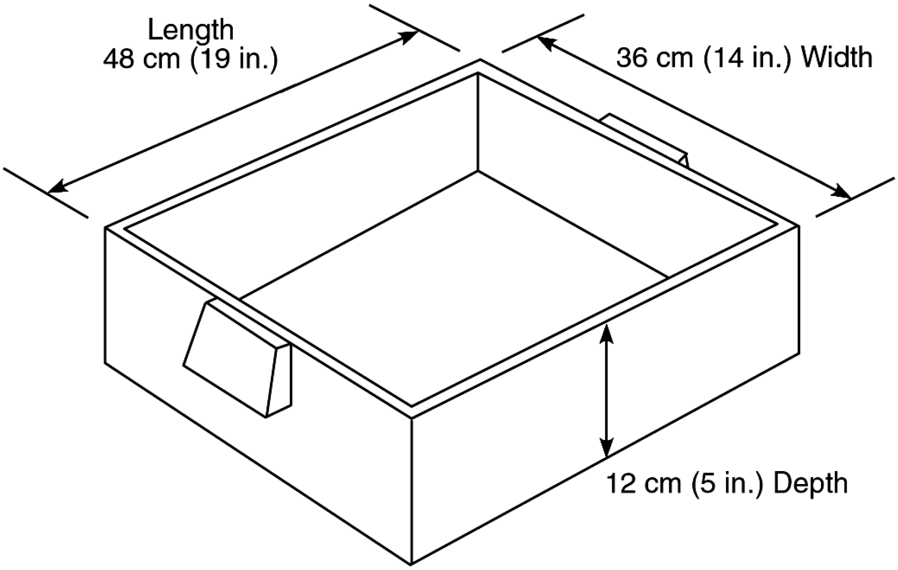
Factors That Contribute to Acceptable Weights for Lifting

The Size of the Object Lifted: Container Design

The amount of weight that is safe to lift will depend on many factors, including the configuration and size of the load and how easy it is to grasp and move. A heavy load that is compact and that can be held with a stable grip throughout its transfer may be easier for many people to handle than a much lighter but bulkier load that requires extended reaches to handle and is controlled using a pinch grip.

TRAY DESIGN The following guidelines for the design of trays address issues that will influence how much weight can be handled in this type of container (see Figure 7.1):

- Tray width determines the horizontal distance of the center of mass of the load from the handler's lumbar spine. Biomechanical stress on the lumbar disks is increased significantly as the load is moved away from the body in the horizontal plane (Chaffin 1988; Garg and Chaffin 1975). Wide trays put high stress on the spine and tend to shift the load to the shoulder, hand, and wrist from the stronger arm muscles. A width of 36 cm (14 in.) or less is recommended for trays with handholds, and it should not exceed 51 cm (20 in.) if the tray is handled manually. "Biomechanics" in Chapter 2 includes more discussion of the impact of increased horizontal distance on the lower back.
- Tray length affects which muscle groups take the load when it is handled manually. In general, trays that are more than 48 cm (19 in.) in length cannot be held without abducting the shoulders. When the shoulders are abducted, the weight of the tray falls more on the shoulder muscles, which are less than half as strong as the upper arm muscles. A recommended tray length is 48 cm (19 in.) or less, with an upper limit of 61 cm (24 in.) for manual handling tasks.
- Tray depth is often determined by the volume of parts, product, or supplies desired in a production process or over a given time period, such as one hour. Parts trays are often less than 15 cm (6 in.) deep because the parts are not stacked, but tote trays and waste trays can be considerably



FfGURE 7.1 Recommended maximum dimensions of a tray

deeper and represent a difficult handling task for many workers. A deep tray may interfere with walking if it has to be carried, and this tends to make the handler hold the tray away from the body and increase the horizontal component of the lift or carry. For these reasons, it is recommended that tray depth be kept at 13 cm (5 in.) or less if the trays are handled manually. Deeper containers should be designed so that they can be pushed and pulled, rather than lifted or carried, and so that they can be emptied without having to take their weight in the process (e.g., tipped up mechanically).

- Loose parts or material in a tray may shift and cause the weight to be borne unevenly between the hands. The use of dividers or dunnage to contain the parts can make this less likely to lead to a loss of control of the load.
- The design of handles or handholds can make a large difference in the acceptable weight of the loaded tray. Molded trays often have rolled edges or ledges where the tray is grasped, resulting in both high pressure on the fingers and the need to use a small power grip or a pinch grip to control them. A study of acceptable loads was done using a standard production tray to handle parts to and from a high volume manufacturing line (Eastman Kodak Company 1986). The contoured gripping block was found most comfortable to handle and permitted the most weight to be lifted at low and high locations (see Figure 7.2). Because the location of the lift influences which handle design is best for the tray, dimensions for cutout and drawer pull handles that are

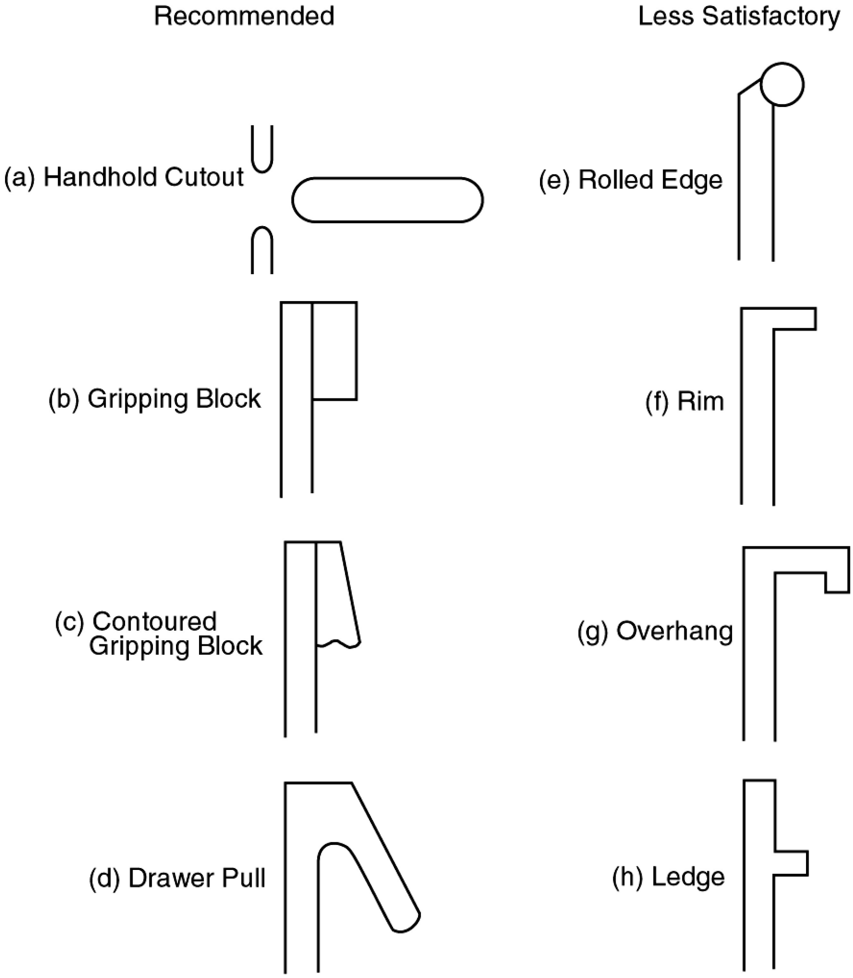


FIGURE 7.2 Examples of tray handholds
Handhold cutouts and drawer-pull handles are less satisfactory for high lifts (above shoulder height) than for low lifts (below chest height).

good for lifting at heights under 102 cm (40 in.) are included in Figure 7.3 along with the contoured gripping block dimensions. Handle dimensions for parts or components of equipment are given in Figure 7.4.

- Tray handholds should be positioned so that the center of mass of the loaded tray is close to the point at which the tray is supported on the fingers and hand. Trays where the handles are above the load tend to put more stress on the wrist and hands for stabilizing the load and are less satisfactory for lifting trays above waist height. Studies of handle posi-

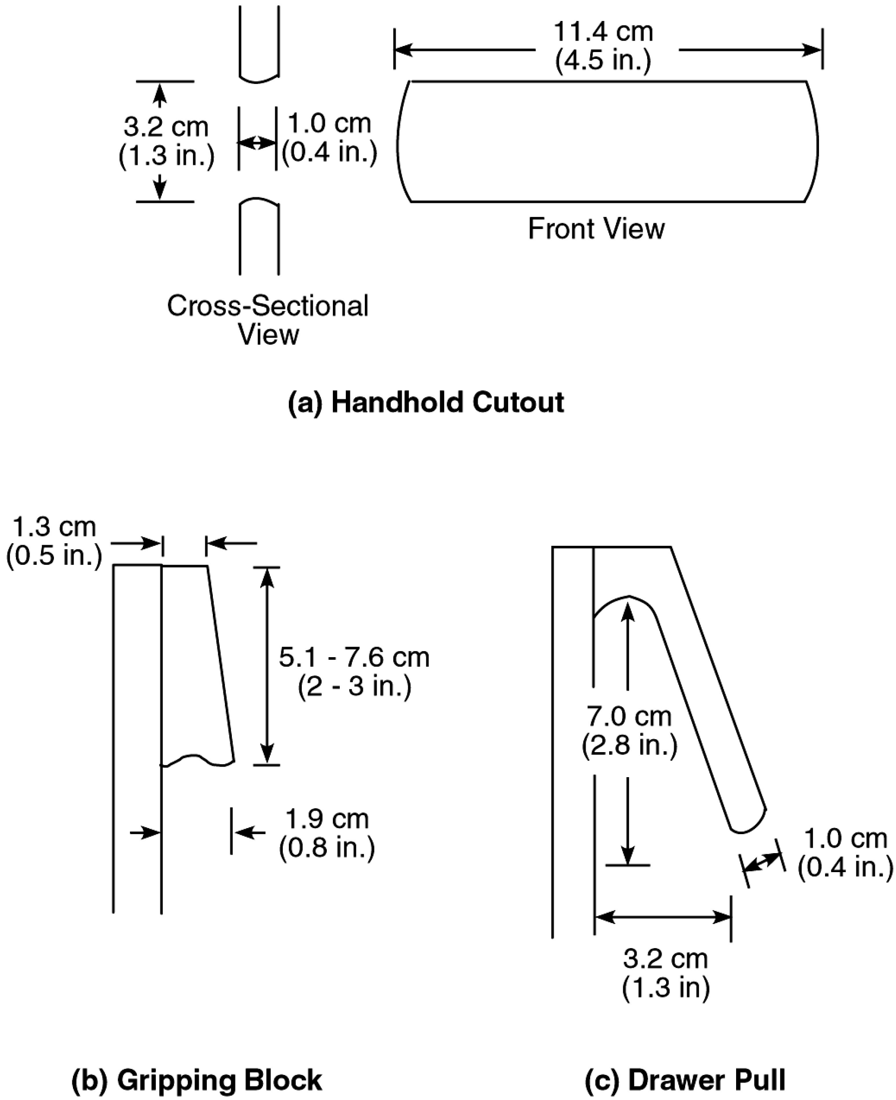
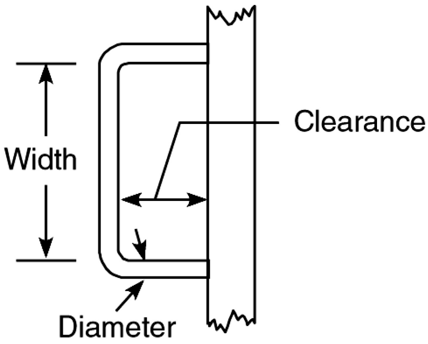


FIGURE 7.3 Recommended dimensions for handholds on trays

The handhold clearances (height and length) for the cutout (a) should be increased by 2.5 cm (1 in.) if gloves are worn while handling the trays. The gripping block (b) thickness at the bottom should permit the curvature to be gradual and sloped, not be a V-shaped cutout that would cause fingertip discomfort. The drawer pull handles (c) should be curved at the top so the fingers do not get jammed into a crevice during the lift. If gloves are worn, the slope should be gradual and the clearances increased about 1 cm (0.4 in.) from the tray to the bottom of the handhold.



	Clearance		Width	
	cm	in.	cm	in.
One hand	6.4	2.5	12	4.8
Two hands	6.4	2.5	24	9.5

Minimum Diameter for Comfort

Diameter		Range of Object Weight	
cm	in.	kg	lb.
0.6	0.25	< 7	< 15
1.3	0.5	7-9	15-20
1.9	0.75	> 9	> 20

Maximum diameter for full encirclement by hand is:	3.8 cm (1.5 in.)
Exposed edges should be rounded to a minimum radius of:	1 mm (0.04 in.)
Exposed corners should be rounded to:	13 mm (0.5 in.)
Fingers should be able to curl to a minimum of:	120° (as in a hook grip)

FIGURE 7.4 Recommended dimensions for handles on equipment components or on containers to be carried with one hand
Note: As object weight increases, the handle diameter should increase so that the force per unit area on the hand is kept below 150 kPa (22 lb / in.^{2}). If gloves are worn during handling, an additional 2.5 cm (1 in.) of clearance and width is advisable.

tion on cases indicate that a 30° to 45° angle (higher end toward the handler) is preferred for the whole range of lift heights (Wang, Chung, and Chen 2000).

While tray dimensions should be able to be controlled with ergonomic designs for many operations, there are times when larger containers or packages are needed to accommodate the size of the part or product being made. Handling conduit in electrical work and lumber in carpentry, forestry, or fabrication tasks usually will not meet the size guidelines suggested above for safe handling. Using handling assists that bring the grasp points closer to the body and stabilize the load (e.g., straps, board carriers) reduces the risk of manually handling some of these items. Two-person lifting may also be required if the lifts are done occasionally and another person is available to help.

CASE DIMENSIONS Case dimensions to minimize stress and maximize acceptable load are similar to the tray dimensions given above. The main difference is that most cases do not have handholds and are lifted at opposite corners of their bottom and top sides. This means that case width is even more critical as a factor determining acceptable load. The stress on the back and shoulders of lifting a case that is 51 cm (20 in.) or more in width becomes the limiting factor for many package-handling tasks. The biomechanical stress on the lumbar spine effectively limits the acceptable load to less than 9 kg (20 lb.) for objects 51 cm (20 in.) wide lifted at 76 cm (30 in.) above the floor (see "Biomechanics" in Chapter 2).

Providing handholds on cases is not done very often because the cost can be very high, and the handle design requires several additional layers of corrugated material to be deep enough to accommodate the hand. Cutout handholds may be unsatisfactory because the product inside the case interferes with the hand placement for lifting. Handholds that are near the top of the case put extra stress on the wrists and hands during lifting because the center of mass of the loaded case is below the hands. There are some advantages of handholds that may make it appropriate to consider them for some products and parts:

- If a case weighs more than the recommended value (see methodologies for determining acceptable weights for lifting in Chapter 2), adding handles to it can increase the recommended weight by up to 10 percent (Garg and Saxena 1980; Eastman Kodak Company 1986).
- For cases that are lifted frequently on and off floor pallets, the metabolic workload is about 11 percent greater if no handholds are available (Eastman Kodak Company 1986).
- If cases have to be carried for long distances, handholds give the handler the option of carrying them in one- or two-handed postures. Without handholds, a two-handed carry is required, and fatigue of the forearms and upper back may occur if it takes several minutes to do the transfer.
- Large cases—for example, sheet materials or advertising posters—are difficult to lift or carry with two hands. Putting a diagonal handhold into the case so that the case can be tucked under an arm and grasped in the middle of the wide and long surface will reduce the stress on the back and shoulder and allow more weight to be carried.

In addition to trays and cases, workers have to handle other types of containers, such as pails, bags, carboys, tanks, flasks, and drums. These are discussed later in this chapter in "Special Considerations in Manual Lifting Task Design."

Location of the Lift

HORIZONTAL DISTANCE FROM THE HANDS TO THE LOWER SPINE The factor that has the most impact on acceptable weight for a two-handed lifting task is the horizontal distance that the load is handled from the lower spine. The biomechanical analysis that defines the risk for excessive forces on the fifth lumbar disk as a function of horizontal lift location is presented in Chapter 2 (see also Nachemson and Elfstrom 1970).

HORIZONTAL LOCATION OF A LIFT This is measured at the beginning and end of a transfer and may be measured during the transfer if that distance is greater. The measurement is made by:

- Taking the midpoint of the distance between the ankles
- Taking the midpoint of the distance between the hands
- Projecting the midpoints on the floor and joining them
- Measuring the distance between the midpoints, which is H in the NIOSH lifting equation of 1991 (NIOSH 1994)

The 1991 calculation accounts for the more dynamic postures seen in many lifting tasks where some asymmetry exists and where foot position is varied to keep the load closer to the spine.

VERTICAL HEIGHT AT THE BEGINNING AND END OF THE LIFT The height of the lift determines which muscle groups are available to move the load. Lifts below waist level and close to the body can be made with the stronger leg, arm, and trunk muscles, while lifts above shoulder height have to depend on upper-body strength, which averages 40 to 50 percent of leg strength for most people (Laubach 1976). At 76 cm (30 in.) above the floor, the legs can still be involved in a lift, and this has been chosen as the base point to which the actual vertical height is compared. The final destination of the lift should also be evaluated in terms of its vertical height (and horizontal distance at that height) because many items are handled between floor pallets and shelves. The lift may be acceptable at the beginning of the lift and unacceptable at its destination.

VERTICAL DISTANCE OF THE LIFT The difference between the starting and ending vertical heights of a lift, regardless of sign, is the vertical distance traveled. The larger the vertical distance, the more time the lift will take and the more likely it will be that the smaller upper-body muscles will be involved. This correction factor in the NIOSH Manual Lifting Equation is limited to reducing the acceptable weight by no more than 30 percent.

THE DEGREE OF ASYMMETRY OF THE LIFT The 1981 Manual Lifting Guidelines assumed that all lifts were made in the sagittal plane (in front of the body) with no twisting or turning of the trunk to either side. Because many lifts are made across the body or with some degree of rotation of the trunk, an asymmetry correction was included in the 1991 revision. The correction is limited to a horizontal plane of rotation around the spine and in front of the body, which encompasses 135º. The more the rotation, the lower the acceptable weight in that location because of the interaction of twisting and shearing and compressive forces at the lumbar spine (Marras et al. 1995).

The Type of Grip Used

The NIOSH 1991 Manual Lifting Guidelines include a coupling factor, which relates to how well the object can be handled during transfers. The categories are summarized as good, fair, and poor and are described in terms of grip stability, type of grip (Jacobsen and Sperling 1976), grip span, force per unit area on the hands or fingers, and distribution of the load in the hands. A few general guidelines for acceptable grip forces have been given in "For Whom Do We Design?" in Chapter 1. Additional guidelines are summarized below:

- Pinch grip strength is only about 20 to 25 percent of power grip strength; so acceptable loads are around 3.5 to 4.5 kg (8 to 10 lb.) when pinch grip is the primary grasp being used (Rodgers 1987).
- Power grip strength decreases at spans of less than 5 cm (2 in.) and more than 8 cm (3 in.). If the grip is cylindrical, the upper and lower points where grip strength decreases are 3 and 4.5 cm (1.25 and 1.75 in.). Power grip strength is 40 to 60 percent less with a grip span of 12 to 13 cm (4.5 to 5 in.) or when gripping a cylinder that is 6 to 7 cm (2.5 to 3.0 in.) in diameter (Eastman Kodak Company 1986; Rodgers 1987). Acceptable weights for items controlled with a power grip fall to about 9 kg (20 lb.) if wide or very narrow grip spans are used even in the optimal lifting locations.
- If the grip used results in extreme wrist angles being required during the lift, the acceptable weight may be further reduced by 25 to 60 percent (Rodgers 1987).

Environmental Factors

Acceptable weights for repetitive lifting tasks that make up a significant part of the shift's workload are affected by the temperature at the work site, especially by heat. This is because the body has to regulate body temperature and still provide enough blood flow to the working muscles. The heavier the work, the greater the demand for blood flow to the muscles. The body defends body temperature first and may need up to 60 percent of the cardiac output for that in ambient temperatures above 35°C (95°F). This is discussed in "Thermal Comfort" in Chapter 8.

Some other impacts of environmental factors on safe handling are described below.

STABLE FOOTING This is very important in manual handling tasks, especially pushing and pulling tasks. A slippery floor or uneven surface can reduce the effective forces transmitted to a handcart or piece of mobile equipment and increase the force needed to keep it in motion. Slip-and-fall incidents during handling tasks have been linked to oil, fine powders, ice, wax strippers, or other liquids or gels on the floor. Treating the floor to reduce its slipperiness by using particulates in a sealant or other special surfaces has been one way to improve the coefficient of friction without making the surface difficult to walk on.

STABLE GRASPS These are also important in manual handling. In addition to the gripping characteristics of the items handled (discussed above), the use of gloves should be considered when determining acceptable weights to be handled. Special gloves with rubber dots on the surface have been developed to increase grip stability on surfaces that are slippery (e.g., some corrugated cases without handles). The glove design itself, however, may actually decrease power grip strength, especially if the hand has to do work to deform the glove or if the tension across the back of the hand is high. The loss of power grip strength ranges from about 20 percent with cotton gloves to 40 percent with heat-resistant gloves (Rodgers 1987). Wearing cotton gloves inside a chain mail glove in meat cutting was found to reduce a meat cutter's power grip strength about 55 percent compared to bare-hand strength. Wearing two pairs of light cotton gloves inside a neoprene glove with curved fingers (used in refueling commuter aircraft) was found to reduce the refueling crews' grip strength about 55 to 60 percent (Rodgers 1992). Acceptable weights or forces have to be determined after considering all these aspects of grip stability. For example, a meat cutter who is using his left hand to hold the meat down and using his right hand to cut it can have stress on his left hand because of a wide grip, an extended wrist, the cotton and chain mail glove combination, and environmental stress from the cold meat. If the design guideline starts at 18 kgf (40 lbf) to accommodate most workers, these grip factors could reduce that by another 55 to 75 percent, so even a 4.5 to 6.7 kg (10 to 15 lbf) force would be a heavy load on the hand and wrist.

STABILITY OF THE LOAD This is assumed in the NIOSH 1991 Manual Lifting Guideline, although there are many two-handed lifting tasks done where the load is shifting (e.g., bags of grain or powdered chemicals) or the weight of the object is not symmetrically distributed (e.g., motors, metal parts, power supplies). Acceptable loads are reduced when the load is not stable.

Guidelines for the Design of Occasional Lifts

The 1991 NIOSH Guidelines for the Design of Manual Lifting Tasks are presented in "Quantitative Methods" in Chapter 2 and should be referred to for more detailed use of the equation. This discussion will review some of the types of calculations that can be made and presents a different graphical representation of part of the original 1981 equation, expressed in terms of the percentage of the population (50/50 male/female) that would find a given load acceptable.

NIOSH Guidelines for the Design of Occasional Manual Lifts

The NIOSH Manual Lifting Guidelines (NIOSH 1994) were originally developed to give engineers and designers guidelines for safe handling of materials and products so that about 90 percent of the potential workforce would be able to do the jobs with a low risk of musculoskeletal injuries. With the stimulus of increased concern about manual handling injuries, the tendency for the past fifteen years has been to use them for compliance purposes. The equation identifies what an object should weigh if it is located in a given position and is handled at a specific frequency. The recommended weight is compared to the actual weight, and an assignment of the degree of risk is made according to how close the two figures are. Most people agree that if the actual weight is twice the recommended weight, action should be taken to improve the task. Some plants take action on anything that exceeds the recommended weight, while others focus on the tasks where the ratio of the actual to recommended weight is greater than 2.

The equation to calculate the recommended weight for lifting items in specific locations is:

$$RWL = LC * HM * VM * DM * AM * FM * CM$$

As shown in Chapter 2, the RWL will not be more than 23 kg (51 lb), which is the load constant (LC). The horizontal (HM), vertical (VM), vertical distance (DM), asymmetry (AM), frequency (FM), and coupling (CM) modifiers are multiplied together to determine how much less than 23 kg (51 lb) the recommended weight (RWL) will be. The lifting index (LI) is calculated by dividing the actual weight by the RWL for conditions at the beginning and end of the lift.

In many lifting tasks there is more than one type of item being handled or more than one destination and starting point for the lifts. In that situation, the recommended weights for each of the primary lifts are calculated separately and combined to get a frequency-independent composite lifting index. The frequency modifier is included later in the final calculation of the composite lifting index. For more discussion of the various ways to analyze jobs with the NIOSH 1991 Manual Lifting Guidelines, see the NIOSH 1994 monograph.

Percentage of Population Finding Lifts Acceptable Based on Location and Weight

The weight of the object handled is often not something that can be altered (e.g., it is the product, such as a tire).Thus, the solutions for improving manual handling tasks that do not meet the NIOSH guidelines will often include making it unnecessary to handle the objects manually (e.g., using conveyors to make the transfers), sliding instead of lifting the objects, and using assist devices (hoists, zero gravity balancers). Another way of determining the degree of priority that should be assigned to resolving a given handling task is to evaluate what percent of a mixed male and female population will find the task acceptable at the given weight. If less than 50 percent of the population would find the lift acceptable, it is a problem job because that represents about 75 percent of the women and 25 percent of the men who are at risk for overexertion injuries. If from 50 to 75 percent would find it acceptable, good initial training, job fitness, and a graded introduction to the task initially should reduce the risk of injuries on the task. If less than 5 percent of the population would find the task acceptable, there is a high risk of injuries and the task must be improved. From 5 percent to 50 percent acceptability, some action should be taken to make the job more acceptable; this may involve assist devices, semiautomation, and/or changing the materials flow patterns.

The percentage of population data are based on the psychophysical studies by Ciriello and Snook (1983) with a biomechanical overlay to exclude weights that would not meet the criteria for acceptable lumbar disc pressures. Only the horizontal and vertical locations have been used in the graph in Figure 7.5, and it is a determination of acceptable load for occasional lifts (≤ 1 per 5 min) only. If the load is acceptable (from the design standpoint, in this case, more than 75 percent of a male/female workforce would find the lift acceptable), then the other factors for reducing the acceptable load based on the 1991 NIOSH equation should be applied. See “NIOSH Revised Lifting Equation” in Chapter 2 for the additional correction factors.

The percentage of the population finding the lift acceptable suggests there may be a substantial proportion of the workforce that can do the given task safely. However, one has to validate the selection test, as discussed earlier in this chapter, if a decision is made to put the stronger people on the job. Using the graph in Figure 7.5, it is possible to predict what impact changes in the horizontal and vertical location of the load will have on the percentage of the population accommodated. Using the weight of the object handled, one moves along the horizontal (weight) line to the intersection of the vertical height (L, M, H) with the appropriate horizontal distance zone (shown at the top by figures representing postures that can be observed). This intersection point will fall into one of the percentage-of-population zones. By checking to see how much of the potential workforce population would find the lifts acceptable, one can estimate the risk of the existing or planned lift. Additionally, one could determine what location (H and V) would accommodate the most people and try to determine how the lift could be placed there.

For example, a task that requires a worker to handle a 57 kg (125 lb) part off a floor pallet and place it on a table is acceptable to very few people. If the pickup is made 36 cm (14 in.) in front of the body and at 25 cm (10 in.) above the floor, so the worker is bending forward while lifting, less than 5 percent of the potential workforce would find it acceptable. By placing the part so that it can be lifted at 51 cm (20 in.) above the floor (e.g., using three pallets) and

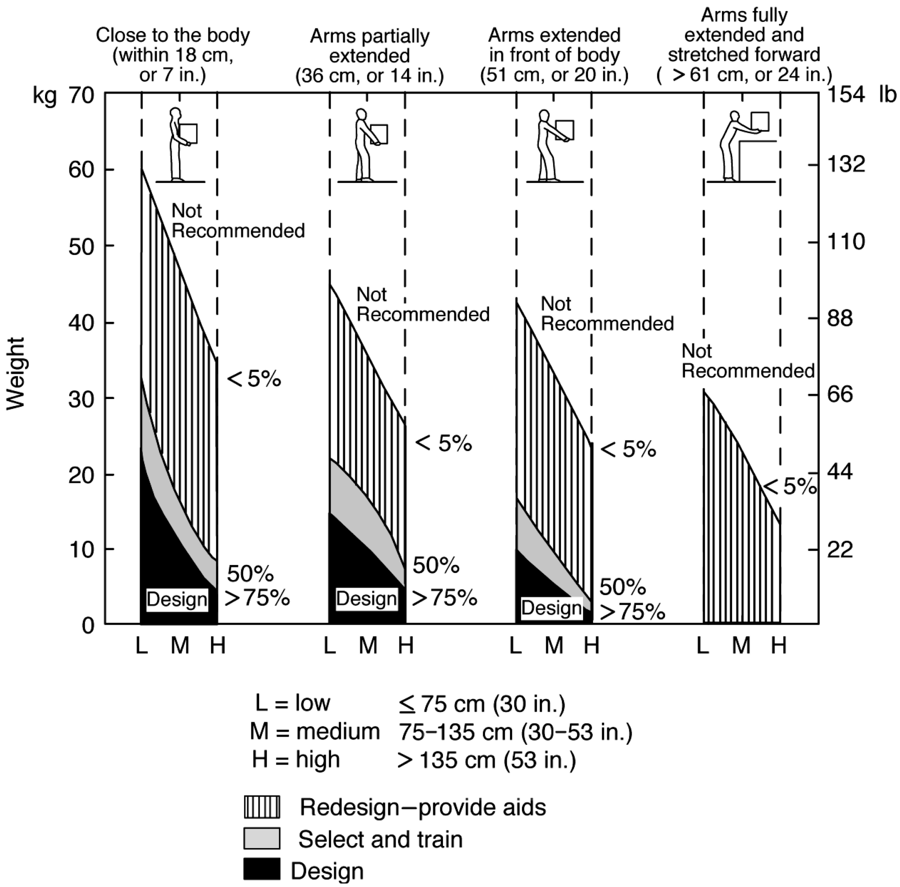


FIGURE 7.5 Acceptable occasional lifts based on weight and horizontal and vertical locations of the load—percentage of 50/50 male and female population accommodated
The objects handled are assumed to be compact, have good handholds, and are lifted in the sagittal plane less than once every five minutes.

within 18 cm (7 in.) of the body, one might be able to find 10 percent of the workforce who could do the task. Nevertheless, it is still a bad lift because of the weight. The load should not be manually handled. The 1991 NIOSH Manual Lifting equation has an intercept of 23 kg (51 lb) for the maximum weight to be handled manually.

Similarly, it may not be the weight but the horizontal location of the load that limits who can handle it safely. Loading and unloading parts from pallet boxes or Gaylords includes the need to reach down 91 cm (36 in.) and 76 to 91 cm (30 to 36 in.) away (H), a position that is biomechanically unsafe for everyone even without a load in the hand. Some plants have put tilt tables under the pallet box so that the parts are brought nearer to the worker, but the final reach distances are still 60 to 76 cm (24 to 30 in.) away. Even if the parts weigh less than 4.5 kg (10 lb) each, the tilted box still does not bring the parts close enough to make the lifts acceptable for most people. It is better, but not good enough. Using the graph in Figure 7.5 allows one to make a quick determination about the acceptability of specific lifts before the other variables are added in. Moreover, it allows one to check out a number of strategies for improving manual lifting tasks in a quantitative way before changes are instituted and found to be only partially effective at reducing injuries on the job.

Examples of the use of these guidelines to solve a manual handling problem in a car plant and to determine the best use of shelf storage in a chemical warehouse are given below.

HANDLING DOORS INTO A CAROUSEL ON A CAR ASSEMBLY LINE Workers were handling doors weighing 15 kg (33 lb) each from a horizontal conveyor to a carousel (dial) indexing storage unit from which the door was removed in sequence by the assemblers. When the door was placed on the carousel, it was held 61 cm (24 in.) in front of the handler's feet. It was lowered to the point where the hands were 68 cm (27 in.) above the floor from a starting height of 114 cm (45 in.) and a horizontal distance of 18 cm (7 in.). The doors were about 91 cm (36 in.) long and could be handled so the hands were 51 cm (20 in.) apart.

The H value is 18 cm (7 in.) when the door is picked up and the vertical hand height is 114 cm (45 in.) above the floor; hence the 15 kg (33 lb) door is acceptable to about 75 percent of the workforce. That part of the task is probably not a problem unless there is strong involvement of the other factors, such as lift asymmetry or poor handholds. The disposal of the door on the carousel has an H factor of 61 cm (24 in.) and a height of 68 cm (27 in.) for the hands. On the graph in Figure 7.5, one cannot see the 50 percent line at an H of 61 cm (24 in.), so all lifts at that horizontal distance need to be improved. Tracing back along the 15-kg (33-lb) line to the low height at 51 cm (20 in.), one can pick up about 60 percent of the potential population, and at a 36 cm (14 in.) horizontal distance, the lift falls into the design zone where 75 percent of the workforce should find it acceptable. Because the door is being handled to the carousel with one hand in front of the other, there will be some asymmetry in the lift, and the correction factor for that will mean that the better solution would be to move the lift to within 36 cm (14 in.) of the body. Because the carousel rotates and indexes for loading at the same place each time, one can provide an extension at that point. This allows the handler to place the door down while keeping the load close to the body and then slide it into position on the carousel by pushing it from behind. The extension and individual sections of the carousel have to be treated to prevent scratches to the door surface, but that is not difficult to achieve with carpeting scraps.

HANDLING ITEMS TO SHELVES IN A CHEMICAL STOREROOM Containers, cases, buckets, bottles, and small fiber drums weighing from 4.5 to 25 kg (10 to 55 lb), mostly quite compact, are stored in a small storeroom for use in research and development projects. The shelves in the room are at 51, 102, 152, and 203 cm (20, 40, 60, and 80 in.) above the floor. Several people have complained about the difficulty of getting materials from and returning them to the shelves. A step stool has been provided, but it is awkward to maneuver with items held in the arms.

With multiple items and fixed-height shelves, one can use the lifting graphs in Figure 7.5 to determine the maximum item weight that should be put on each shelf. The lowest shelf would be the floor, and the lack of clearance for the body means that horizontal distances of 51 cm (20 in.) would not be unusual when storing or retrieving items there. It is in the low zone at an H of 51 cm (20 in.). To be in the design zone where 75 percent of the people would find a lift acceptable, the maximum item weight should be about 25 lb. At the 51 cm (20 in.) shelf height, the worker might be able to get closer to the load, so using an H of 36 cm (14 in.) and a low vertical height, an acceptable item weight is 35 lb. or less. At the 102-cm (40-in.) shelf, the compact items can be held close to the body. With an H of 18 cm (7 in.) and a medium vertical location, 75 percent of the workforce would be accommodated with a 15 kg (33 lb) load. This is actually probably up to 22 kg (48 lb) because it is close to waist level; the top part of the medium lift zone is where shoulder strength becomes limiting, thus bringing down the acceptable values for that whole zone. At the 152-cm (60-in.) shelf, the items can be handled close to the body, but the smaller and weaker shoulder muscles are doing the work. With an H of 18 cm (7 in.) and a high vertical location, the acceptable maximum load is 5.5 kg (12 lb) for 75 percent of the potential workforce to find the lifts acceptable. The 203 cm (80 in.) high shelf presents a new problem because many people cannot reach 203 cm (80 in.) above the floor, much less lift something to that height. It would be wise to block off this shelf and not use it for chemical storage, or to only place items on the shelf that weigh less than 4.5 kg (10 lb) each and are rarely used.

Another way of looking at this problem is to alter the shelving to accommodate the usual items and put everything in a near-optimum location. Putting more shelves in the 51-to-127-cm (20-to-50-in.) vertical space is one way of getting the strongest muscles to do most of the heavy work. This depends on item height on the shelf and adequate clearances for the hands. If most items are 20 to 30 cm (8 to 12 in.) high, for instance, one might be able to go from 51 cm to 89 cm to 140 cm (20 in. to 35 in. to 55 in.) and have the last shelf at 178 cm (70 in.) for items under 4.5 kg (10 lb). This would be reachable for most workers.

Guidelines for the Design of Frequent Lifting Tasks

In addition to the biomechanical stresses and strength requirements of manual handling tasks, local muscle fatigue and the metabolic demands of lifting may affect the acceptable weights for workers (NIOSH 1994; Rodgers 1997).

When lifts lasting only a few seconds are done and the frequency of lifting is less than 1 per minute, local muscle fatigue is not likely to be present unless the worker's postural muscles are continuously loaded. Metabolic demands are most often found to be a problem with low lifting when the body has to be lifted as well as the load. Lifting at rates greater than 4 times per minute is going to involve some metabolic determinant of acceptable loads and may be associated with an accumulating fatigue in the active muscles (Rodgers and Yates 1991). When the lifting frequency gets up to 15 per minute, the movement time takes up most of the available lift cycle time, and muscle fatigue accumulates quickly unless recovery time is designed into the job. The longer this pattern of work is sustained, the longer it will take the worker to recover (see "Designing to Minimize Fatigue" in Chapter 6).

Metabolic Factors Contributing to Acceptable Loads

Some frequent lifting tasks have intensive lifting for a few minutes followed by light activity before another intensive handling period. An example of this is loading a tractor trailer, where the handler moves a palletload of cases into the trailer, unloads it, moves the pallet out, and gets a new one. The pallet unloading may take about 2 minutes at a lifting rate of 20/min, with a time for recovery of 3 minutes before the next pallet is ready to unload. To reduce the double weighting of frequency in this type of job, NIOSH has recommended that lift frequency be calculated over a 15-minute period, not just over the period of fast lifting (NIOSH 1994). This acknowledges a strategy used by many people who do intermittent handling tasks whereby they do the lifting faster than is dictated by the system in order to get some recovery time afterward. Using the example started above, a typical frequency of lifting in a shipping and receiving job can be 20/min for 2 minutes followed by 0/min for 3 minutes, and repeating this pattern for ten palletloads. This would average out to 8/min for the 15-minute period on the handling task. The workload of doing sustained handling at a rate of 8/min is still high enough to make this job difficult for more than half of the potential workforce if it is done over the full shift. For less than two hours a shift when the rest of the work is not very strenuous (light or moderate), the 8/min frequency of handling light or low-moderate-weight boxes can be acceptable to most workers. The more control that the worker has over the work pattern, the less likely it will be that overexertion injuries related to whole-body fatigue will occur.

The metabolic demands of jobs and guidelines for the design of jobs so they are within the aerobic capacities of most people have been discussed in Chapter 2. For the NIOSH Manual Lifting Guidelines (NIOSH 1994; Waters et al. 1993), the aerobic capacities (whole body and upper body) of a 50th-percentile woman serve as the comparison values for others on aerobically demanding jobs. There are three work duration categories: 1 hour continuously, 2 hours continuously, and 4 or more hours continuously. Each of the job tasks should be evaluated to determine where it falls in terms of workload.

Hence the pattern of those tasks in a typical workday can be used to see if the recovery tasks are adequate to average out the workload over the shift to the recommended value. An hour of moderately heavy or heavy work can be alternated with an hour of light or light-moderate work to allow the worker to stay within a nonfatiguing work pattern while still doing up to 4 hours of heavy work per 8-hour shift. In extended-hours work patterns (overtime, 12-hour shifts, or 16-hour double shifts), the recovery tasks have to be longer in order to accommodate the lower percentage of work capacities that are acceptable to use beyond 8 hours. For example, a lifting task performed in an 8-hour shift may be acceptable if it does not exceed an average of 27 percent of aerobic capacity. When the work is extended to 12 hours per shift, the acceptable load will fall to about 23 percent of the aerobic capacity for those muscle groups (Rodgers 1997). See Chapter 6 for further discussion of acceptable total workloads.

If the oxygen consumption of the task has not been measured, one can get a reasonable idea of the workload by looking at the heart rate elevation above the resting values during the shift (Brouha 1973; Eastman Kodak Company 1986; Rodgers 1985, 1997). The assumption is made that there are not significant environmental or emotional stressors present because these will influence the heart rate independent of the oxygen consumption of the active muscles. Upper-body work is more strenuous than whole-body work because there is less muscle mass available for it. Thus, a smaller elevation in heart rate still means a heavier workload because the range of heart rate available is only 70 percent of the range available for whole-body work. "Dynamic Work: Heart Rate Analysis" in Chapter 2 discusses this method of quantifying stress and total workload. Other methods of estimating the aerobic demands of tasks are included elsewhere in Chapter 2 and in the literature (Bernard and Joseph 1994; Kilbom 1994).

When adjusting the percentage of population finding the weight of an object acceptable for lifting frequency, it is necessary to determine what the weight would be (if it is a single lift) that would accommodate at least 75 percent of the potential workforce. This value can be corrected by the frequency modifier for the type of lift being made (floor to knuckle, knuckle to shoulder, or above shoulder). The final value is the recommended upper limit for the weight of items handled in that position at that rate.

Local Muscle Fatigue Determinants of Acceptable Loads

In frequent lifting tasks, the heights of the lifts, the coupling interfaces with the hands, and the transfer distances are particularly important in determining if local muscle fatigue will develop (Rodgers 1997). Postural fatigue from continuous bending over or from reaching out more than 38 cm (15 in.) in front of the body repeatedly can accumulate rapidly in the active muscle groups if the loads are moderately heavy. Fatigue of the arms and hands as well as of the muscles of the shoulders, back, and legs can accumulate if there is inadequate recovery time between lifts or at the end of a lifting segment. This is especially apparent in high-frequency lifting tasks (≥ 15 lifts per min) (Petrofsky and Lind 1978). Fatigue reduces the capacity of the active muscle group. Each additional load becomes "heavier," in effect, because the percentage of capacity used rises as capacity is lost to fatigue. More discussion about local muscle fatigue is found in Chapter 2.

For example, endurance grip tests are administered every 20 minutes to a person who is fatiguing his or her forearm muscles on a job-related force exertion task (e.g., exerting a maximum force on a grip dynamometer). One might see a lower maximum strength and a faster fatigue rate within the second or third reading, so that instead of a 27 kgf (60 lbf) grip strength initially, the value falls to 18 kgf (40 lbf). The same 14-kg (30-lb) item being handled at the fortieth minute of the task might be heavy (75 percent), whereas it was moderately heavy (50 percent) at the beginning of the task. The weight of the item has not changed, but the capacity for handling it has diminished, and the perceived exertion is greater. See "Psychophysical Scaling Methods" in Chapter 2.

Guidelines for the Design of Carrying Tasks, Shoveling, and One-Handed Lifting Tasks

As was mentioned at the beginning of this section, the NIOSH Guidelines for Manual Lifting Task Design are not appropriate for use for one-handed lifting or for carrying tasks because they assume the lift times are less than 6 seconds and that the grips are not limiting. Shoveling has specific characteristics that make it different from lifting, yet many construction, agricultural, and chemical-making operations involve this type of manual handling. These three tasks are part of manual lifting jobs, and guidelines for their design are included here.

Liberty Mutual's guidelines for carrying tasks can be found in Chapter 2 (Snook and Ciriello 1991). The limiting factor in carrying tasks is usually the handgrip, although the dimensions of the load can also be limiting if they force the carrier to hold the item away from the legs or side. The weight or force exerted to stabilize the load will determine the effort level for the active muscle groups, and the holding time will identify how much recovery time is needed to restore the muscle after the carrying is completed. That pattern has to be evaluated in relation to the frequency of carrying or to the demands of other tasks after the carry in order to determine the risk of overexertion injury on the job.

Carrying (Two-Handed)

The Liberty Mutual carrying guidelines were developed in laboratory simulations of tasks, and the National Bureau of Standards (NBS) has also studied "portability" in conjunction with the development of standards for the weight

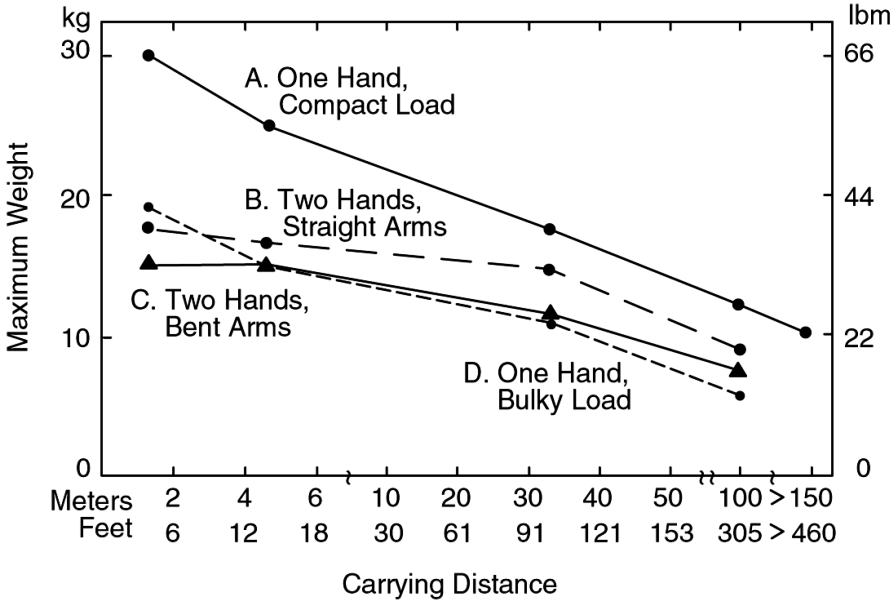


FIGURE 7.6 Carrying—one-handed and two-handed
For each instance, it is assumed that the object has a good handhold that allows the handler to use a hook or power grip. Note that bulky objects tend to place more load on the weaker shoulder muscles, and that if carrying with a straight arm, the object carried should not interfere with walking.

of equipment and appliances to be carried manually (McGehan 1977). Figure 7.6 shows the results of several studies on carrying, both one-handed and two-handed, for different distances. It is clear from the graphs that long carries (>91 m or 300 ft.) should not be required if an object weighs more than 9 kg (20 lb). The use of a cart or other assist device to transport the items is recommended for loads greater than 7 kg (15 lb) transferred more than 15 m (50 ft.), even if they have a good gripping interface. Bulky items, items with poor handholds and shifting or uneven loads, and items that put a high force per unit area on the hands (e.g., paint can palings) should all be transferred with carts as well if the distances take more than 10 seconds to travel.

Shoveling

Shoveling is a hybrid of one- and two-handed lifting since both hands are involved, but they are not usually equally loaded during transfer of the load. The load is automatically farther from the spine than it would be if the hands were doing the lifting, so there is increased concern about the biomechanics of the lift. When the load is released from the shovel, there may be a twisting motion in the trunk as one arm is raised to turn over the shovel pan. During the transfer of material on the shovel, control is required to prevent rotation of the pan, and this increases the load on the smaller shoulder muscles. All of these factors affect the acceptability of weight in the shovel pan.

Shoveling tasks often involve frequent lifting for periods of 15 minutes to an hour at a time. The metabolic workload may be of concern, and this will be affected by the heights of the lifts and by the degree of precision needed to place the material at its destination. For example, digging a hole to lay a water main may be a less precise task than digging a hole to set a cemetery headstone. Alternatively, shoveling chemicals into a smelting furnace can be less precise than shoveling the finished product onto a large and shallow tray that is put into a drying oven. Studies on shoveling loads show that a 15-minute task can be done at a total load of 750 kg (1,650 lb) if it is low and not very precise. If it is above 102 cm (40 in.) and not precise, 530 kg (1,165 lb) can be transferred in 15 minutes, and 245 kg (535 lb) if it is low and needs precision control (Eastman Kodak Company 1986). Typical shovels weigh from 1.5 to 3 kg (3.3 to 6.6 lb) each. For the calculations above on maximum loads per 15 minutes of shoveling, it was assumed that the shovel weighed 2.3 kg (5.1 lb) and that the transfer distance was 1 m (3.2 ft.). When frequent shoveling is a substantial part of the job, and the job is being done in an environment that permits assist devices to be used (e.g., not outside away from a building or power supply), other transferring devices should be considered. Examples of these are diggers and front loaders, air conveyors, and screw conveyors.

One-Handed Lifting

The acceptable weights of items lifted with one hand are largely determined by the handler's grip strength and the hand-item interface that affects wrist, hand, arm, and shoulder postures. If the item is handled with a pinch grip, the acceptable weight will be about 20 percent of the value one would find acceptable when using a power grip with a span of 5 to 7.5 cm (2 to 3 in.). The impact of grip type, angles, span, and glove use on grip strength has been discussed earlier in this chapter. If the grip is not limiting, then one-handed lifts can be close to the acceptable weights for two-handed lifts. Figure 7.7 shows acceptable weights for one-handed lifts of items that are from 1.2 to 13 cm (0.5 to 5 in.) wide, where the lifts are made between 64 and 127 cm (25 and 50 in.) above the floor, and the lifting frequency is ≤ 1 every 5 minutes. The upper curve shows the effect of span on acceptable weight for barehanded lifts, and the lower curve shows the same for lifting with a cotton glove on the hand. It is assumed that the wrist angles to make the lifts are not far from their neutral postures. If the task requires frequent lifting (e.g., 3 to 4 per min) and the transfer times are less than 4 seconds, the acceptable weights will be reduced by a small amount, but it is unlikely that local muscle fatigue will accumulate. At frequencies of 10 to 12 lifts per minute, the handler may decide to alternate hands on the task in order to reduce the accumulating fatigue in his or her upper extremities.

One-handed lifting has been shown to have an increased risk of low back

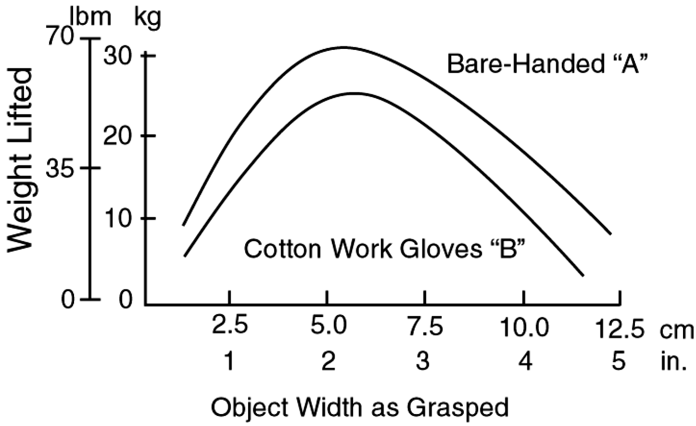


FIGURE 7.7 One-handed lifting with and without gloves
The maximum weights that can be lifted are found in those objects that permit the handler to use a power or hook grip. Other factors such as wrist angle will affect total grip strength and may reduce the weight.

stress from the asymmetry of the lift and resulting shear forces in the lumbar spine (Allread, Marras, and Parnianpour 1996). Frequent lifting tasks using two hands are preferred over one-handed lifting for this reason.

Special Considerations in Manual Lifting Task Design

Lifting and exerting forces to move bags, empty pallets, drums, carboys, bottles, and sheet materials are common manual handling tasks in many jobs. Because of the load configuration and interfaces for handling them, there are some special needs for transferring them safely.

Manual Pallet Handling

Wooden pallets are used throughout industry to move parts, supplies, and products between receiving, production, and distribution departments as well as to the customers. In the United States, 102 × 122 cm (40 × 48 in.) pallets are commonly still used, while 81 × 102 cm or 81 × 122 cm (32 × 40 in. or 32 × 48 in.) pallets are more common in Europe and in many other parts of the world. They can weigh from 17 to 50 kg (37 to 110 lb.). Their size and weight make them awkward to handle; hand splinters, foot and lower extremity contusions, and shoulder and back strains have all been associated with manual handling of pallets.

Rather than lift them, most skilled handlers slide the pallets on and off horizontal stacks. Figure 7.8 illustrates this technique; in a and b, the handler drops the pallet to the floor by controlling its fall along the stack, while in c and d, he stacks the pallets by tilting them down from the upright position. Using these techniques, the handler never takes the full weight of the pallet.

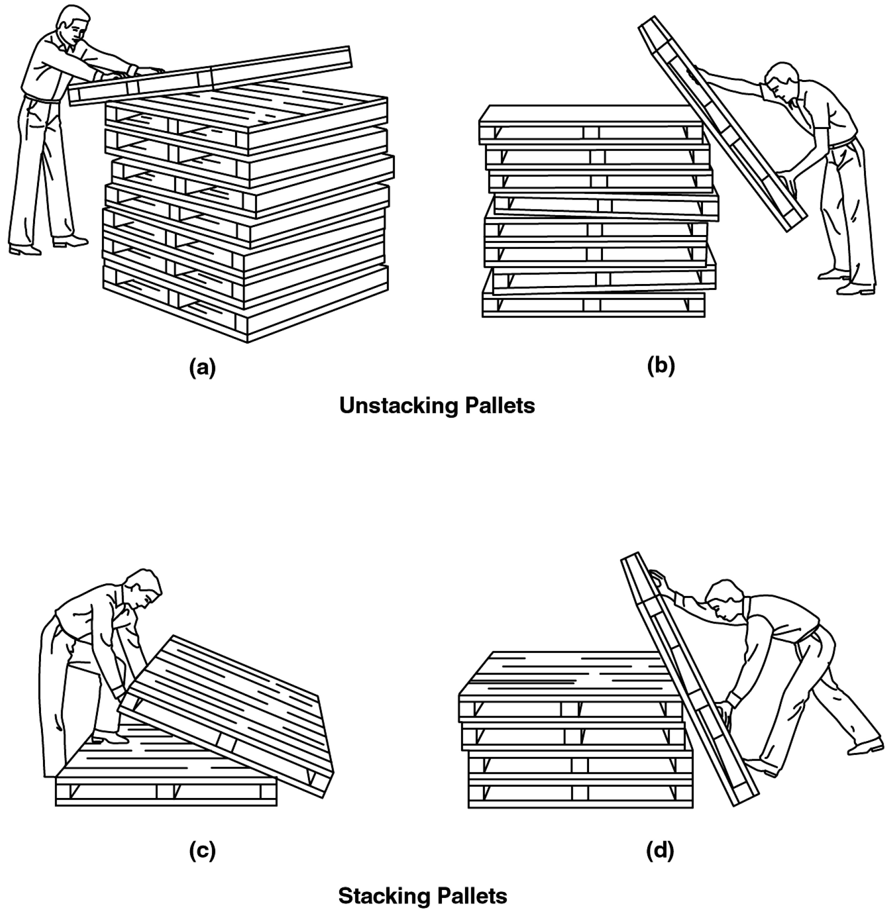


FIGURE 7.8 Manual handling of pallets
The techniques illustrated feature sliding rather than lifting and using hook grasps through the slat openings to control the pallet's motion.

Whenever possible, it is recommended that pallets be stacked and unstacked using a forklift truck or stacker instead of manually handling them. If this is not feasible and a second person is available, two-person handling is the next best alternative. Where many pallets are handled in a shift, as at the end of a production machine or in a warehouse, pallet dispensers may be justified. In addition, in some applications, a smaller and lighter plastic pallet may be preferable over the larger wooden one.

When wooden pallets need to be handled manually and infrequently, the following guidelines should be followed to reduce the risk of overexertion injuries (Eastman Kodak Company 1986):

- Individuals should not stack pallets more than six high.
- Individuals should not procure pallets from a stack more than nine high.

- If a second person is available, pallets can be stacked to nine high and unstacked from twelve high.
- Pallets should always be placed right side up and with the wood grain aligned for easy sliding.
- Broken or damaged pallets should be removed from the work area for repair or destruction.

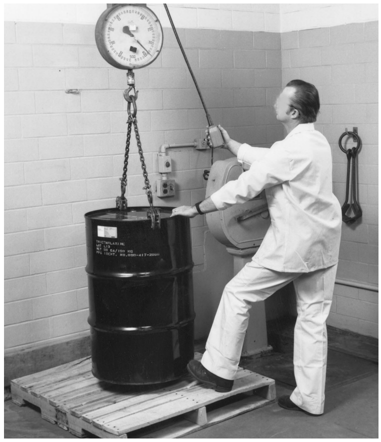
Pallet alternatives are under development to improve shipping processes, including plastic pallets that are smaller and easier to slide product onto, slip sheets, triwall corrugated containers, shrink-wrap packaging, breakdown plastic boxes, Gaylords, hoppers, and metal skids. Shipping containers and unitized loads are also reducing the numbers of pallets used in some businesses. These require powered handling equipment to transport them and may not be cost-justifiable in smaller operations.

Drum Handling

Liquid and powdered materials are often stored in metal or fiber drums. These are handled manually by rotating them on the edge of their base, or chime. Drum trucks slide under the base and grab on to the top chime to stabilize the drum for longer transfers. Metal drums typically have a capacity of 208 liters (55 gal.) and weigh about 23 kg (50 lb.) empty and from 45 to 295 kg (100 to 650 lb.) when filled. Most weigh less than 240 kg (530 lb.). Plastic drums are used when the chemical in them is corrosive to metal. They do not have distinctive rims and can be slippery to handle if they are wet. Often they weigh more than 240 kg (530 lb.), making them the most difficult drums to handle manually. They can be handled with specialized drum trucks that can clamp across their top rim for stability during transfers. Fiber drums tend to be lighter and have metal bands at each end but are less easy to chime. They are often 91 cm (36 in.) high, but shorter drums (<76 cm or 30 in. high) or taller ones (>114 cm or 45 in. high) are also used and are difficult to chime because of their heights. Smaller drums are usually lifted, not chimed. Figure 7.9 illustrates metal, plastic, and fiber drums being moved or weighed in a production workplace. Three types of drum and carboy carts are illustrated in Figures 7.9 and 7.10. The preferred drum cart is the four-wheel version, which allows the drum to be placed up on a pallet or platform. Forklift trucks can also be fitted with a drum clamp for moving drums inside the plant, and this is done when large numbers of drums are used in a production or warehouse situation.

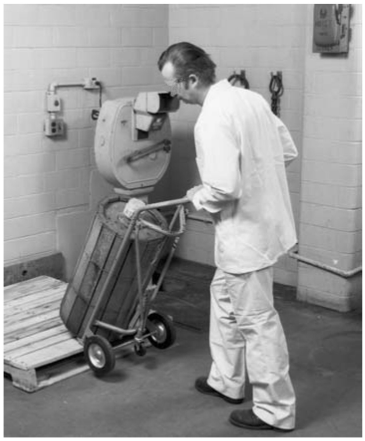
Unless the drums are almost empty, manual tipping of them from the vertical to the horizontal orientation is not recommended. A tipster (see Figure 7.11) or a forklift truck drum attachment may be used to tip out the contents of the drum, or a siphon pump can be inserted in the upright drum to remove the liquid near the bottom. It is an acquired skill to chime a drum and still maintain control over it, so the new handler should have the opportunity to practice this activity and develop the skill. Raising the drum up on a pallet is a very skilled activity and is best prevented by recessing the scale into the floor.

Plastic Drum



Metal Drum

Fiber Drum



Carboy

FIGURE 7.9 Examples of plastic, metal, and fiber drums and a carboy

Once a drum goes out of control during a manual transfer, it is best to let it go because the combination of its weight and the acceleration of the load make it an excessive force to contend with.

The following drum handling guidelines are based on observations and measurements in the field:

- Drums weighing more than 115 kg (253 lb) should be handled with a handcart or other lifting assist device.
- Drums weighing more than 227 kg (500 lb) should be handled with powered equipment.

Four-Wheel Cart

Two-Wheel Cart

Fork Truck with Drum Handling Attachment

FIGURE 7.10 Drum handling

- Conveyors, pallets, and scales should be recessed in the floor on drum lines so the drums do not have to be raised 14 to 25 cm (6 to 10 in.) above the floor.
- Air pumps and siphons should be used to remove liquids from drums, and airveyors or screws should be used to remove powdered chemicals, in order to reduce the need for the drums to be tilted over to a horizontal position manually or with a handcart.
- Small drums that are handled manually should weigh less than 18 kg (40 lbm) and should be compact. A drum 31 cm (12 in.) in diameter is comfortable to handle manually, even when there are no defined handholds.
- Drums weighing more than 104 kg (225 lb) should be handled with drum carts or other assist devices.

- Where feasible, fiber drums should be securely strapped to a pallet or skid for transportation via a forklift truck or stacker.

Carboy and Large-Bottle Handling

Carboys are glass or plastic bottles encased in a wood or plastic frame, and they often contain inorganic acids and bases. The bottles have capacities in the range of 7 to 95 l (2 to 25 gal), the most common being 19 to 38 l (5 to 10 gal). They often weigh more than 18 kg (40 lb) and are best transported for longer distances by being strapped to a pallet and moved by a forklift truck or a stacker. When handling a carboy manually to tip out its contents, the handler has to hold both the neck of the bottle and the bottom of the frame. Precise control is needed to prevent exposure to the often corrosive material in the carboy. An example of a carboy being transported on a cart is shown in Figure 7.9d. Figure 7.11 shows a tipping device that stabilizes the load and controls the pour from a carboy, thereby relieving the handler's back of sustained static stress. Use of a siphon or pump to remove the liquid, where feasible, is recommended for carboys.

Liquid dispensing in a laboratory setting entails the filling, transport, and emptying of containers. Of particular issue are the large-bottle dispensers, carboys, and dispensing jugs (see Figure 7.12). A common difficulty in the laboratory is lifting large containers to and placing them on high shelves above the laboratory bench. Once the bottle or jug is positioned, dispensing may be convenient by using the faucet at the bottom. However, usually this involves an extended reach to the back of a bench and occasionally increases forces on the arms and hands if the beaker has to be held while it is filling. Consider alternatives to lifting such containers onto hard-to-reach shelves. For example:

- Rearrange the area so that large bottles are not kept on the high shelves. Keep lighter items high.
- If a high shelf is used, dedicate an area at the end of a bench and use an assistive device to raise the load onto the shelf (e.g., a lift or hoist).
- Keep large containers on an adjustable-height cart so that the load can be placed easily onto the cart; raise the height for ease of use of the bottom-mounted valves. The cart could also be moved close to where it is needed during a procedure.

Some additional handling issues and suggestions are:

- Avoid using containers that have to be lifted for dispensing, compared to bottom-dispensing vessels. This is especially important in containment cabinets or glove boxes, where any lifting would be awkward to perform at best (see "Laboratory Workspaces " in Chapter 3).
- If the container cannot have a bottom valve, use vessels that have two handles or indentations to help with gripping while tipping them.

FIGURE 7.11 A tipping stand to control flow from a carboy
The frame is counterweighted so the operator can control the angle of the tip without having to grasp it tightly.

- Alternatively, consider other means of dispensing the liquid, such as suction or vacuum methods.
- Use clamps for beakers or test tubes so that the person does not have to hold the beaker. By steadying the beaker or test tube, two hands can be used to pour from a jug.
- If small amounts of liquid are used often, consider decanting liquid into a squeeze bottle rather than frequently handling a large, heavy container.
- Transportation of large and/or heavy items such as bottles, carboys, and jars should be by cart.

Another common bottle-handling task involves transporting water bottles to dispensers in both public and private buildings. The driver loads the bottles

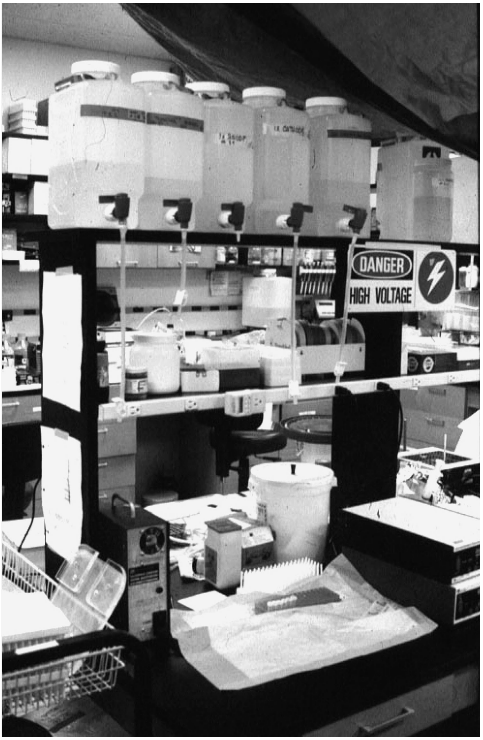


FIGURE 7.12 An example of an organized laboratory bench with large bottle dispensers on the top shelf. The location is convenient for use but creates a manual material handling concern to place full bottles on the shelf.

into a truck before delivering them to the customer. The necks of the bottles are about 7.5 cm (3 in.) in diameter, making the gripping surface very wide when they are pulled out of the truck and carried to the dispenser sites. Once a bottle has been brought to the customer, it may have to be lifted up and inverted into the dispenser. This is usually done before the muscles that are already fatigued from transporting the bottle to the customer have had an opportunity to recover. Back injuries and shoulder and arm strains are not uncommon among people who deliver water bottles. One part of the increased risk of this work is the tendency of the bottle to jerk the arm and shoulder as it moves from the horizontal position in the truck to the vertical position when being carried. Countering the fall of about 18 to 27 kg (40 to 60 lb) of water will put a large strain on the handler's upper extremity (NIOSH 1996).

Several approaches have been used to improve bottle handling in the water delivery business. Some of the delivery trucks include indexing locations on each storage bay that allow the driver to load and unload the bottles at the same location every time. This is a big improvement over having to climb up on the truck and control the bottles as they are moved out of the upper locations. The latter is an unstable posture and increases the risk of falling when the weight of the full bottle is dropped down. Another approach has been to use smaller bottles that are easier to handle (<16 kg or 35 lb); this has the additional advantage that the customer can more safely load them into the dispenser. The total number of bottles handled may be greater with this option, but the weight and safety issues are less likely to be a problem with the smaller ones.

Some assist devices have been tried to help convey the bottle between the truck and its final destination. These must be compact and sturdy, and the delivery truck driver may only be able to use them up to the front of the building because of stairs or other barriers to access by small handcarts or trucks. More developmental work on such assist devices is needed to provide useful conveyances that are not difficult to move up short flights of stairs inside or outside buildings.

Bag Handling

Large amounts of powdered and pelletized chemicals and foodstuffs are handled in heavy paper or plastic bags, usually in 15, 20, 23, 25, 38, 45, or 50 kg (33, 44, 50, 55, 80, 100, or 110 lb) units. They tend to lie flat on a pallet or skid (or in a pallet box) and are from 46 to 91 cm (18 to 36 in.) long and often weigh in the range of 23 to 25 kg (50 to 55 lb.). They are often handled from the top or at the gussets, or across the middle when carried for more than a few seconds. Burlap bags may be handled with a hook if they contain material that will not be damaged by the hook. Plastic bags are often handled across the opposite corners or at the neck of a cylindrical bag, both of which imply that a wide grip will be used to stabilize them. If the internal grip circumference exceeds 5 cm (2 in.), people with small hands may have difficulty handling bags where the plastic is gathered at the neck of the bag.

Bags offer the following advantages over fiber drums for some materials:

- They are lighter and can be held closer to the body. As they empty, one can continue to get closer to the bag.
- They lie flat on a pallet or skid or in a box and dead-stack well in a cargotainer to form a stable and efficient load.
- The handler has more options for how to handle them (e.g., from the top, on the corners, or on the sides). Figure 7.13 illustrates a handler using end and middle grips on a large bag.
- The corners can be opened so they form a trough, and this allows the handler to control the outward flow of the material better.

Some disadvantages of bags are:

- They are not rigid and the load can shift or be uneven during the transfer, putting an extra strain on the upper extremities and the back.
- Lifting bags from the floor or pallet level requires the handler to go into a full squat, making it hard to stand up again with the heavier bags.

FIGURE 7.13 Bag handling—large bag
Typically the contents of a bag will shift as it is lifted. It is difficult to get a firm handhold on shifting material, so an open palm combined with a hook or pinch grip is most often used.

- Lifting bags over shoulder height is a difficult task because the load is not stable and could shift, causing the handler to lose control of it.
- Bags can be damaged more easily than fiber drums.
- Plastic bags can be slippery and result in poor gripping surfaces for the handlers.
- The depth of the bag when it lies flat can be 7.5 to 15 cm (3 to 6 in.), which is too wide for an effective power grip.
- In large-volume operations, fiber drums can be handled better by forklift truck attachments. Bags do not lend themselves to powered equipment handling unless they are on pallets or skids.

The following guidelines for bag handling are based on studies of acceptable lifting weights (Ciriello 2001; Ciriello and Snook 1983; Ciriello, Snook, and Hughes 1993; Snook and Ciriello 1991) and observations of bag handling in industry:

- If bags are handled more than 450 times a shift, at any weight, the workplace should be set up to permit them to be slid instead of lifted. For example, provide roller bearing tables to reduce the frictional resistance for sliding the bags from station to station.
- Bags weighing less than 7 kg (15 lb) can be handled comfortably at waist height by most people. Bags weighing 11.4 kg (25 lb) become a problem for lifts made higher than 127 cm (50 in.).
- Rotating people in and out of frequent handling jobs or tasks can reduce the total aerobic work in frequent bag handling and reduce accumulating muscle fatigue, especially in the arms and hands.
- Bags weighing more than 23 kg (50 lb) should not be manually lifted. If there is no feasible way to handle them with assist devices, they should be lifted in the height range of 51 to 102 cm (20 to 40 in.) or slid instead of lifted.
- If the bags are located on a pallet on the floor, place two more pallets or a fixed platform of 38 cm (15 in.) under the pallet to reduce the need to bend over while lifting.

The chemical and food industries have developed improved packaging for their products in bulk that reduces the need to manually handle 23- or 25-kg (50- or 55-lb) bags when blending powders. The use of Super-Saks and similar large-volume bags that act as hoppers to meter chemicals or grains into blenders or mixing kettles has improved the handling workload for many workers. These sacks are placed on a hoist and lifted above the reaction vessel or mixer, so they also take up less space around the work area. A load cell and a large display are added to help the operator see how much of the raw material, by weight, is being delivered to the desired mix. In some industries, a metal hopper is used in a similar manner, and the raw materials come into the work area in the hopper from the vendor. The raw materials delivered in

Super-Saks or hoppers have to be able to flow well and not clog up in the outlet tube. Very flaky chemicals or hygroscopic ones that cake easily are not suitable for use in these sacks and hoppers.

Large-Size Sheet or Wallboard Handling

In construction and some manufacturing activities, large sheets of wood, metal, glass, cardboard, or plastic must be manually handled. These sheets have no handholds, require that the handler control them with pinch grips, and are too wide or long to grasp across. They are usually less than 2.5 cm (1 in.) thick and often are not very rigid.

If the sheet material weighs less than 13 kg (29 lb), a person can usually transport it for short distances in a nonwindy environment using a handling aid (see Figure 7.14). This assist device provides support for the sheet while allowing the handler to control the lift and carry it using a power grip on a J- or D-handle. Very long sheets may not be able to be balanced on this type of assist, however, and two people with assists may be needed.

Sheets weighing more than 13 kg (29 lb) may be too fatiguing for the handler, especially if the sheet has to be carried for several feet. Other transport aids, such as carts and trucks, should be used to move the sheets over longer distances or to handle the heavier sheets, where feasible. Sheets weighing more than 20 kg (44 lb) may be too fatiguing for two-person handling because of the gripping and shoulder muscle stress, so assists are needed.

Assist for handling large sheets

Vacuum-based lift assist for lifting boxes

FIGURE 7.14 Handling assists

Small wallboard hand trucks are used by some carpenters and facilities maintenance crews to transport sheet materials to a construction or remodeling site. The truck supports the sheet near the center and can be swiveled easily from either end to maneuver it through doors and around corners. These trucks are less satisfactory for pushing long distances, but they are very useful for taking six to ten wallboards into a work site at a time. Larger powered trucks can often be used to deliver thirty to fifty sheets to the area. Smaller numbers of sheets can be procured and transferred to the smaller hand truck, as needed.

THE DESIGN OF FORCE EXERTION TASKS

The use of muscle force to slide an item in place of lifting or carrying it is a common occurrence in many jobs. The amount of force needed to do each task depends upon the load and the coefficient of friction of the load on the surface on which it is being moved. The amount of muscle effort used to move the load will be dependent on the posture taken and which muscles can be used. The larger the muscle groups and the better the posture, the less effort (as a percentage of maximum strength) needed to create the necessary force. The coefficient of friction of the handler's shoes with the floor must also be enough to translate the developed force to the load rather than dissipate it through the feet to the floor. The goal of ergonomically designed force exertion tasks is to get the work done with the least effort so that unnecessary fatigue does not accumulate in the active muscles during the shift.

Examples of forceful exertions in businesses include:

- Pushing and pulling handcarts and trucks
- Operating controls and tools
- Sliding items on a flat surface such as worktables, conveyors, or shelves
- Opening and closing doors or access ports
- Forming and bending cardboard or corrugated board
- Clearing jams in machine assembly or packaging tasks

In this section, the forces are classified as horizontal, vertical, transverse, and those developed by the hand. The horizontal forces are those used to push and pull handcarts and trucks or to move materials into or out of a machine or on a work surface. Vertical forces are used to hoist materials or to stabilize them during their transfer, in packing tasks, and during tool use. Transverse or lateral forces are used to move materials across a workplace or on a conveyor and may be used in some assembly tasks to hold parts together. Hand forces are used to clear jams, stabilize and control tools, and hold assemblies together.

Horizontal Forces Away from and Toward the Handler: Handcart and Truck Design Guidelines

Low back pain is often associated with force exertion in cart and truck handling, and the force intensity, distance traveled, handle height, and frequency and velocity of exertions are considered risk factors for musculoskeletal problems in these manual handling tasks (Hoozemans et al. 1998; Eastman Kodak Company 1986). The angle of application of a hand force to an item being moved will influence the effectiveness of the muscle effort in a pushing or pulling task. A straight horizontal push allows the body weight to contribute to the force applied by the arm, shoulder, and back muscles. When cornering a hand truck, however, the force is applied at an oblique angle to the handle and truck, and there is less muscle capacity available for the task. Much of the work is done by the small shoulder and forearm muscles, so the perceived effort is higher than when the biceps, triceps, larger shoulder muscles, and upper trunk muscles are involved. The preferred handle height for straight horizontal pushing is at about elbow height, or about 91 cm (35 inches) above the floor (Hoozemans et al. 1998). When a cart or truck is being cornered or maneuvered, however, somewhat higher handles are preferred. Vertical handles may make the force translation easier on taller carts. Figure 7.15 illustrates several different cart and truck designs used in industry. For flexibility, a combination of horizontal and vertical handles is recommended for manual carts and trucks that have to be maneuvered in a workplace as well as pushed horizontally in corridors and aisles.

Most carts or hand trucks that are pushed are also pulled, so the guidelines for safe force exertion are based on the weaker of the motions. Pulling is often done with one hand and with a twist in the trunk, so pushing is the preferred method of handling handcarts and trucks. Pulling is also more likely to result in foot and ankle injuries from the cart or truck riding up on them during the transfers.

A very general set of guidelines for pushing and pulling handcarts and trucks is (developed from information in Ciriello and Snook 1978; Haisman, Winsmann, and Goldman 1972; Nielsen and Faulkner 1967; Strindberg and Petersson 1972):

- Keep the starting forces to 23 kgf (50 lbf) or less. This is measured with a force gauge by placing the wheels or casters out of alignment with the direction of travel so that they have to be moved into alignment with the initial force application.
- The rolling force should be less than 18 kgf (40 lbf). If the force has to be sustained for a minute, or if the truck/cart has to be pushed for more than 3 m (10 ft.), it should drop to 11.5 kgf (25 lbf) or less.
- If it is sustained without a break for 4 minutes, the acceptable force drops to about 3.5 kgf (7.5 lbf). Long transfers are better done with

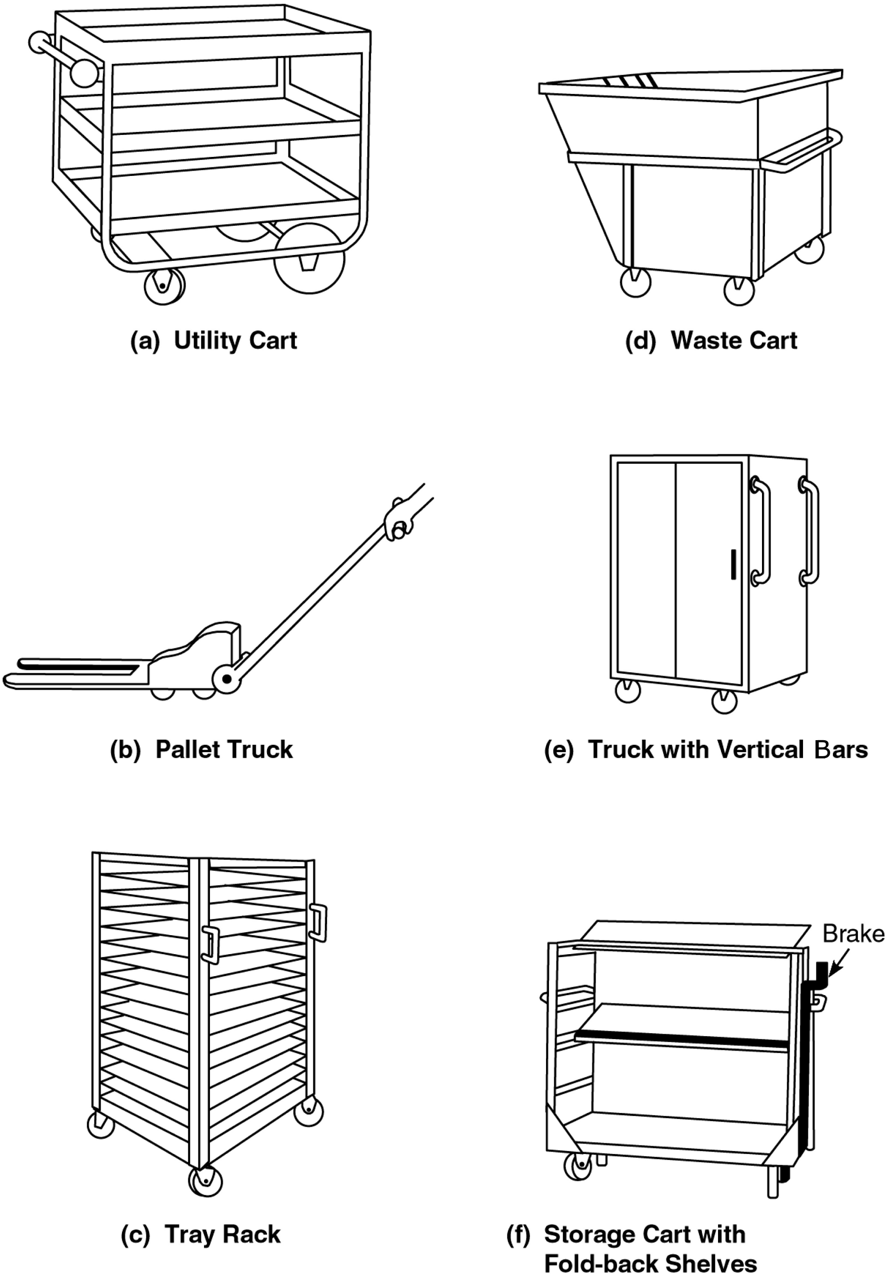


FIGURE 7.15 Examples of handcarts and trucks

Note: The vertical handles shown in (e) are only recommended for narrow trucks, less than 50 cm (20 in.) wide. Although storage carts with fold back shelves and brakes are more expensive than standard utility carts, they provide functional storage and are inherently safer.

powered equipment since few hand carts and trucks are light enough to be pushed with forces as low as these.

- Emergency stopping forces of more than 36 kgf (80 lbf) should not be needed to bring the cart or truck to a stop within 1 m (3 ft.).

The above guidelines are based on the assumption that the cart or truck design permits the handler to exert the force around waist height or a little higher and the coefficient of friction of the handler's shoes with the floor is about 1.0.

A table of acceptable horizontal pushing and pulling forces for different distances can be found in Tables 2.8 and 2.9. These values were determined by having the trained industrial workers push against a handrail on a self-powered treadmill for different lengths of time. Time and stepping rates represented distance traveled, as if they were pushing a handcart or truck. The force at the hands was measured with a strain gauge in the handrail, and their preferred push force for each distance was determined psychophysically after several trials. The values do not reflect the effort of maneuvering a hand truck at different handle heights or with handholds on the sides of a cart or on a centered handle, as would be found in manual pallet truck use. All of those acceptable forces would be lower than the ones shown for horizontal push and pull tasks.

When forces exceed the guidelines, there are several ways to improve the situation. Some of the factors that can be addressed are:

- *Floor characteristics:* Uneven or sloped floors require greater force exertions. Drains or troughs in the floors may create hazards by capturing a wheel or caster. Wet, oily, or dusty floors reduce the coefficient of friction of the handler's shoes with the floor, and the forces exerted may result in some body rotation instead of cart movement.
- *Cart or truck characteristics:* The height of the handle(s), the distance between handles, and the size of the gripping surface may all influence the amount of strength the handler has to control the cart or truck movement. The size of the cart or truck—its wheelbase, length, width, and height—can influence the way the force has to be applied to control its movement. The size, type, and design of the casters or wheels can profoundly affect the ease of handling of handcarts and trucks.
- *Handler's footwear:* A coefficient of friction of about 1.0 is desirable between the handler's shoes or boots and the floor. If the footwear has a smooth surface and slips on the floor, more effort will have to be expended to move the cart or truck.
- *Size of the load on the cart or truck:* Heavier loads require higher forces to move them. If other improvements are inadequate in bringing the force requirements down within the guidelines, the load should be reduced or a power assist should be provided. In general, loads greater than 227 kg (500 lb) should not be transported on a hard cart or truck.

Modifying the casters or wheels on a handcart or truck, usually by increasing the diameter, is an effective way of improving cart handling. In choosing to place larger casters on a cart or truck, it is important to determine if the increased height of the modified equipment will create additional problems for handling materials on and off it or for interfacing it with other equipment. Sometimes a different caster design of the same diameter is preferable. Crowned treads may be preferable when the cart has to be maneuvered in tight places. Pneumatic wheels are less appropriate for carts or hand trucks that carry heavy weights and remain sitting while loaded for several hours at a time. The weight tends to flatten out the tires, making the starting forces very high.

Heavy handcarts or trucks, such as a mechanic's tool chest, may have to be pushed and pulled across pavement and gravel between buildings as well as used inside a plant. They may also be pushed up ramps between buildings. A battery-powered pusher can be provided to help move the tool chest in these places and reduce excessive stress on the mechanic's back and shoulders. In locations where long ramps must be negotiated with hand trucks (often when two buildings have been joined and the floors are not on the same level), a powered winch can be used to assist the handler in bringing a handcart or truck up the ramp.

When there is a liquid load to be transferred in a pail or open kettle or other vessel (e.g., soup kettle, chemical or lubricating solutions for maintenance tasks or cleaning, mixing tanks), the handler has to apply force slowly and continuously to avoid spills. Any sudden stops or cracks in the floor are likely to cause spills and require increased force by the handler to control the motion of the liquid and minimize the spill. Designing the containers and vessels to minimize spills and reducing the required forces to start and stop them when they are being pushed or pulled are ways to work around these stability problems. For large-volume operations, it is probably better to pipe the liquids to the appropriate locations instead of using intermediate containers and carts.

Modification of the handcart and truck handles and their dimensions may be needed if caster or wheel modifications are not sufficient to reduce the forces exerted to safe levels for most people. Some approaches are:

- Use swivel casters on one end of the cart and place the handle at that end, too.
- If an adjustable T-handle is used, as on hand pallet trucks (or jacks), it should be long enough to protect the handler's feet from being struck by the pallet during pulling transfers. At least 20 cm (8 in.) of horizontal extension is needed.
- Fixed horizontal handles should be 91 cm (36 in.) or more above the floor but not greater than 112 cm (44 in.). Vertical handles should cover this range and may go 15 cm (6 in.) higher to 127 cm (50 in.), especially on tall and narrow trucks and carts.

- The distance between handles on each side of a cart or truck should be kept to 46 cm (18 in.), if possible. Wider separations put higher loads on the weaker shoulder muscles.
- Handles should have 12.5 to 15 cm (5 to 6 in.) of clearance for the gloved hand, and preferably 20 cm (8 in.). They should be at least 15 cm (6 in.) long, and the handle should be 2.5 cm (1 in.) or 3.8 cm (1.5 in.) in width for a comfortable grip.
- Trucks or carts that are longer than 1.3 m (4 ft.) or wider than 1 m (3 ft.) are difficult to maneuver in standard aisles. Too wide or deep a truck or cart will also make handling of parts into the shelves more difficult with extended reaches required.
- The preferred height for trucks should be less than 127 cm (50 in.) high so that the shorter handler can see over them when pushing them in the aisles. This also keeps the handling of parts on the carts within the safer range of below shoulder height for most people.
- Shelf heights in carts and trucks should be in the best lifting range of 50 to 115 cm (20 to 45 in.) whenever possible.
- Hand and wheel/caster brakes should be provided on carts and trucks that are transported on sloped floors or have to be aligned with equipment in the workplace.
- Powered assists or powered trucks should be used when the push or pull forces are greater than the recommended values given above.

Other Horizontal Forces—Overhead, Seated and Kneeling

If the horizontal force is exerted low or high or when seated, the amount of muscle force available is limited by the smaller muscles that are involved (Eastman Kodak Company 1986). Pushing or pulling an overhead crane pendant, for instance, with the hand over head height, drops the acceptable force down to 5.5 kgf (12 lbf) to accommodate most people. Kneeling removes the legs from the pushing and pulling force generation unless the handler has a structure against which to brace the feet. Acceptable forces to pull out a motor from a kneeling posture are 21 kgf (42 lbf) if the body can be stabilized.

Pushing forces while seated assume that the chair will not move when forward force is exerted, that is, it is not on casters. Upper-body strength generates the push or pull force, and the recommended upper value for this is 13 kgf (29 lbf) to accommodate most workers. If the force is exerted at full arm extension, the acceptable amount is limited further, as the biceps and triceps muscles are not as strong in this posture. Techniques to reduce the coefficient of friction of the object being pushed or pulled on the work surface are recommended to make the transfer of materials from a seated position less stressful. Omnirollers, polished wood surfaces, and containers with slides on the bottom are ways to reduce the frictional coefficient.

Vertical Pushing and Pulling

Vertical pulls down from overhead are a strength that is related more to body weight than to muscle power as long as the object being pulled on does not limit the handler's grip strength (Eastman Kodak Company 1986). The other maximum recommended forces in Table 7.1 are determined by the location of the push or pull and, therefore, which muscles are used to generate the forces. Pulls from locations below the knees use leg, trunk, and arm and shoulder muscles, while pulls at and above elbow height lose leg muscle strength, and boosts above shoulder height depend primarily on the upper-extremity muscles. Pushes down at elbow height, as would be made in packing operations, depend on shoulder and arm strength, while pulls up at elbow height use the arm muscles at a mechanical disadvantage and the smaller shoulder muscles. Pulls down at shoulder height are generated by smaller shoulder muscles, and the arm muscles are at a mechanical disadvantage.

The values given in Table 7.1 are for maximum forces exerted in a standing posture. If the handler is seated, the values are usually lower for locations where leg strength is involved (low pulls up, especially), and about 15 percent less for other locations. The height of the hands when the force is exerted is used to define the location of the push or pull. As a general practice, if forces

TABLE 7.1
Upper Limits for Vertical Push and Pull Forces in Two-Handed Tasks, kgf (lbf) (developed from information in Hunsicker 1957; Keyserling et al. 1980; Kroemer 1974; Yates et al. 1980)

Conditions	Upper Limit of Force	Examples
Pull down:		
Above head height	54 kgf (120 lbf)	Activating a control using a hook grip (safety shower handle, throttle)
Shoulder level	20 kgf (45 lbf)	Operating a chain hoist using a power grip on the chain <3cm (1.2 in.) in diameter
Pull up:		
25 cm (10 in.) above the floor	32 kgf (70 lbf)	Stringing cable, threading up a paper machine, activating a control
Elbow height	15 kgf (33 lbf)	Raising a lid or access port
Shoulder height	8 kgf (17 lbf)	Raising a lid, palm up
Push down elbow height	29 kgf (64 lbf)	Wrapping, packing, and sealing cases
Boost up, shoulder height	20 kgf (45 lbf)	Raising a corner or end of an object, like a pipe; boosting an object to a high shelf

greater than 4.5 kgf (10 lbf) are used frequently during a shift, a standing or sit/stand workplace is preferred to a seated one.

Transverse or Lateral Forces Applied Horizontally

Barriers to access in some workplaces result in a need to move materials or objects across the body instead of being able to get behind them to push or pull them with the whole body. This situation limits the force generation to the weakest shoulder muscles: the pectoralis and teres muscles, which move the arm across the front of the body in the horizontal plane. The upper limit for force in this movement drops to 7 kgf (15 lbf) when the arm is extended fully (Eastman Kodak Company 1986). In a crane cab, transverse motions may be required to control the movement of the bucket or part. These forces should not exceed 11.5 kgf (25 lbf).

Hand Forces

Information about grip strength has been presented in Chapter 1 in "For Whom Do We Design?" The guidelines given below have been drawn from that data to accommodate the large majority of the potential workforce, older workers and women as well as younger workers and men.

- The power grip strength of a 25th-percentile woman is about 18 kgf (40 lbf). This is used to set guidelines for force exertions using a power grip where the wrist is in a neutral position and the power grip is over a span of 5 to 6 cm (2 to 2.5 in.) or a diameter of 4 to 5 cm (1.5 to 2 in.). This is for grips lasting only a few seconds and repeated less than once every 5 minutes.
- If gripping is done frequently, the maximum force will drop to lower values. See "The Design of Repetitive Work" in Chapter 6 for additional information.
- If a pinch grip is used to clear a jam or control a tool, the upper limit for force will be from 3 to 4.5 kgf (7 to 10 lbf), and this is for infrequent and short efforts as defined above.
- If the forces required to remove a part or pull or push it into position are greater than the upper limit values given above, a tool should be provided to assist the handler or machine operator with additional leverage.

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Some examples of sources of equipment for materials handling tasks:

AliMed: www.alimed.com

Avtek: www.avteksales.com

Ergosource: www.ergosource.com

ErgoWeb: www.ergoweb.com

Southworth: www.southworthindustries.com

Thomas Register: www.thomasregional.com

8 Environment

The workplace environment is of concern to specialists in occupational safety and health and industrial relations as well as ergonomists. This chapter will not deal with chemical agents and many physical agents but will limit itself to:

- Lighting and color
- Noise
- Thermal conditions
- Vibration

These factors affect comfort, performance, and health. Guidelines are presented that will address all of these factors to some extent. While performance decrements may contribute to accidents, they are usually seen before health effects. A safety and health professional should be consulted when there is suspicion that they have reached levels that may affect health.

LIGHTING AND COLOR

Work in today's offices and industrial workplaces has a wide variety of visual demands associated with it. For example, computer interaction, product inspection, computer-aided design work, manual assembly work, chemical solution pipetting, and lathe operation all have unique visual demands. In most tasks, vision is the main sensory channel for workers to receive information or feedback on their performance. Appropriate lighting conditions are critical to allow quality visual work to occur. The amount and quality of light at a workplace as well as the color of the equipment, walls, and work surfaces can influence a worker's vision and may affect job performance.

In this section, guidelines are provided for the design of workplace lighting, including general, task, and special-purpose lighting, which should make visual tasks suitable for a large majority of industrial workers. A short summary of information about the use of color in the workplace concludes the section.

Visual Work Demands

To provide appropriate lighting conditions, the designer should first understand the visual demands of the tasks. What are the activities that are performed in this area or workplace? What does the worker look at to do each task? How does the worker stand and observe the object? How frequently and how long must the task be done?

In most tasks, the visual demands can be described with some basic characteristics:

- The size and three-dimensional shape of the object to be viewed (smaller, thinner, and flatter are more difficult)
- The contrast between the object and the background (low contrast is more difficult)
- The viewing distance (longer distances are more difficult)
- The motion of the object
- The field of view around the task (cluttered fields are more distracting)
- The sensitivity of the visual task to error
- The frequency of each task to be performed
- The time available to perform the tasks

Basic Light Terminology

Illuminance, or illumination, is a photometric measure of the amount of light falling on, or incident to, a work surface or task from ambient and local light sources. It is measured with an illuminance meter (in units of lux or foot-candles), which is set directly on the work surface. The farther away the surface is from the source of light, the less the illuminance will likely be.

Luminance, on the other hand, is a photometric measure of the light reflected off a surface and is associated with the subjective sensation of brightness. Luminance does not vary with the distance between the surface and the observer, and it is measured with a photometer located at a convenient distance from the surface and pointed toward it.

For additional information, see the glossary of lighting terminology in *The IESNA Lighting Handbook* (Rea 2000).

Recommended Illuminance Levels

The Illuminating Engineering Society of North America (IESNA) has developed a comprehensive lighting design guide (Rea 2000) to identify appropriate illuminance levels for tasks. The sequence of tasks for a designer to follow includes the following steps:

Step 1: Consult the design guide to identify the task closest in similarity from the list provided. It is divided between indoor, outdoor, industrial, and security-based activities, locations, and tasks.

Step 2: Identify the recommended horizontal and vertical illuminance categories for the task.

Step 3: From the design guide and handbook, understand the design or quality issues that most influence the task.

Step 4: Modify the recommended values as necessary to account for other lighting design or quality issues.

Table 8.1 lists illuminance levels in terms of the working plane. Horizontal illuminance is the amount of light (in layman's terms) falling on a horizontal surface. Analogously, vertical illuminance is the amount of light falling on a vertical surface. Emphasis should be placed on the most appropriate direction for the task of concern.

The minimum lighting level is the level that is sufficient for people performing the most difficult and critical tasks to be done. Variations based on quality issues and user populations should not vary more than 30 percent from the IESNA recommended level. Measured illuminances should be within 10 percent of the final design values.

Quality Issues

Several design issues must be addressed to provide quality lighting conditions. Quality issues of importance in office and industrial workplaces are listed below:

Age of the User

Designers may adjust recommended illuminance levels based on expected user populations. For example, persons over 45 years of age traditionally have the most difficulty with very demanding visual tasks. With age, there is a thickening of the lens of the eyes and a constriction in pupil size. Compared to a 20-year-old, the amount of light received on the retina is significantly less in a 60-year-old person. The designer may consider an increase in illumination to offset the impact of these age-related changes. However, with increasing illumination, glare from reflected light is more probable, and older persons are usually more affected by the glare of reflected light. Hence, measures to control glare in the field of view must also be considered.

Glare

In the visual field, glare is an exceptionally bright and distracting (or uncomfortable) amount of light. The user can be affected by glare directly from the light source (direct glare) or by reflections off a glossy or polished surface

TABLE 8.1
Recommended Range of Illuminance for Various Areas and Tasks Typical in Work Settings (adapted from Rea 2000)

Type of Activity or Area	Illuminance (lux) Horizontal	Illuminance (lux) Vertical
Public/Service areas		
Exit from building	10	10
Walkways (minimum)	10	22 (at 1.8 m above path)
Parking lots (uniformity ratio 15:1)	2	1
For security	5	2.5
Lobbies	100	30
Copy rooms	100	30
Mail-sorting rooms	500	30
Rest rooms	100	30
Stairways	50	—
Elevators	50	30
Conference rooms		
Meetings	300	50
Video conferences	500	300
Office areas		
Open-plan office, intensive VDT use	300	50
Open-plan office, intermittent VDT use	500	50
Private office	500	50
Control panels, VDT observation	100	30
Drafting/graphic-art work		
Computer workstations only	100	30
Mix of computer and paper-based tasks	300	30
High-contrast media	500	100
Low-contrast media	1000	300
Reading tasks		
VDT screens (data processing)	30	30
Keyboard	300	—
6-point type, maps, telephone books	500	—
Inkjet/laser printer, typewriter output (at 8 points or larger)	300	—

TABLE 8.1 (Continued)

Basic industrial tasks	Illuminance on Task Plane
Visual demands are not high:	
Coarse processing of raw material,[1] warehousing and storage of bulky items with large labels, loading inside trucks and freight.	100
Performance of visual tasks—high-contrast items or large size:	
Medium processing of raw materials, wrapping, packing, labeling, shipping and receiving, picking stock and classifying, warehousing and storage of small items with small labels, manufacture of large components, simple assembly or inspection, rough bench or machine work, coarse manual crafts[2]	300
Performance of visual tasks—medium-contrast items or small size:	
Fine processing of raw materials, manufacture of medium-size components, rough grinding, medium buffing and polishing, ordinary automatic machines, maintenance work, medium craft work	500
Performance of visual tasks—low-contrast items or very small size:	
Very fine processing of raw materials, fine component manufacturing, difficult assembly and inspection, fine automatic machines, medium grinding, fine buffing and polishing, fine manual crafts	1000
Performance of exacting visual tasks:	
Extra-fine bench or machine work (fine grinding); exacting assembly and inspection, precision manual arc welding, exacting manual crafts	3000

1. Processing of raw materials includes activities such as cleaning, cutting, crushing, sorting, and grading.
2. Manual crafts includes activities such as engraving, carving, painting, stitching, cutting, pressing, knitting, polishing, and woodworking.

Notes: The measured illuminance should be within ±10 percent of the recommended values. The above values may be modified by other important factors, such as glare (direct and reflected), daylight integration and control, flicker, light distribution on surfaces and task plane, and the luminance of the room surfaces.

(reflected or indirect glare). Veiling reflections are reflections off a semipolished surface that reduce contrast of an object in the visual field. Glare in all these forms should be avoided or eliminated in typical lighting designs. The zones for direct and indirect glare are shown in Figure 8.1. Methods for controlling direct and indirect glare are given in Table 8.2.

Shadows

The opposite of glare, shadows are an absence of light created by a lack of coverage by fixtures, a blockage of light by other objects, and so on. Shadows

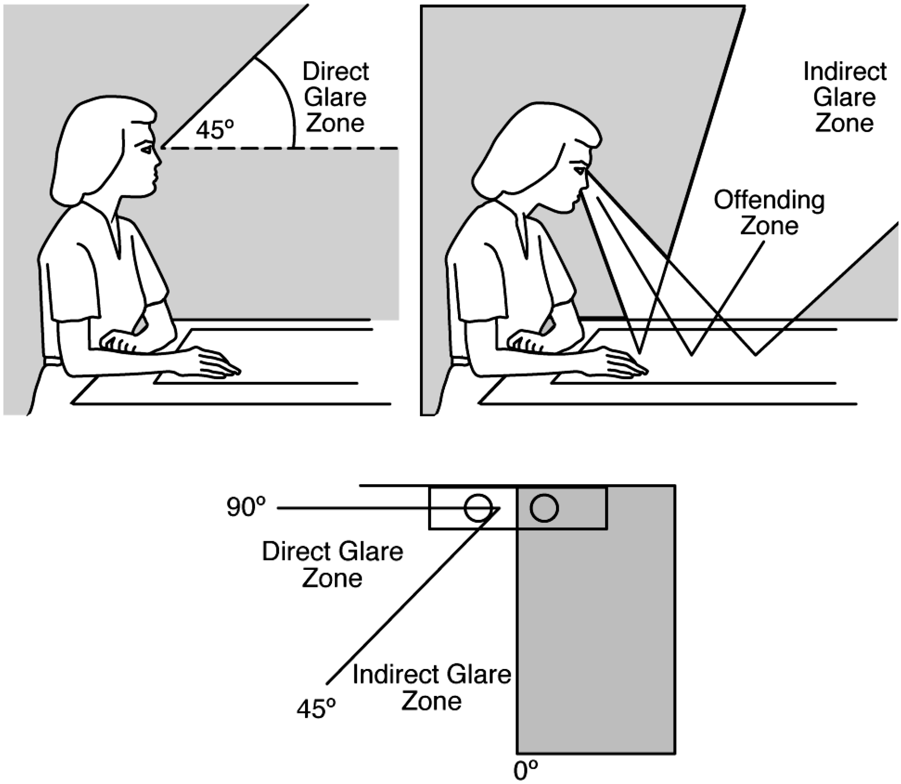

FIGURE 8.1 The zones for direct and indirect glare (adapted from Lum-I-neering Associates 1979)
The direct glare zone (on the left) is shown as the region described by a 45° arc above the operator's line of sight. Indirect glare (on the right) is reflected off the working surface to the operator's eye. The direct glare zone for a lighting source is in the area between the horizontal plane of the luminaire, or lighting unit, and a 45° angle downward. The indirect glare zone is in the area between the 45° line and a vertical line drawn from the center of the luminaire to the working surface.

should be avoided or eliminated in typical lighting design. Increasing the density of lighting fixtures across the space, or the addition of task lights, may eliminate shadows.

Room Appearance

The luminance or brightness of room walls and ceilings should be balanced with the lighting provided for the workplace or task performed in the room. Ceilings and walls should not have extremely different brightnesses from adjacent work areas. Table 8.3 provides a list of maximum luminance ratios for offices and industrial conditions. The work surfaces themselves should have a relatively low reflectance (25 to 45 percent). Ceilings and walls should have a

TABLE 8.2
Techniques for Controlling Glare (adapted from Rea 2000; Morgan et al.1963)

To Control Direct Glare	To Control Indirect Glare (Veiling Reflections and Reflected Glare)
Position luminaires as far from the operator's line of sight as practical.	Avoid placing luminaires in the indirect-glare offending zone
Use several low-intensity luminaires instead of one bright one	Use luminaires with diffusing or polarizing lenses, or indirect luminaires
Use luminaires that produce a batwing light distribution,* and position workers so that the highest light level comes from the sides, not from the front and back	Use surfaces that diffuse light, such as high-reflectance matte finishes, nongloss paper, and textured finishes
Use luminaires with louvers or prismatic lenses	Change the orientation of a workplace, task, viewing angle, or viewing direction until maximum visibility is achieved
Use indirect lighting	Reorient freestanding or mobile arm task lights
Use light shields, hoods, and visors at the workplace if other methods are impractical	Limit luminaire light output at angles > 55° from vertical

*The effectiveness of the batwing distribution varies with the orientation of the workplace and worker. It can also be used to control indirect glare, because maximum output is in the arc between approximately 35° to 45° angles.

high reflectance (walls 40 to 60 percent; ceiling 80 percent to 90 percent) to scatter light and reduce the undesirable effect of a high-contrast fixture against the ceiling or walls. Matte or satin wall finishes of light value (such as white painted walls) and/or lighting fixtures that are dedicated to illuminating the wall or are located close to the wall to distribute more light onto them are methods to increase brightness. Average wall luminances of 30 to 100 cd/m^2 (ceiling luminance of 425 cd/m^2 or less) are preferred in typical office work spaces (Rea 2000).

Natural Sunlight

Windows to the outdoors provide important psychological benefits, and sunlight can increase the amount of illuminance in a work area. However, glare may be an undesirable outcome. Glare caused by light transmitted through windows can be reduced with balanced use of the following:

- Cover windows either partly or completely with draperies, blinds, woven woods, or movable louvers.
- Cover windows with neutral-density filters to reduce transmittances.

TABLE 8.3
IES Recommended Maximum Luminance Ratios for Visual Tasks (adapted from Rea 2000)

Conditions	Luminance Ratios: Office	Luminance Ratios: Industrial
Between tasks and adjacent darker surroundings	1	3 to 1
Between tasks and adjacent lighter surrounding	1 to 3	1 to 3
Between tasks and more remote surfaces	10 to 1	10 to 1
Between luminaires (or windows, skylights) and surfaces adjacent to them	20 to 1	NC*
Anywhere within normal field of view	40 to 1	NC*

* NC means limited or not controllable in practice.

- Add awnings or other devices to shield the windows from direct rays of the sun.

Lighting Design

A lighting design made up of specifically selected fixtures or luminaires with specific locations or patterns must be developed to transform the final design value of illuminance into reality. In practice, lighting is best provided by a combination of ambient room lighting and specific task lighting. Ambient lighting should address basic design issues such as the size of the room, the reflectance or finish of the room's walls, interaction with natural light, location of the workplace(s), and methods to minimize glare. Task lighting should address additional illumination levels for special users or special tasks, the direction of light on work surfaces, and methods to minimize glare. Finally, the design must balance illumination levels with the implementation and operating costs. Only when all of these factors are carefully considered can a satisfactory design be achieved.

Types of Lamps

A combination of lamp and fixture design must be selected to provide the illumination desired. Table 8.4 below gives the efficiencies and color-rendering characteristics of commonly used artificial light sources.

In the selection of artificial light sources for illuminating work areas and workplaces, the two most important considerations are efficiency, in lumens per watt (lm/W), and color rendering. Color rendering is the degree to which the perceived colors of objects illuminated by various light sources

TABLE 8.4
Artificial Light Sources (adapted from National Renewable Energy Laboratory 1995)

Type	Efficiency (lumen/Watt)	Color Rendering	Comments
Incandescent	8–22	Good	Standard lamps have the shortest lives and are the least efficient. Tungsten halogen lamps have a higher efficiency but are more expensive.
Fluorescent	30–83	Fair to Good	Fluorescent lamps last about 10 to 15 times longer than incandescent, but need to be on for several hours at a time for best efficiency. Thy cause less direct glare than do incandescent bulbs.
High-intensity discharge (mercury vapor, metal halide, high-pressure sodium)	22–132	Metal halide lights have much better color rendering than mercury vapor. Color rendering for high-pressure sodium ranges from poor to fairly good, depending on the design and use.	These lamps provide the longest service life of any luminaire. High-pressure sodium lamps have a high efficiency (75–130 lumens/Watt).
Low-pressure sodium	70–152	Poor (all colors rendered as tones of yellow or gray).	These are the most efficient source of artificial light and have the longest service life, maintaining their output levels better than other luminaires. These lamps are typically used for highway or security lighting.

match the perceived colors of the same object when illuminated by standard light sources. Efficiency is a very important factor because it is inversely related to operating costs. Operating costs for commercial and industrial lighting systems tend to be much higher than initial costs (system design, materials, and installation costs) and maintenance costs. Use of efficient light sources also helps reduce energy consumption. Unfortunately, the more efficient light sources are often not suitable for tasks requiring color discrimination because of their poor color rendering. For additional information, see Rea 2000.

Direct and Indirect Luminaires

A luminaire is a fixture that produces, controls, and distributes light. Fixtures that face downward generally provide direct lighting; those that face upward give indirect (reflected) light off the ceiling. Fixtures called semidirect or semi-indirect combine the best of both designs. These fixtures cast 60 to 90 percent of the light either down or up, with the remainder being cast in the opposite direction. General diffuse light fixtures cast an equal amount of light in both directions.

Well-designed indirect lighting can minimize both direct and reflected glare, as well as eliminate shadows. However, it is more expensive than direct lighting and generally less efficient on a lumens/watt basis. If semidirect lighting is used and the downward component is not too great, it offers the added benefit of higher illuminance levels with fewer lights and without excessive ceiling luminance.

If indirect lights are used in an office areas where reading VDT screens is the predominant task, the maximum ceiling luminance should not exceed 850 cd/m^2 and should have a uniformity ratio of 8:1 or less. The preferred ratio would be less than 4:1, dropping down to 2:1 if the screens have a dark background.

Task or Supplementary Lighting

In traditionally designed offices and industrial areas; a typical scenario is to provide a uniformly illuminated area based on a pattern of fixtures that meet expectations for illuminance. For example, a large office area might have an overall level ranging from 300 to 500 lux. Specialized workplaces such as offices for computer-aided design (CAD) often find it preferable to provide a lower level of ambient illumination, such as 300 lux, and use supplementary desk fixtures to illuminate the reading task. This style of design aids the visual task by increasing contrast on the screen and provides adequate illumination for other tasks.

In this style of design, a serious attempt to minimize direct and indirect glare is required. Supplementary lighting should come from the left and right sides of the workplace or over the shoulder. Desk lamps that are directly in front of the worker are potential sources of indirect glare, especially when located in the offending zone (see Figure 8.1). These sources should be avoided for task lighting whenever possible.

Special Lighting Conditions

Computer Workplace Lighting

For computer operations, the main lighting concerns are direct and reflected glare and veiling reflections, which may cause fatigue, discomfort, or annoyance. To minimize glare, a number of improvement opportunities are available:

- Purchase display screens with antireflection coating (standard design feature)
- Incorporate antiglare filters on the display screen. Coated glass, nylon micromesh, and polarized contrast-enhancing versions are available. This approach may reduce the contrast of the screen.
- Mount an antiglare hood on the front of the display.
- Lower the ambient lighting, if feasible. Parabolic wedge louvers can be used to reduce the reflected brightness of lighting units.
- Paint walls with moderate-value colors, satin or matte finish only. Desktops and other work surfaces should have matte finishes. Have the operator sit with his or her back toward a dark-colored wall
- Avoid placing clocks, mirrors, backlit displays, bulletin boards, and similar items in areas where they will be reflected in display screens.
- When all else fails, tilt the screen downward, or move it slightly to the left or right, to eliminate specific reflected images. This approach may cause postural problems.
- Install the computer at right angles to the window and/or parallel with and between the rows of illumination fixtures.

Inspection Workplace Lighting

Product and material inspection is one of the most demanding visual tasks. A small, low-contrast object on a moving product is a common example of a difficult visual inspection task. The main strategy for the lighting designer is to provide high illuminance while aggressively controlling direct and reflected glare, veiling reflections, and shadows in order to maximize detection at the location of inspection. More than one type of light is needed to detect multiple defect types in a single-pass, 100 percent inspection task, as occurs in many product acceptance operations. The combination of lights may be tailored to the importance and relative visibility of the defect types most likely to occur. Other suggestions to control inspection workplace lighting are as follows:

- Minimize illumination reflectance by (1) painting the walls with a medium to dark hue (medium chocolate, mauve, gray, or black), matte or satin finish, (2) painting the ceiling with a dark-valued hue, matte or satin finish, and (3) providing floor tile or carpeting in a medium- to dark-valued hue.

- Eliminate ambient overhead lighting and primarily use inspection lighting to control light scatter in the room, reduce veiling reflections on the object, and increase contrast on the object.
- Incorporate floor-to-ceiling opaque light curtains to reduce light trespass in rooms where multiple inspection workplaces are used.
- Use hoods, cylinders, and directional vanes on spotlight fixtures to reduce direct glare and focus the light to the inspection field.
- Use opaque masks on the borders of the object when using transmitted light sources to minimize light scatter.

For further information, see "The Design of Visual Inspection Tasks" in Chapter 6.

Darkroom Lighting

Darkrooms used when developing exposed film and paper products can incorporate a variety of safelight technologies, including traditional beehives (for incandescent lamps); electroluminescent rectangles, strips, and other shapes; light-emitting diode cables; and fiber-optic cables. The last two technologies are designed to show a line of small points of light to the user. This line of light may outline a room, doorway, egress path, storage zone, equipment, or work surface. This lighting technique provides a geographical perspective for the user in a darkroom and facilitates room and equipment interaction, reduces dark adaptation time, and improves productivity.

Manufacturing darkroom facilities are challenged with means of egress issues relative to exit light signage or minimum corridor illumination. Recommended design guidelines for darkroom exit pathway lighting (Eastman Kodak Company 2000): a 2.5-cm (1-in.) wide continuous strip mounted on the wall, 137 cm (54 in.) off the floor, with the point of light separated every 7.6 cm (3 in.). This is sufficient to allow a user to progress at slow walking speed along a corridor.

Color

The purpose of color in the workplace is not so much to inspire workers as to enable them to improve safety, reduce eyestrain, improve visibility, and increase efficiency by reducing monotony and visual fatigue. The material in this section was developed from information in Burnham, Hanes, and Bartelson 1963; Grandjean 1980; Birren 1988; Beach, Wise, and Wise 1988; Hopkinson and Collins 1970; Ramkumar and Bennett 1979; Woodson, Tillman, and Tillman 1992; Mahnke and Mahnke 1993, and Mahnke 1996.

The influence of color on people in a production or office workplace has not been rigorously examined. Most studies on the effects of environmental color have been preference studies, where aesthetics are the prime consideration. From these examinations the following observations about preferences can be made:

- The reaction to color is consistent across age, gender, and cultural differences. Generally speaking, blue and green shades are considered cool and relaxing colors, while red, orange, and yellow are considered warm and cheerful. Red is described as stimulating and exciting.
- Color can influence a person's perception of size and distance within a closed space. Walls covered with light, desaturated colors are said to recede, while walls covered with the dark, saturated colors are said to advance. Thus, pale blues and greens cause a room to appear larger, while dark blues and greens achieve the opposite effect.
- The formation of a reaction to a color takes time, and the reaction, once formed, is subject to adaptation. Thus, a person's initial reaction may be quite pronounced, but it will tend to diminish in magnitude with the passage of time. The end result after complete adaptation has occurred could be relative indifference.
- As the saturation (intensity) of the color is lowered to a pastel level, the perceptual and psychological effects of the color diminish.

Following are some guidelines for application of specific colors, brightness, and saturation levels in the workplace:

- For large areas, colors that give uniform reflectivity should be chosen. Good visual contrasts can be obtained without significant brightness contrasts. For example, doors, protruding wall segments, or other barriers may be painted in a different hue of the same brightness as the overall wall space. Thus, these features will be easily identifiable without unnecessarily calling attention to them or distracting the workers by using highly contrasting brightness.
- Bright, or highly saturated, primary colors should be avoided. They are undesirable because they might cause a negative afterimage, a persisting sensation after the stimulus has ceased. Pastel colors are generally preferred for walls, large room units, and tabletops or work surfaces.
- In temperate climates, the normal preference in the interior of buildings is for a balance of color on the warm side. Thus, in windowed buildings and rooms, use poorly saturated warm colors on walls and equipment to balance the coolness of white areas and the grays of metal and other equipment.
- Green and blue-green wall colors are good for tasks that require high concentration.
- Most people prefer a workplace that is predominantly "light," but with the smaller equipment and other objects a stronger color, to provide some visual interest (Beach, Wise, and Wise 1988). Furniture and other

small equipment should have a reflectance of 20–40 percent (Birren 1988).

- A large area can be functionally divided by color to give identity to different groups working within it. Separate rooms can be keyed to a certain basic color to accomplish the same effect.
- Surrounding surfaces should be similar in brightness to the work surfaces. If a large surface such as a wall is constantly in the field of view, there should not be a brightness contrast between the equipment and the wall. This may increase eyestrain by increasing unnecessary eye adjustments.
- In assembly tasks, contrast should be provided between the work surface and the components being assembled. A neutral surface with 30 percent reflectance is best. If all the components are the same color, the work surface should be a complementary color. Similarly, there should be a color contrast between machines and the material being fabricated in the machine.
- Tasks that require full attention or have a high visual demand should have distracting visual background blocked off by screens.
- Critical parts of a machine should be highlighted by bright or contrast colors, to help locate parts quickly; however, no more than five such accents should be used.
- The selection of color schemes should be coordinated with the decisions about illumination type. For example, high-pressure sodium lighting has only fair color-rendering characteristics; subtle shadings of color that would be appropriate under white light will be lost under this type of illumination.

NOISE

Noise is ubiquitous in industrial settings. In terms of effects, noise may:

- Contribute to hearing loss
- Interfere with communications
- Annoy or distract people
- Alter performance

Because noise from production equipment, office equipment, and construction tasks is common for many industrial workers, noise exposure guidelines have been developed to minimize health and performance effects on people. This section gives a brief outline of the guidelines for noise, focusing less on the primary health issue of hearing loss and more on those issues that an ergonomist will need to address. These guidelines are discussed in the sections that follow.

Hearing Loss

Because the health effects of noise have long been known, hearing conservation programs are well established (OSHA 1983; NIOSH 1972, 1998). Occupational hearing loss represents gradual, irreversible damage to the inner ear. The degree to which hearing is affected depends on the level and duration of exposure, as well as individual susceptibility. Early stages of noise-induced hearing loss usually produce diminished hearing for the high-frequency components (3,000–6,000 Hz), resulting in reduced quality, clarity, and fidelity of speech sounds. Occupational hearing loss is in addition to that associated with aging.

Extended exposure to noise levels in excess of 85 dBA (decibels on the A scale of a sound level meter) for 8 hours per day for several years may cause hearing loss (NIOSH 1998). For those whose 8-hour time-weighted average noise exposure exceeds 85 dBA, a hearing conservation program must be established, and engineering controls or hearing protection should be implemented. The limiting duration of the exposure decreases with increasing noise intensities; therefore, short exposures to higher levels may be acceptable if the other exposures are below 80 dBA.

A sound level meter is a useful tool to measure sound levels in a given area and to assess potential hearing loss situations, providing the individual's noise exposure is predominantly in that area. If the worker is exposed to fluctuating sound levels caused by changes in work location or varying machine noise in the production cycle, a noise dosimeter is preferable for evaluating individual noise exposure. A dosimeter integrates the varying sound levels and presents the results as a percentage of the daily permissible limits. Most textbooks on safety, industrial hygiene, and occupational medicine have a fuller discussion of noise exposure and hearing loss. Further discussion of noise measurement techniques is presented below.

For short duration noise (e.g., alarms etc), the noise levels should not exceed 140 dB (NIOSH 1998) for 0.1 second. If sound pressure levels exceeding 100 dBA are intentionally introduced into the workplace for auditory information transfer, an occupational noise survey or consultation with someone familiar with occupational noise exposure is appropriate.

Annoyance and Distraction

Although noise levels below 80 dBA do not constitute a risk to hearing loss, they may contribute to performance decrements caused by distraction or annoyance. Three principles to bear in mind to minimize this are (Kjellberg and Landstrom 1994):

- The higher the demand for information processing and concentration, the lower the noise levels should be.

- Avoid exposure to noise that is unrelated to the work being performed.
- Keep the occupants in the area informed about the steps taken to abate noise and the costs for further improvement.

In some types of tasks, noise from office or production equipment can reduce the effectiveness of communications and make it difficult for people to concentrate. As a general rule, such noise should be kept below 50 dBA, or 40 dBA for high-concentration tasks (Kjellberg and Landstrom 1994). In areas with hard walls, speech itself can be the noise. In such situations, ambient noise should be kept below 55 dBA, and absorptive treatment of the room may be needed to reduce speech contributions to the overall noise level.

In other situations, lack of noise may be undesirable. In an extremely quiet environment, even a slight noise can be an annoyance or a disturbance (as sometimes seen in libraries). This effect has been observed in some landscaped offices where white noise generators had to be installed in an attempt to improve the noise environment for office personnel. The white noise served to mask some of the speech from neighboring cubicles; it also provided a steady background against which intermittent sounds were less disturbing. White noise levels of 48 dBA can be effective in masking some office sounds, but levels above 52 dBA may be distracting and annoying (Nemeck and Grandjean 1973).

Typically, the ergonomist is concerned with noise levels in the work area or "occupied spaces." The ANSI Standard S12.2-1995, Criteria for Evaluating Room Noise (ANSI 1995), suggests using the NCB (noise-criteria-balanced) curves to evaluate the acceptability of noise levels in such spaces. These curves also help measure noise generated by multiple sources such as the HVAC system, people, and equipment.

In setting criteria for the acceptability of noise in the workplace, one has to consider the needs for both communication and speech privacy. The NCB rating provides guidelines for ambient sound pressure levels in each of ten octave band levels (Beranek 1989a, 1989b). They are based on the assumptions that the most important factor is the ability to carry on speech communication satisfactorily (or to enjoy listening to music), and that the quality of the noise plays a key role in acceptability of noise.

The NCB curves (see Figure 8.2) are not to be used for intermittent noise. They are applicable only to noise that has a continuous frequency spectrum containing no more than a few nonsignificant pure-tone components.

To evaluate the noise in a particular workplace:

- Using an octave band analyzer, measure the noise levels for bands from 31.5 to 8000 Hz.
- Choose from Table 8.5 the preferable NCB curve level for the area (NCBxx).
- Plot data on a graph with the preferable NCB curve.
- If the NCB curve is exceeded in any band, the design goal is not met.

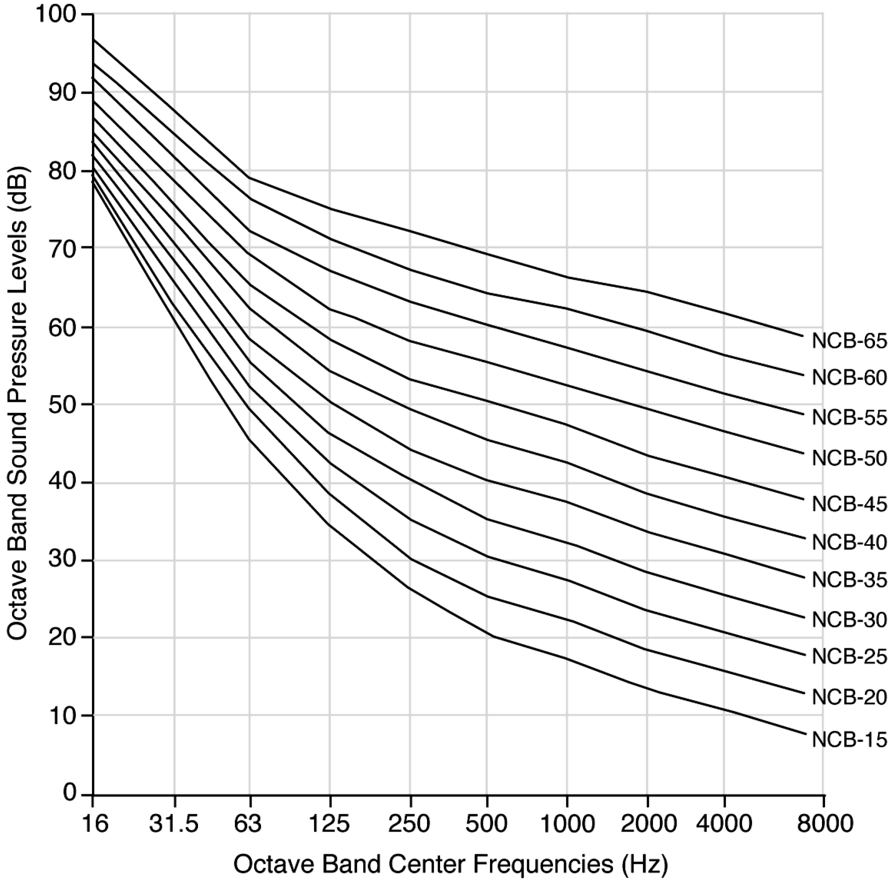

FIGURE 8.2 NCB curves (adapted from Beranek 1989a)

An example of the use of the NCB curves to evaluate a noise complaint follows. A group of designers was relocated to be close to the production areas. After the move, there were a number of complaints from the designers about the noise level, which was highest near a fan room. The octave band sound pressure levels measured in one office near the fan room are shown in Figure 8.3. The recommended levels for a drafting or engineering room are the NCB curves from 40 to 50. The data were compared to the middle level of the NCB 45 curve.

The data indicate that noise was a nuisance only when the air handlers were running in the adjacent fan room and that the NCB curve was exceeded only in frequencies below 1,000 Hz. Approaches to reducing the noise included improving the seal around the fan room door and installing sound absorption panels on the inside walls of the fan room door.

TABLE 8.5
Recommended NCB Curves and Sound Pressure Levels for Several Categories of Activity (Beranek 1989a)

Acoustical Requirements	NCB Curve	Approximate L_A (dBA)
Listening to faint musical sounds or distant microphone pickup used (concert halls, opera houses, recital halls)	10 to 15	18 to 23
Excellent listening conditions (large auditoriums, large drama theaters, large churches)	Not to exceed 20	28
Close microphone pickup only (broadcast, television, and recording studios)	Not to exceed 25	33
Good listening conditions (small auditoriums, small theaters, small churches, music rehearsal rooms, large meeting and conference rooms or executive offices, conference rooms for 50 people with no amplification)	Not to exceed 30	38
Sleeping resting or relaxing (Bedrooms, sleeping quarters, hospitals, residences, apartments, hotels, etc.)	25 to 40	38 to 48
For good listening conditions (private or semiprivate offices, small conference rooms, classrooms, libraries, etc.)	30 to 40	38 to 48
Conversing or listening to the radio and TV (living rooms in dwellings)	30 to 40	38 to 48
Moderately good listening conditions (large offices, reception areas, retail shops and stores, cafeterias, restaurants, etc.)	35 to 45	43 to 53
Fair listening conditions (lobbies, laboratory work spaces, drafting and engineering rooms, general secretarial areas)	40 to 50	48 to 58
Moderately fair listening conditions (light maintenance shops, industrial-plant control rooms, office and computer equipment rooms, kitchens and laundries)	45 to 55	53 to 63
Just acceptable speech and telephone communication (shops, garages, etc.)	50 to 60	58 to 68
Speech not required but no risk of hearing damage	60 to 75	63 to 78

Interference with Communication

Speech interference resulting from noise is fairly common around production machinery and business equipment. The steps to be taken to improve the noise levels in the environment will depend on how critical the acoustically communicated information is to the task being performed.

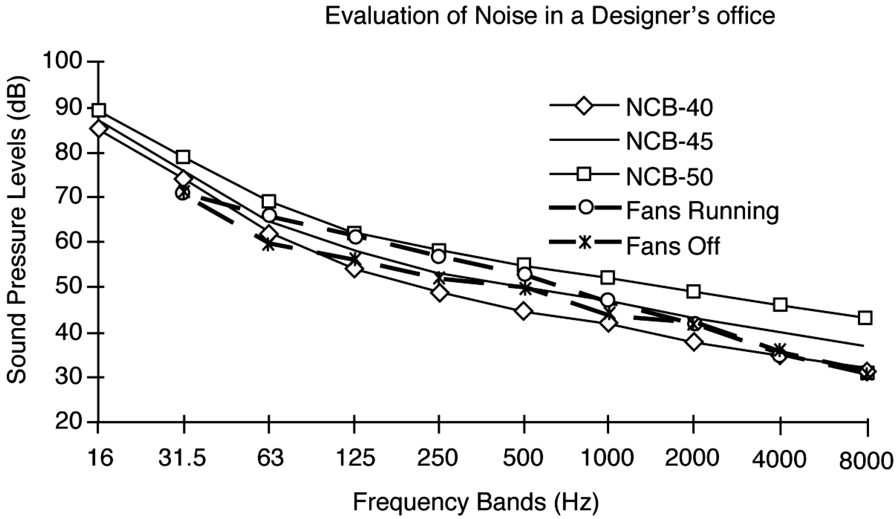

FIGURE 8.3 Noise levels in a designer's office (adapted from Chengalur 2001)

The most common method for rating the speech interference effects of noise is called the preferred speech interference level (PSIL) (Webster 1969). This is the arithmetic average of the sound levels measured in the octave bands centered at 500, 1,000, and 2,000 Hz. The PSIL is used to indicate whether or not there will be a communications problem, not to predict intelligibility. If octave band measurements are not available, then A-weighted sound level can be used.

Curves are drawn to estimate the distance at which communications can take place, based on the distance between the speaker and the listener. Figure 8.4 presents these curves. The curves can help determine those situations when communication aids such as walkie-talkies may be necessary (e.g., during machine setups in noisy areas, or when the team members are far apart). When the ambient noise level is above 85 dBA, people working for extended periods in the area should be wearing hearing protection, which may improve or further reduce communications depending on the level of noise, hearing acuity of the wearer, attenuation characteristics of the hearing protection, and how far apart the people are.

The ability to hear and converse effectively on the telephone is also important and can be predicted by PSIL measurements. A satisfactory phone conversation can occur with a PSIL of 60 dB or less. It will become more difficult between 60 and 75 dB and impossible above 75 dB.

For areas where noise cannot be substantially reduced to meet these levels, special telephone equipment may be necessary to improve communication. For example, sound-deadening booths can reduce the ambient noise around the head of the user, and noise-canceling transmitters are available that attach easily to the handset and help reduce background noise that would otherwise be mixed with a speaker's voice. Amplification devices are useful if the listener

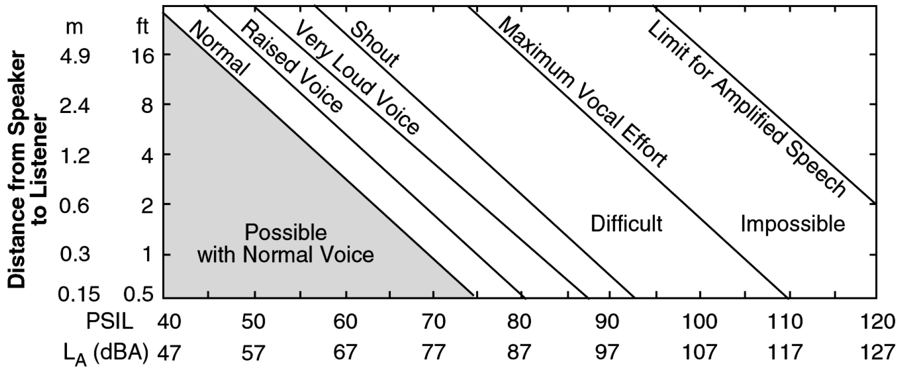

FIGURE 8.4 Preferred speech interference levels (PSIL) as a function of distance and ease of communications (adapted from Webster 1969)

is in a noise area. Enclosures or small booths may improve the situation for both listener and speaker.

There is a more complex index available for speech interference known as the Speech Intelligibility Index (SII), which has been standardized by ANSI (1997). This method requires knowledge of the spectrum level of the speech and noise as well as the listeners' hearing thresholds. The reader is referred to ANSI standard S3.5-1997 for details.

Measuring Noise Levels

In the following discussion, information is included about the measurement of noise and about techniques for making noise surveys as well as the proper time and location for such surveys. As a general rule, noise measurement methods should follow the guidelines established in ANSI S12.99-1996 (ANSI 1996). Another good source is the AIHA *Noise Manual* (Berger et al. 2000).

Instrumentation and Measurement

The audible spectrum of noise is from about 20 to 20,000 Hz. For many noise measurements, a simple sound level meter can be used. The human ear is not equally responsive at all frequencies and intensities, and to account for this, different weighting scales have been developed. The A-weighted sound level (dBA) is the most commonly used scale and can be used in the workplace for measuring background noise to determine its acceptability in terms of interference with speech communications and in terms of exposure to high levels of noise. The basic instrument consists of a microphone, a frequency-weighted (A-weighted) amplifier, and an indicator. Such a meter allows the surveyor to identify the sound pressure levels and to classify the noise according to its potential to interfere with communication or contribute to hearing loss over time. These levels are read directly on a sound level meter with the meter set to “A” and slow response.

A feature that some sound level meters may have is octave band filters that permit noise to be segmented into predetermined frequency bands. These meters are often used to determine the effectiveness of different noise control techniques and to help in the identification of the specific machine component that needs isolation to reduce noise generation. An octave band analysis is done from readings made in the following center frequencies: 31.5, 63, 125, 250, 500, 1,000, 2,000, 4,000, and 8,000 Hz. The results are plotted on a graph of frequency (in Hz) versus sound pressure level (in decibels). Noise-criteria-balanced (NCB) curves are plotted on the same graph to demonstrate the impact of the noise on people in the workplace.

Speech interference levels can also be measured at the octave bands centered at 500, 1,000, and 2,000 Hz; an average is taken of the three values. The average can be plotted on a graph of sound level versus the distance between speaker and listener in order to assess the ease of communication in the workplace. For example, see Figure 8.4.

Noise dosimeters are available to record an individual’s exposure to noise over a shift. These are more often used to determine the exposure of an individual to noise levels that may result in hearing loss.

When and Where to Make Noise Measurements

The time to monitor noise is when it is a concern to people in the workplace. It should be monitored where people work, rather than where noise originates. Measuring noise at the source can help to identify a faulty machine part or can suggest a way to reduce the problem. The interpretation is best done by someone familiar with the principles of noise control.

If the noise is more apparent during a particular manufacturing process or at a specific machine speed, arrangements should be made to evaluate it under those conditions. In many instances, the noise is not problematic until a large number of machines are operating simultaneously in the same work area. It is important to determine how frequently this condition occurs, and to monitor noise during the period of worst-case noise occurrences. The data should be interpreted in terms of the frequency of occurrence when deciding what steps should be taken to reduce the noise level.

How to Make Noise Measurements

When measuring noise, determine the area of concern. Note should be made of the communication and hearing requirements of people working on jobs in noisy work areas. The effect of the noise level on performance can be interpreted appropriately, assuming it is below 80 dBA, the level at which hearing loss may be a factor. Time history dosimeter data may help identify these problems if used in conjunction with a diary of the person's job activities throughout the shift.

General considerations for noise measurements include:

- Equipment should be calibrated before and after taking the sound measurements.
- Allow several seconds for the meter to stabilize whenever the range is changed.
- Hold the meter away from your body, at the subject's ear level (at a normal work position, whenever possible), orienting the microphone as indicated by the manufacturer's instructions (some microphones are designed to point at the source and others to point in a perpendicular direction).
- Care should be taken to avoid shielding the microphone with persons or objects.
- If there is a fan in the immediate vicinity or noticeable air movement, a windscreen should be used.
- Readings should be taken at various operator positions and recorded. When recording the noise levels, it helps to keep a diagrammatic record of the locations. This sometimes helps to pinpoint the source of the noise or to define the area affected.

Performance Effects of Noise

The effect of noise on the performance of a task, be it mental or physical, has been investigated (Kjellberg 1990; Karageorghis, Drew, and Terry 1996; Umemura, Honda, and Kikuchi 1992; Suter 1992; Kryter 1970; Miller 1971). These studies have shown mixed results that may be due to the variation in the type and duration of the task, sound levels, and their spectrum, as well as the periodic properties of the noise. Differences between individuals and the influence of factors such as heat, sleep deprivation, motivation, and attitude toward the noise source all interact with noise levels, making it difficult to predict the effect of noise on performance.

When evaluating the influence of noise, it may be best to interview those affected to determine which particular characteristic(s) impact their performance. Some characteristics of noise that can affect performance are:

- Variability in level or content
- Intermittency
- High-level repeated background noise (e.g., hammering on metal)
- High frequencies (e.g., above 2,000 Hz)

The following general observations apply to situations where noise may affect performance:

- Noisy work areas can result in decreased productivity and increased error rates, particularly when the operator is working:
  - At or close to full capacity
  - On multiple tasks
  - On vigilance tasks that require the detection of infrequent or irregular signals
- Performance in a noisy area decreases as the time on the task increases.
- Any task that involves the use of noise cues may be negatively affected by noise.
- Sudden changes in the noise level could also affect task performance, especially if unexpected.
- Simple tasks are generally not adversely affected by noise. In some cases, a rhythmic noise pattern may improve the performance of simple repetitive tasks if the natural work pace and the noise pace are nearly synchronous. However, continuous or repetitive noise can make people sleepy.
- Noise can be detrimental to the performance of complex tasks that require continuous performance, vigilance, or intellectual activity. In particular, intermittent noise that is unpredictable (no particular rhythm or rate) can cause decrements in the performance of such tasks.

Approaches to Reducing Noise in the Workplace

There are many ways to reduce the noise to desired limits in both new and existing installations. Noise reduction is a specialized field and is best accomplished by those with the appropriate training and experience. Often, simple solutions can be found, such as the use of a muffler on the exhaust outlet of a noisy pneumatic cutting machine. Such a device can lower the overall noise level, and it is particularly effective in reducing the high-frequency components that are characteristic of high-pressure pneumatic systems.

Noise reduction methods can be applied at the noise source, in the path of noise transmission, and at the location(s) where work might be affected. Methods of reduction involve the following techniques:

- Reducing the level or altering the spectrum of the generated noise
- Using barriers to reduce noise transmission through air or structures
- Absorbing incident or reflected noise.

In practice, combinations of methods are usually used. Often reduction of the noise source may be prohibitively expensive, and other methods must be employed. For example, one might use enclosures (barriers) with porous linings (absorbers) around engine-driven air compressors or grinders.

Special Considerations

Few studies have been done to investigate the influence of background music in factories on the work environment and productivity. The following observations of music in the workplace are based on information in Faulkner 1969; Grandjean 1961; Karageorghis, Drew, and Terry 1996; and Skrainar et al. 1987, plus experience on a limited number of production jobs:

- There has been no conclusive proof that the presentation of music increases productivity, although there are many claims to that effect.
- Most, but not all, production workers are likely to enjoy hearing music when they work. This result is particularly true in areas where repetitive assembly tasks or heavy physical work is done. In jobs where more concentrated attention is required, music may be an undesirable distraction.
- Those who do not enjoy the music will probably complain.

If music is presented, the following guidelines should be considered:

- Do not provide music if the background noise level is more than 70 dBA. The addition of music at a level high enough to be heard distinctly may make the employees regard the music as simply more noise, and the music will further interfere with oral communication.
- Presentation should use quality systems, and usually the level should be only slightly higher than background noise. The level is particularly critical if personal radios are used.
- The employees who hear the music should have input concerning the type and the schedule, that is, whether it is presented continuously or only at specified intervals.
- Use of personal portable radios and headsets may be risky in a noisy workplace. The following general guidelines should be followed for such use:
  - The maximum power output (per the manufacturer's specifications) should not exceed 82 dBA.
  - The job should be largely sedentary and should not require essential or frequent speech communication.
  - There should be no vehicular traffic in the work area.
  - Employees should not move around or walk around while wearing a radio headset.
  - Warning signals should not be auditory.

THERMAL ENVIRONMENTS

The principal concern for the thermal interaction between people and their work environment is the movement of heat to and from the person. When there is good balance in the heat flow with little physiological adjustment, the environment is generally considered comfortable. When the balance is disturbed so that there is a significant physiological involvement, discomfort and health effects are more likely. These departures from comfort are heat and cold stress.

Heat stress can add to the cardiopulmonary burden to increase the likelihood of fatigue, and it may lead to a heat-related disorder. In addition, increasing levels of heat stress may lead to increased frequency of accidents and overexertion injuries and drops in quality and productivity. Heat stress is found in situations where environments are warm, work demands are high, or the clothing requirements reduce sweat evaporation. Warm environments are found in most outdoor work (i.e., summer in most locations), in indoor locations without conditioned air, and workplaces associated with process heat. High work demands such as manual materials handling or extensive climbing can lead to heat stress conditions in environments that would be considered comfortable or cool by an inactive person. Finally, clothing that restricts the evaporation of sweat, such as multiple layers or vapor barriers, can create heat stress even in cool environments. Any combination of these factors raises the level of heat stress.

Cold stress is more associated with loss of cognitive and psychomotor function than with increased cardiopulmonary demands. While cold-related disorders are possible, the decreases in manual manipulation performance and increased risk for accidents and injuries are important effects of cold stress. Outside work during the winter in cold climates, as well as in unconditioned spaces during cold weather, is one contributor, as are refrigerated spaces and working with cold water.

Ideally, thermal environments for work are judged by most occupants as comfortable. Many work environments are thermally uncomfortable, and the concern should be to avoid levels of stress that may represent a risk to health and well-being. That is, along a thermal environment continuum, comfort occupies the middle zone, which is flanked immediately by cool and warm discomfort zones. These, in turn, are flanked by the cold stress and heat stress zones that mark health risk.

Thermal Balance

To appreciate thermal stress, two conceptual models are useful. One model focuses on the body as a whole and is concerned with the degree of physiological adjustment as a marker of health risk. The other model looks to heat transfer on a local patch of skin, and local skin temperature is the marker of risk.

Heat Exchange for the Whole Body

Considering the whole-body model, the first feature to appreciate is that normal metabolic processes add heat to the body. These processes are the basal metabolic rate to support life functions and the added metabolic activity of the muscles performing work. From this starting point, heat stress is largely a problem of removing the heat from the body and cold stress is a problem of conserving it. The avenues of heat exchange between the person and the environment are influenced by environmental conditions and clothing. The factors affecting thermal comfort, heat stress, and cold stress are described in Table 8.6, and their relationships are described in the following equation (Bernard 2002):

$$S = M + C + R + K + E$$

Sign convention: Positive values of factors means a heat gain and a negative value means a heat loss. Sometimes a similar equation is used with +, –, and ± to describe qualitatively the direction of heat flow.

Storage rate (S) is the cumulative effect of the other factors and the indicator of risk for hyperthermia (positive value) during heat stress or hypothermia (negative value) during cold stress. When the storage rate is near zero, there is thermal equilibrium and the risk of excessive heat or cold stress is low.

Metabolic rate (M) is largely driven by the amount of external work performed. The greater the oxygen consumption associated with the effort, the greater the rate of metabolic heat generation. While some presentations of heat balance reduce the heat gain by the mechanical work accomplished, this component is usually less than 10 percent of M and can be safely ignored.

Convection (C) is the net flow of heat between the skin and air, some of which may occur through clothing. The direction of the heat flow (gain or loss to the body) depends on the air temperature with respect to skin temperature. If air temperature is higher, it is a gain; conversely, if air temperature is lower, it is a heat loss. Note: Air temperature is often referred to as dry bulb temperature. The greater the difference, the greater the rate of heat flow. This rate can be increased (or diminished) by larger (or smaller) air speeds and by less (or more) clothing insulation, but the direction is not changed.

Radiation (R) is the net rate of heat flow between the person and the solid surroundings caused by infrared radiation. Like convection, the direction and magnitude are set by the difference between skin temperature and the average surface (blackbody) temperatures of the solid surroundings. In principle, surface temperatures greater than skin temperature contribute to heat gains, and lower surface temperatures contribute to a heat loss from the body. The greater the difference, the higher the rate of heat transfer. Clothing insulation will reduce the rate of heat transfer. Air motion has no direct effect on radiant heat transfer.

Conduction (K) occurs when there is direct contact between the person and a solid surface in the workplace. The contact can occur through some clothing. Conductive heat gain or loss that affects the whole body is not common, but it cannot be ignored. Similar to convection, the direction and magnitude of the heat transfer depends on the temperature difference between the skin and the solid surface. The rate can be reduced by adding insulation between the skin and the surface.

TABLE 8.6
Avenues of Heat Exchange

Symbol	Factor	Influences
S	Storage rate Net rate of heat exchange that is reflective of change in body temperature	M + C + R + K + E
M	Metabolic rate Rate of metabolic heat generation inside the body	Rate of external work Type of work
C	Convection Rate of heat transfer between the body and the air surrounding the person	Difference between air temperature and skin temperature Speed of air movement Clothing insulation
R	Radiation Rate of heat transfer between the body and the solid surroundings by infrared radiation	Difference between average surface temperature of the solid surroundings and skin temperature Clothing insulation
K	Conduction Rate of heat transfer between the body and solid surfaces in direct contact with the person	Difference between average surface temperature of the solid and skin temperature Clothing insulation
E	Evaporative cooling	Difference in water vapor pressure on the skin and in the air (humidity) Speed of air movement Clothing permeability to water vapor

Evaporative cooling (E) is the loss of heat due to the evaporation of sweat from the skin and hence always has a negative value. The rate of evaporative cooling is limited physiologically and environmentally. Physiologically, it depends on the sweat rate. Environmentally, it depends on humidity, air motion, and clothing. The higher the humidity (water vapor content in the air), the lower the evaporative cooling that can be supported. Evaporative cooling rate is enhanced by increased air speed, but there is a limit to the beneficial effects (air speed less than 3 m/sec and air temperature less than 40°C).

Heat Exchange for Local Skin Surface

The framework for heat exchange on a local patch of skin is to consider the heat gain or loss to the environment, where the dominant avenues are conduction and convection. Radiant heat is an important avenue when there is an intense source of infrared radiation. The local losses or gains from the environment must be balanced by the circulatory ability to supply or remove heat so that there is little change in the local tissue temperature. Excessive heat gain leads to painful sensations and burns. Excessive losses lead to painful sensations and tissue damage caused by freezing or prolonged cold exposure.

The amount and integrity of insulation placed between the skin surface and a hot or cold surface will dictate the heat flow rate.

Assessment of the Thermal Conditions

Assessment of thermal conditions requires a blending of considerations among the environment, work demands, and clothing.

ENVIRONMENT In most circumstances, the minimum requirements to assess the environment are air temperature and humidity. Air temperature (often called dry bulb temperature) can be measured with a standard thermometer. While mercury in a glass thermometer is the classic method, electronic sensors are common and acceptable. If there are sources of radiant heat such as the sun or hot surfaces, the dry bulb sensor should be shielded from the source. In practice, electronic sensors have very small profiles and are not affected much by radiant heat. Air temperature is important across the zones of thermal environment from cold to hot.

Humidity is the amount of water vapor in the air. Relative humidity is the fractional amount of water vapor expressed as a percentage of the maximum amount of water that the air can hold (saturation point). The saturation amount increases dramatically with air temperature and thus makes relative humidity very sensitive to air temperature. Absolute humidity is the partial pressure of water vapor in the air and is independent of air temperature as long as it is below the saturation point. The classic method to assess humidity is to measure dry bulb and psychrometric wet bulb temperatures and then find the humidity (either relative or absolute) from a table or chart. A psychrometric wet bulb temperature is one in which the temperature sensor is inside a wetted wick and ambient air is forced over the wick at a speed greater than 3 m/sec. The forced air movement maximizes the degree of evaporative cooling of the wick with an equilibrium temperature that depends on the dry bulb temperature and amount of water vapor in the air. Using the psychrometric chart in Figure 8.5, the dry bulb (air) temperature is found on the horizontal scale at the bottom and the psychrometric wet bulb temperature is located among the family of diagonal lines with a downward slope. When the intersection of these two values is located, the relative humidity is interpolated from the family of upward-sloping curves and the absolute humidity (water vapor pressure) is read from the scale on the left side.

Dew point is an alternative way of expressing absolute humidity. It is the

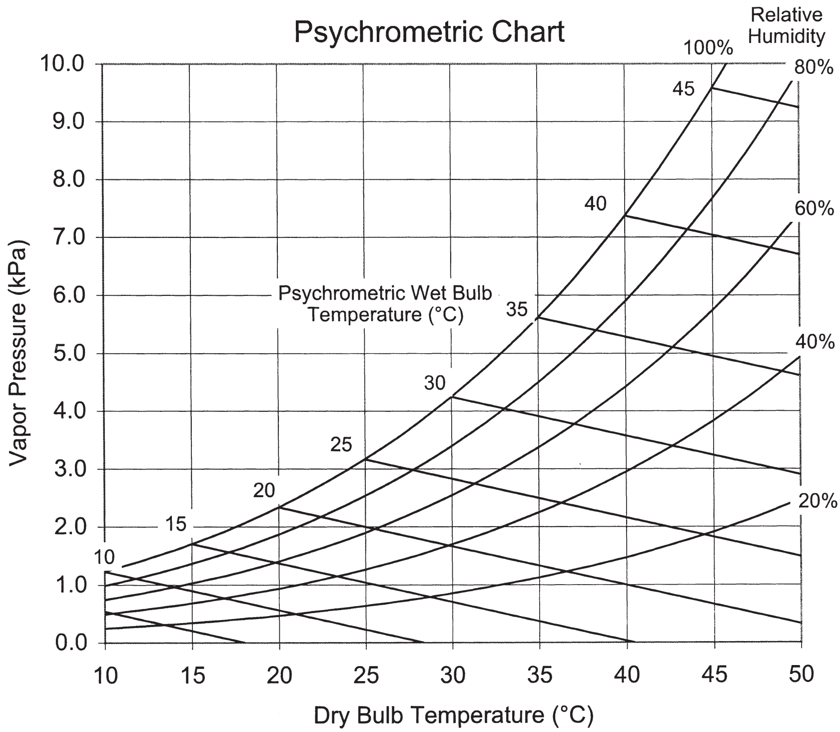

FIGURE 8.5 Psychrometric chart

On this chart ambient dry bulb temperature is plotted on the horizontal axis; water vapor pressure is on the vertical axis. Psychrometric wet bulb temperatures are shown as parallel lines with a negative slope. The relative humidity curves slope upward on the chart.

temperature at which water will begin to condense from the air. That is, it is the saturation temperature, and is found by moving to the right on the psychrometric chart to the 100 percent relative humidity line and reading the air temperature at that point.

An alternative to psychrometric wet bulb is to measure relative humidity directly. Again, the psychrometric chart shown in Figure 8.5 can be used to find the psychrometric wet bulb temperature, water vapor pressure, and dew point from the intersection of dry bulb temperature and relative humidity lines.

Natural wet bulb temperature is similar in concept to a psychrometric wet bulb temperature, except that the air motion over the sensor is simply the ambient air movement rather than forced movement inherent to the instrument. In most cases, it is good enough to assume that the difference between the two is 1°C, where natural wet bulb is higher than psychrometric wet bulb. When the ambient air motion is very noticeable (speeds greater than 1.5 m/sec), the difference is virtually zero.

Humidity is most important for heat stress because of the role it plays in limiting the rate of evaporative cooling of sweat. It is important in warm discomfort and thermal comfort. Humidity plays no role in the assessment of cold stress.

With respect to environmental assessment, *air speed* is the movement of air around a person. It can be measured with an anemometer. Air speed along with air temperature is most useful for cool discomfort and cold stress, especially with respect to exposed tissue. It can affect comfort. While it plays a role in warm discomfort and heat stress, its role is usually accounted for in the globe temperature, as described in the following paragraph.

Globe temperature is the internal temperature of a blackened, hollow (thin-walled) copper sphere. The traditional globe is 6 inches in diameter, but most contemporary instrumentation uses one between 1.5 and 2 inches and makes an adjustment in the readout. While small globes may respond differently, there is no practical effect to using a small globe temperature, whether it is adjusted or not. Globe temperature is designed to be responsive to radiant heat gain and loss from hot and cool surfaces, respectively. When the surrounding surfaces are the same as air temperature, there is no difference between globe and dry bulb temperature. In the presence of a net heating or cooling of the globe by radiant sources, the globe temperature is further influenced by air motion over the globe. In this way, globe temperature is sensitive to both radiant and convective heat exchange. It is this feature that makes it useful in the assessment of warm discomfort and heat stress. It is not used to assess cool and cold environments.

WORK DEMANDS Metabolic rate is a consideration because it reflects the amount of heat generated inside the body. For comfort, warm discomfort, and heat stress, it is the amount of heat that must be dissipated to the environment. For cold stress, it represents the potential for keeping the body warm. Metabolic rate is discussed in more detail in Chapter 2. Table 8.7 presents five categories of metabolic rate, the representative metabolic rate for the category, and some associated work demands.

The consideration of work demands usually reflects an average metabolic rate. If there are cycles of work that repeat within an hour, take an average for the hour. In this regard, heavy and very heavy work is seldom seen. Heavy and very heavy may exist for periods shorter than an hour, but when averaged over an hour the work demands are usually moderate or less.

CLOTHING Clothing influences the rate of heat exchange by convection and radiation and modifies the rate of evaporative cooling.

Clothing insulation is the characteristic that affects heat exchange by radiation and convection. The traditional unit for reporting of clothing insulation is the clo. One clo is the insulation provided by a heavy business suit and is equal to 0.155 m^2–°C/W (degrees Celsius per watt per square meter of body surface area). Table 8.8 is a list of selected clothing ensembles and the amount of insulation that they provide. For cool discomfort and cold stress, increasing

TABLE 8.7
Categories of Work Demands, a Representative Metabolic Rate, and Some Representative Activities

Category	Representative Metabolic Rate (W)	Representative Activities
Sedentary	110	Resting, sitting with no regular activity
Light	200	Sitting with light manual work such as writing, typing, using small tools, inspection, and driving Standing with light hand work such as minding a drilling or milling machine Intermittent walking at slow speed
Moderate	300	Sustained hand and arm work with little effort Walking Pushing and pulling lightweight carts
Heavy	400	Intense arm and truck work Carrying, lifting or pushing/pulling heavy materials Fast walking
Very heavy	500	Very intense activities such as shoveling or digging, which require frequent breaks.

levels of clothing insulation are protective and reduce the sensation of discomfort and the risk of excessive cold stress.

For warm discomfort and heat stress, the resistance to evaporative cooling is the dominating role of clothing. Water vapor permeability and evaporative resistance are related inversely (i.e., as permeability goes up, resistance goes down). While evaporative resistance generally increases with insulation in woven fabrics, this may not be the case for nonwoven fabrics, common in protective clothing. To account for clothing effects in heat stress, the practice is to assign an offset to the environmental measure that reflects the added burden of the clothing. This is described more fully in the section on warm discomfort and heat stress.

Qualitative Assessment

Figure 8.6 provides a framework to qualitatively place a workplace in the comfort zone, in a discomfort zone or a health risk zone. It was developed as a qualitative exposure assessment tool for heat and cold stress (see Malchaire, Gebhardt, and Piette 1999) and adapted here for the expanded ranges.

TABLE 8.8
Selected Clothing Ensembles and Their Insulation Values in clo

Clothing	clo
Sleeveless blouse, light cotton skirt, sandals	0.3
Shorts, open-neck shirt with short sleeves, light socks, sandals	0.3–0.4
Long lightweight trousers, open-neck shirt with short sleeves	0.5
Long lightweight trousers, open-neck shirt with long sleeves	0.6
Cotton fatigues, lightweight underwear, cotton shirt and trousers, cushion-sole socks and boots	0.7
Typical business suit; pant suit (with full jacket)	1.0
Typical business suit and cotton coat (lab coat)	1.5
Heavy traditional European business suit, long cotton underwear, long-sleeved shirt, woolen socks, shoes; suit includes trousers, jacket, and vest	1.5–2.0

One clo is the insulation provided by a heavy business suit and is equal to 0.155 m^2–°C/W

Note: A wool sweater adds approximately 0.3 to 0.4 clo of insulation to the above clothing ensembles (McIntyre and Griffiths 1975). Clothing made from nonbreathing fabrics, such as nylon, will add up to 0.6 clo to the values given above (Nevins, McNall, and Stolwijk 1974). Insulation increases with increased layers of clothes and with fabrics, such as wool, that incorporate an air layer. Artificial fabrics often have higher insulation values but may not breathe. Their low moisture permeability can limit their usefulness because they reduce evaporative cooling in hot environments and trap moisture near the skin in cold environments.

Seven scales are used to rate the job factors separately. In principle, each qualitative scale ranges from -3 to +3. In practice, the scales are limited to a narrower range. For instance, humidity plays no role in cold stress. The scales are described first in the figure followed by a scoring grid.

The job or workplace is judged by the greatest deviation from 0 (zero). As is usually the case for qualitative exposure assessments, no attempt is made to finesse the interrelationships that exist among the job factors.

As originally conceived, the ideal range of the qualitative assessment is a condition that is not likely to contribute to any health risk. If all of the scores are 0, the likely conditions are thermal comfort. +1 is indicative of warm discomfort. +2 and +3 are indicative of potential heat stress. Similarly, -1 suggests cool discomfort, and -2 and -3 point toward cold stress.

Thermal Comfort

Under optimal comfort conditions, 2.5 percent of the population is too warm and 2.5 percent is too cold (Fanger 1970). Individual variability in assessing comfort levels is very high. The levels vary with time of day, season, diet, health status, and clothing choices, as well as the presence of job stress and cultural variables and expectations.

Screening for Heat Stress—Checklist*

Job	Analyst
	Date
Description of Climate, Work Demands, Clothing	Special Conditions

Complete the following checklist for each potential heat stress situation.

Job Factor	Yes	No
Obvious sweating		
Environment perceived to be warm		
Work requires a break at least every 2 hours		
Wearing regular work clothes would be more comfortable		
Reports of fatigue, weakness, loss of coordination, dizziness, headaches, nausea, heat exhaustion, cramps		
Absenteeism, employee irritability, or worsening employee relations can be associated with these work conditions		
Increases in accidents and injuries and/or decreases in production and quality indices can be associated with these work conditions		

A yes to the presence of any of these job factors would indicate that a further investigation and controls are appropriate.

* This checklist is a prototype for discussion. It is based on the professional judgment of the author but has not been validated.

FIGURE 8.6 Qualitative Exposure Assessment for Heat Stress (by permission of the British Occupational Hygiene Society.)

Screening for Thermal Stress—Observational Analysis*

Job	Analyst
	Date
Description of Climate, Work Demands, Clothing	Special Conditions

Complete the following matrix by consensus of observers very familiar with the workplace and possible exposure situations. Table of scores and qualitative descriptors for each of the categories follows on the next page.

Scores	**−3**	**−2**	**−1**	**0**	**+1**	**+2**	**+3**
			Ideal Zone				
Air temperature							
Humidity							
Thermal radiation							
Air movement							
Workload							
Clothing							
Worker opinion							

Actions should be taken to bring scores outside of the ± 1 range into this range.

* This observational method is adapted from J. Malchaire, H. J. Gebhardt, and A. Piette, "Strategy for evaluation and prevention of risk due to work in thermal environments." *Annals of Occupational Hygiene* 43:367–376, 1999.

FIGURE 8.6 *(Continued)*

Score	Qualitative Descriptors
Air Temperature	
−3	Generally freezing (below 0°C/32°F)
−2	Generally between 0 and 10°C (32 and 50°F)
−1	Generally between 10 and 18°C (50 and 64°F)
0	Generally between 18 and 25°C (64 and 77°F)
+1	Generally between 25 and 32°C (77 and 90°F)
+2	Generally between 32 and 40°C (90 and 104°F)
+3	Generally greater than 40°C (104°F)
Humidity	
−1	Dry throat and/or eyes after 2–3 hours
0	Normal
+1	Moist skin
+2	Skin completely wet
Thermal Radiation	
−1	Cold on the face after 2–3 minutes
0	No discernable radiation
+1	Warm on the face after 2–3 minutes
+2	Unbearable on the face after more than 2 minutes
+3	Immediate burning sensation
Air Movement	
−2	Cold, strong air movement
−1	Cold, light air movement
0	No noticeable air movement
+1	Warm, light air movement
+2	Warm, strong air movement

FIGURE 8.6 *(Continued)*

Workload	
0	Office work; easy, low muscular contractions; occasional movement at normal speed
+1	Moderate work with arms and legs; use of heavy machines; steadily walking
+2	Intense work with arms and truck; handling of heavy objects; shoveling; walking rapidly; carrying heavy loads
+3	Very intense work at high speed; climbing stairs or ladders
Clothing	
0	Light, flexible, no interference with work
+1	Long, heavier, slight interference with work
+2	Clumsy, heavy, specially designed barrier for radiation, water vapor, cold
+3	Special coveralls with gloves, hoods, shoes
Worker Opinion	
−3	Shivering, strong discomfort for the whole body
−2	Strong local discomfort; overall sensation of coolness
−1	Slight, local cool discomfort
0	No thermal discomfort
+1	Slight sweating and discomfort; thirst
+2	Heavy sweating; strong thirst; modified work pace
+3	Excessive sweating; very tiring work; special clothing

FGURE 8.6 *(Continued)*

Thermal Comfort Zone

The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) has defined winter and summer comfort zones for sedentary and light work largely based on psychophysical data gathered on several thousand people (ASHRAE 1997; Fanger 1970). The actual guidelines are provided in ASHRAE 1997 and in ASHRAE Standard 55. In addition, many secondary sources are available. The following are reductions of the guidelines.

For summertime workplaces, the assumed clothing insulation is 0.5 clo. The environmental conditions should fall within the following ranges:

- Air temperature between 23 and 27°C (73 and 80°F).
- At the lower limit of humidity, dew point greater than 2°C (36°F) or the equivalent water vapor pressure of 0.7 kPa (0.2 in. Hg). As an approximation, the relative humidity should be greater than 25 percent.
- At the higher limit of humidity, psychrometric wet bulb should be less than 20°C (68°F). Limits that are more restrictive would be below a dew point of 17°C (63°F) (or water vapor pressure of 2.0 kPa or 0.6 in. Hg) or relative humidity below 55 percent.

For wintertime workplaces, the assumed clothing insulation is 0.9 clo. The environmental conditions should fall within the following ranges:

- Air temperature between 20 and 24°C (68 and 75°F).
- At the lower limit of humidity, dew point greater than 2°C (36°F) or the equivalent water vapor pressure of 0.7 kPa (0.2 in. Hg). As an approximation, the relative humidity should be greater than 30 percent.
- At the higher limit of humidity, psychrometric wet bulb should be less than 18°C (64°F). Limits that are more restrictive would be below a dew point of 14°C (58°F) (or water vapor pressure of 1.6 kPa or 0.5 in. Hg) or relative humidity below 60 percent.

Factors Affecting the Feeling of Comfort

The following factors will affect the individual's sense of comfort within the thermal comfort zone:

- Temperature
- Humidity
- Air speed
- Workload
- Clothing
- Radiant heat.

TEMPERATURE The range of temperatures between the ankles and head should not change by more than 3°C (5°F) (ISO 1984).

The upper and lower ambient dry bulb temperature limits must be adjusted to produce the same feeling of comfort when humidity, air velocity, workload, clothing insulation, and radiant heat load are varied from the levels described in the previous section. Subjective discomfort is primarily related to skin temperatures greater than 34.5°C or less than 32.7ºC (94° and 91ºF) (Hardy 1970) for sedentary or light work conditions. With increased workload, lower skin temperatures (<30°C, or 86°F) are needed for comfort. Brief descriptions of each of these modifiers of comfort follow.

HUMIDITY As humidity increases, discomfort will be felt at the upper end of the thermal comfort zone. All other things being equal, raising the humidity from 50 to 90 percent at 26°C (79°F) can significantly increase the feeling of discomfort (Fanger 1970) for a person doing light work. Humidities below 55 percent are preferable in the summer months.

Too little humidity can produce discomfort for some people (ASHRAE 1997; McIntyre 1978). Where feasible, it is recommended that humidity values above 25 percent be used for extended (more than 2 hours) exposures (ASHRAE 1997).

AIR SPEED The rate of airflow is measured as the average value at the workplace. Local drafts can make a workplace feel very cool even when it is well within the comfort guidelines for dry bulb temperature (Fanger 1977). This discomfort from local drafts increases as ambient (room) temperature falls and can be a major cause of complaints. At the upper end of the temperature spectrum for comfort, increased airflow is a positive comfort factor. The mean air speed should be less than 0.15 m/sec (30 ft./min) during the winter and less than 0.25 m/sec (50 ft./min) in the summer (cooling) (ISO 1984).

Air speeds of 0.1 to 0.3 m/sec (20 to 60 ft./min) are typical in the comfort zone for sedentary and light assembly work. So that complaints from drafts at the workplace are minimized, the lower limit air temperatures should be raised 3°C (5°F) at velocities greater than 0.1 m/sec and less than 0.5 m/sec (20 and 100 ft./min) and by 4°C (7°F) at higher velocities (McIntyre 1973). Often, fans are brought into work areas as the air temperatures move to the warm end of the comfort zone or above. This reflects the increasing number of people who are dissatisfied with the environment at the comfort limits. Allowing fans at worker discretion can increase the level of comfort for those who may feel unacceptably warm. The ISO standard on thermal comfort describes a means to predict the proportion of people who will not be satisfied with an environment (ISO 1984).

WORKLOAD As workload increases, the thermal comfort zone shifts to cooler ambient temperatures to help rid the body of heat generated by the muscles. The heavier the work, the lower the upper limit must be in order to preserve comfort. Most moderate to heavy industrial workloads average 175 to 350 W (150 to 300 kcal per hour), with heavier work being sustained only for shorter periods (Rodgers 1978). Because periods of effort are interspersed with periods of light or sedentary standby activity in the same environment, one has to trade off the best environment for each and compromise on a temperature level that will provide the best heat balance opportunities. The situation will therefore often lead to relative discomfort for the worker for at least part of the work cycle.

CLOTHING The amount and type of clothing worn and its insulation characteristics will determine how far the lower limit of the thermal comfort zone can be extended in the workplace as well as how much the upper limit can be modified. The insulation value of clothing is expressed in clo units. Table 8.8 shows the clo values for a number of common clothing ensembles.

The use of jackets, sweaters, and gloves to increase comfort in a cool environment may not always be feasible, such as in the following situations:

- When the production process requires the operator to wear a certain uniform, as in clean room operations, that reduces the options for adding insulation
- When the additional clothing binds the arms, hands, or body and reduces the available range of motion for the tasks to be performed
- When gloves would interfere with a task requiring fine manual dexterity
- When the job includes periods of heavy work where sweating occurs, which reduces the quality of the insulation of the additional clothing

At the upper limit of the thermal comfort zone, some improvement may be gained by wearing loose-fitting clothing and shedding unneeded layers. However, this option is not feasible in the following types of activities:

- When waterproof, fireproof, or chemical proof protective clothing must be worn
- When the operator is working around moving equipment and loose clothing could be entangled in it
- When a clothing regulation exists as protection for the product or as part of a professional requirement, such as whites in a clean room or, in some professions, a tie

RADIANT HEAT The difference between dry bulb and globe temperature defines the amount of radiant heat present in a workplace. Some common sources of radiant heat are the following:

- Exothermic (heat-producing) chemical reactions in vessels
- Furnaces
- Radiant-heat lamps
- Coil heaters
- The sun
- Drying or cooking ovens

At the upper limit of the thermal comfort zone, radiant heat produces discomfort; at the lower limit, comfort is increased. The latter property can be used to improve comfort in offices or areas of light work when local drafts or cold walls and floors make winter building temperatures uncomfortable.

In addition to the above factors, surfaces in the workplace, such as windows, walls with inadequate insulation, and slab floors, that lose heat faster than other parts of the operator's work space can be a source of discomfort within the lower part of the thermal comfort zone (Emmerson 1974; Nevins and Feyerherm 1966). These factors are a common source of complaints of cold discomfort in the workplace when ambient dry bulb temperatures are maintained in the range of 18° to 21°C (65° to 70°F). The heat-losing surface increases the net heat loss from the body. The feet, legs, arms, or hands are most commonly affected, and this local discomfort is sensed by the operator. The cold surface also results in the creation of temperature gradients between head and foot level at a seated workplace. Some engineering changes include:

- Insulating walls and areas around window frames
- Using curtains or blinds over windows
- Putting rugs, mats, or other insulating surfaces over slab floors
- Rearranging the work area to reduce exposure to the heat-losing surface

For example, office areas are sometimes placed in buildings that were designed for other purposes, such as warehousing. Walls that were not necessarily constructed for careful internal temperature regulation become a problem during winter cold extremes. The use of additional wall insulation often abates the problem without requiring additional energy use, even saving some. In office areas where large windows predominate, curtains or blinds may reduce the impact of the heat-losing surface on people. Care must be taken, however, to avoid disturbing the airflow pattern from heaters that may be placed under the windows; a long curtain may trap the hot air by the window and not permit it to reach the rest of the room.

Warm Discomfort and Heat Stress

Remember that thermal balance depends on considerations of the environment, work demands, and clothing, as well as the physiological responses necessary to achieve that balance. Two physiological responses that influence the sensation of comfort are elevated skin temperature and sweating. For sedentary work, discomfort is associated with sweating. As work demands rise and thus metabolic rate increases, some sweating is tolerated without a sensation of discomfort (ASHRAE 1997).

Warm Discomfort

The warm discomfort zone is a loosely defined zone that lies between comfort and health risk. Therefore, the first task of this section is to set a lower limit on the health risk zone, which is the upper limit of the discomfort zone. A reasonable upper limit would be a generally accepted occupational exposure limit for the least tolerant workers, such as the Recommended Alert Limit of the

National Institute for Occupational Safety and Health (NIOSH 1986) and the ACGIH TLV for unacclimated workers (ACGIH 2002). These exposure limits are based on an index for the environment called wet bulb globe temperature (WBGT), which is computed from the natural wet bulb temperature (T_{nwb}) and globe temperature (T_g) as:

$$WBGT = 0.7\ T_{nwb} + 0.3\ T_g$$

Instrumentation is commercially available to measure and compute WBGT. An approximation to WBGT can be made from the top section of Table 8.9. The table is entered with knowledge of the air temperature and relative humidity.

It is important to remember that relative humidity is highly dependent on air temperature, and air temperature and relative humidity must be assessed at the same time. A classic misuse is to match a very high relative humidity, often 90 percent, on a summertime morning to the midday temperature. In reality, the midday relative humidity is closer to 60 percent. This occurs because the water vapor pressure (absolute humidity) does not change much on many days, and so the water content stays the same even as the capacity to hold water increases substantially with air temperature.

The approximate WBGT is entered on line 1a of the second section of the table. Adjustments are made depending on the level of air movement and presence of radiant heat sources, and a final estimate (or a measured value) is placed on line 2a.

A clothing adjustment is found based on the information in line 2b. These adjustments are based on experimentally derived differences in environments that can support thermal equilibrium (O'Connor and Bernard 1999; Bernard 2002). In effect, they represent an equivalent environmental burden that the clothing contributes over ordinary work clothes. The clothing adjusted WBGT is called the effective WBGT here.

The transition from the discomfort to health risk zones is mapped out in Table 8.10. For a combination of work demand category and the proportion of work (versus rest or nondemanding work) in an hour, the transition value for effective WBGT is provided.

Moving through the discomfort zone from thermal comfort to health risk, the number of unsafe acts increases up to 50 percent from the baseline level (Ramsey et al. 1983), and the number of accidental and overexertion injuries increases as expected. It is also likely that productivity and quality of work will diminish for similar reasons. There is, however, little risk for a heat-related disorder (health effects) in the warm discomfort zone.

Reducing the work demands and clothing requirements, where practical, have the greatest potential to reduce warm discomfort. The next is lowering the humidity, followed by increasing air motion if it is below 0.5 m/sec (100 ft./min). More details about controls for heat exposures are discussed under "Heat Stress," below.

TABLE 8.9
Approximate Values of WBGT (°C) for Different Combinations of Dry Bulb Temperature and Relative Humidity with Adjustments for Air Movement, Radiant Heat, and Clothing

*Approximation of WBGT in °C from air temperature and relative humidity**

T_{db} [°C]	Relative Humidity* (percent) 20	30	40	50	60	70	80	90	T_{db} [°F]
24	16	17	18	19	21	22	23	24	75
26	17	19	20	21	22	23	24	25	79
28	19	20	22	23	24	25	26	27	82
30	20	22	23	25	26	27	28	29	86
32	22	23	25	26	28	29	30	31	90
34	23	25	26	28	29	31	32	33	93
36	24	26	28	30	31	33	34	35	97
38	26	28	30	31	33	34	36		100
40	27	29	31	33	35	36			104
42	29	31	33	35	37	38			108
44	30	33	35	37	38				111
46	32	34	36	38					115
48	33	36	38	40					118
50	35	37	40						122

*Air temperature and relative humidity must be measured at the same time.

WBGT Adjustments

	If estimating WBGT, start with 1a **If WBGT is known, start with 2a**	**WBGT (°C)**
1a	Estimate WBGT from preceding table Use air (dry bulb) temperature and relative humidity that were assessed concurrently	
1b	Enter air movement adjustment: No obvious air movement: +1°C Sensible air movement: 0	
1c	Enter radiant heat adjustment: Surface temperatures near air temperature: 0 Some hot surfaces but no obvious radiant heat on skin: +1 Obvious radiant heat (i.e., warms skin): +3	
2a	Known value of WBGT in °C or add lines 1a, 1b and 1c	
2b	Enter clothing adjustment: Ordinary woven work clothes or coveralls: 0 Nonwoven particle-barrier coveralls: 1 °C Liquid-barrier vapor-permeable coveralls: 3 °C Nonwoven particle barrier coveralls over work clothes: 5 °C Limited-use vapor-barrier coveralls: 9 °C Limited-use vapor-barrier coveralls over work clothes: 11 °C	
3	Effective WBGT: add lines 2a and 2b	

TABLE 8.10
Transition Thresholds of WBGT (°C) for Work with Some Periods of Nondemanding (Sedentary) Work in the Same Location (TLV for Unacclimated Workers adapted from American Conference of Governmental Industrial Hygienists (ACGIH®) *2002 TLVs® and BEIs® Book*. Copyright 2002. Reprinted with permission.)

*WBGT (°C) Transition Thresholds**

Proportion of Hour Working	Work Demands (see Table 8.7)			
	Light	Moderate	Heavy	Very Heavy
75 to 100 percent	27.5	25.0	23.2	NR
50 to 75 percent	28.3	26.1	24.5	NR
25 to 50 percent	29.2	27.5	26.1	25.0
0 to 25 percent	30.3	29.2	28.3	27.5

*The thresholds are for the effective WBGT determined from Table 8.9, which includes any adjustment for clothing other than ordinary woven work clothes or coveralls. These limits mark the transition from warm discomfort to health risk. The thresholds are based on the highest percentage of work in each work cycle and the representative metabolic rate. NR means that the work rate is not recommended regardless of the environment.

Heat Stress

Because heat stress is very common in many workplaces and a common experience among employees and supervisors, the risks of work under conditions of heat stress are often underappreciated. Heat stress is present when the combination of environment, work demands, and clothing requirements exceeds the transition effective WBGT values mapped out in Table 8.10 (in other words, in the health risk zone). This is the equivalent concept of an action level in industrial hygiene (e.g., the point at which a hearing conservation program is started for noise exposure). While there is no statutory requirement, as there is for noise, a heat stress management program should be instituted for those working in the health risk zone as a prudent course of action. Guidance for establishing a heat stress management program can be found in most textbooks on industrial hygiene and in the ACGIH TLV for heat stress and strain documentation (ACGIH 2002). Some highlights are provided here.

GENERAL CONTROLS When work takes place in the health risk zone, there is a set of measures that should be implemented independent of the specific exposure conditions (Bernard 2002; ACGIH 2002). These are general controls and include training, heat stress hygiene practices, and surveillance. As with any other workplace hazard, employees and others working in those locations should have an adequate amount of training to understand the hazards and what to do to protect themselves and others. The training is part of the sitewide health and safety training.

Heat stress hygiene practices are those preventive actions that an individual can take to lower individual risk of experiencing any heat-related disorders. The hygiene practices are:

- *Self-determination.* The individual is trained in the early recognition of heat-related disorders and is given the latitude to stop an exposure with extreme discomfort or the early symptoms of heat disorders. Further, the individual is given as much control as possible over the pace of the work and the taking of recovery breaks.
- *Fluid replacement.* During exposures to heat stress, an individual may lose up to one liter or quart of water per hour. Thirst is not an early marker of dehydration, therefore, because of digestive and comfort considerations, it is best to replace the water with frequent drinking of small quantities and not wait for thirst. Commercial fluid replacement drinks are not necessary, but there is evidence to suggest that more water is consumed with them than with water alone.
- *Lifestyle.* Eating a healthy diet and getting adequate sleep are important as well as avoiding unnecessary heat exposures off the job. Alcohol should be consumed with care and moderation (and never before or during work), and recreational drugs carry serious risk for heat stroke. Those on a weight loss diet should consult their physician and be assured that the loss is not dehydration.
- *Health status.* Those being treated for a chronic health condition of any type should inform their personal physician about heat stress exposures at work. Anyone with an acute illness should not report to work or should report the illness to his or her supervisor. Acute illness may place unacceptable risk on the individual.
- *Acclimation.* Acclimation (or acclimatization) is a physiological adaptation to heat stress that confers some added tolerance on the individual. Generally, heat stress work for 2 hours per day for 5 of 7 days induces most of the benefits of acclimation. Acclimation is lost at a rate of 1 day for every 3 days away for routine or injury reasons. For illness, the loss is 1 for 1.

Surveillance is the routine activities of the health and safety function in monitoring the environment's heat stress conditions as well as monitoring employee health through preplacement and periodic physicals and tracking the illness records.

JOB-SPECIFIC CONTROLS Job-specific controls should be considered when the exposures to heat stress are associated with effective WBGTs that are more than about 3°C above the transitional WBGTs in Table 8.10. They follow a traditional health and safety hierarchy of engineering controls, administrative practices, and personal protection.

Engineering Controls. Engineering controls are changes in the level of heat stress resulting from changing the fundamental conditions of the environment, work demands, or clothing. Because the greatest source of heat gain is metabolic, providing powered assists will reduce the work demands and the level of heat stress.

Among the environmental factors, reducing the humidity can be very effective because it will increase the rate of evaporative cooling and the efficiency of sweat evaporation (less dripping). Reduction of air temperature usually goes hand in hand with humidity control. Local ventilation to remove sources of water vapor and heat before they enter the general environment and air-conditioning of the work space are two approaches. The ability and cost depend on the size of the space, the amount of water vapor in the air, and the temperature of the inlet air. Another approach is to use a local air-conditioning system to provide spot cooling with dehumidified air. Portable air-conditioning systems are especially helpful for nonroutine and maintenance tasks. All of these approaches have been used with success.

Air temperature can be reduced by ventilation, as mentioned above, as well as by isolating hot surfaces with insulation and high-emissivity shells. The insulation reduces the heat losses to the environment, which may also help the economics of the process. For some high-temperature systems, placing a shiny metal surface over the insulation further reduces the heat loss by radiation.

An approach to control heat exposure to workers from radiant heat sources is to place a shield between them and the hot surfaces. The goal is to block the line of sight for infrared radiation. Shields made of shiny materials are the most effective, but anything that interrupts the flow helps considerably. Sometimes a screen made of chains that allows some access is a solution, as is a window with infrared absorbing or reflecting materials if visual inspection is necessary.

Increasing air speed is helpful under some conditions. For most work clothes, increasing the air speed to 2 m/sec (400 ft./min) can improve the heat loss (Kamon and Avellini 1979). The lower the air temperature below 35°C (95°F), the more effective the increase will be. There is a diminishing return between 35 and 40°C (95 and 104°F). If the people are wearing multiple layers of clothing, higher speeds may enhance the penetration under the layers to improve evaporative cooling.

Changing clothing requirements can have a positive effect on the level of heat stress and the level of discomfort. In general, any action taken to reduce the evaporative resistance of the clothing (i.e., decrease body surface area covered and increase the permeability of the clothing to water vapor) will reduce the level of heat stress. A simple guide is the order of clothing listed in Table 8.8. The lower the clothing adjustment factor, the lower the effective WBGT and the lower the level of heat stress. For instance, after a careful hazard analysis of a chemical mop-up operation, the use of only chemical-resistant pants rather than a whole suit may provide adequate protection from splashes and improve the rate of evaporative cooling.

Administrative Practices. Administrative practices or controls are ways that an exposure to heat stress is managed to lower the risk. If work under heat stress conditions is anticipated, setting up cycles of work and recovery is an administrative control. Table 8.10 can provide some direction. If the work force is acclimated, the effective WBGT can be reduced by 2°C. If the recovery occurs with different clothing and/or in a different environment, then a time-weighted average of the effective WBGTs is appropriate.

There are other situations in which a high heat stress exposure may take place for a single exposure. Because of the wide variety of circumstances, it is difficult to provide specific guidance. It is best to work with a health and safety person with knowledge of heat stress evaluation and control.

When working in the health risk zone, a buddy system should be in place so that no person is left completely alone.

Personal Protection. When evaporative cooling is not sufficient to maintain thermal equilibrium, personal protection in the form of personal cooling systems can extend the work time. Personal cooling systems can be categorized as:

- *Circulating air systems*. These deliver air under the clothing and ideally near the skin. The circulating air enhances evaporative cooling and may enhance convective heat loss. The air can be delivered from a compressed-air source or from a fan-powered source such as an adapted PAPR (powered air-purifying respirator). The air may be delivered to one spot under the clothing, such as at the waist, or through a supplied air hood vented under the clothing or distributed through a web of tubes or a perforated vest. In addition, compressed air systems may add a vortex tube technology to cool the air to enhance the convective heat loss. In any case, the air must meet breathing air standards.
- *Circulating water systems*. These systems are closed loops with circulating water in which the chilled water is brought into close contact with the skin by a network of thin-walled tubes or similar devices. The warmer water is returned to a heat sink, where it is chilled and returned. The heat sinks are usually ice but could be a refrigeration unit or other means to remove heat. The power supply, pump, and heat sink may be worn by the user, portable in that it is carried in, or in a fixed location and the user plugs in when at the work area.
- *Passive cooling systems*. These work by direct conduction from the skin to the heat sink. The ice vest is the most common of the passive systems. An important consideration is the capacity of the heat sink, which depends on both weight and the heat of fusion. Water ice has the greatest capacity per unit weight, at about 80 kcal/kg; and is the standard by which others should be judged.
- *Others*. Two broad categories of others are evaporative systems that are wetted, where the evaporation of the water provides cooling, and other passive systems like headbands, hat liners, bandanas, and so on. These are not particularly effective in reducing heat stress and will not be discussed further.

The effectiveness of personal cooling systems depend on the metabolic rate, the body surface area that is covered, the capacity of the heat sink, the maximum gross rate of cooling, and the environmental conditions.

Because it is a metabolic rate in excess of evaporative cooling that is likely to cause heat storage and the need for personal cooling, metabolic rate is also a factor in determining the effectiveness of personal cooling. If the imbalance is small, the personal cooling system does not have to have the same capability as when the imbalance is great.

One of the rate-limiting steps is to move heat from the skin to the cooling system. For this reason, cooling system capacity depends on the amount of body surface area covered. The circulating air systems have large surface area coverage when the air is vented out cuffs or otherwise has long travel paths. The circulating water systems have configurations that can cover most of the body. The passive cooling systems cover about 30 to 40 percent of the body.

The greater the capacity of the heat sink, the longer the cooling can be provided before recharging. The circulating air systems have an infinite heat sink as long as an air supply is available. The circulating water systems are usually designed to have an easily recharged heat sink. The passive systems can be recharged, but some thought has to be given to the logistics.

The gross rate of cooling relates mostly to the circulating air and water systems and depends on the inlet temperature and bulk flow rate. The cooler the temperature and the higher the flow rate, the greater the cooling rate.

The warmer the environment, the more likely some of the cooling capacity will be lost to the outside environment. As a rule of thumb, about 50 percent of the cooling capacity is lost to the outside environment.

SPECIAL CASES: HOT SURFACES AND BREATHING HOT AIR The sensations of discomfort, pain, and burn depend on the temperature of the skin. The highest sustainable skin temperature that is tolerated by most people is about 38°C (100°F) (Bernard and Foley 1993). When the temperature exceeds about 43°C (109°F), pain is usually reported, and tissue damage will follow (Siekmann 1990). Burns will occur as early as 48°C (118°F) for a brief sustained contact (Siekmann 1990). Severe pain and burns may occur with incidental contact. Under these conditions, the thermal conductivity of the contacted surface must be considered because this will limit the rate of heat transfer to the skin. Table 8.11 is a list of minimal surface temperatures to cause pain or burn with an incidental contact of 1 second for different materials. Notice that as the thermal conductivity goes down, the minimal surface temperature goes up.

As a rule of thumb for breathing hot air, there is little risk of causing injury to the respiratory passages if the wet bulb temperature of the air is less than 45°C (113°F). Above a wet bulb temperature of 50°C (122°F), the probability of individual discomfort will increase (Bernard 2002).

TABLE 8.11
Minimum Surface Temperatures to Cause Pain or Burn with an Incidental Contact to Skin for Different Materials (adapted from Faulkner 1974; based on data in the literature, especially Wu 1972)

Material	Pain Threshold °C (°F)	First-Degree Burn Threshold °C (°F)
Polystyrene GP	77 (171)	138 (281)
Wood (average)	76 (169)	135 (275)
ABS resins	74 (166)	131 (268)
Phenolics (average)	60 (141)	99 (210)
Brick	59 (138)	95 (202)
Heat-resistant glass	54 (129)	82 (180)
Water	53 (127)	80 (176)
Concrete	50 (122)	73 (164)
Steel	45 (113)	62 (143)
Aluminum	45 (112)	60 (141)

Note: Data are based on a 1-second contact by the finger.

The temperature of several materials (column 1) are shown at which pain (column 2) or a first-degree burn (column 3) will result from a 1-second finger contact. These values are maximum temperatures, so designs should not exceed them. Lower temperatures are desirable, since they accommodate longer contact times, contact with other skin (such as on the forearm), or the presence of breaks in the skin from cuts or abrasions.

Cool Discomfort and Cold Stress

Cool discomfort and cold stress depend on factors affecting the loss of total body heat and local skin cooling. The environmental conditions described by air temperature and air movement, metabolic rate, and amount of clothing insulation help to understand the potential for loss of body temperature and hypothermia. Air temperature and movement will affect the potential for discomfort or local tissue disorders of exposed skin.

Cool Discomfort

The cool discomfort zone covers the range of conditions (i.e., combinations of environment, work demands, and clothing) for which people will report a cool to cold thermal sensation but are not necessarily at risk for a cold-related disorder. The practical lower limit of the cool discomfort zone is 10°C (50°F) (Holmér, Granderg, and Dalstrom 1998). Below this point, conflicting sensations from different contributors may cause significant discomfort and, under some conditions, cold stress.

The discomfort zone applies to the whole body rather than a particular area. That is, local tissue cooling is not considered; if it exists, it may be cause for severe discomfort or even a health risk. Much of the sensation is caused by skin temperature, and the principal environmental factors that influence skin temperature in cool and cold conditions are air temperature, air motion, and radiant heat sources or sinks. The more comfortable (higher) limit of the cool discomfort zone is marked by an approximation to Fanger's comfort equation (Holmér, Granderg, and Dalstrom 1998).

$$T_{high} = 33.5 - 3\ I_{clo} - (0.044 + 0.028\ I_{clo})\ M$$

T_{high} is the air temperature in °C when the surface temperatures are approximately the same as the air temperature, I_{clo} is the clothing insulation in clo, and M is the metabolic rate in W.

In contrast, the required insulation (IREQ) method of assessing cold stress can be used to set the lower-bound temperature (Holmér, Granderg, and Dalstrom 1998). The difference is due to the assumed skin temperature, which is lower for IREQ. While the published method accounts more fully for all the factors, a rough approximation for a skin temperature of 33°C (91°F) is

$$T_{low} = 33 - (I_{clo}\ M) / 11.5$$

The differences between the low and high bounds are not great under most circumstances. However, both equations demonstrate the role of clothing and metabolic rate in establishing an air temperature that is in the discomfort zone.

Table 8.12 indicates the range of clothing insulation to stay within the discomfort zone for different metabolic demands and air temperatures. The higher value in the range helps provide some level of comfort; the lower value is a point where the discomfort may become unacceptable.

In the lower end of the cool discomfort zone, there may be a loss of finger dexterity to exposed hands, as well as some loss of cognitive and psychomotor capacity. The hands can begin to show a loss of flexibility and dexterity at temperatures as high as 15°C (59°F) for prolonged exposures. As the temperatures become lower, the time without performance decrements becomes shorter. See Figure 8.7. For instance, a 15 percent loss of dexterity would take 90 minutes at 13°C (55°F) and 30 minutes at 7° (45°F). In addition, there may be an increase in accidents (Ramsey et al. 1983).

The bounds of the discomfort zone assume low air speeds. In the presence of moderate to high air speeds (noticeable air movement), discomfort is more likely due to cooling of exposed skin surfaces. One response to elevated air speed is to add clothing insulation and cover exposed skin, and another is to reduce the air speed (consistent with the health purposes of the ventilation). The reductions can be through reducing or redirecting ventilation, relocating the workstation, and shielding to break up the air stream.

The sensation of cold is also affected by metabolic rate. Often, the work is sensed as comfortable to slightly warm during work but cool to cold during periods of inactivity. To the extent possible, the work demands should be kept relatively even and inactive periods spent in a warmer location. For work

TABLE 8.12
Range of Clothing Insulation (clo) for the Discomfort Zone at Different Temperatures and Work Demands

The higher level of insulation helps maintain minimum discomfort, and the lower value is the least required to avoid extreme discomfort based on the equations provided in the text. While the cold stress threshold is 10°C (see section on cold stress), caution must be exercised in allowing extreme discomfort.

	Air Temperature					
Work Demands	**10°C 50°F**	**12°C 54°F**	**14°C 57°F**	**16°C 61°F**	**18°C 64°F**	**20°C 68°F**
Sedentary	2.4–3.9	2.2–3.5	2.0–3.2	1.8–2.9	1.6–2.5	1.4–2.2
Light	1.3–2.7	1.2–2.5	1.1–2.2	1.0–2.0	0.9–1.7	0.7–1.5
Moderate	0.9–2.0	0.8–1.8	0.7–1.6	0.7–1.5	0.6–1.3	0.5–1.1
Heavy	0.7–1.6	0.6–1.4	0.5–1.3	0.5–1.1	0.4–1.0	0.4–0.9

demands greater than 175 W, the likelihood of sweating increases and the subsequent evaporation during inactive periods enhances the heat loss and sensation of cold (Enander, Ljungberg, and Holmér 1979).

Clothing is another powerful method to manage thermal discomfort in cool or cold environments. Some simple principles follow. Air pockets are very effective as insulation, so choosing clothing fabrics that inherently trap air (e.g., wool) is a good strategy. Clothing that is tight-fitting (with respect to trapping air inside) is a further advantage. Exterior shells that stop air penetration (e.g., windbreakers) help preserve the insulating characteristics of the clothing. Provisions for pockets, and for pocket warmers, will help keep the hands warm.

Because sweating may occur, drying cabinets or areas should be available in break rooms so that the insulating characteristics of the clothing can be preserved. If not, the exposure periods should be progressively shortened during the course of the shift to allow for the reduced insulating capability (Morris 1975).

Radiant heat sources are another means of warming people working in a cold environment without changing the air temperature. They can also be used in enclosures such as crane and heavy equipment cabs. These are usually effective as a spot warming method.

Cold Stress

Because cold stress is a problem of both hypothermia and local tissue cooling, both must be considered in the decision about when the health risk zone is entered. Hypothermia may occur at air temperatures as high as 10°C (50°F), and for this reason it becomes a reasonable threshold for cold stress. The wind

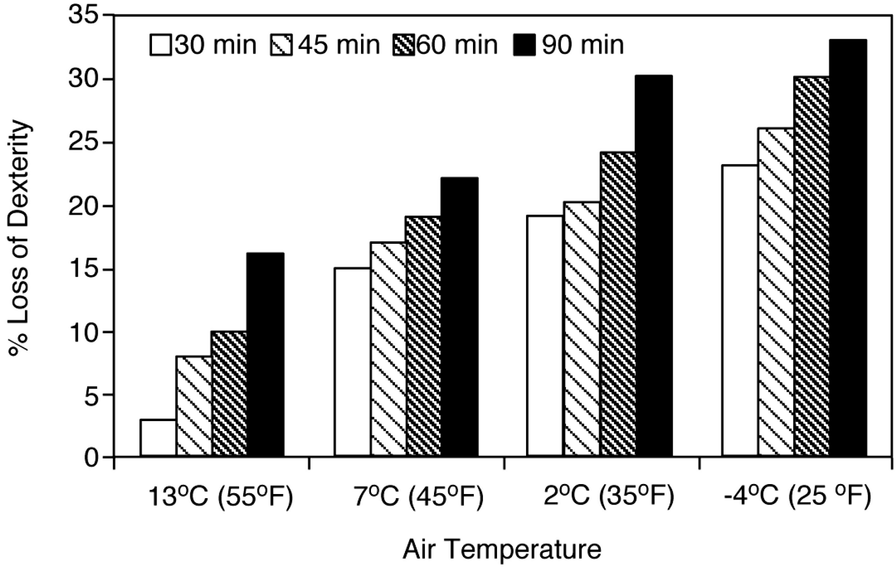

FIGURE 8.7 The effects of exposure time to four different ambient dry bulb temperatures at low to moderate air movement on performance of a moderately difficult manipulation assembly task. The loss of dexterity is referenced as a percentage loss compared to the same task at 22°C (72°F) (Kodak 1983).
The losses at 90 minutes and at -4 °C are estimated.

chill index in Table 8.13 is a rough correlate of exposed skin cooling and is the most often used indicator of risk. A health risk zone threshold based on wind chill is –27°C (–17°F) to protect exposed skin.

To reduce the risk for hypothermia, the ISO Required Insulation (IREQ) draft standard is a useful tool (Holmér 1994). A rough approximation of IREQ is

$$I_{clo} = 11.5\ (33 - T_{air})\ /\ M$$

where I_{clo} is the total insulation of the clothing in clo, T_{air} is the air temperature in °C, and M is the metabolic rate in watts (W). If the required insulation cannot be achieved, cold stress is presumed.

As with heat stress, general and job-specific controls should be considered (Bernard 2002).

GENERAL CONTROLS When the air temperature can be below 5°C (41°F), cold stress training should be provided with an emphasis on proper clothing as well as self-determination and cold stress hygiene practices. If air or surface temperatures are below 0°C (32°F) or if the required insulation cannot be achieved, the training should also include safe work practices and recognition of cold-related disorders and their first-aid actions.

TABLE 8.13
Wind Chill as a Combination of Air Temperature and Air Speed (calculated from the equation provided by the National Weather Service, effective November 2001)

National Weather Service Wind Chill Chart

Air Speed		Temperature [°C]																	
m/sec	mph	4	2	−1	−4	−7	−9	−12	−15	−18	−21	−23	−26	−29	−32	−34	−37	−40	−43
		Temperature [°F]																	
Calm	Calm	40	35	30	25	20	15	10	5	0	−5	−10	−15	−20	−25	−30	−35	−40	−45
2	5	2	−1	−4	−7	−11	−14	−17	−20	−24	−27	−30	−33	−37	−40	−43	−46	−50	−53
4	10	1	−3	−6	−9	−13	−16	−20	−23	−27	−30	−34	−37	−40	−44	−47	−51	−54	−58
7	15	0	−4	−7	−11	−14	−18	−21	−25	−29	−32	−36	−39	−43	−46	−50	−53	−57	−61
9	20	−1	−4	−8	−12	−15	−19	−23	−26	−30	−34	−37	−41	−45	−48	−52	−56	−59	−63
11	25	−1	−5	−9	−13	−16	−20	−24	−27	−31	−35	−39	−42	−46	−50	−53	−57	−61	−65
13	30	−2	−6	−10	−13	−17	−21	−25	−28	−32	−36	−40	−43	−47	−51	−55	−59	−62	−66
16	35	−2	−6	−10	−14	−18	−22	−25	−29	−33	−37	−41	−44	−48	−52	−56	−60	−64	−67
18	40	−3	−7	−11	−14	−18	−22	−26	−30	−34	−38	−41	−45	−49	−53	−57	−61	−65	−69
20	45	−3	−7	−11	−15	−19	−23	−27	−31	−34	−38	−42	−46	−50	−54	−58	−62	−66	−70
22	50	−3	−7	−11	−15	−19	−23	−27	−31	−35	−39	−43	−47	−51	−55	−59	−63	−67	−71
25	55	−4	−8	−12	−16	−20	−24	−28	−32	−36	−40	−44	−48	−52	−56	−60	−64	−67	−71
27	60	−4	−8	−12	−16	−20	−24	−28	−32	−36	−40	−44	−48	−52	−56	−60	−64	−68	−72
Time to Frostbite								30 min		10 min		5 min							

Special precautions must be taken when the wind chill is lower than −27°C (−17°F).

Cold stress hygiene practices include the following. Hydration remains important in cold stress, but the emphasis is on warm, sweet, noncaffeinated drinks. A balanced diet should be encouraged. An exposure should be stopped with extreme discomfort or any of the earliest symptoms of a cold-related disorder.

For work in air temperatures less than 2°C (36°F), clothing should be replaced immediately anytime it becomes wet. When working with liquids that have boiling points below 4°C (39°F), care should be taken to avoid soaking the clothing with the liquid.

JOB-SPECIFIC CONTROLS

Engineering Controls. Fundamental environmental conditions can be altered in several ways:

- General or spot warming and warming shelters
- Hand warming for fine work below 16°C (61°F)
- Shielding workers from unnecessary air motion
- Minimizing of conductive cooling of the hands and other body surfaces from cold surfaces

Administrative Controls. Lowering the risk of cold stress can be accomplished by managing exposure in the following ways:

- Schedule work for warmer times.
- Move work to warmer areas.
- Avoid long periods of inactivity.
- Allow for productivity reductions due to protective clothing.
- Provide for a buddy system.
- Schedule work and recovery cycles.

Personal Protection. Personal protection against cold stress includes:

- Adequate insulated clothing, including wind breaks and considerations of extremities and exposed skin
- Active warming systems (e.g., circulating water and electric heaters)

VIBRATION

Introduction

Occupational exposure to vibration is a frequent occurrence, particularly from encounters with vibrating machines, vehicles, and equipment in the workplace. A person becomes exposed to vibration from direct contact with a vibrating source, which usually transmits energy to the human body through the hands, seat, or feet.

Whole-body vibration is vibration transmitted to the human body, usually through a seat or a platform. Common occupational sources of whole-body vibration include riding equipment, machinery, and modes of transportation such as construction vehicles, trucks, buses, rail, and aircraft. The frequency range of whole-body vibration is typically between 1 Hz and 80 Hz. Maritime workers are often exposed to low-frequency vibration (1 Hz or less) aboard boats and ships, which is sometimes considered whole-body vibration as well but will not be considered here.

A common experience for whole-body vibration is sitting in a rattling bus while riding on a bumpy road. The vibratory motion is transmitted to the feet resting on the floor and to the buttocks through the seat. In terms of subjective reports of people exposed to whole-body vibration, they will report difficulty reading, performing precision tasks such as writing, and concentrating as well as somatic problems such as headaches, nausea, motion sickness, or the urge to urinate. Long-term effects of whole-body vibration include mechanical insult to the back and digestive system.

There is strong epidemiological evidence of an association between occupational exposure to whole-body vibration and back disorders, including lower back pain (Bernard 1997). Experimental and epidemiological evidence suggests that whole-body vibration may act in combination with other work-related factors such as prolonged sitting, lifting, and awkward postures to increase the risk of a back disorder. Laboratory studies have demonstrated that whole-body vibration affects the vertebrae, intervertebral discs, and supporting musculature. In addition to health effects, whole-body vibration has been also shown to affect discomfort and visual performance.

Hand and arm vibration is vibration transmitted to the hands through direct contact with the vibrating body. Sources include industrial power hand tools such grinders, sanders, chain saws, chipping hammers, or jackhammers. Other common sources of hand and arm vibration include vehicle steering wheels, gasoline-powered garden equipment, and motorcycle handlebars. The frequency range of hand and arm vibration is typically between 8 Hz and 1,500 Hz. In addition, very high-frequency (above 2,000 Hz) vibration from some dental instruments has been considered a source.

A common experience with hand-arm vibration is grasping a buzzing electric razor or handling a gasoline-powered garden tool. Subjective reports include tingling sensations in the hands and a decreased ability to guide or manipulate vibrating equipment.

Exposure to high levels of hand and arm vibration is associated with a variety of vascular and neurological symptoms, classified as hand and arm vibration syndrome. Vascular disorder symptoms include blanching of the digits after the use of vibrating hand tools (Gemne 1997). Vibration-induced white finger (VWF), also known as Raynaud's phenomenon of occupational origin, includes peripheral vascular and sensorineural symptoms. The disorder derives its name from the blanching observed in the fingers caused by vasospasms occurring during an attack. In the mild stages, vascular symptoms include occasional attacks affecting only the tips of one or more fingers. In severe cases, as the condition progresses, patients experience more frequent attacks, eventually affecting all phalanges of most fingers.

There is also evidence supporting an association between exposure to hand and arm vibration and carpal tunnel syndrome (Bernard 1997) and ulnar nerve entrapment (Palmer, Crane, and Inskip 1998). Sensorineural symptoms include intermittent numbness with or without tingling, and they may progress to stages where numbness is persistent and accompanied by reduced tactile discrimination or manipulative dexterity.

Measurement of Vibration

Vibration is simple or complex oscillatory motion. Human vibration exposure is measured by its properties: magnitude of acceleration, frequency, direction, and exposure time. Magnitude is conventionally reported as RMS (root mean square) acceleration (m/sec^2 or ft./sec^2; or as g, which is equal to 9.8 m/sec^2) of the vibrating object. The typical RMS acceleration can be a great as 20 m/sec^2 for whole-body vibration and 200 m/sec^2 for hand and arm vibration. Workers with high exposures to hand and arm vibration, such as forestry workers, stone drillers, stonecutters or carvers, shipyard workers, or platers, are typically exposed to acceleration levels of 5 to 40 m/sec^2.

Frequency is the rate at which a vibrating object oscillates and it is reported as cycles per second or hertz (Hz). It is mechanically related to the speed of moving parts of machinery or equipment, such as rotating shafts or motors, as well as repeating movements of components such as the gear teeth or mechanical couplings. A machine vibrates at greater frequencies when its moving parts rotate faster. A rotating spindle, for instance, can produce vibration when the shaft is slightly off center. The faster the rotation speed, the more frequently the shaft shifts back and forth. Furthermore, the more unbalanced the shaft is, the great the vibration magnitude.

Human vibration measurements are always referenced to a directional coordinate system of three orthogonal axes. The convention used to measure whole-body vibration direction is based on the international standard coordinate systems for whole-body vibration (ISO 2631) and hand and arm vibration (ISO 5349). Illustrations of these coordinate systems can be found in most descriptions of human vibration exposure in textbooks or the ACGIH TLVs. The coordinate systems are (1) biodynamic, which are relative to anatomical structures of the body, and (2) basicentric coordinates, which are relative to objects in contact with the body. The basicentric system approximates the biodynamic coordinates and is more practical to measure since vibration sensors are mounted on the vibrating object rather than on the person. In either coordinate system, the three axes are mutually perpendicular (orthogonal) to each other. In the whole-body basicentric coordinate system, the critical axis is the z-axis, and it is parallel to (along the length of) the spine whether the person is standing, sitting, or lying on a surface. For standing or upright sitting, the z-axis is perpendicular to the ground. The x- and y-axes are front to back and side to side, respectively. The hand-arm basicentric coordinates are aligned with a handle grasped by the hand, rather than the hand itself, with its origin at the interface between the hand and the vibrating object. The exact identification of the axes is less important for hand-arm vibration, but the convention is that the y-axis is along the length of the handle being grasped by the hand, while the z-axis is perpendicular to the y-axis and runs between the handle and the center of the wrist. The x-axis is perpendicular to both the y- and z-axes. The use of triaxial sensors (see below) ensures orthogonal placement.

Exposure time is the total daily time that an employee is exposed to vibration in the course of a work period, usually expressed in units of hours or minutes. Continuing the rattling bus example, exposure time is related to the time that the bus actually travels on a bumpy road, compared with the time that the bus stops or travels on smooth roads. Only the total time the bus produces rattling motion is summed to measure the vibration duration. Exposure time is measured using similar methods as time study.

Accelerometers

The most common vibration measurement sensor is the accelerometer, which is an electronic device that measures the acceleration of an object when it is rigidly coupled to it. (It is not acceptable practice to attach it to a body part.) An illustration of accelerometers attached to various pneumatic power hand tools is shown in Figure 8.8. In many cases, both hands are used, and therefore accelerometers are mounted in two locations and near the point of contact. Considerations should be made for the mass of the accelerometer and its frequency range.

Acceleration measurements in different directions are made by orienting the accelerometer accordingly. A triaxial accelerometer combines three accelerometers mounted at right angles to each other and is a convenient package. When whole-body vibration is measured, it is usually from the seat or standing surface. Specialized accelerometers for whole-body vibration measurements are available. Hand and arm vibration measurements use accelerometers directly mounted on a handle or near the location where the vibrating object is grasped. Commercial hand-arm vibration mounts are also available.

Vibration Frequency Analysis

The acceleration time series illustrated in Figure 8.9 are for various industrial power hand tools shown in Figure 8.8. Observe that each type of tool has its own characteristic vibration. Some tools, such as the hand grip orbital sander (A) or the vertical polisher (H), have relatively simple patterns. Other vibration signals, such as for the heavy-duty right-angle sander (D), are much more complex.

Frequency analysis is an alternative way to view vibration. Instead of the

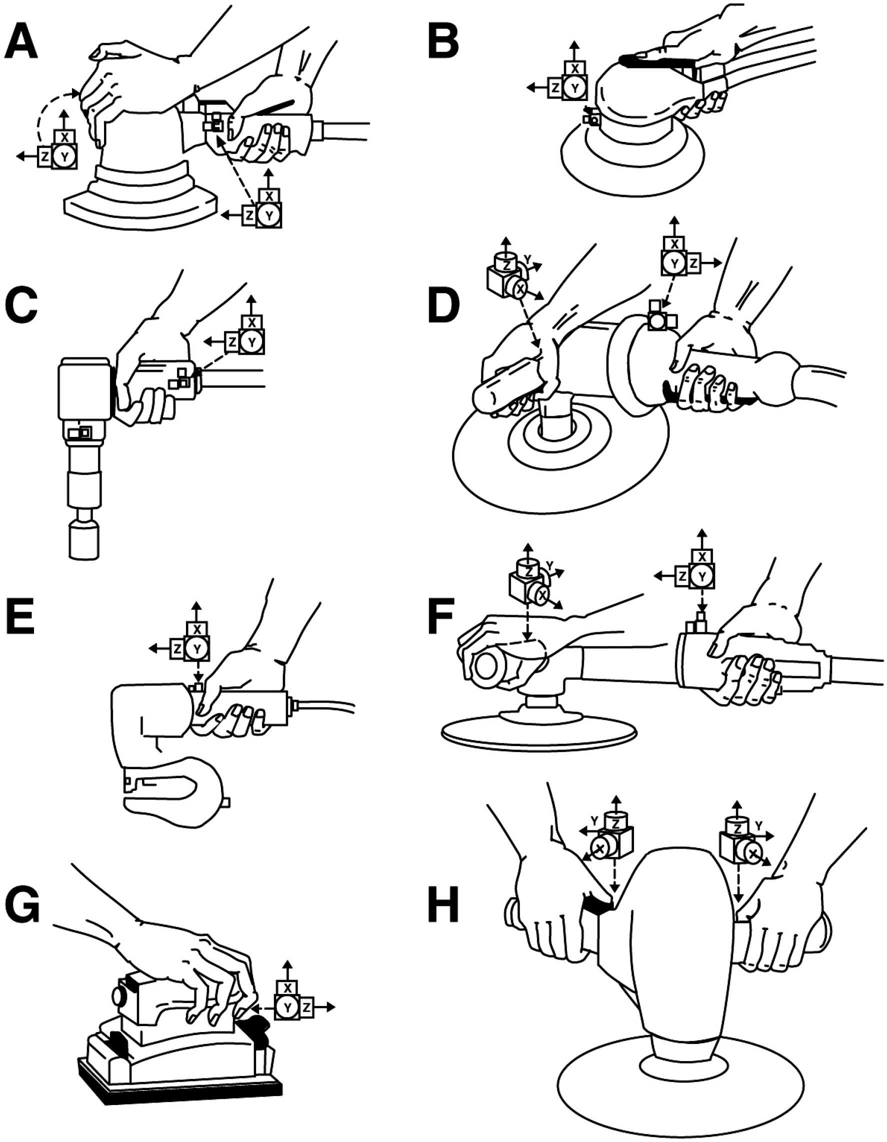

FIGURE 8.8 Handle grip posture for eight representative vibrating industrial power hand tools. Accelerometer locations and corresponding coordinates on the x-, y-, and z-axes are included (from Radwin, Armstrong, and Van Bergeijk 1990).

(A) Hand grip orbital sander
(B) Palm grip orbital sander
(C) Impact wrench
(D) Heavy-duty right-angle sander
(E) Trimming shear
(F) Light-duty right-angle sander
(G) Jitterbug sander
(H) Vertical polisher

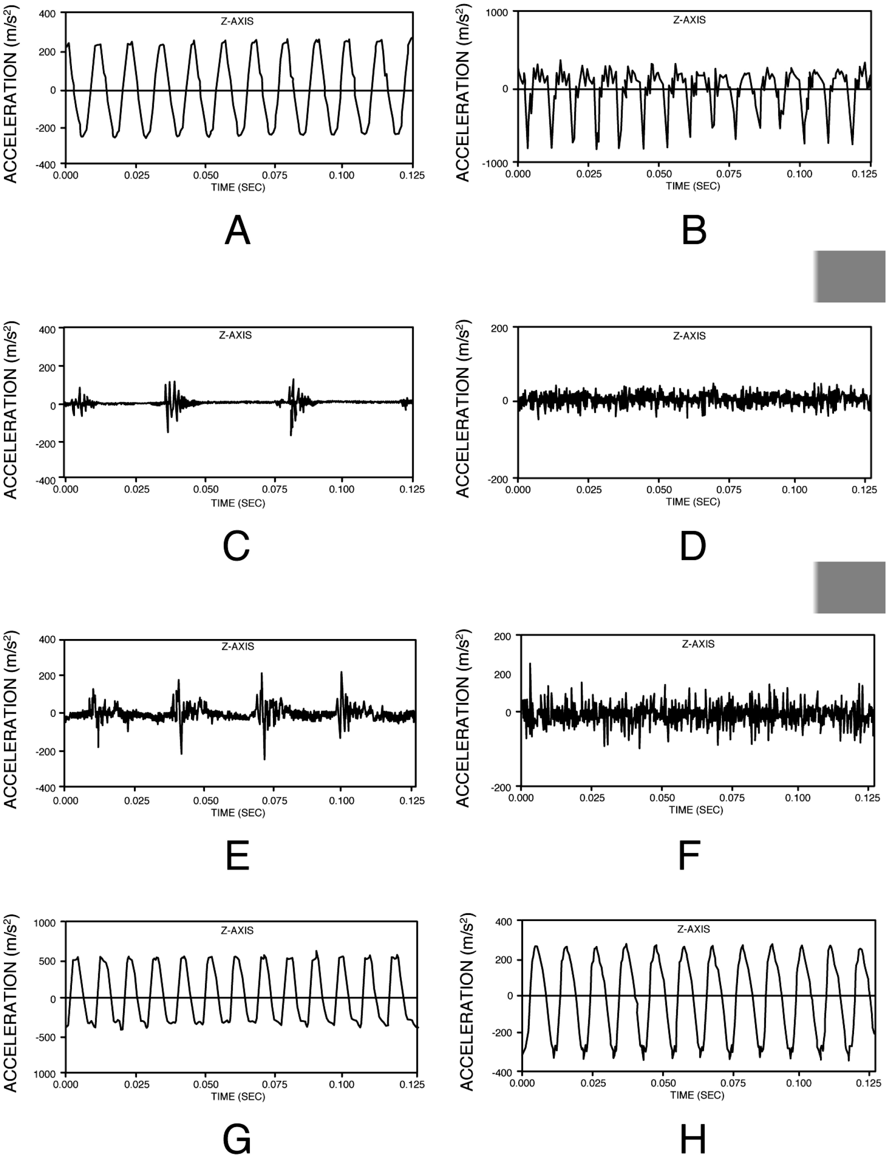

FIGURE 8.9 Representative acceleration-versus-time plots for eight representative vibrating industrial power hand tools in the z-axis (from Radwin, Armstrong, and Van Bergeijk 1990)
(A) Hand grip orbital sander
(B) Palm grip orbital sander
(C) Impact wrench
(D) Heavy-duty right-angle sander
(E) Trimming shear
(F) Light-duty right-angle sander
(G) Jitterbug sander
(H) Vertical polisher

time domain, the vibration is described in the frequency domain, and this is especially useful for complex vibration. In addition, it is conceptually the same process as used for noise. The analytical method used to resolve a complex signal into each of its frequency components is called spectral analysis.

In noise, the energy is reported in frequency bands with center frequencies f_m that progressively increase as a power of 2, or by an octave. These types of filters are known as octave band filters. One-third octave band filters provide more frequency resolution by dividing each octave into three bands. Field instruments to perform a spectral analysis are reasonably accessible and quite suitable for industrial ergonomics applications.

The power spectra in Figure 8.10 correspond to the tools in Figure 8.8. Observe the strong dominating spectral peaks for the hand grip orbital sander (A), the jitterbug sander (G), and the vertical polisher (H). Additional peaks at frequencies greater than the fundamental peaks are observed for harmonic frequencies for most of these tools.

Resonance

When a simple mechanical system is initially excited by a transient force of shock and left to freely vibrate, it oscillates at a single sinusoid frequency known as its natural frequency (f_n), also called the resonant frequency. When the mechanical system is excited at a different frequency, it responds differently for different frequencies of excitation. When the excitation frequency is much less than the system natural frequency, the system motion follows the driving motion closely. When the excitation frequency approaches the natural frequency, the system motion responds disproportionately to the excitation motion. This phenomenon is called resonance. A system in resonance often vibrates with an acceleration many times greater than the excitation acceleration at the natural frequency. This is why it is important to avoid exposing humans to frequencies where anatomical structures of the body may go into resonance. As the excitation frequency increases beyond the natural frequency, the movement is attenuated. This relationship is important in the design of mechanical vibration isolation systems that limit vibration transmissibility from the source.

Evaluation of Human Vibration

Human vibration measurements are normally evaluated using one of two methods. The first compares the RMS acceleration at each one-third octave against reference levels for each center frequency and for the total daily duration of vibration exposure. If any of the spectrum components exceeds the maximum RMS amplitude permitted for a given duration, the guideline is exceeded. This type of analysis is used in the ISO 2631 standard and ACGIH

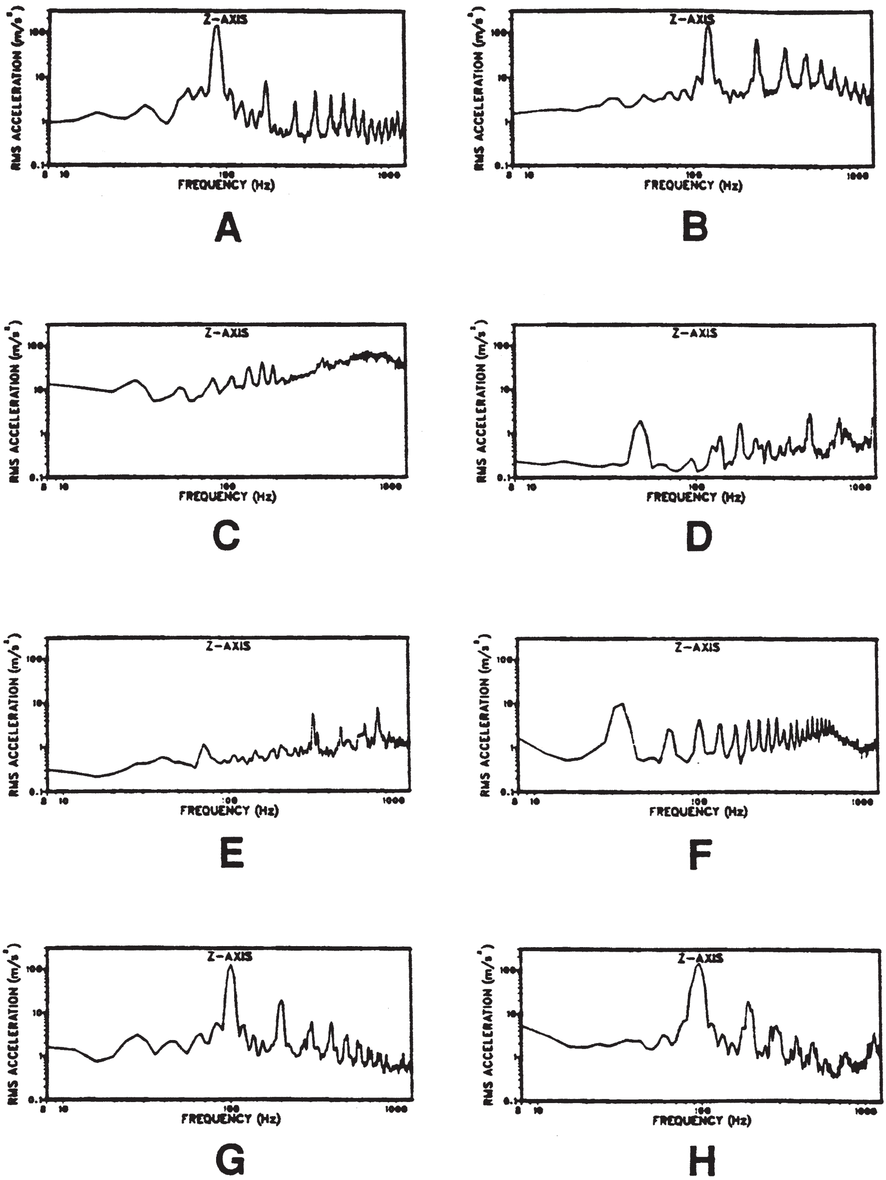

FIGURE 8.10 Representative power spectra for eight representative vibrating industrial power hand tools in the z-axis (from Radwin, Armstrong, and Van Bergeijk 1990)

(A) Hand grip orbital sander
(B) Palm grip orbital sander
(C) Impact wrench
(D) Heavy-duty right-angle sander
(E) Trimming shear
(F) Light-duty right-angle sander
(G) Jitterbug sander
(H) Vertical polisher

threshold limit value (TLV) (ACGIH 2002) for whole-body vibration, and for the ISO 5349 and ANSI S3.34 hand and arm vibration standards. This analysis method necessitates having equipment for measuring the vibration and its spectrum. Spectrum analyzers run the gamut from very expensive and sophisticated digital systems to relatively inexpensive adaptations of sound level meters. For a detailed understanding and analysis of vibration, these instruments and the associated frequency component analysis have great value.

The second evaluation method is the one that is assumed for this chapter. It involves summing all of the vibration spectrum frequency component amplitudes using a frequency-weighted sum. The weighting factors emphasize the frequencies near the resonant frequency of the body, and play down the effects of vibration proportionately as it moves farther away from the resonant frequency. Each center frequency of the spectrum is assigned a specific weighting factor that is multiplied by the associated one-third octave frequency RMS amplitude component, and all of the frequency-weighted RMS amplitude components are summed together as the root sum of squares. The weighting factors can be found in some of the publications mentioned in this section. The frequency-weighted sum is compared against standard levels for a given daily exposure time. If the frequency-weighted sum is greater than the reference level, the exposure guideline is exceeded. This method is used as an alternative analysis for the ISO 2631 whole-body vibration standard and for the ACGIH TLV for hand and arm vibration. This type of analysis can be accomplished using spectrum analysis equipment that performs the summations electronically, thus making it as straightforward as the use of as a sound level meter. The particular weighting filter network used depends on whether measurements are for whole-body vibration or for hand and arm vibration. In the case of whole-body vibration, different weighting filters are used depending on the direction of the vibration measurement, which means that the z-axis in particular must be carefully aligned along the length of the spine.

Common to most human vibration exposure, analyses is an accurate assessment of daily occupation exposure time to vibration. This analysis should include a time history of vibration exposure, accounting, as far as possible, for variations in intensity of vibration and any interruptions in vibration exposure that may occur in the period in question, normally on a daily basis. Such a study can be conducted in a manner similar to that for a time and motion study. Sufficient time data should be recorded so that the total daily exposure time estimate is statistically valid. The time-weighted average is based on the root time-weighted sum of squares of the acceleration, as described here:

$$\left(a_{eq}\right)=\left[\frac{1}{T}\sum_{i=1}^{n}\left(a_i\right)^2 T_i\right]^{1/2}=\sqrt{\left(a_1\right)^2\frac{T_1}{T}+\left(a_2\right)^2\frac{T_2}{T}+\ldots+\left(a_n\right)^2\frac{T_n}{T}}$$

where $T=\sum_i T_i$, T is the total daily exposure duration and a_i is the *i*th frequency-weighted RMS acceleration component with duration T_i.

Whole-Body Vibration Exposure Guidelines

Continuous RMS acceleration measurements are made using accelerometers in the three basicentric coordinate axes simultaneously and recorded for at least one minute. The criteria in whole-body vibration standards are most restrictive at human vibration resonance of 4 to 8 Hz for the z-axis (foot to head) and in the 1 and 2 Hz frequency range for the x-axis (front to back) and y-axis (side to side). These guidelines are not intended for building vibration, for offshore structures, or in ships.

There are three different exposure criteria contained in the ISO 2631 standard for whole-body vibration. These include exposure boundaries that are intended to preserve comfort (reduced comfort boundary), fatigue-decreased proficiency, and health and safety (exposure ceiling limit). These limits are illustrated in Figure 8.11. Fatigue-decreased proficiency means that vibration exposure exceeding those boundaries is regarded as having a significant risk of impaired working efficiency in numerous tasks, particularly those in which time-dependent effects of fatigue are known to reduce performance, such as driving a vehicle. Occupational exposure limits such as the ACGIH TLV are usually based on the fatigue curve. The remaining two criteria are proportional to the fatigue-decreased proficiency boundaries. Reduced comfort is the level at which exposure makes it difficult to carry out operations such as eating, reading, or writing. The health and safety exposure limit corresponds to twice the acceleration levels for the fatigue-decreased proficiency boundary. The health and safety limit should be treated as a ceiling limit, with no exposure above it.

Hand-Arm Vibration Guidelines

The American National Standard Guide for the Measurement and Evaluation of Exposure to Vibration Transmitted to the Hand (ANSI S3.34) reports vibration exposure measurements as vibration spectral data for one-third octave band RMS acceleration in meters per second and as an overall frequency-weighted RMS acceleration. The standard assumes that there is good coupling between the tool and hands, combined with relatively uninterrupted exposures. For time-varying exposures, averaging based on task analysis as described above must be performed. The overall exposure should not exceed the ACGIH TLV curve shown in Figure 8.12. The action limit curve is based the recommendation of Pelmear and Leong (2000). These guidelines may not be sufficient to protect against some musculoskeletal disorders, such as carpal tunnel syndrome.

Vibration Reduction and Control

Vibration exposure can be reduced using two general approaches. These include methods aimed at controlling vibration at the source, path, and

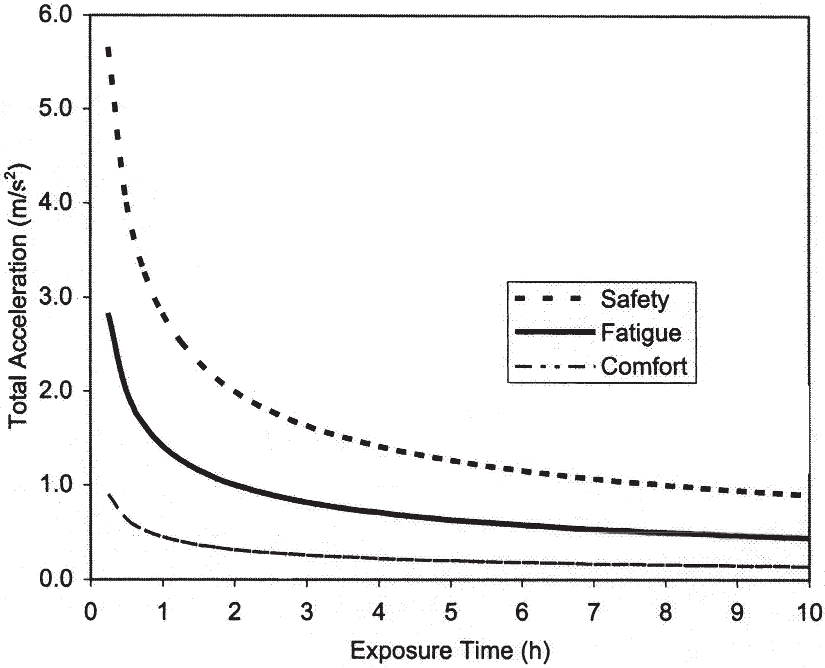

FIGURE 8.11 Recommended exposure limits for whole-body vibration based on a combined-axis, time-weighted root mean average based on comfort, fatigue, and health and safety limits. Total exposure time is compared to the allowed time associated with the acceleration as determined from the appropriate curve.

receiver. In addition, a conscientiously applied medical surveillance program is appropriate.

Source Control

Limiting vibration at the source is the most direct way to control exposure. Source control identifies the vibration origin and responds appropriately to reduce it. Occupationally, this translates to using equipment that has the least vibration. For instance, select power grinding tools that are designed to have the least frequency-weighted RMS acceleration. For example, grinder vibration may be reduced by using grinding wheels that are better balanced, or using abrasives that cause less vibration. Of course, it is important to also consider that changing the abrasive may increase the amount of time needed to perform the grinding task, therefore reducing the vibration amplitude but consequently increasing the exposure time. It may also increase the force needed, which has additional considerations.

Whenever practical, alternative processes that reduce vibration or eliminate the need for using vibrating equipment entirely are the most effective way of controlling exposure. For example, if parts that are currently deburred

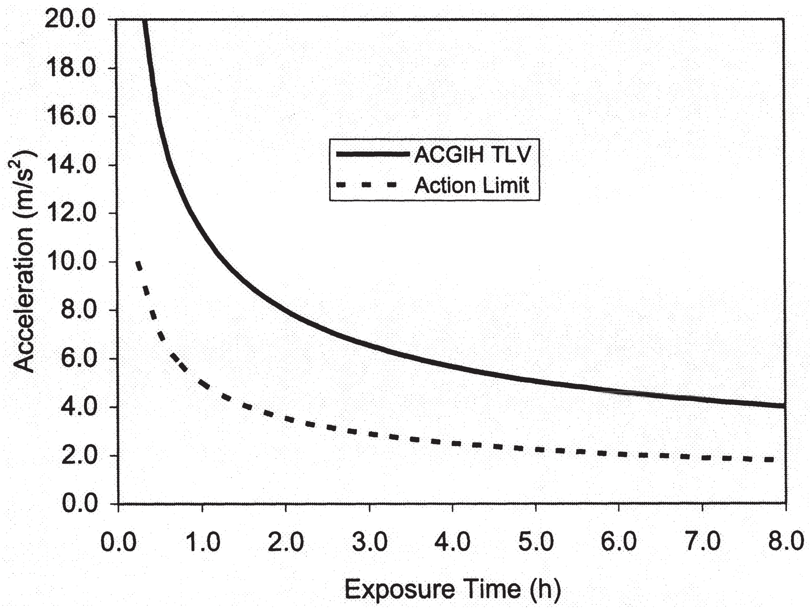

FIGURE 8.12 Recommended exposure limits for hand-arm vibration based on a combined-axis, time-weighted root mean average based on TLV and action limits. Total exposure time is compared to the allowed time associated with the acceleration as determined from the appropriate curve.

using a dye grinder can be manufactured using a process that avoids burrs, the grinding task is not necessary.

The vibration exposure standards and guidelines described earlier in this chapter show that exposure limits are dependent on vibration frequency as well as amplitude. Consequently, it may be possible to have two power hand tools that have similar vibration amplitude, but one has less frequency-weighted acceleration because it operates at a faster speed and hence produces higher-frequency vibration. Sometimes the frequency of the vibrating source can be altered independently of amplitude in order to reduce vibration exposure, by increasing rotational speed, changing gears, or other modifications.

Path Control

Path control reduces vibration exposure by acting on the interface between the human and the vibrating object. The most common method is by interposing a vibration isolation system between the vibrating source and the human. An example is shown in Figure 8.13. It is not always possible to add a vibration isolation system because it could make the tool too cumbersome to handle. When the vibration source has frequencies that are relatively low (less than a few hundred Hertz), isolation systems are very difficult to design.

Gloves are often more effective as vibration isolators for high frequencies, but they are less suitable as vibration isolators for low frequencies. The mate-

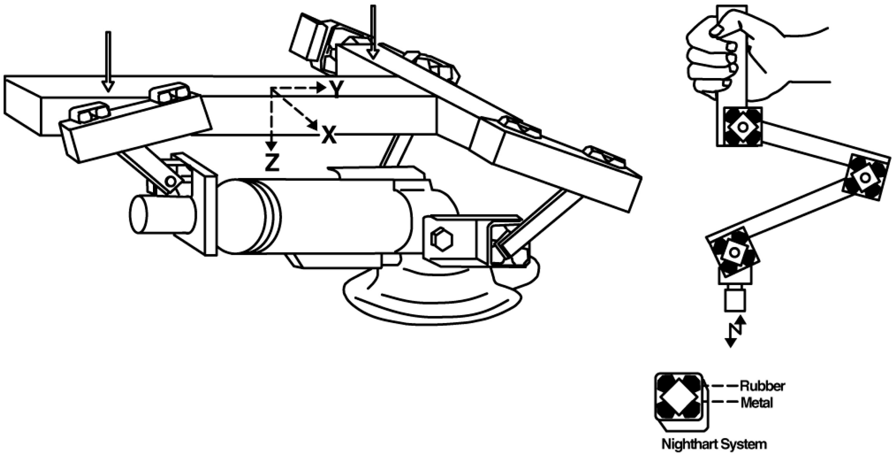

FIGURE 8.13 Conceptual drawing of an isolation system for hand and arm vibration (adapted from Radwin, Armstrong, and Van Bergeijk 1992)

rials used in many vibration isolation gloves are often very viscous, which provides damping. In practice, gloves are quite difficult to effectively match for specific vibration isolation purposes.

Another path control method is by reducing the coupling between the vibration source and the human. This can sometimes be achieved by reducing the weight of the objects being held or by improving the handles using large gripping surfaces, high-friction material, and flanges for better distributing the forces in the hands.

Receiver Control

The most common method is using administrative measures to limit the time that an operator is exposed to the vibration source. This may be accomplished by providing rest or through worker rotations. The various exposure standards and limits discussed in this chapter can provide guidance with regard to the amount of exposure time that is appropriate based on vibration measurements. As the case with most administrative controls, this is the least desirable method, because it depends on adherence and limits an operator's productivity by limiting time at a given task involving vibration exposure.

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Appendix A
Case Studies

In this section problems typical of those seen in industry are analyzed by using information contained in previous chapters. The primary ergonomics principle of concern is identified after each problem is described, and the methods for evaluating the human capacity or capability data in relation to the job demands are outlined. Although solutions for the problems are given, similar problems in different conditions may suggest other approaches.

A large number of the examples discussed here are based on a manufacturing environment. The problems encompass both new designs and the redesign of existing workplaces or jobs. For new designs the ergonomics practitioner can often use directly the guidelines given in this book. For existing designs the book's guidelines may be used to evaluate how close the situation is to the recommended design. The ergonomist must combine this information with data on the number of people affected by the design, the cost of redesign, and the impact on people's safety and health to determine the course of action.

WORKPLACE DESIGN: SEATED WORKPLACE

How can a camera assembly workplace be modified to reduce complaints of sore arms and shoulders by operators working a full shift?

Background

In a camera assembly job, the operators are lined up on each side of a conveyor belt. Parts are provided in trays or bins placed around them. The line is run over multiple shifts. The parts supply is adequate for a couple of hours, the forces required are minimal, and the parts are small. Most operators sit to do the work.

The assembly process is split into two parts. One operator builds up half a camera and places it on a 10-cm-high (4 in.) ramp on the right to feed to the next operator. As the camera often does not slide down the ramp, the operator has to push it along the ramp. The next operator finishes the assembly and places the camera on a conveyor belt in front of him or her to be sent to an automated turntable for further processing.

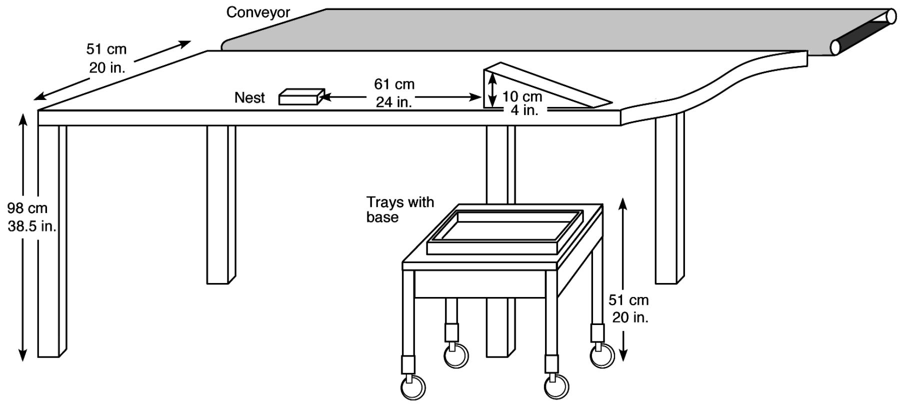

Figure A.1 Camera Assembly Workplace

The work surface is fixed at a height of 98 cm (38.5 in.) to match the conveyor height. The conveyor height is fixed to match the height of the automated turntable it feeds. The workbench is about 2.5 cm (2 in.) thick. The distance from the center of the workspace to the ramp is 61 cm (24 in.). The distance from the front end of the table to the conveyor is 51 cm (20 in.).

The base for the camera is provided in trays stacked on a 51 cm (20 in.) high cart next to the workbenches.

Ergonomic Principles and Information Used to Solve the Problem

Sore arms and shoulders suggest that static loading of these muscle groups is occurring. The static loading is probably associated with the need to reach to the side or forward to place the finished product from each station. The discussion of sitting and standing workplaces in Chapter 3 indicates that the assembly task could be a seated task. However, the height of the workstation and the reaches required make the workstation design more suited to a sit/stand workstation. The critical factor is that the operators prefer to sit and work.

To improve the workstation to enable the operators to sit and work, the following sections of the book include the information necessary:

- General workplace layout and dimensions (in Chapter 3)
- Sitting Workplaces (in Chapter 3)
- Seated Workplace Height (in Chapter 3)
- Anthropometric Data (in Chapter 1)

Based on the principles discussed in the above sections, it is apparent that the operators need adjustable footrests to enable them to sit comfortably and work. It is also clear that the reach to the side (to the ramp) and forward (to the conveyor) is greater than that recommended for frequent tasks.

Conclusions

The following modifications can be made to decrease the risk of shoulder and arm complaints at these workstations:

- Install adjustable footrests (range 28 to 46 cm or 11 to 18 in.) to enable most operators to sit comfortably at these workstations.
- Decrease the reach from the center of the workspace to the side ramp to less than 41 cm (16 in.) and increase the slope of the ramp (raise the height to 15 cm or 6 in.), and decrease the friction characteristics of the ramp to help the cameras slide down easily.
- Decrease the reach to the conveyor to less than 35 cm (14 in.).

WORKPLACE DESIGN: STANDING WORKPLACE

There have been some concerns around the space and layout of the workstations in a packing and shipping area. Back and shoulder problems are reported by the operators.

Background

This workstation is part of a warehouse that picks and packs orders. Once the items are picked, the operators at the packing workstation pack them into boxes for shipping. The boxes are pushed down a conveyor, at the end of which is the metering station, where the boxes are weighed, labeled, stamped, and palletized.

Cardboard boxes for packing are placed on shelves that are above and behind a table that is 86 cm (34 in.) high and 107 cm (42 in.) long and 61 cm (24 in.) wide. The shelves go up to 165 cm (65 in.) from the floor. The boxes stored on these shelves are of different sizes; their maximum depth is 51 cm (20 in.). There are about twenty-five different sizes of boxes. The table is placed at right angles to the conveyor, and once the box is packed, it is lifted up and placed on the conveyor. The boxes can weigh up to 18 kg (40 lbs).

Ergonomic Principles and Information Used to Solve the Problem

The following sections of the book include the information necessary to analyze the work station design and decrease the risk of back and shoulder problems:

- General Workplace Layout and Dimensions (in Chapter 3)
- Standing Workplaces (in Chapter 3)
- Anthropometric Data (in Chapter 1)

Because of the forces/weights associated with this task, it is better suited to a standing workplace. Because the size of the boxes vary, the worktable should have an adjustable height, to help set the top of the boxes close to elbow height for each operator.

Based on the reach envelope for the 5th percentile working population, the shelves used for storing the boxes are beyond the recommended guidelines. For 50 percent of the population, 61 cm (24 in.) is full arm's length, indicating that half the operators would have to lean forward repeatedly to pick up the empty boxes. This could contribute to or aggravate disorders of the back. The boxes can be up to 51 cm (20 in.) deep, so the operators could be packing at 137 cm (54 in.), close to shoulder height. This could increase the stress on the shoulders and elbows.

Conclusions

The following modifications can reduce the risk of back and shoulder problems:

- Relocate the packing table to be in front of the conveyor instead of at right angles to it. Place a height- and angle-adjustable packing table in front of the conveyor. This will allow the operator to push the packed box onto the conveyor rather than lift and turn to place it.
- Provide a height and angle adjustment mechanism for the packing table.
  - The height adjustment will allow each operator to set the packing table height so that the top of the box is close to elbow height. Once the box is packed, the operator can raise the table to match the height of the conveyor. At this height, the operator can push the boxes onto the conveyor, rather than lift them.
  - The angle adjustment will allow the operator to tilt the boxes toward him or her when packing, decreasing the reach into the box.
- Store the stack of empty cardboard boxes in a vertical lazy-Susan type of storage system. This increases the space used for storage while keeping the access points at a location that is convenient for the operator.

CONTROLS PROBLEM

What type of control and force criteria should be used for activating a bench garment ticketing machine? At present, there is a push button and the operators of the machine are experiencing hand and wrist pain.

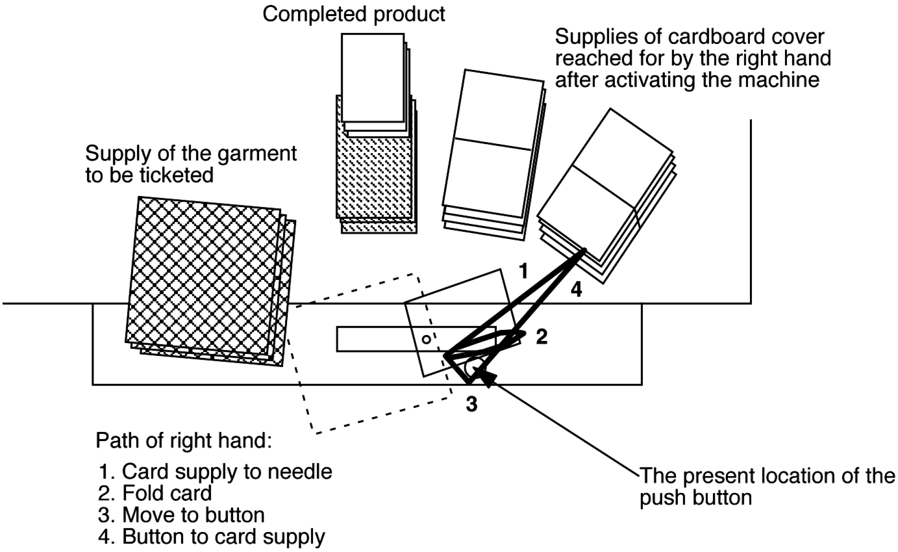

Figure A.2 Diagram of a garment ticketing machine illustrating the original push button activator and the path of the right hand during a cycle, including operating the push button. Note the sharp side turn of the path of the hand to the push button.

Background

The ticketing machine is air-pressure-driven and fires a tag through the edge of clothing and the cardboard that describes the garments, so as to hold the items together. The cardboard has a hole or hook at the top by which the clothing item may be hung in the store for sale. An operator stands to perform the task. The operator assembles the bundle of clothing by laying the card over the needle sheath, placing the garment next, then folding the cardboard over the top and holding it with the left hand. The operator uses the right thumb or finger to push a small push button to activate the machine, sending a tag through the bundle. The movement to operate the push button is awkward and entails marked deviation of the wrist caused by the location of the control. Often the button is under the packaging card that is being attached (see Fig. A.2 for a schematic of the original layout). Various sizes of garments and cards are assembled at these workstations, and the task is performed at a high repetitive rate.

Human Factors Principles and Information Used to Solve the Problem

Several operators performing the operation were videotaped and observed. A detailed task analysis was conducted to determine how the control was activated and to identify the movement patterns involved with activation in relation to the other steps of the task cycle. The force to activate the push button was measured at 29 N (6.45 lbf) with a force gauge. However, this was when using high air pressure for the machine. With decreased air pressure the activation force was 20 N (4.5 lbf).

"Types of Controls" in Chapter 4 provides recommended design force values for different controls. Push buttons are described in Table 4.9. The recommended resistance or force to activate a push button with finger activation is a minimum of 3 N (0.6 lbf), maximum 11 N (2.5 lbf). Whenever high frequency is involved, the lower values should be taken.

In addition to the push button requiring a high activation force, several other factors in the existing design increased the forces exerted by the operators.

- The push button was small at 1.0 cm (0.4 in.) and therefore demanded more precise movement to ensure it was pressed. Table 4.9 provides recommended diameters for finger activation and palm or thumb activation. The minimum recommended diameter is larger for thumb use at 1.9 cm (0.75 in.).
- The location of the control was too close to the operator and provoked an awkward side movement that opposed the natural arcs of movement the operators used to accomplish the rest of the task.
- The control was too close so that the operators' wrists were deviated when activating the control, which increases the exerted force. The center of the push button was 2.5 cm (1 in.) from the edge of the table and approximately 13 cm (5 in.) from the body, close to the operators' body.
- A lack of sufficient feedback from the control provoked the operators to press the button harder than necessary to ensure that it was activated. As discussed in the controls section, the displacement of a control should be appropriate, and there should be either a tactile, auditory, or visual feedback of effect of activation, or a combination of these effects. The feedback that was present with the push button was the noise of the needle after the button was released; there was no tactile sense of the button being adequately pressed to activate the machine, such as a slight gradual increase of resistance until there is no resistance at full displacement of the button, so all the operators pushed be button even harder than was needed.

In summary, the issues are:

- High force to activate the control
- No feedback of the push button
- Poor location of the control
- Poor choice of control for the task.

Several different types of controls that could be used for the task initially appear feasible. A finger beam switch that would activate the machine when a beam is broken by a finger would be quick and require no force; however, it would be too easily activated by accident and prevention would not be feasible without locating it out of the work envelope. A larger push button would require less accuracy and would be a possibility. The minimum resistance would prevent inadvertent activation. A small lever switch would be better than a push button, as the movement to activate it would be horizontal and within the natural arc of movement toward picking up the next card for a bundle. The design values would be set at the minimum recommendations, as shown under toggle switches in Table 4.9. The switch would be spring-based to return to the original position after activation.

Cycle time and productivity data should also be collected as in any detailed analysis. Increased productivity is anticipated if the switch is more efficient to use.

Conclusion

Change the type of control from a small push button to a small finger lever switch of approximately 3.5 cm (1.5 in.) with minimum resistance forces, but feedback for activation and a spring-based return. Set the location so that it is within the arc of movement within the task, within comfortable reach but beyond the area where most of the products lie when being tagged. This would be approximately 20 cm (8 in.) from the location of the push button, well within a 38 cm (15 in.) reach for the operator. The supplies just beyond the lever should be at about 38 cm (15 in.), as they are accessed frequently. See the section on work envelopes for more detail of this principle. Figure A.2 illustrates the original push button location and Figure A.3 the recommended lever position. The numbered thick lines show the path of the right hand during a cycle.

TOOL DESIGN: OPENING A CLAMP TO HOLD A HOSE ON A WASHING MACHINE DRAIN

Background

Assembly operators on a washing machine production line have to put a 30 cm (12 in.) length of polyethylene hose on the drain outlet and clamp it in place. The first assembler slides the hose onto the drain, and the next assembler uses a large set of reverse pliers (squeezing the handles together opens the pliers jaws) to spread the heavy wire spring clamp and place it on the hose about 2.5 cm (1 in.) up the drain interface. These operations are done on a moving conveyor line, so the clamp assembler usually loads the clamp in the tool before the washing machine comes into the station. It takes about 8 seconds to do each operation if all goes well. Durations of up to 20 seconds have been measured when the clamp fell out of the pliers or when the

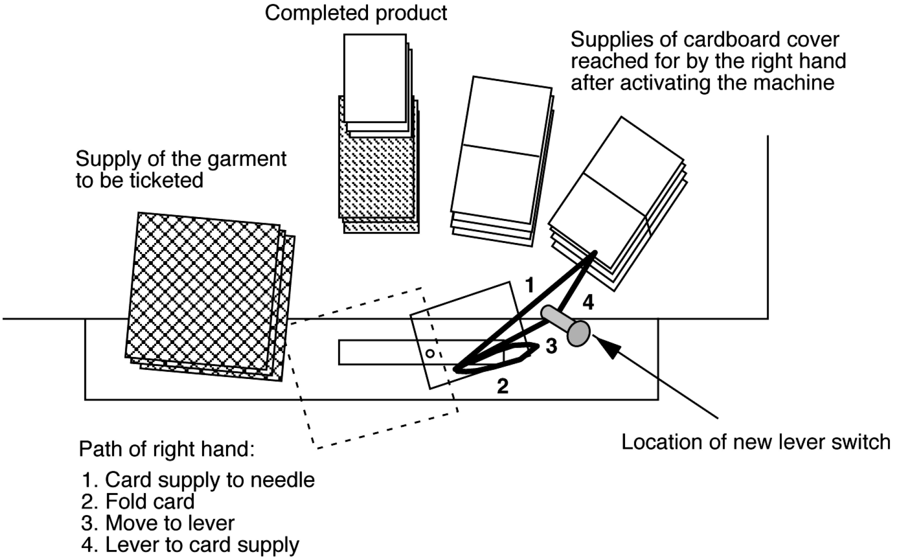

Figure A.3. Diagram of a garment ticketing machine illustrating the lever activator and the path of the right hand during a cycle, including operating the lever. Note the smoother and shorter path taken by the hand going via the lever.

hose did not fit well on the drain. A new washing machine comes into the station every 12 seconds. The clamp pliers handles are 18 cm (7 in.) long with a span of 10 cm (4 in.) at the point where pressure is applied to open the clamp. People who do the clamp assembly job have all experienced significant discomfort in the forearm, elbow, wrist, and hand on the side that holds the tool.

Ergonomic Principles and Information Used to Solve the Problem

The ergonomic issues are related to both the tool design and the job design. The tool is designed with a wide grip at the pressure application point (10 cm or 4 in.), where most workers will lose about 40 percent of their power grip strength (see "Design and Selection Recommendations for Hand Tools" in Chapter 4). To open the clamp is a maximum effort for most workers, and because of the loss of strength associated with the grip span, all but a few workers will be working close to their maximum strength each time they open a clamp.

Observing the assemblers on the assembly line and timing the holding times at high effort on the clamp assembly showed that the average holding times were 4 seconds with a range from 2 to 6 seconds. Lighter effort was used in the rest of the cycle of 12 seconds before the next washing machine came into the station. The fatigue and work-recovery patterns of this work shows an accumulated fatigue of about 1 second per cycle (see “Special Considerations: Design of Ultra-Short-Cycle Tasks” in Chapter 6) if the holding time is 4 seconds, or 5 seconds per minute on a line where a new machine comes into the station every 12 seconds. If the holding time increases to 6 seconds, a situation observed in about 15 percent of the cycles measured, the accumulated fatigue per minute of work (5 machines) increases to 50 seconds. The assembler will not be able to sustain the latter pattern of work for more than a few minutes. There will be a tendency to try to work faster in order to reduce the holding time at the very heavy effort level, and there will also be an increased possibility that the clamp will fly out of the tool and possibly cause an injury to the assembler.

Conclusion

In evaluating the assembler’s clamp positioning task, it was agreed that the holding time had to be reduced at the heavy effort level. The repetition rate for a maximum grip force of 5 times a minute for less than 6 seconds each (see “Rodgers Muscle Fatigue Assessment” in Chapter 2) left inadequate time for muscle recovery. Because the likelihood was low of being able to slow down the line to give the assembler more recovery time, the ergonomics team decided to develop a tool that would hold the clamp open until the tension was released by the assembler. Although the assembler still had to open the clamp initially, that holding time was less than 1 second before the tool took over and stabilized the clamp in the open position. When the next washing machine came into the station, the assembler had to place the clamp over the hose and slide it to the junction with the drain, press the release button, and pull off the clamping tool. The cycle effort time dropped to 4 seconds, leaving 8 seconds for recovery time before the next washing machine arrived, compared to 8 seconds of effort time and 4 seconds of recovery time. This change was successful both in reducing the musculoskeletal discomfort of the assemblers and in making it easier to place high-quality clamps on the hose/drain interface. As part of the tool modification, the designers were able to bring the grip span for the reverse pliers down to 3 inches, so the power grip strength was not reduced as much as it had been on the 4-inch-span tool. Because of the heavy wire clamp’s thickness, the effort was still a heavy one, but it was about 10 percent less heavy with the smaller span tool.

TOOL DESIGN: BENCHING (GRINDING) METAL PARTS TO REMOVE BURRS AND BEVEL EDGES

Background

Operators working on a seated subassembly task were shaping the edges of metal parts and removing burrs from them by placing them in a holding fixture and running them up against a rotating grinding disk. This had been considered a good job, but one of the longer-service employees began to develop signs of carpal tunnel syndrome and tendonitis. This occurred shortly after a change was made in the grinding disk supplier and after a directive went out to get maximum utilization of the sandpaper disks by using them until they were only 5 cm (2 in.) in diameter (from a starting size of about 10 [4 in.] in diameter). It is possible to overbench in this job and to have to rework the part if this happens. About 25 percent of the parts had some rework after the disk supplier was changed. At that time, orders were not as strong, and they handled the rework as a regular part of their job. An analysis of several benching cycles showed that the benching done with the new disks was taking 40 percent more time than the same work done with the old grinding disks. When the disks got down to a diameter of 6 cm (about 2.5 in.), benching time on the parts increased compared to when it was done with the larger-diameter disks, and there was more rework needed.

Ergonomic Principles and Information Needed to Solve the Problem

The data gathered on cycle times for benching a part using the old disks and new disks and using the disks from two different vendors led the ergonomics team to evaluate the grit on each disk and the backing materials. Because none of the subassemblers had experienced symptoms before the disks were changed, it was hypothesized that the disks required different forces or precision for the benching work. Although there were several ways to improve the working postures of the people doing this subassembly task, they resisted workplace design changes because they were accustomed to sitting close together and socializing. They identified the new disks as the problem because they knew that they were doing much more forearm work now. Working with small disks increased the possibility for overbenching the part, and this had become a more significant part of their total workload. See "An Ergonomics Problem-Solving Technique" in Chapter 1 to see how the problem-solving process can be used to identify root causes of injuries and illnesses.

Conclusions

In a discussion of this problem with departmental supervision, it was found that the vendor had been changed because the new vendor had a wider array of grits and paper-backed disks. The subassemblers demonstrated the problems they had with paper-backed disks breaking down, especially when the metal parts had prominent burrs on them. The canvas-backed disks performed much better, even with the smaller disk size, although one saw diminishing returns when the disk size fell below 5 cm (2 in.).

Based on this input, the production supervisor decided to specify the canvas-backed disks for the benching operation. The just-in-time ordering strategy was changed to be sure that there would be enough disks available so that the people doing the benching work would not be forced to use the disks with a diameter of 5 cm (2 in.) or less. Making this change resulted in more comfort on the task, faster benching times, higher productivity when the orders went back up, and a successful return to work of the sub-assembler who had been restricted because of her forearm, elbow, wrist, and hand pain. This problem illustrates the importance of evaluating the ergonomic impact of making a cost-cutting change in the workplace without considering its effect on human performance.

THE DESIGN OF SHORT-CYCLE JOBS

Background

A packaging line for frozen stuffed baked potatoes is being set up, and there is concern about the potential for musculoskeletal injuries and illnesses in workers operating the line. The frozen stuffed potato halves are packaged two to a box, and the line rate is 30 boxes per minute. The workers take the product off large trays, drop them into the molded plastic that sits in the bottom of the box, and, after an inspection station, close up the box and send it on to the automatic casing machine. Each case holds ten boxes of two stuffed potato halves and weighs about 9 kg (20 lb.). At the end of the casing machine, a worker removes the case after stamping a date on it and puts it on a pallet. The maximum required palletizing rate is 3 per minute, and the worker usually inventories ten cases on the line before putting them on the pallet. This worker is also responsible for keeping the casing machine supplied and for repairing minor problems on it.

Currently there are plans for hiring seven people to run this packaging line, and it is assumed that they will all be capable of doing all of the jobs and can rotate between them on a schedule of their own choosing. The line will run for the full 8-hour shift.

Based on the desired production rate and crew size for the packaging line, is there any risk of exceeding ergonomic guidelines for safe repetitive work with the upper extremities?

Ergonomics Principles and Information Used to Solve the Problem:

The seven people will probably be distributed between the tasks on the line as follows:

- One person who sets the boxes on the conveyor lines with their tops open
- One person who supplies the trays of frozen stuffed potato halves to the line
- Two people who put the potato halves in the boxes on the line
- One person who inspects the product and removes defects
- One person who closes up the boxes
- One person who monitors the casing machine and palletizes the cases

To identify if there are ergonomic problems on the line, one has to know what the work patterns are and how paced the workers are at each location. We will assume that the trays of potato halves are placed perpendicular to the conveyor line on which the boxes are traveling and that the movements are lateral transfers to the boxes taking about 2 seconds each. The two box fillers work across from each other and each fills his or her side of the box.

Based on the line rates:

- The box setter has to place boxes on the line at a rate of 30 per minute using mostly pinch grips and light efforts.
- The potato supplier has to handle 2 to 3 trays per minute to the loaders and also has to keep the frozen potatoes supplied from the freezer to the line.
- The potato loaders have to transfer one stuffed potato half every 2 seconds with a moderately heavy effort because of the wide grip.
- The inspector has to inspect 60 halves per minute but does not have to handle them, and has to remove defects at a rate of about 1 every 2 minutes on a bad day.
- The box closer has to use several fine finger movements per box at a rate of 30 boxes per minute.
- The caser monitor and palletizer has to palletize at a rate of about 3 per minute, on the average, and has to supply the caser with corrugated and label stock every half hour. This worker also stamps a date on each case, a moderate hand stress.

Based on the rates, it appears that the hardest jobs on the line are the box setter, potato loaders, and the box closer. This is because they are working at rates of 30 boxes per minute, and their motion times are equal to the time they have to do each task. Consequently, they will accumulate fatigue in their distal upper extremities, especially their fingers, quite rapidly and need a recovery activity to reduce the fatigue. The rate of 30 muscle efforts per minute does not allow much muscle relaxation between boxes, so blood flow will not be fully reestablished until the activity is stopped. The Moore-Garg Strain Index in Chapter 2 can be used to determine the risk of musculoskeletal stress on these jobs. The Rodgers Muscle Fatigue Assessment will underestimate fatigue of the hands and forearms because it is only accurate up to 15 exertions per minute.

The other three jobs can be analyzed using several of the methodologies in Chapter 2, with the Rodgers Muscle Fatigue Assessment giving some quantification of the amount of recovery time they would provide for people coming off the other four jobs. The lightest of these jobs is the inspection of the potatoes before the boxes are closed. However, it is perceptually very demanding because there is only 1 second per item available to pick up a defect, and if a defect has to be removed, it is likely that some of the product will not be inspected during that time.

Conclusion

A conclusion from the data can be that there is little spare capacity available to several of the workers on this line. It may be acceptable when the line is running well, but it will be a problem if there are quality problems with the product or the packaging elements. Either the labor allocation has to be increased to cover potential problems on the line, with a backup for the people tied directly to the machine pace, or the line may have to be run at a slower rate. Ergonomically, it is recommended that low-tech automation be used to load the boxes on the line and to close them before the casing machine. That should free up at least one more worker to assist the loaders and provide a "floater" who can fill in when needed.

Another ergonomic approach that would take some of the load off the upper extremities of the potato loaders and could assist the supply person would be to form a hopper/chute from the trays to the conveyor. In that case, the potatoes can be handled into the boxes from directly above them, not moved laterally from the trays on the side of the conveyor. Because damage to the product would not be tolerated, this approach would have to be made gentle enough to simulate the human hand.

Other types of semiautomation could be considered on these jobs, but the human touch is important in the presentation of food, and the goal of the design of this line would be to assist the people, not replace them. The preferable approach is to free up more people to handle the food by reducing the number of people who are working with the supplies.

MANUAL MATERIALS HANDLING: FORCE EXERTION

Background

A receiving department handler was experiencing low back, arm, hand, and shoulder pain associated with transferring palletloads of parts to a production department on the other side of the plant. It took approximately 6 minutes to move the pallet manually on a floor pallet truck between the receiving department and the assembly department, including 2 minutes waiting for and using the freight elevator to the second floor. The manual pallet truck pulling was done in 2 minutes of continuous work on either side of the elevator ride. Along the route, there were several cracks in the concrete floors and a ramp with a 20 percent grade that led to a door that opened out on the ramp through which the handler had to pull the load.

A push-pull gauge was used to measure the forces used to pull the pallet truck when it contained a fully loaded pallet and when it was returned to receiving with an empty pallet on it. The results of the tests where one-handed horizontal pulling was done were:

- Force to pull the loaded pallet truck when stationary and with the wheels out of alignment from the direction of pull = 289 N (65 lbf)
- Force to pull the unloaded truck with an empty pallet on it = 200 N (45 lbf)
- Force to sustain the motion of the loaded pallet truck = 200 N (45 lbf)
- Force to sustain the truck motion with an empty pallet on it = 111.2 N (25 lbf)
- Force to pull the loaded truck over a crack in the floor = 378 N (85 lbf)
- Force to pull the loaded truck in and out of the elevator = 378 N (85 lbf)
- Force to pull the unloaded pallet and truck over cracks and into elevators = 289 N (65 lbf)
- Force to pull the loaded pallet truck up the ramp without stopping first = 422.6 N (95 lbf)
- Force to pull the loaded pallet through the door at the top of the ramp (from a stopped position near the top of the ramp) = 533.8 N (120 lbf)

Could the people who set up the job requirements in this plant have anticipated the discomfort felt by the handler? What are the largest contributors to the handler's discomfort, and how can they be addressed to reduce the stress on his or her back, shoulder, arm, and hand during pallet handling?

Ergonomics Principles and Information Used to Solve the Problem

Guidelines for force exertion when pushing or pulling manual carts and trucks are given in Design of Force Exertion Tasks in "Manual Materials Handling" (Chapter7). The recommended starting force is 222 N (50 lbf), and the force to sustain motion for 1 minute continuously is 111 N (25 lbf). An emergency stop force can be up to 356 N (80 lbf). Comparing the values collected on this activity, it is clear that the starting forces are too high except when the pallet is empty and that the sustained forces are much too high for a 2-minute sustained pull. A 2-minute effort would have to use a force that is about 40 percent of the maximum effort that can be applied, so 890 N (20 lbf) of force would be appropriate for this job. Even pulling the empty pallet on the floor did not reach this guideline value. Overall, it is clear that moving the parts on a manual pallet truck from one end of the plant to the other is not ergonomically appropriate.

The worst situation measured in this study was the 533.8 N (120 lbf) effort to pull the loaded pallet through the door at the top of the ramp near the assembly area. The 20 percent grade of the ramp and the door that has to be opened out on the ramp almost ensure that the handler will be working with a twisted trunk while pulling the truck through the door, a high risk for a back muscle overexertion injury. A guideline in “Floors, Ramps, and Stairs” in Chapter 3 suggests that powered equipment is needed to negotiate ramps that are more than 15 degrees from the horizontal. Palletloads may not be stable enough to go up a steep ramp, especially when there is a door at the top.

The shoulder soreness experienced by the handler on this task appeared to be related to the need to corner the loaded pallet truck when moving it before and after the elevator ride and when positioning it on the elevator. Although the forces remain the same unless one gets into an awkward position during the turn, the shoulder muscles are taking much of the load. They are only about 40 percent as strong as the horizontal pulling muscles (back and upper arm muscles and body weight all participate in exerting those forces), and they also contribute to twisting of the trunk during the cornering.

In summary, the use of a hand pallet truck to deliver parts to the assembly area from receiving should be reconsidered because it requires too much strength for the time the force is exerted and fatigues the back, shoulder, arm, and hand muscles significantly. Pulling the loaded truck through the door at the top of the ramp is an especially risky activity, because it requires very high pull forces and comes at a time when the handler’s muscles re already fatiguing.

Conclusions

When using the problem-solving process to define the root cause of this job’s risk factors, it was found that the task is done about once per shift and that a palletload of parts will usually last more than one shift in the assembly department. The vendor delivers two pallets of parts each morning, and after that is received, one pallet is taken to the assembly floor and the other is stored in receiving until the beginning of the second shift.

The freight elevator is in the middle of the building, and the receiving and assembly departments are almost equidistant from it. There are other assembly and packaging departments on the second floor near this assembly department that also have to be supplied from the receiving department, and the long travel distances have been of concern to them as well. A series of alternatives should be generated by the receiving and assembly people as well as by the facilities and maintenance specialists to determine how to improve materials flow in the plant. A few examples might be:

- Set up a marshaling area for parts destined for the distant departments near the freight elevators in the center of the building. Pull the pallet-loads from there instead of from the receiving department so that less continuous effort is required on each transfer.
- Try to find a better way to deliver the parts that does not require the use of the ramp into the assembly area. If this is not feasible, put an automatic door on the entrance at the top of the ramp so that it can be opened from the bottom position. Provide a motorized winch to assist the handler in pulling the loaded truck up the ramp.
- Consider using a "walkie" or stacker to move the loaded pallets if a forklift truck cannot be used in some of the areas. This would reduce the load on the handler and help with the ramp handling as well.
- Consider having the parts shipped into the plant on a mobile cart that can be pushed instead of pulled. This would reduce the load on the shoulder, especially, and would keep the parts more separated than they would be on a pallet. In addition, there would be less likelihood that the parts would be handled near the floor because they would not be on pallets. Push-pull forces would have to be within the guidelines set forth in Chapter 7, "Manual Handling in Occupational Tasks," and this could be done with a well-designed, adjustable handcart (see "Horizontal Forces Away from and Toward the Handler: Handcart and Truck Design Guidelines").

If a new plant is built or the old one is renovated, one of the driving design goals should be to place the receiving and shipping departments as close to the production departments as possible so that the distances for handling parts and product are minimized

GLOSSARY OF TERMS

The terms listed here are commonly used in industrial ergonomics work. This glossary is intended primarily to assist the reader in understanding the terms found in this book. For a more comprehensive listing of ergonomics and human factors terms, see K. North et al., *Ergonomics Glossary* (Utrecht: Bohn, Scheltema, and Holkema, 1982), available through International Publications Service, 114 East 32nd Street, New York, New York 10016

50-50 Mix: equal numbers of men and women for a hypothetical design population. The capabilities of each separate population are combined statistically to estimate the percentage of the 50-50 mix accommodated by a given design. It is most commonly used in applying anthropometric and strength data to workplace, task, and equipment design.

Abduction: movement of a limb away from the body's midline axis, such as elevating an elbow or raising an arm to the side.

Absenteeism Rate: the number of days lost from work out of the total workdays scheduled, usually measured over a year. It can be calculated for an individual or for a group of workers and is usually expressed as a percentage.

Acceptable Load: the amount of weight a person chooses to lift in a specific container for a defined time period at a specific location. In psychophysical experiments, the handler determines this amount by adjusting the weight of the container to an amount that appears suitable for the duration of the lifting task.

Accommodation of Workers: the design approach that matches job task demands to the capabilities of the workforce so that most people can perform the required work. It can also be the provision of aids, such as platforms or step stools, and tools that permit people to fit the design even if the original design is not suitable for their size or strength.

Acromial: of or pertaining to the distal shoulder above the upper arm. The acromion provides a bony crest from which anthropometric measurements of the shoulder and arm are often made.

Acromion: the distal shoulder above the upper arm. It is the bony crest from which anthropometric measurements of the shoulder and arm are often made.

Adaptation: adjustment to conditions in the environment. In biological rhythms, an adaptation is an adjustment in amplitude and phase in response to altered hours of work, specifically night shift work. Adaptation to temperature changes is referred to as acclimatization.

Adduction: movement of a limb toward the midline axis of the body, such as moving an arm across the front of the body.

Adenosine Triphosphate (ATP): a chemical compound that stores phosphate in high-energy bonds and makes it available for chemical reactions in cellular processes such as muscle contraction. When the energy is released, ATP becomes adenosine diphosphate (ADP) or adenosine monophosphate (AMP).

Administrative controls: changes in the way that work in a job is assigned or scheduled, that are designed to reduce the magnitude, frequency, or duration of exposure to the risk factors for musculoskeletal disorders.

Aerobic Metabolism: the breakdown of foodstuffs to carbon dioxide and water in the presence of oxygen. Large amounts of adenosine triphosphate (ATP) are produced in this process, which supports muscle activity and body processes such as growth, hormone secretion, and tissue repair.

Anaerobic Metabolism: the breakdown of starch or sugar molecules to lactic and pyruvic acids in the absence of oxygen. Small amounts of adenosine triphosphate (ATP) are produced in anaerobic metabolism, but the accumulating lactic acid eventually limits useful work by causing severe muscle fatigue.

Anthropometry: the study of people in terms of their physical dimensions. It includes the measurement of human body characteristics, such as size, breadth, girth, and distance between anatomical points. It also includes segment masses, the centers of gravity of body segments, and the ranges of joint motion, which are used in biomechanical analyses of work and postures.

Arbitrary Work Breaks: interruptions in work that are not scheduled and do not relate directly to the primary tasks. They are often used to release the worker from prolonged short (1 to 2 minutes) and include getting a drink of water, visiting the lavatory, talking to another worker, or taking a short walk in the corridors. If rest breaks are scheduled regularly on a highly repetitive or paced job, arbitrary work breaks are virtually eliminated.

Arm Work: physical effort that takes place in locations that can be reached without bending the knees or the trunk frequently. For example, work on a counter that is at least 90 cm (35 in.) high and does not require reaches more than 38 cm (15 in.) in front of or to the sides of the body will be done primarily by the muscles of the arms, shoulders, and upper trunk. Arm work capacity, or upper body work capacity, is about 70 percent of whole body aerobic work capacity as measured in a standardized treadmill stress test.

Asymmetric Lift: a manual handling task where the hands do not share the load equally, either because the object being lifted is not symmetrical or because the posture assumed does not permit equal use of the hands. Asymmetrical loads usually put more load on the back and upper limb muscles (for the same weight) and can increase the risk for overexertion injuries.

Atlanto-occipital Joint: the place where the vertebral column joins the cranium.

ATP: *see* Adenosine Triphosphate

Automation: the use of machines or mechanical devices to perform a stereotyped task automatically. In the automation process, the worker becomes machine monitor rather than task performer.

Axis of Rotation: *see* Fulcrum.

Ballistic Lifting: a style of lifting during which large forces are developed early in the load displacement so that the resulting momentum will assist in completion of the lift.

Biceps (Biceps Brachii): a long muscle on the ventral (front) side of the arm that flexes, reducing the elbow angle of the forearm.

Biomechanics: the application of mechanical principles, such as levers and forces, to the analysis of body part structure and movement. This includes studies of range, strength, endurance, and speed of movements, and mechanical responses to such physical forces as acceleration and vibration.

Body Segment: a portion of the body that falls between two joints (such as the upper arm, forearm, upper trunk, lower leg) and that can influence the body mechanics in postural or manual handling activities.

Body Weight (BW): the mass of the body and the force with which it is attracted to the earth by gravity. It is expressed in kilograms in the SI system and pounds in the English system. Oxygen consumption is expressed per kilogram of body weight in order to normalize workload measurements.

Boredom: a state of weariness associated with performance on a tedious or monotonous task. It is an individual response, varying among individuals for the same work.

Bulk Materials: raw materials or products that are not packaged for the trade; includes many construction supplies and large bags or boxes of food or chemicals.

Bursitis: inflammation of a bursa, a sac found near a joint such as the shoulder or knee. The inflammation is attributed in some cases to excessive use of the joint.

Candelas per square meter (cd/m^2): a measure of luminance (emitted or reflected light) obtained by means of a photometer. High values usually indicate a source of glare. In SI units 1 cd/m^2 = 0.29 foot-lamberts (fL).

Capacity: the maximum ability of a person to perform in a given set of conditions. Aerobic work capacity will vary with the number of muscle groups involved and environmental conditions. A person's strength capacity is known as a maximum voluntary contraction and will change with joint angle and the duration of application, among other factors.

Carboy: a large glass or plastic bottle surrounded by a wooden case that protects the bottle during transport. Caustic or corrosive liquids, such as sulfuric acid, are often stored in carboys.

Carpal Tunnel Syndrome: entrapment of the median nerve of the hand and wrist in the passageway (tunnel) through the carpal bones of the wrist. It usually results in numbness in the fingers and pain on gripping and may be accompanied by changes in electromyographic (EMG) patterns and nerve conduction velocities, indicating a pressure block of the nerve.

Caster: a wheel or set of wheels mounted in a swivel frame. They are attached to trucks, furniture, and handcarts to permit easier movement.

Center of Gravity: the center of mass of an object that determines its symmetry and ease of handling. The centers of gravity of limb segments are used in biomechanics to determine torque around joints.

Chiming: turning a cylindrical container, such as a metal drum or a compressed gas tank, on the edge of its bottom rim (chime) to move it between locations. An alternative to using a drum cart.

Circadian Rhythm: a physical measurement, such as body temperature, or a chemical response, such as the excretion of catecholamines, that varies periodically over 24 hours.

Clo Unit: a measure of the thermal insulation provided by clothing. One clo is 0.16 degrees Celsius per watt per square meter of body surface area. The 0.16 becomes 0.18 if watts are changed to kilocalories. As clothing is added to the body, the clo value increases and it is more difficult to lose heat to the environment.

Combination Shift Schedules: work hours that use more than one type of shift schedule. For example, combining a rapidly rotating shift with weekly rotating shifts or mixing five and seven-day shift schedules to cover a department that needs more than a five-day shift schedule but less than a full seven-day schedule. Combination shifts are often used instead of fixed overtime schedules.

Comfort Rating: a psychophysical measure of the degree of well-being experienced by a person in a specific set of environmental or task conditions. Used to assess local muscle and joint stress in handling activities, or to rate environmental temperature and humidity conditions.

Compact Load: an object that is comfortably handled within 25 cm (10 in.) of the front of the body with the arms spread no more than 50 cm (20 in.) apart. It is usually not more than 30 cm (12 in.) deep.

Compatibility: the consistency with which a response meets human expectations. For controls and displays, the consistency of the operator's movement of a control compared to its displayed response.

Compressed Workweek: defined as a work schedule that is less than five days long, such as four 10-hour days or three 12-hour days.

Compressive Force: a force that is applied perpendicular to a surface; for example, the pressure placed on the intervertebral discs because of forces generated during lifting or maintaining a posture.

Concentric Muscle Contraction: shortening of the muscle as it exerts force against a resistance, as in elbow flexion. *See* Eccentric Muscle Contraction.

Confounding Factor: a variable that appears at the same time as the effect of one variable on another response is being studied. It makes interpretation of the data collected less easy because the confounding factor may interact with the other variable being studied. Physical work may confound studies of the effect of time of day on body temperature levels, for example. *See* Hawthorne Effect.

Contingency: a possible but not certain condition or event. Job design must consider contingencies but should not be totally determined by them.

Continuous Work: a workload, such as the exertion of a muscular force, that is sustained and uninterrupted. In dynamic work, it is the sustained pattern of work without rest or light effort breaks. Continuous work, especially when the work is demanding, results in earlier fatigue and less productivity than does intermittent work.

Contrast: the brightness relationships of two nonspecular adjacent surfaces viewed under the same illumination and in the same immediate surroundings.

Control: a mechanical or electronic device that directs the action of a mechanism or produces a change in the operation of a system or process.

Critical Defect: a flaw in a product or subassembly that will make the product function improperly or not at all.

Cross-sectional Area: the surface exposed when a muscle is cut transversely, perpendicular to its axis. The amount of force a muscle can generate is proportional to its cross-sectional area.

Cumulative Trauma Disorder (CTD): one of the many terms used to describe a special category of musculoskeletal disorders. A CTD is typically the result of an accumulation of stressors, rather than the result of a one-time event. Examples are tendonitis, tenosynovitis, carpal tunnel syndrome, epicondylitis (elbow), and bursitis. Other commonly used terms are *repetitive motion disorder* or *repetitive stress/strain disorder*.

Cursor: a moving element on a display. It is used to show the desired position or error on an instrument, and, on visual displays, to mark row and column positions or to indicate where the next activity will occur.

Cycle Time: a time interval during which a regularly recurring sequence of events is completed. It can be the time to complete a task with many elements or the time to complete a single operation in a repetitive task.

Cylindrical Grip: the contact of the hand with an object where the palm and fingers hold the object securely and the angle of curl of the fingers is similar. The thumb is not essential for a cylindrical grip.

dBA: decibels on the A-weighted scale, which de-emphasizes frequencies less than 1,000 Hz. A measurement of sound pressure level, most commonly used to assess the noise exposure of workers.

Decibel: a logarithmic scale often used to express quantities of sound or electrical power, relative to a specified reference level.

Decrement in Performance: a decrease in human proficiency on a task. It may be associated with fatigue, distraction, or discomfort. It is characterized by increased errors and misjudgments, omission of task elements, and reduced intensity of effort.

Defect: an imperfection, fault, or deficiency in a product or part that will influence the product's performance. There are several levels of defects, from ones that are more cosmetic than functional, to ones that are critical and may affect product safety. Inspectors have to learn to recognize defects and to remove that product before it goes on to the next workplace or the customer.

Desynchronization of Rhythms: the disruption of a normal rhythmic relationship between a physiological measure and the time of day, caused by a changed behavior or activity pattern. For example, a person who rotates weekly among day, afternoon-evening, and night shifts may experience desynchronization of body temperature, heart rate, hormonal, and sleep rhythms for the first part of the week on the night shift.

Detectability: the quality of a signal, display, stimulus, or error that affects the probability of its presence being perceived.

Displacement: the difference between the initial position of an object and its position at a later time. In biomechanics, the object may be the body or a particular body segment.

Display: the presentation of information from a device or system in a form designed to be seen or heard by the human operator.

Distal: far from the origin; refers to a point farthest from the body's midline. For example, the distal phalanx of a finger is the fingertip.

Distraction: an event or condition that diverts attention from the primary task. For example, thermal discomfort, either too hot or too cold, may distract a worker from concentrating on the job's activities.

Double Product: an indirect estimate of the work of the heart, found by multiplying the systolic blood pressure, in millimeters of mercury, by the heart rate, in beats per minute.

Drum Cart: a two- or four-wheeled vertical carrier, possessing a hook to grasp the top rim of a metal drum and a narrow platform to slide beneath the drum.

Dynamic Muscle Work: muscle contraction where muscle length changes during activity, resulting in motion around a joint. Most handling and assembly tasks are accomplished with dynamic work. *Also see* Static Muscle Work.

Dynamic Visual Acuity: the measure of visual acuity used when the object being observed moves with respect to the operator.

Dynamics: the biomechanical aspects of the human body in motion.

Dynamometer: a device for measuring the force of muscle contraction; for example, a hand grip dynamometer measures power grip strength.

Eccentric Muscle Contraction: muscle force exertion while the muscle is being forcefully lengthened, thereby counteracting its normal shortening. This occurs when a muscle is under an external load that exceeds its ability to exert force, as in trying to lift a too-heavy object.

Efficiency: the effectiveness with which a task or operation is done; usually measured in energy spent, cost, or time required. For muscular work, efficiency is a measure of how much of the energy is translated into useful mechanical work compared to the total amount: mechanical plus that dissipated as heat. Most muscle work is less than 25 percent efficient.

Effort, Physical: the amount of muscle work performed on a job, often referred to as the physical workload. It is often defined by the number of objects handled per shift, their weight, the distance they are transported, and how long the task is performed.

Effort Equivalencies: a way to categorize the physical effort levels of various industrial tasks according to the percentage of maximum work capacity that they usually require. This permits recognition of similarities in effort levels when, because of the amount of muscle mass involved, different amounts of aerobic work capacity are available. For example, the same energy expenditure that would be heavy work in an arm task is only moderate work in a whole-body task because arm work aerobic capacity is only 70 percent of whole-body aerobic capacity.

Electrogoniometer: an instrument used to measure angles. It is placed across a joint, such as the elbow or wrist, with each arm of the instrument aligned over a major bone on either side of the joint. As the joint angle changes, the instrument transforms the change to an electrical signal, which can be recorded throughout the work cycle to measure the biomechanics of the task.

Electromyography: a scientific technique for recording the electrical activity of muscles. In ergonomics, it is used to evaluate the active muscle groups in various job studies, and is especially useful when qualitative, not quantitative, measures are needed.

Endurance: the ability to sustain an activity over time. For example, muscle endurance is described by the length of time a muscle force can be held. Dynamic work endurance is described by the amount of time a given level of aerobic work can be sustained.

Energy Expenditure: the power used during activity or rest. It is usually expressed in watts, in kilocalories per minute or hour, or in milliliters of oxygen per kilogram of body weight per minute (ml O_2/kg BW/min).

Engineering controls: physical changes in the job or product that reduce the operators exposure to risk factors for musculoskeletal disorders.

Environment: the circumstances, conditions, and influences that affect the behavior and performance of people in the workplace. Physical factors such as noise, vibration, lighting, temperature, humidity, and airflow are important environmental factors in job design.

Equilibrium: the point at which all forces are balanced and there is no movement. Static equilibrium in the biomechanical analysis of a lifting task is achieved when the torque tending to rotate the body forward is counteracted by a torque in the opposite direction.

Ergonomic Design of Jobs: the use of principles relating people's capacities to job demands in the assignment of tasks and levels of effort required in a job. Designing jobs so that a large majority of the potential workforce can do them without risk of injury or illness.

Ergonomics: the study of the design of work in relation to the physiological and psychological capabilities of people. One of several terms used to define similar fields of interest; others are *human engineering, human factors,* and *human factors engineering*. Ergonomics has been used predominantly outside of the United States. The aim of the discipline is the evaluation and design of facilities, environments, jobs, training methods, and equipment to match the capabilities of users and workers, and thereby to reduce the potential for fatigue, error, or unsafe acts.

Error Rate: the number of mistakes or omissions per unit time or per number of pieces or actions. For example, the number of defects missed per 100 units inspected or the number of improperly recorded readings per 8-hour shift are two types of error rate. Ergonomic job design intends to reduce the opportunities for error and thus reduce the error rate.

Extended Hours: defined as additional hours worked per shift compared to the standard 8-hour work day. Ten- and 12-hour shifts are extended-hours schedules, even if the total hours per worker per week do not exceed 40. Longer work shifts and overtime have implications for the development of fatigue in physically demanding jobs and for the adjustment of exposure times in environments where chemicals, heat, cold, noise, and other physical factors may be present.

Extension: the straightening of a joint whereby the angle between adjacent bones usually increases. Exceptions are extension of the foot and of the wrist.

Fatigue: the reduction in performance ability caused by a period of excessive activity followed by inadequate recovery time. Could be either mental or physical. Muscle fatigue is accompanied by a buildup of lactic acid in the working muscle.

Feedback: the return of the effects of a given action or process to its source. In ergonomics, it refers to information about an activity that is passed back to the operator for evaluation and, if necessary, adjustment of the activity. For example, feedback on product quality can influence the performance of an assembler or inspector.

Flexibility: the ability to adjust to changing conditions. During absences caused by illness or vacation, it is easier to cover a job if the population capable of performing it has not been limited too severely by the job design. Management has more options and, therefore, more flexibility if more people have the needed skills or capacities.

Flexion: the bending of a joint whereby the angle between adjacent bones usually decreases.

Flextime: a work schedule, usually on the day shift, that requires employees to be at work for the core hours usually between 10 A.M. and 3 P.M., with the remaining work hours being chosen according to individual needs or work preferences. Each person is expected to work 40 hours per week. The schedule has been successfully applied in white-collar jobs in Europe and the United States.

Font: an assortment of printer's type, with characters of all one size and style.

Foot-candle (fc): in the English system of measurement, the measure of illuminance, or light falling on a surface. It is measured with an illumination meter laid on the surface of interest. One foot-candle is equal to 10.8 lumens per square meter (lux) in the SI measurement system.

Foot-lambert (fL): in the English system of measurement, a unit of luminance (emitted or reflected light). It is measured with a photometer pointed at the surface of interest. High values indicate possible glare sources in the workplace. One foot-lambert is equal to 3.43 candelas per square meter in the SI system.

Footrest: a support used primarily in sitting workplaces to help accommodate differences in the size of workers and relieve postural stresses.

Force: a push or pull, defined as mass times acceleration, that an object exerts on another object. It is measured in newtons (N) or pounds of force (lbf). *See* Torque.

Force Arm: in a lever system, that part of the lever between the axis of rotation (fulcrum) and the point of application of muscle force.

Force Transducer: an instrument that, most commonly, converts the deformation of a piece of metal into an electrical signal or a needle movement, thereby quantifying the deforming force. Strain gauges and push-pull gauges are force transducers.

Forklift Truck: a powered, open vehicle having two horizontal prongs, often about 90 cm (36 in.) long, which are adjustable vertically and sometimes horizontally. The forklift truck is used to handle pallets of materials or products and can be adapted to handle metal drums, large containers, or other materials.

Frequency of Lifting: the number of lifts made per minute or other short time period. It should be related to the distribution of rest or recovery periods in order to determine the intensity of the workload.

Fulcrum: the axis of rotation for a lever. In the human body, the joints serve as fulcrums for the body's lever system.

Gastrocnemius: the largest and most external muscle in the calf.

Glare: a sensation produced by a luminance within the visual field that is sufficiently greater than the luminance to which the eyes are adapted. It can produce annoyance, discomfort, or distraction of the worker, or a reduction in visibility of the object of regard.

Gravity (g): a measure of acceleration expressed as a rate of change of velocity per second. Vertical vibration of the body or limbs is often expressed in g units. Values below 0.3 g are of less concern than those above 1 g, which are associated with vibration illnesses.

Gripping Block: a 5-to-8-cm (2-to-3-in.) wide modification to the sides of a tray that permits a person to get a stable grip for handling. It is used in designing plastic trays because molding requirements make it difficult to use other handle styles.

Gussets: triangular sections in the corners of a bag that give it strength and provide a place for a hook grasp during bag handling.

Handhold: the part of an object that enables it to be lifted or handled manually. It should be designed to provide adequate clearance for the hand and should have rounded edges that do not concentrate the object's weight on a small part of the fingers.

Handling: lifting, lowering, conveying, pushing, pulling, or sliding an object in order to move it from one place to another. If the motion is powered by a person's muscles, it is termed *manual handling*.

Handling Aids: devices that aid a person in moving an object from one location to another. Examples are hoists, scissors tables, conveyors, hooks and clamps, and handcarts or trucks.

Hawthorne Effect: refers to a study at the Hawthorne plant of Western Electric Company that illustrated a confounding factor in work studies in which the attention paid to the workers was considered to have a profound effect on the success of the workplace intervention.

Heart Rate: a physiological measure of the frequency with which the heart contracts. Expressed in beats per minute, it can be used as an estimate of job stress, workload, or environmental stress.

Heat Stress: the physiological load induced by working in a hot environment. Heat stress produces increased heart rate, body temperature, and sweat rate, and often increases an operator's feelings of fatigue. Severe heat stress can produce exhaustion or heat stroke.

Heavy Effort: physical work that can be sustained for only 1 hour or less; also the handling of objects weighing more than 18 kg (40 lbm) and the application of forces greater than 250 newtons (56 lbf).

Hertz (Hz): the unit for frequency, in cycles per second, in the SI system. 1 Hz = 1 cycle per second. Noise levels are expressed in hertz for specific frequency bands when an octave band analysis of a workplace or product is done.

Hue: the attribute of color determined primarily by the wavelength of light entering the eye. Spectral hues range from red through orange, yellow, green, and blue to violet.

Human Operator: a person who participates in some aspect of the operation or support of a system and its associated equipment and facilities.

Humerus: the long bone of the upper arm.

Humidity: the atmospheric water vapor pressure. It can be measured with a natural wet bulb thermometer, a sling or electric psychrometer with a wetted thermometer covering, or with a relative humidity meter.

Hyperextension of the Spine: extension of the trunk beyond the upright position, forming a more extreme backward arch and changing the distribution of pressure on the spinal discs. Seen, for instance, in work done above shoulder height. May aggravate back pain symptoms in susceptible people.

Incentive: in work situations, usually refers to a pay plan whereby performance above the standard level for a job is financially rewarded up to some fixed level, often 115 percent. It can be an individual incentive, as on some piecework tasks where performance is measured by the number of good units produced per shift by an individual worker, or it can be a group incentive, where the performance of a production team or a department is rewarded.

Incident: an event, action, or situation whose occurrence or near-occurrence is noted. In safety research, it may be an accident, a near-accident, or an illness.

Indicator: an instrument or device for displaying task-related information such as location, speed, pressure, or overload. Indicators may be mechanical, electrical, or electronic; examples of each are pointers, warning lights, and visual display units.

Inferior: lowermost or below. For example, the foot is inferior to the ankle.

Information: a quantitative property of a group of items that enables them to be categorized or classified. The amount of information in a group is measured by the average number of operations needed to categorize the items. Examples of operations are statements, decisions, and tests.

Innervate: to supply nerves to a part of the body.

In-Process Inventory: the buildup of products or parts on or just off a production line, permitting individual workers some control of their work pace. For example, 2 to 3 minutes of in-process inventory space at the supply and takeoff ends of a production machine can give the operator more flexibility in loading and unloading the machine.

Input: the information or energy entered into a machine or system that is the quantity to be measured or otherwise operated upon. Also called *input signal*.

Intensity-Duration Relationship: the observed pattern that the longer a physical workload is sustained, the less percentage of maximum work capacity or strength is available for use. This is important both for static work where the available percentage of maximum voluntary strength is reduced as holding time increases and for dynamic work where the available aerobic work capacity is affected.

Interface: the common physical boundary between an operator and the equipment used, such as a control, display, seat, or workbench.

Intermittent Work: physical effort (usually moderately to highly demanding) that is interrupted regularly by short rest or light work periods lasting a few seconds to a few minutes. These rest periods permit the muscles to replenish their oxygen and energy stores and to reduce their accumulation of lactic acid.

Isokinetic: exerting muscle force at a constant velocity in a dynamic task.

Isometric Muscle Work: force that is developed without significantly changing the length of muscle fibers. Because there is no motion associated with an isometric contraction, no external work is done. Static muscle work, such as maintaining a posture or holding on to an object, are examples of isometric muscular contraction. The workload can be estimated by measuring the force required, relating it to the maximum force available, and determining how long it must be sustained.

Isotonic Muscle Work: *see* Dynamic Muscle Work.

Job Analysis: a study to determine and identify duties, tasks, and functions in a job, together with the skills, knowledge, and responsibilities required of the worker. It is accomplished through measurement, observation, and interviews.

Job Demands: the physiological, psychological, and perceptual requirements of a job that determines the suitability of a given workload for the potential workforce.

Job Design: the arrangement of tasks over a work shift, whether in terms of the distribution of light and heavy physical work or the arrangement of rest breaks in a mentally or perceptually demanding task, such as visual inspection. Good job design reduces the opportunities for fatigue and human error.

Job Restriction: a medical response to helping an injured or chronically ill person return to work. Specific tasks or jobs that would tend to aggravate the illness or injury are designated as not suitable for that person. The restriction exists as long as the condition remains.

Job Rotation: the movement of a worker from one defined task to another, particularly when more than one workstation is involved.

Job Satisfaction: a multidimensional psychophysical measure that compares and rates a person's opinions about job requirements to individual goals for meaningful work.

Job Sharing: an agreement between the employer and two employees that a job can be accomplished by having two part-time workers instead of one full-time person. This is often done to accommodate people with young children or who are attending classes.

Joule: a unit of work or energy in the SI system; equal to approximately 0.25 calories, 107 ergs, or 0.7376 foot-pounds.

Kilocalorie: the amount of heat required to raise one kilogram of water from 14°C to 15°C; 1,000 calories. It is used to express workload and the energy value of food when it is oxidized in the body. One kilocalorie per minute equals approximately 70 watts or 0.2 liters of oxygen per minute.

Kilojoule (kJ): the measure of work or energy in the SI system; 1,000 joules or approximately 0.2 kilocalories.

Kilopascal (kPa): the measure of pressure in the SI system of measurement. It is equal to 1,000 newton-meters or 0.15 pounds per square inch.

Kinematics: a dynamic biomechanical analysis dealing with the descriptive aspects of movement without considerations of mass or force.

Kinesthesis: a person's sense that informs the brain of the movements of the body or of its members and their location in space. This awareness of movement is accomplished through activation, usually by pressure or stretch, of special receptors in the muscular tissue, tendons, and joints.

Kinetics: in biomechanics, the study of the forces that influence movement of the human body.

Lactic Acid: a three-carbon acid ($C_3H_6O_3$) formed in the breakdown of a glucose molecule if sufficient oxygen is not available to complete the degradation to carbon dioxide and water. In the blood, lactic acid takes the form of sodium lactate. High muscle and blood levels of lactate accompany exhaustive exercise.

Lateral: toward the side of the body away from the midline in a plane parallel to the midsagittal plane that divides the body into right and left halves.

Learning: any change in behavior or performance that occurs as a result of teaching, practice, or experience.

Legibility: the ease with which a label, document, or display can be read and understood. The design and size of characters, contrast, illumination, color of characters and background, and construction of textual information all affect legibility .

Light Assembly Tasks: work with low energy expenditure demands that is often performed in a seated position. Muscles of the hands, arms, and shoulders are usually most actively involved in these tasks, and the repetitiveness of the work can be high.

Light Effort: physical work that can be easily sustained for at least 8 hours a day; also the handling of objects weighing less than 5 kg (11 lbm) and the application of forces less than 100 newtons (22.5 lbf).

Load, Sensory: the number and variety of stimuli requiring operator response. For example, the load on the visual system is greater if several different classes of stimuli must be discriminated than if only one or a few types are present.

Long-Term: occurring over or lasting a relatively long period of time. It can be a change that takes years to become apparent, such as an illness associated with psychological stress.

Lost Time Illness or Injury: time lost from work that is associated with an illness or injury sustained at work. Lost time usually indicates a more serious injury or illness, but it may also reflect a lack of alternative work. Low back pain and wrist soreness are among the leading occupational contributors to lost time in industry.

Loudness: the attribute of auditory sensation by which sounds may be ordered on a scale extending from soft to loud. The unit for measuring loudness is the sone.

Lumbar Disc: the intervertebral discs between the lumbar vertebrae in the back. They are usually under the greatest stress when a person is lifting, bending forward, or sitting in a slumped posture without back support.

Lux: a measure of illuminance, or light falling on a surface, in the SI measurement system. It is measured with an illumination meter that is set directly on the surface of interest. Low values may be problematic in difficult visual tasks such as detecting low contrast defects in a product. One lux unit is equal to 0.09 foot-candles.

Maintainability: the design of hardware, software, and training to match the capabilities and characteristics of maintenance personnel. Guidelines for the design of instruments and fasteners, manual and visual access to equipment, efficient handling, ease of use of tools, identification of parts, and consideration of experience and knowledge are covered under maintainability.

Maneuvering a Handcart or Truck: moving a vehicle in a limited space and turning it, using changes in direction rather than pushing or pulling in a straight line. This method of maneuvering usually limits the acceptable forces for moving a handcart or truck.

Manual: operated or done by people rather than by machine.

Manual Dexterity: the ability to manipulate objects with the hands. Various degrees and types of dexterity have been identified through tests. There are three primary types: fine finger or precision dexterity, tweezer dexterity, and gross hand dexterity. The latter involves more of the physical hand and is much less precise than the other two.

Masking: the amount by which a sound's threshold of audibility is raised by the presence of another (masking) sound, as in white noise. It is measured in decibels.

Materials Handling: the movement of parts, raw supplies, chemicals, subassemblies, finished products, or other materials between sections of a manufacturing system or through distribution systems to the customer or client. The movement may be done by hand, as in lifting cases and pushing hand trucks and carts, or with automated equipment or aids, as in using forklift trucks, storage and retrieval systems, or conveyors.

Maximum Aerobic Work Capacity: the highest oxygen consumption rate that can be achieved in a given work situation or on a standardized test. For most healthy people, it is determined by their cardiovascular fitness level.

Maximum Grip Span: the largest distance between the thumb and fingers that permits the exertion of force on an object in a power grip. Grip strength is reduced to less than 50 percent of the strength at an optimal grip span of about 5 cm (2 in.).

Maximum Heart Rate Range: the difference between the predicted maximum heart rate (220 – age) and the resting level as measured under controlled conditions. The range represents the reserve capacity for elevating blood flow and thereby oxygen delivery to the muscles during work. Elevations in heart rate above resting values can be expressed as a percentage of the heart rate range in order to estimate the percent of aerobic work capacity being used on the job.

Maximum Voluntary Contraction: the largest force that can be developed by a muscle or muscle group under a given set of conditions. Joint angle, available muscles, degree of worker motivation, and duration of holding all determine the maximum voluntary contraction strength.

Medial: relating to the middle or center; nearer to the median or midsagittal plane, which divides the body into right and left halves.

MET: a conventional way of describing workloads in relation to the resting metabolic rate; used especially in cardiac rehabilitation. One MET is resting metabolism, usually about 3.5 ml O_2/kg BW/min. Aerobic work capacities of 10 and 15 METs are average values for working women and men, respectively; an average workload of 4 to 5 METs is a moderately heavy to heavy job demand for an 8-hour shift.

Metabolism: the sum of all the physical and chemical processes by which living matter is produced and maintained; also the process by which energy is transformed for use by the body in muscular work and other processes.

Metacarpals: the long bones of the hand located between the wrist and the finger bones (phalanges).

Meter: the standard unit of length or distance in the SI system of measurement; equal to approximately 39.37 inches.

Micropauses: a very short (0.5 to 3 seconds) recovery period during a physically demanding task that allows some regeneration of the energy supply for the working muscles. Heavy work can be sustained for longer periods if it is interrupted by micropauses than if it is sustained continuously until completion. *See* Intermittent Work.

Midsagittal: the plane that divides the body vertically through the midline into right and left halves.

Milliliter (m): 0.001 liter; used to quantify the oxygen used, or the carbon dioxide produced, per minute during rest or work.

Moderate Effort: physical work that can be sustained for about 2 hours without a major work break; also the handling of objects weighing up to 18 kg (40 lbm) and the application of forces up to 250 newtons (56 lbf) for short periods.

Moment: *see* Torque.

Momentum: the product of the mass of an object and its velocity.

Monitor: to observe, listen in on, keep track of, or exercise surveillance over a process or activity; for example, to monitor radio signals, the quality of product in an assembly line, the progress of a chemical reaction, or the manufacturing steps in a production process.

Monotony: lack of variety, sameness; sometimes applied to highly repetitive tasks that require little decision making and that might be done better by machines. Individuals can overcome inherent job monotony with creative "games playing" provided that the games do not detract from the primary task.

Motor Skill: the ability to coordinate movement of hands, fingers, legs, or feet in a smoothly flowing sequence resulting in the performance of some act.

MTM (Methods Time Measurement): a technique for evaluating individual efficiency of motion, especially on highly repetitive jobs; work is broken down into elemental tasks such as "move, grasp, turn." It is used to set production standards in some plants and to identify where new methods can increase productivity. MTM is based on the work of F. Gilbreth in the early 1920s.

Multidimensional Scaling: a psychometric method used to describe stimuli that have more than a single attribute. Examples of such stimuli are foods, which may be evaluated for flavor, appearance, and texture, or photographs, which may be described for color, contrast, exposure, and sharpness of detail.

Musculoskeletal: pertaining to the muscles, bones, and joints.

Musculoskeletal Disorder (MSD): disorders of the muscles, tendons, ligaments, joints, cartilage, nerves, blood vessels or spinal discs. Some examples are muscle strains, ligament sprains, joint and tendon inflammation, pinched nerves, and spinal disc degeneration.

Myositis: muscle inflammation often associated with heavy exertion or repeated use of a muscle group with inadequate recovery time. It is sensed as a sore muscle.

Natural Selection on Heavy Jobs: the process whereby people of lower capacity, whether strength, endurance, or visual ability, move out of the more demanding jobs because they cannot sustain them for the required durations. The difficulty of the job will determine what percent of the people starting it will eventually be able to do it on a full-time basis. In most instances, natural selection is an expensive alternative to ergonomic job design.

Nerve Entrapment Syndromes: any of a group of neuromuscular problems where a nerve is partially blocked as it passes through or across a bony structure. For example, carpal tunnel syndrome is an entrapment of a median nerve in the wrist bones.

Neuromuscular: pertaining to the muscles and the motor side of the nervous system.

Neutral Posture: the position of least stress or highest strength for each joint.

Newton (N): a measure of force in SI units. The force required to move a control, such as a lever, is expressed in newtons. One newton is equal to 105 dynes, approx. 0.102 kilogram-force, and approx. 0.225 pound-force.

Newton-Meter (Nm): a measure of torque (rotational force) in SI units. This measure is used to describe the force needed to rotate a control or turn a wheel. It is also used in biomechanical analyses of movements around a joint.

NIOSH: the National Institute for Occupational Safety and Health, a research institute of the Department of Health and Human Services. Provides information to the Occupational Safety and Health Administration (OSHA).

Noise: unwanted signals that interfere with the detection of desired signals. Noise can be audible, such as voice communications, or visible, as in the case of radar or hard copy.

Noise-Criterion-Balanced (NCB) Curves: any of several versions of criteria such as sound criteria (SC), noise criteria balanced (NCB), or preferred noise criteria (PNC). These criteria are used to rate the acceptability of continuous indoor noise.

Noninvasive Measurement Techniques: methods for measuring the effects of work that do not require penetrating the skin or causing significant discomfort. Examples are the electrocardiogram (ECG), motion detection techniques, and measurements of oxygen consumption.

Oblique Grip: a variant of the cylindrical grasp in which the object is held in the palm along the base of the thumb and the fingers take different degrees of flexion.

Operator Inputs: information received or sensed by the operator from instructions, displays, or the environment.

Operator Outputs: action taken by the operator based on some input, such as the activation of controls or verbal communication.

Operator Overload: the condition in which a person is required to perform more decision making, information handling, signal detection, or muscle work than he or she is able to handle effectively within a given time period.

Optimum Location Principle in Equipment Design: the principle of arrangement of displays and controls so that each is placed in its optimum location in relation to some criterion of use: convenience, accuracy, speed, or force applied.

Overtime: defined as time worked that exceeds the standard hours required of the employee in a week. In the US, if more than 40 hours are worked in a 7-day period, the additional hours are overtime. These hours are usually paid at 1.5 to 3 times standard pay, depending on when they occur; weekend and holiday hours are usually paid at a higher rate than additional hours per weekday.

"Overuse" Syndromes: *see* Repetitive Motion Disorders.

Oxygen Consumption: the rate at which the body, or its tissues and cells, use oxygen. Expressed in liters per minute per unit of body or tissue weight. It is quite consistent from person to person for a given task.

Pacing: controlling a worker's rate of movement through external means, such as a continuous conveyor moving at a fixed speed, production pressures, peer pressure, or pay incentives. Too-rigid pacing can have a negative effect on individual productivity.

Pallet: a wooden or plastic double-sided platform, often 14 cm (5.5 in.) high and 102 × 122 cm (40 × 48 in.) in width and length (U.S.), on which materials are stored and transported.

Parallax: the difference in the apparent position of an object or pointer when a display is viewed from different angles.

Part-Time Employment: working less than 35 hours a week (or the contracted minimum hours) and thereby often being ineligible for certain employee benefits such as full medical coverage or a pension plan. There is usually partial coverage for vacation time.

Pascal (Pa): l Newton per square meter, the unit of measure for pressure in the SI system. 1 Pa = 0.00015 psi.

Pay Differential for Shift Work: the difference in hourly pay between day, afternoon-evening, and night shifts. The night shift generally has the highest pay rate.

Peak Load: the heaviest work done or weight lifted during the shift. *See* Short Duration Heavy Effort.

Perceived Exertion: a psychophysical measure of the amount of effort required for a given action or task. Measured on a 3-, 7-, or 15-point scale, using word descriptions such as "heavy," "very heavy," "light" or "uncomfortable," "slightly uncomfortable," and so on. The work of G. Borg on whole-body and local muscle perceived exertion is the most extensive.

Perception: the process for interpreting sensations. Also, the sensory awareness of external objects, qualities, or relations.

Perceptual Skill: the detection and interpretation of information received through sensory channels.

Perceptual Work: tasks that are done using the senses to gather information and to determine what action should be taken. For example, using auditory or visual information to identify a product or part that is defective, not running to specification, or tending to move out of the acceptable quality range.

Performance Curve: a measure of the accomplishment of a given task against a variable such as time or the number of trials. The task can be measured in a number of ways: the number of acceptable units produced, the time to complete one cycle or to make one unit, the number of errors made, and others. It could also be a measure of the physiological response to a given workload over several weeks of physical training.

Performance Decrement: a decrease in human proficiency that may be associated with operator overload, stress, or fatigue. It is characterized by increases in errors and misjudgments, omission of task elements, and reduced intensity of effort.

Performance Measurement: measuring the effectiveness of an individual on a task or job. Productivity, job performance samples, proficiency and job knowledge tests, and evaluation checklists are used as objective measures. Peer, self, and supervisory ratings are subjective measures.

Period: the reciprocal of frequency (f), or 1/f, measured in units of time per event. For biological rhythms, the period is the time it takes to complete one cycle, usually 24 hours.

Peripheral Vision: the ability to see things to the side; primarily sensed by the rods of the eyes. For optimal perception, an object has to be focused on the cones in the retina's fovea. Peripheral vision is the major pathway for detecting moving defects in inspection tasks; it also plays a major role in providing vision in areas of low illumination.

Personal Protective Equipment: in ergonomics typically are items such as antivibration gloves, knee pads.

Phalanges: the finger bones. The bones nearest the palm are the first phalanges, and the tips of the fingers are the third phalanges. The distal end of a phalanx is farthest away from the palm; the proximal end is nearest. Interphalangeal joints are located between the first and second and the second and third phalanges of the fingers.

Phase Shift: movement of a circadian rhythm's acrophase (maximum value) in time indicating that physiological adaptations are occurring. The amount of change is measured as a phase angle, and this value is used to measure the person's adaptation to external factors, such as shift work.

Physical Effort: the use of muscles to accomplish a task. The amount of effort depends on the number of muscles involved, the intensity of their activity, and the duration of the task. It is measured by the amount of oxygen used (above resting levels) or by the elevation of the heart rate above resting values if there are no major environmental or emotional stressors present.

Pinch: applying pressure between the thumb and the ends of the fingers or the side of the hand (lateral pinch). The strength is about 25 percent that of a power grip. This grip does not involve the palm of the hand.

Popliteal: of or pertaining to the back of the knee, opposite the kneecap.

Population Stereotype: a behavioral sequence that is predictable, or the way most people expect something to be done. For example, rotating an electrical control in a clockwise direction is expected to increase the value of the setting; a design in which a clockwise rotation *decreases* the value would violate the population stereotype.

Posture: the relative arrangement of body parts, specifically the orientation of the limbs, trunk, and head during a work task. Posture can influence productivity since static muscle loading reduces the amount of continuous work a person can do.

Potential Workforce: the distribution of male and female, younger and older workers that could appear at the company's employment office on any given day to apply for work. For convenience, it is assumed that there is an equal probability of men and women (a 50-50 mix) applying, with a wide age distribution. Job design should attempt to accommodate a large percentage of this potential workforce.

Predicted Maximum Heart Rate: the highest rate a person's heart can be expected to attain during maximum physical whole-body work levels; it is estimated by subtracting a person's age from 220 beats per minute. The accuracy of this prediction is about plus or minus 10 percent. Submaximal aerobic capacity testing is used to estimate the work capacities of people who are also studied as they do their job.

Predictor Display: the means by which the operator is shown some measure of what will happen to the system in the future. These displays can be symbolic or pictorial, and they may predict system input, equipment output, or both. They provide advance information that allows the operator to anticipate the need for future action.

Production Machine: a piece of equipment or system of interlocking machines that performs a specific function, such as manufacturing or packaging a product. There are often several workstations on the machine where supplies are loaded, inspection done, or jams cleared to keep it running smoothly.

Productivity: the amount of good product completed during a shift in relation to the number of people and amount of money needed to produce it. In manufacturing operations, it is often expressed as the number of good parts produced per operator or the time required per piece assembled. Productivity is affected by worker characteristics and motivation, workplace and job design, supervisory style, and environmental factors.

Pronation: rotation of a joint forward and toward the midline of the body; for the hand and arm, palm down and thumb next to the body.

Proximal: nearest the origin; refers to a point nearest the midline of the body. The proximal phalanx of a finger is the joint nearest the palm.

Psychology: the study of the human mind and behavior.

Psychomotor Ability: the action of a muscle resulting directly from a mental process, as in the coordinated manipulation of tools in assembly tasks.

Psychomotor Task: a muscle activity requiring skill and coordination, and often spatial perception as well, such as hand-eye coordination. Most light assembly tasks require psychomotor skills.

Psychophysical Measures: data collection instruments that permit a person to evaluate the heaviness of an object or its importance by trying it. Its weight is adjusted upward and downward until it meets some set of criteria, such as the ability to lift it 4 times per minute throughout the shift. The selection of an acceptable load depends on the integration of many factors.

Psychophysical Methods: standardized techniques for presenting stimulus material to a person for judging, or for recording the results of judgments. Originally developed to determine functional relationships between physical stimuli and correlated sensory responses, but used more widely now.

Psychosocial: referring to factors that produce both psychological and social effects. For example, prolonged time on the afternoon-evening shift can isolate a worker from his or her children because they are often either in school or asleep when the shift worker is home; this produces social isolation and is often accompanied by psychological responses of concern or guilt. Psychosocial factors are the primary determinants of the acceptability of various shift work schedules.

Quantitative Display: a display that provides numerical values, in contrast to one giving only descriptive information (a qualitative display).

Radial Deviation: movement of the hand (with the palm outstretched) toward the thumb side. *See* Ulnar Deviation.

Radius of a Handle: the amount of bend in a handle that determines the surface area in contact with the hands during lifting or holding. The smaller the radius, the more uncomfortable the object is to support or hold as its weight is increased.

Rapidly Rotating Shift Work Schedules: hours of work wherein the shift workers work all three shifts within the course of a week. The usual rotation schedule is 3-2-2 or 2-2-3 on day, evening, and late-night shifts or late-night, evening, and day shifts, respectively, for a seven-day schedule. These schedules are advantageous in that they increase social interactions among the shift workers and their families and friends during the workweek as compared to full weeks on the afternoon-evening or late-night shifts in weekly rotating schedules. These schedules are used more frequently in Europe than in the United States.

Recovery Time: work periods when task demands are light or when rest breaks are scheduled, permitting a person to recover from heavy effort work or exposure to an environmental extreme, such as high temperatures.

Redesign: recommended changes to an existing workplace or to production equipment to make it suitable for more workers. Also, the reexamination of job requirements and their pattern of occurrence. Redesign is a more expensive alternative to incorporation of ergonomic principles in the initial design.

Reliability, Human: the ability to perform with minimum errors. Reliability decreases with increasing task complexity and with task-related and environmental stresses.

Repetitive Motion Disorders: a family of musculoskeletal or neurological illnesses or symptoms that appear to be associated with repetitive tasks in which forceful exertions of the fingers, or deviations or rotations of the hand, wrist, elbow, or shoulder are required. Also called *cumulative trauma disorders (CTDs)*. Examples are tendonitis, tenosynovitis, carpal tunnel syndrome, epicondylitis (elbow), and bursitis.

Repetitive Strain/Stress Injury: an alternative term for cumulative trauma disorders.

Residual Time: the amount of time spent doing activities that are not primary physical effort. These activities are recognized through supplementary effort requirements analysis.

Resistance: a counteractive force, such as the force a muscle develops to counteract the weight of an object being held or lifted.

Response: (1) physiological: the muscular contraction, glandular secretion, or other activity of a person resulting from stimulation; (2) psychological: a behavioral action, usually motor or verbal, that follows an external or internal stimulus.

Rest Allowances: recovery time in addition to regularly scheduled work breaks. They are usually provided in jobs where heavy physical work or exposure to environmental extremes occurs. Rest allowances are built into the job standard so that productivity ratings recognize the need for additional recovery time in these jobs.

Rest Pause: a brief interval during which a particular muscle group or joint is not used.

Robotics: the use of computer-programmed machines to simulate humans in work tasks that are highly repetitive or must be done in hostile environments.

Sagittal: any plane parallel to the midsagittal plane dividing the body into right and left halves; used in describing symmetrical lifting tasks using two hands.

Saturation: the extent to which a chromatic color differs from a gray of the same brightness. It is measured on an arbitrary scale from 0 percent (gray) to 100 percent.

Secondary Work: activities that are related to the main job activity but not directly linked to productivity on the job. They may include the procurement of supplies, discussions with supervision or colleagues about product quality, or adjustments to the equipment.

Selection Testing: the use of performance or capacity measurements to determine the suitability of a worker for a job requiring above-average capacity. If it is used to select people for initial employment or progression, a selection test must be validated to the job demands.

Sensation: a subjective response aroused by stimulation of a sense organ.

Sequence-of-Use Principle in Equipment Design: the principle of arranging controls and displays so that those used in sequence are physically situated in order of their respective operation, as on a control console.

Shape Coding: varying the configuration of controls to make them distinctive. Shape coding is effective because the difference can be both seen and felt. The shape of a control should suggest its purpose, and it should be distinguishable not only with the bare hand, but also when wearing gloves.

Shear Force: a force that is applied tangentially to a surface. *See* Compressive Force.

Sheet Materials: products that are very wide and long with very little depth, such as plywood, glass plates, paper sheets, and cardboard. Their dimensions make it necessary to handle them with a pinch grip and often require the arms to be spread widely apart.

Shift: a period of work, most often 8 hours long, through which workers may rotate to provide 16- or 24-hour coverage of a production process or service.

Shift Work: the rotation of a worker's hours over a specified time period, often one week on each 8-hour shift. Shift work is done in order to provide 24-hour service to cover operations that cannot be easily shut down, or to make use of manufacturing equipment to the fullest extent so that the unit cost of the product can be reduced. Many shift work schedules have been developed to try to match the manufacturing and service needs to human behavior and needs.

Shipping Case: a cardboard container containing single or multiple units of product for distribution to a customer or to a regional warehouse and distribution center.

Short-Duration Heavy Effort: a period less than 20 minutes in length when very demanding physical effort work is done. This effort level often requires more than 70 percent of a person's maximum aerobic capacity for that type of work.

Short-Term: lasting or requiring a relatively short period of time.

Short-Term Memory: the storage of recently received information for a few seconds or minutes.

Signal: an event describing some aspect of the work process that the operator should sense and respond to. It could be an auditory signal, such as an alarm bell, or a visual signal, such as a flashing light, indicating a product defect in an inspection task.

Simulation: a set of test conditions designed to duplicate field operating and usage environments. A good technique to help the designer of a workplace or a new piece of equipment anticipate human factors problems.

Siphon Pump: a method of transferring liquid from one container to another using gravity and air pressure.

Situational Factors in Job Analysis: job characteristics that are not inherent in the jobs themselves but are associated with external factors; for example, supervisory style, management policies, and production deadlines.

Skid: a metal platform, similar in dimensions to a U.S. wooden pallet, that is most often handled by a forklift truck. It can hold more weight than a pallet and is generally used in storage and transport situations where a wooden pallet is not sufficiently rugged.

Skill Acquisition: the development of improved performance on a psychomotor task that is associated with practice, experience, or other learning. A motor pattern (engram) is produced in the central nervous system that permits the skill to be accessed as needed.

Sleep Satisfaction: a psychophysical rating of how rested a person feels after a period of rest. Satisfaction ratings are generally lower for people who work the late-night shift and have to sleep during the day than for people on the other two shifts who can sleep during the night.

Slip Sheet: a plastic or cardboard sheet, approximately the size of a pallet, that can be used in some applications to transfer materials into a truck without using wooden pallets.

Social Isolation: a possible result of shift work schedules that require long periods of work on the afternoon-evening and night shifts. The worker is not free during times when his or her children and many other people are usually free, so interindividual contacts are reduced.

Specular Reflection: scattering of light rays, as from a mirror, where the reflected radiation is not diffused. Also called regular, or simple, reflection.

Speech Interference Level (SIL): a gross measure used for comparing the relative effectiveness of speech in the presence of noise. It is the simple numerical average of the noise decibel level in the three octave bands with centers at 500, 1,000, and 2,000 Hz.

Stability: the property of a system to return to equilibrium after it has been disturbed. In biomechanics, stability is the return of the torques around the joints to dynamic equilibrium after a change in posture.

Stacker-Retriever System: an automated warehousing system that permits a worker to store or take out a truck or pallet that holds a particular product using a computer-controlled handling system. It reduces the amount of manual handling and is especially useful for the storage of product in the intermediate stages of a manufacturing process that requires several steps.

Static Muscle Work: muscle contraction without motion; also known as isometric work. Standing is an example of static postural work; gripping or holding are examples of static manual work. Some muscles do static work while other muscles are doing dynamic work. An estimate of static work can be made by multiplying the force of a static contraction by its duration. *See also* Isometric Muscle Work.

Statics: the biomechanical aspects of bodies at rest or forces in equilibrium.

Stature: the vertical distance from the top of the head to the floor. The subject stands erect and looks straight ahead.

Steady State: a state or condition that does not change over time; equilibrium. In work physiology, it means that the muscles' demands for oxygen are met by the appropriate adjustments in respiration, heart rate, and blood flow. A steady physiological state is characterized by a steady heart rate over time unless the workload is very heavy.

Stimulus: internal or external energy that excites a receptor.

Strain: indices of stress, such as heart rate and oxygen consumption. Also, the deformation of part of the body, such as a finger, in response to increased force per unit area.

Strain Gauge: *see* Force Transducer.

Stress: (1) deformation of a part of the body in response to increased force per unit area; (2) the effect of a physiological, psychological, or mental load which may produce fatigue and degrade a person's proficiency.

Submaximal Aerobic Capacity Testing: the prediction of a person's maximal aerobic capacity from a multistaged test that does not include a maximum workload.

Supination: rotation of a joint backward and away from the midline of the body; for the hand and arm, palm up and thumb away from the body.

Surround Brightness: the brightness of an area immediately adjacent to the visual work area.

Susceptibility: the tendency of a person to respond to a stress with a specific type of illness; a weakness. For example, some people are more susceptible to low back pain or repetitive motion disorders than others. The reasons for greater susceptibility are not clear but many have genetic, nutritional, or development bases.

System: a composite of equipment, skills, and techniques, including all related facilities, equipment, material, services, and personnel, capable of performing and/or supporting an operational role.

System Analysis: identification of the dynamic, or functional, relationships between elements of an operational system.

System Engineering: the study and planning of a system where the relationships of various parts of the system are fully established before designs are committed. Also relates to the study of existing systems in which improvements may be sought.

Systems Approach: the design of manufacturing, materials handling, or other systems through consideration of the whole process and not just its separate parts; for example, designing materials handling systems to eliminate or reduce multiple rehandling of items, using conveyor systems to move products between workstations, and consistent record keeping to permit tracking the product with minimal paper work.

Task: a group of related job elements performed within a work cycle and directed toward a goal. They can include discriminations, decisions, and motor activities required of a person to accomplish a given unit of work.

Task Analysis: an analytical process that measures behavior on a job against time, to determine the physiological and psychological demands of a job on the workers. It involves measuring, over time, the detailed performance required of a person and a machine, their interactions, and the effects of environmental conditions and malfunctions. Within each task, behavioral steps are described in terms of the physical demands, perception, decision making, memory storage, and motor skills required, as well as the expected errors. The data may be used to establish criteria for equipment design and for personnel training.

Task Element: the smallest definable set of perceptions, decisions, and responses a person is required to perform in completing a task. An example of a task element is an operator responding to a signal on a display by actuating a control, and seeing that the response has produced the desired effect.

Tibial: of, or pertaining to, the shin bone of the lower leg.

Timbre: the attribute of auditory sensation that permits a listener to discriminate between two sounds of similar loudness and pitch but of different tonal quality.

Time-sharing: the division of an operator's perceptual, decision-making, or response time among activities or tasks that must be performed at or about the same time. For example, operating a production machine often includes loading, monitoring, inspecting product, and making repairs and adjustments to it. These activities are time-shared according to the need to keep the equipment running.

Training: the instructions, planned circumstances, and directed activity by which a person acquires and/or strengthens new concepts, knowledge, skills, habits, or attitudes that will allow for the assigned performance of duties with maximum reliability, efficiency, uniformity, safety, and economy.

Transmittance: the percentage of light going through a material, such as plastic, divided by the amount of ambient light falling on that material. *Selective transmittance* is the passage of particular light wavelengths through a transparent or translucent material, such as a red filter.

Transverse: movement across the front of the body that is in a horizontal plane perpendicular to the body's midline axis that divides the body into right and left halves.

Trunk: the torso of the human body.

Ulnar Deviation: movement of the hand (with plam outstretched) toward the little finger side. See Radial Deviation.

Validity of a Test: the degree to which a test measures what it was designed to measure. It is estimated using a coefficient of correlation between test scores and a criterion measure, such as actual on-the-job performance.

Video Analysis: in ergonomics, the use of videotape to record and measure body motions when performing a task. This technique is very useful in situations where quantification of joint angles, static muscle loading times, and postures are needed but are difficult to measure directly.

Viewing Angle: the angle formed by a line from the eye to the surface of the object being viewed.

Vigilance: an activity involving continuous visual or auditory watch; also the individual's ability to detect signals of varying frequencies during these observation periods.

Visual Acuity: the ability to see detail at various distances from the object of regard. It is the reciprocal of the visual angle, in minutes of arc, occupied by the smallest discriminable detail.

Visual Field: that space that can be seen when the head and eyes are motionless. Or, all visual stimuli that act upon the unmoving eye at a given moment.

Watt: a unit of power in the SI system; equals 1 joule per second, approximately 0.014 kilocalories per minute, or 0.0013 horsepower.

White Noise: noise that is a combination of many sound waves of different lengths that reinforce or cancel one another in a nonuniform, random fashion. The spectrum density is substantially independent of frequency range.

Whole-Body Work: using most of the body's muscles to accomplish a task. The large muscles of the legs and buttocks as well as the muscles of the trunk, arms, and shoulders are involved. Work that is located lower than 75 cm (30 in.) above the floor requires whole-body effort.

Wind Chill: a scale that indicates the combined effects of wind velocity and temperature and is used to express the severity of cold environments.

Work: an expression for human effort measured in physical units or in performance-output results. Also, a general description of a task.

Work Cycle: the total series of actions and events that characterize or describe an integral work assignment or a single operation.

Work Pace: the rate at which a task or activity is done. Work may be paced externally, as by machine rates or by other people on the assembly line, or it may be self-paced by the worker.

Work Physiology: the study of the body's response to physical and/or mental effort. Measurement of stress on the cardiovascular, respiratory, nervous, and musculoskeletal systems, in particular, are included.

Workplace: the physical area in which a person performs job activities; includes tables or counters, chairs, any controls and displays necessary, the lighting, and other environmental controls.

Work-Rest Cycles: the job pattern that defines how more demanding work is organized with respect to lighter tasks or rest. High work/rest ratios, measured as continuous time on each type of activity, have higher potential for fatigue.

Work-Rest Ratio: for a particular muscle group or joint, the ratio of the time that it is active to the total cycle time.

Workspace: the physical area in which a person performs work.

Work Space Layout: the design of the working area of a workstation, including provisions for seating, physical movement of people, operational maintenance, and adequate contacts between people and equipment and among people.

Workstation: a workplace that is included in a production system or on a piece of manufacturing equipment and at which the operator may spend only a portion of the working shift. One operator may work at several workstations but have only one workplace for other types of work. Both workstation and workplace should be designed according to ergonomic principles, but workplace design is more critical because of the amount of time spent there per shift.

Work Study: the analysis of work methods, techniques, and procedures.

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