Karl H. E. Kroemer
Hiltrud J. Kroemer
Katrin E. Kroemer-Elbert

Engineering Physiology

Bases of Human Factors Engineering/Ergonomics

Fourth Edition

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Karl H.E. Kroemer
3624 Laurel Drive
24060-8562 Blacksburg, VA
Virginia
USA
kroemer@vt.edu

Hiltrud J. Kroemer
3624 Laurel Drive
24060-8562 Blacksburg, VA
Virginia
USA
kroemer@vt.edu

Katrin E. Kroemer-Elbert
133 St. Paul Street
07090-2144 Westfield, NJ
USA
elbertecture@msn.com

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A Few Words at the Beginning

Gunther Lehmann published his book “Practical Work Physiology” (Praktische Arbeitsphysiologie, Stuttgart, Thieme) in 1953. He used to say, with his little smile, that some of his learned colleagues accused him of over-simplifying a difficult subject matter while engineers and managers still marveled the complexities of the human body. His book was translated into four languages, and it had its second edition in 1962. The first edition of our “Engineering Physiology”, published in 1986, followed Professor Lehmann’s path and we received similar comments – and the widespread use of that book caused follow-up editions in 1990 and 1997, and now again in 2010.

This fourth edition of Engineering Physiology has the same purpose as the earlier prints: to provide physiological information which engineers, designers, managers and all other persons need who want to make work and equipment “fit the human”.

All chapters have been revised, figures and tables updated. New material is in all chapters of this new edition, especially as it relates to:

Recent experiences with biomechanics and modeling of the body.
Modern replacements of deteriorated and damaged body parts.
Effects of shift work on body functions, attitude and performance.
Changes in body sizes and in measurement techniques, and the resultant changes in applications of that information.

Even an audacious engineer wouldn’t dare to devise a system as complicated as the human body. Yet, devices that engineers design, from simple tools to complicated systems, must fit the humans who use them. Therefore, everybody who is interested in human-centered engineering needs to understand how the human body functions, what it can barely tolerate or, better, do with ease.

We chose the title “Engineering Physiology” in the 1980s to indicate our treatment of the topic. The book does not take the place of the standard (biological-medical-chemical) textbook on human physiology; instead, it models and describes the human body in terms that provide practical, design-directed information on essential features and functions.

Regarding "models":

> When developing models we must realize that selecting certain features, drawing distinctions, making classifications usually imposes artificial divisions of our own choosing upon a universe that is, in many ways, all in one piece. We do such modeling because it helps us in our attempted understanding of the intricate system. It breaks down a set of objects and phenomena too complex to be grasped in their entireties into smaller realms that we can deal with one by one. There is nothing objectively "true" about such models; the only proper criterion of their value is their usefulness. (This is, slightly paraphrased, Isaac Asimov's observation on page 13 in his 1963 book "The Human Body". New York, Signet.)

Such understanding provides the underpinnings for devising work tasks, tools, workplaces, vehicles, work-rest schedules, human-machine systems, homes and designed environments so that we humans can work and live safely, efficiently and comfortably. This is the field of *ergonomics* or *human (factors) engineering*, terms often used interchangeably.

This book also helps lay the foundations for teamwork among engineers and physiologists, chemists, biologists and physicians to create repairs and replacements for worn and damaged parts of the body. Such "bioengineering" topics concern cells and tissues, neural networks, biochemical processes, anthromechanics, bionanotechnology, biosensors and prosthetics, to mention just a few areas of common interest.

About References in This Edition

Basic human physiological characteristics did not change in recent years. The previous editions of this book contain exhaustive listings of pre-1997 publications on human physiology. We don't want to repeat those lists here, so we suggest that the reader interested in history return to the earlier editions or check current physiology textbooks. In this 4th edition we are referring mostly to recent publications, along with a few selected classic references.

Traditional practice was to support statements in the text by listing the names of the authors, and of their co-authors, who wrote previously on that topic. That wordy custom disrupts the flow of reading, especially when there are strings of names and dates. To avoid that problem, we follow other authors' and our earlier practice of simply placing a small marker, * , in the text where references or explanations are desired. These appear, at the end of the chapter, in a separate "Notes" section, which the reader may skip or consult.

We Would Like to Hear from You!

We appreciate your comments, which tell us what we did well and what we should do better. You can contact us at kroemer@vt.edu.

Blacksburg, VA Karl H.E. Kroemer
July 2010

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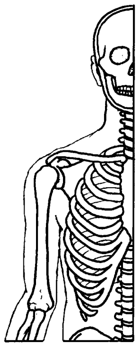
Chapter 1
Skeletal Structures



Overview

The skeletal system of the human body is composed of some 200 skeletal bones, of their articulations, and of connective tissue. They all consist of special cells imbedded in an extracellular matrix of fibers and a ground substance. Bones provide the structural framework for the body. Ligaments connect the bones at their articulations, while tendons connect muscle with bone. The spinal column is often of great concern to the ergonomist because it is the locus of many overexertion injuries.

The Model

The bones provide the basic solid framework for the body and are the lever arms at which muscles exert torque about the articulations of the bones. These joints allow the linked bones various kinds and amounts of motions. That mobility depends on basic joint design, on support by cartilage and on constrains by ligaments and muscles.

Introduction

Human bones and the connective tissues (ligaments, tendons, cartilage) are composed of cells, mostly fibroblasts, embedded in fibers and ground substance. The extracellular matrix encloses the cells and contains collagen fibers and elastic fibers. Collagen fibers (subdivided into several types) have high tensile strength and resist deformation, particularly stretch; whereas elastic fibers can elongate. The ground substance has large sugar molecules with a protein core (proteoglycans), lipids and water and, in bone, calcium and other minerals. The actual composition of the tissues determines their physical properties, especially regarding their deformation and strength, which obviously differ considerably between bone and the other connective tissues. Some connective tissues are loose, irregular, even fatty to form spongy

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wraps for nerves, blood vessels and organs. Dense and aligned connective tissues are called *fascia* when they wrap muscles or other organs, *tendons* when they connect muscle with bone, *ligaments* when they connect bones, *cartilage* at the ends of bones in their joints.

Bones

The main function of human skeletal bone is to provide the internal framework for the body, see Fig. 1.1; without its support, the entire body would collapse into a heap of soft tissue. Bone also provides the mechanical lever arms at which muscles, attached via tendons, articulate body parts against each other in skeletal joints. (More about muscle pulls at bone levers in Chaps. 2 and 5.) Some bones act as shells to protect body organs: the elastic rib cage contains lungs and heart; the skull, firm in adults, encloses the brain. Long hollow bones also provide room in their cores for bone marrow, which serves as a blood cell factory.

One distinguishes between flat axial (appendicular) bones, such as in the skull, sternum and ribs, and the pelvis; and long, essentially cylindrical bones as in the arms and legs. The long bones consist of a shaft (diaphysis) which, toward each end, broadens (metaphysis) and develops into a bulbous form (epiphysis) that contains the actual articulation which connects to an adjacent bone. Both flat and long bones consist of compact cortical and spongy cancellous material. Cortical bone is dense at about 1.3 g/cm^3 or more, while cancellous bone generally has a density of less than 1 g/cm^3. Cortical material is prevalent in the outer layers of the shaft of a long bone and in the thin outer shell at the joint. Cancellous bone exists mostly in the middle layers where, by its ability to deform, it provides flexible structural support when transferring loadings coming from an adjacent bone or from the outside. Smooth white cartilage, closely related to bone, covers the surface of the bone inside an articulating joint; it helps to absorb transmitted shocks.

Bone is compliant in childhood when mineralization is still relatively low: the ratio of the contents of inorganic material, mostly calcium, to organic substance is about 1 to 1. In contrast, the bones of the elderly are highly mineralized, with a ratio of about 7:1, and therefore are stiffer and more brittle.

Bone develops from a soft, woven-fibered material in the earliest childhood into compact, mostly lamellar material with a hard outer shell and a spongy inner section. Growth takes place until about 30 years of age, with increasing elastic modulus (indicating the stiffness of the bone) and yield strength (indicating the nominal stress at which the bone undergoes a specified permanent deformation). Beginning after the third decade of life, bones usually become more and more osteoporotic with larger pores, holes, which decrease the density and the structural strength of the bone. Osteoporotic long bones also tend to show increases in the outer and in their inner diameters, which means a more "hollowed" core; the remaining walls are more brittle then during younger age owing to an increase in mineral content in the existing matter.

The geometric changes in bone allow calculating mechanical parameters relevant to its strength: an increase in cross-sectional area means increasing axial

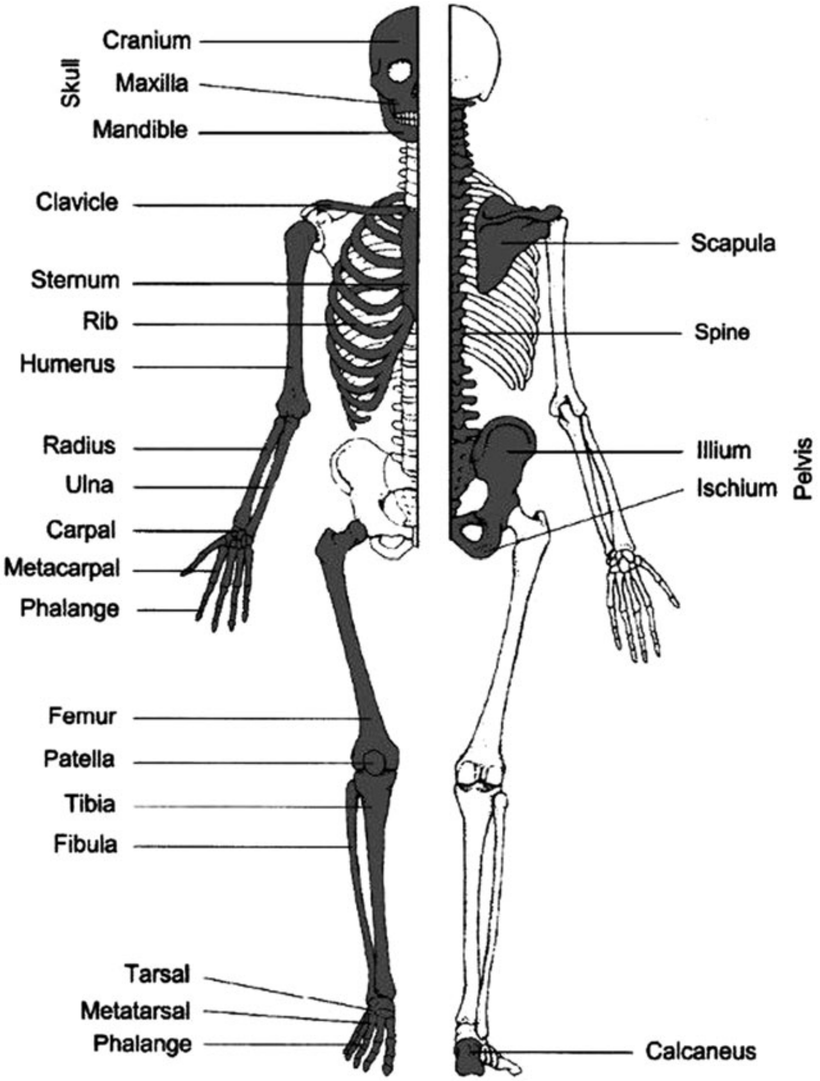

Fig. 1.1 Major skeletal bones (adapted from Langley and Cheraskin, 1958; Weller and Wiley, 1979; Berkow and Beers, 1997)

compression strength, while an increase of the elastic modulus of the section signifies increasing bending strength. Area (A) and section modulus (I/c), respectively, are calculated as follows:

$$A = \pi ({r_{outer}}^2 - {r_{inner}}^2) \quad (1.1)$$

$$I/c = \pi ({r_{outer}}^4 - {r_{inner}}^4)/4\, r_{outer} \quad (1.2)$$

Table 1.1 Effects of age-related dimensional changes in human femurs on strength parameters (adapted from Mow and Hayes, 1991)

	Outer radius	Inner radius	Cross-section area	Section elastic modulus
Young adults	1.09 cm	0.53 cm	2.85 cm^2	0.96 cm^3
Elderly adults	1.25 cm	0.76 cm	3.09 cm^2	1.32 cm^3
Change with aging	+15%	+43%	+8%	+38%

Measurements on the femurs of young and elderly adults, listed in Table 1.1, show that both the outer and inner radii increase with aging, moving the outline of the bone outwards and making it more hollow. The net effect is only a small change in the cross-sectional area of the bone but a larger change in the elastic section modulus, indicating increased bending resistance of the bone.

Bone cells are nourished through canals carrying blood vessels and tubules. Bone is continuously resorbed and rebuilt throughout one's life; local strain encourages growth, while disuse leads to resorption; this is popularly called "Wolff's Law" (it also applies to muscle).

Cartilage

Cartilage (Latin *cartilago*, gristle) is another major component of the human skeletal system. It consists mainly of a translucent material of collagen fibers embedded in a binding substance. While related to the stiff bone material, cartilage allows considerable deformations; it is firm but elastic, flexible, and capable of rapid growth. It supplies elastic structures where required, especially at the ends of the ribs and in the joints of the limbs to absorb shocks and to facilitate smooth movements of the ends of bones against each other; and it makes up flexible structures such as the external ear and the nose.

Cartilage is divided into three types: hyaline cartilage, elastic cartilage, and fibrocartilage. Hyaline cartilage is smooth and glistening, common at the articulating surfaces of long bones such as at the knee joint; it also forms the nasal septum, the larynx (voice box), and the rib connections. Elastic cartilage is generally more flexible than hyaline, and is found at the external auditory canal and the Eustachian tube. Fibrocartilage makes up the annulus fibrosus of the intervertebral disk (discussed below in this chapter) and the meniscus in the knee.

Tendons and Ligaments

The tight tissue that wraps bundles of muscle fibers and the whole muscle condenses at the ends of the muscle to tendons (Greek *tenon*, sinew). These are mostly twisted collagen fibers that work like cables, which can bend but hardly stretch. Tendons connect to bones and serve to transfer the pull force of the muscle to the bone. To allow smooth gliding along other body materials, the tendon is usually encapsulated by a sheath: a fibrous tissue that has an inner lining, synovium, which produces a viscous fluid, synovia, that reduces friction.

Ligaments (Latin *ligare*, to bind) are like elastic straps, made of layers of parallel bundles of fiber, mostly collagen. Rings or bands of ligaments keep the tendon sheaths at the wrist and fingers close to underlying bones; these ligaments act as guides and pulleys during the pulling actions of the tendons and their muscles. Other ligaments directly connect bones across an articulation, such as in the knee joint. Ligaments also wrap the limb joints, such as the knee or the articulating vertebrae of the spinal column.

Articulations

In adults, some bony joints have no mobility left, such as in the fibrous seams in the skull; some have very limited motions, such as the connections of the ribs to the sternum. However, many other articulations allow large displacements: joints with one degree of freedom are simple hinge joints, like the elbow or the distal joints of the fingers. Some joints have two degrees of freedom, such as the wrist. Ankle, shoulder and hip joints have three degrees of freedom, as in a ball-and-socket joint. Figures 1.2 and 1.3 depict motion capabilities and the standard terms to describe them.

Simple mechanical comparisons do not describe adequately many of the more complex body articulations. The wrist joint, for example, has nearly flat surfaces separating the forearm and hand bones. This layout allows, mostly by sliding, flexion/extension as well as ab- and adduction displacements – see Fig. 1.2. However, the twisting supination/pronation of the hand actually takes place within the forearm – as discussed in more detail below in this chapter.

Synovial fluid in an articulation facilitates movement of the adjoining bones by providing lubrication. For example, while a person is running, the cartilage in the knee joint can show an increase in thickness of about 10%, brought about in a short time by synovia seeping into it from the underlying bone marrow cavities. Similarly, fluid seeps into the spinal disks, which act as cushions between the vertebrae, when they are not compressed. The fluid makes the disks pliable, which may explain disk deformations experienced as early morning back pains upon waking and rising. Immediately after getting up, one stands taller than after a day's effort when the fluid is "squeezed out" by the load of body masses and their accelerations.

Body joints have different forms, depending on the required mobility of the articulation and on the mechanical loadings which they must tolerate. The design of the bearing surfaces of adjacent bones, the supply of cartilaginous membranes, the provision of fibrous disks or volar plates, the encapsulation of the joint by ligaments, and the action of muscles together determine the mobility of body joints. Figure 1.4 sketches typical joints of the human body.

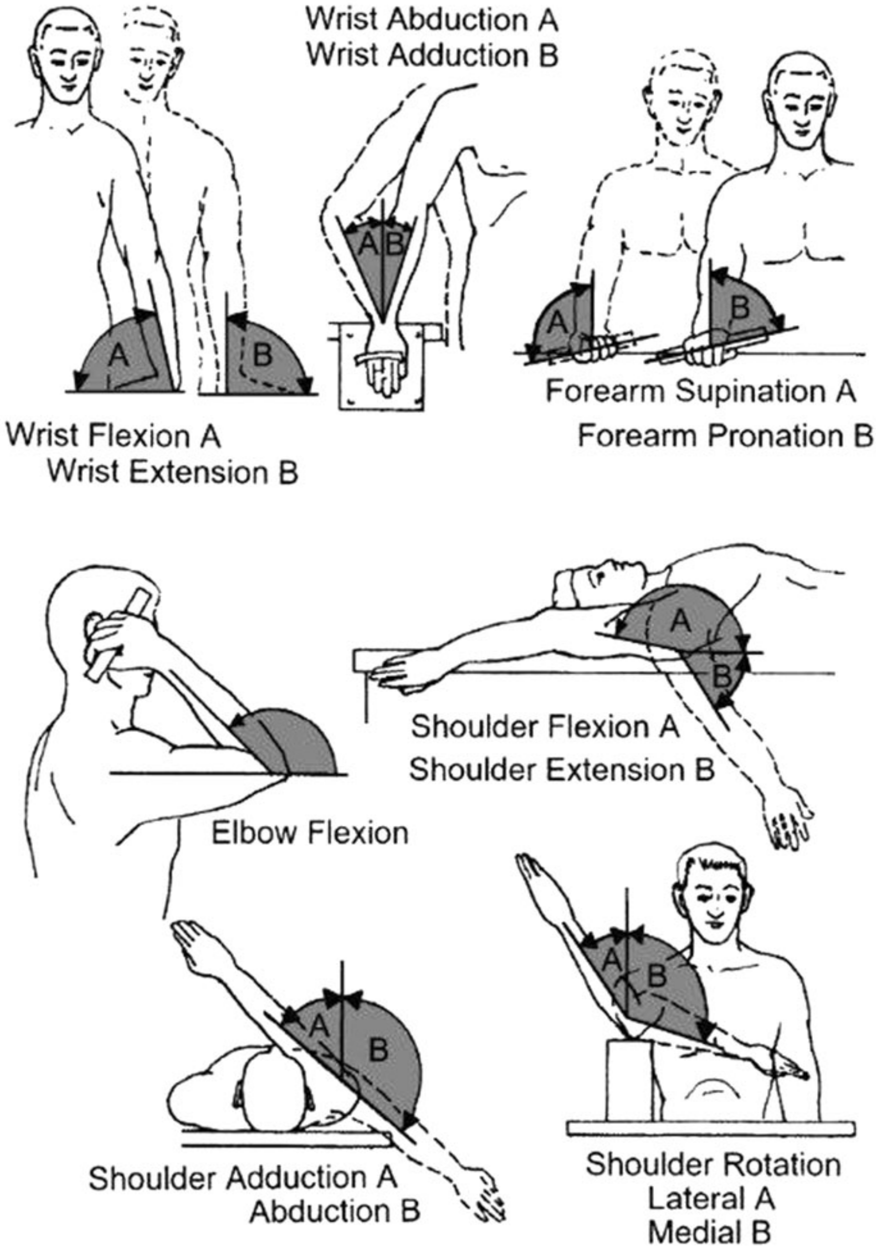

Fig. 1.2 Terms describing hand and arm motions (adapted from Van Cott and Kinkade, 1972)

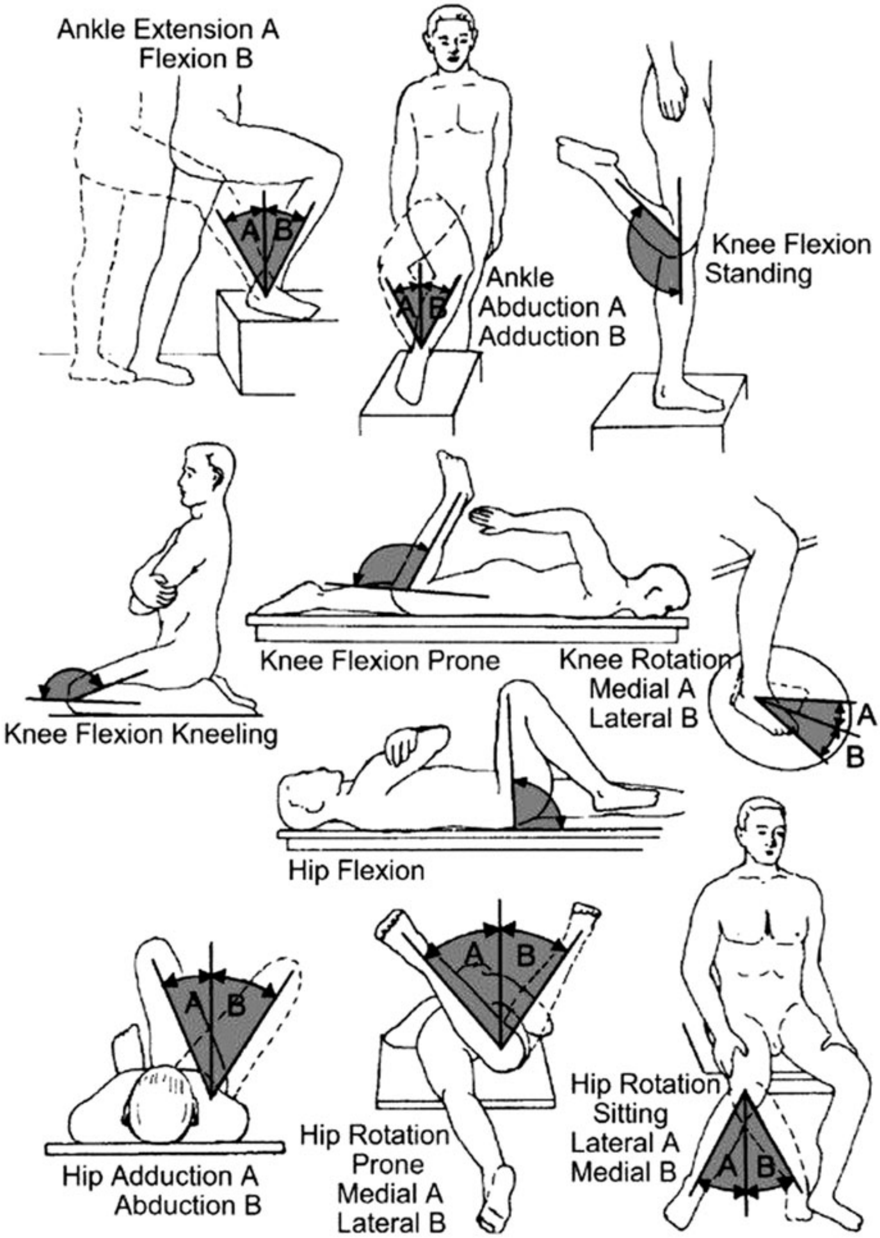

Fig. 1.3 Terms describing leg motions (adapted from Van Cott and Kinkade, 1972)

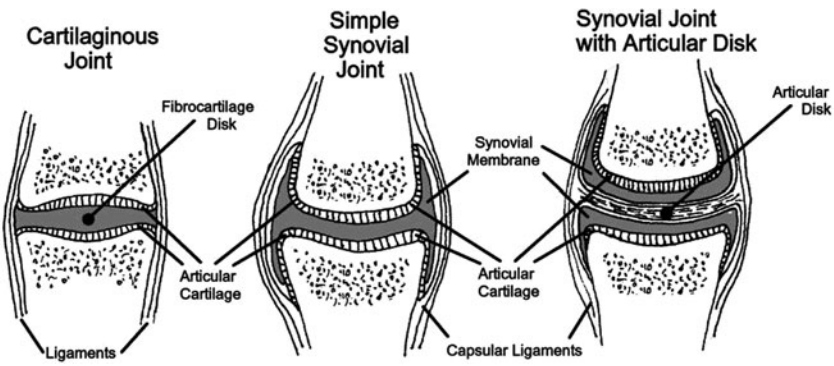

Fig. 1.4 Types of moveable body joints (adapted from Astrand and Rodahl, 1977)

Cartilaginous joints provide very limited movement: in them, cartilage lines the opposing ends of the bones, and a tight ligament covers the articulation and wraps along both bone endings. The spinal column consists of such cartilaginous joints: a flat disk with a fibrocartilage center connects the linings of two opposing vertebral bodies. The disk acts like a cushion; it absorbs shocks, otherwise fully transmitted from one vertebra to the other, and allows limited relative motion between the vertebrae.

In *simple synovial* joints, articular cartilage also covers the opposing bones surfaces, which are separated by a space, lined by a synovial membrane filled with synovial fluid. An elastic ligament loosely encapsulates the synovial joint. This articulation allows substantial relative angulation of the bones.

In a *synovial joint with articular disk*, a fibrocartilage disk or wedge (such as the meniscus in the knee) divides the joint space, supplying additional synovial fluid and controlling its distribution and flow. This articulation provides high mobility and good shock absorption.

Articular cartilage has no blood vessels. Its nourishment is achieved through direct exchange of synovial fluid from the cavities in the end portion of the bone and by direct exchange of synovia between cartilage and articular space.

Mobility

Movements in human body joints range from a simple gliding to rather complex displacements in several planes. Examples in the upper extremity: the rotatory pronation/supination of the hand consists of relative gliding-twisting of radius and ulna within the forearm (one degree of freedom); the angular swing of the forearm from the upper arm occurs in the hinge-type elbow joint (also one degree of freedom); the complex shoulder joint allows spatial circumduction (three degrees of freedom) in the shoulder. The motions themselves are limited by the shapes of the bony surfaces and by the restraining tension generated by ligaments and muscles.

Excepting the spine, most articulations of the human body belong to the synovial group. Mobility, also called flexibility, indicates the range of motion that can be achieved at body articulations, as sketched in Figs. 1.2 and 1.3. Mobility is measured as the difference between the smallest and largest angles enclosed by involved body segments about their common point of rotation in the articulation. However, the actual point of rotation may move with the motion; for example, the geometric location of the axis of the knee joint displaces slightly while the thigh and the lower leg rotate about it*.

The range of motion varies with age, training and physical condition, and gender. It depends on whether only active contraction of the relevant muscles is used, or if gravity, an external load or perhaps even a second person contribute to achieving extreme locations. Finally, of course, the mobility is different in different planes if the articulation in question has more than one degree of freedom.

Table 1.2 provides information about voluntary (unforced) mobility in major body joints. The measurements involved 100 females (ages 18–35 years), carefully controlled to resemble an earlier study on 100 male subjects. On each person, only one measurement was taken for each motion. The instructions were to move the limbs “as far as comfortably possible” using (if applicable) the dominant limb; 85% of the participants claimed to be right-dominant.

Of the 32 measurements, 24 showed statistically significant more mobility by females than by males; men had somewhat larger mobility only in wrist abduction and ankle flexion. This finding confirms earlier studies that also showed generally larger motion capability by women. Given the careful and consistent way the two studies were conducted, one may assume that the data present a realistic picture of mobility of the adult US population within the working age span; mobility commonly slightly decreases (less than about 10° in the extreme positions) in most body joints as people age into their 6th decade.

For engineering purposes, hand motion capabilities are of particular importance. They are the result of a combination of movements in several joints: hand, wrist, elbow, shoulder, and spine. Design of cockpits in spacecraft, airplanes and vehicles, for example, must consider the reach capabilities of the sitting operators, possibly under harsh working conditions such as encumbering clothing and strong accelerations – see Fig. 1.5.

Muscles (see Chap. 2) exert primary control over joint motions by their continuous interplay between counteractive muscle groups. Moveable joints have numerous nervous connections with the muscles that act on them; this establishes local reflex circuits, which usually prevent overextensions. Control of the skeletal system is accomplished by nervous feedback and excitation signals from the central nervous system; Chap. 3 discusses these topics.

Four types of nerve endings exist in the joints. Two of them are located in the joint capsule: these are Ruffini organs that provide information about changes in joint position and speed of movement. A third kind of Ruffini organ, embedded in ligaments, signals the actual location of the joint. The fourth receptor is a free branching nerve, ending in pain-sensitive fibers. Synovial membranes and joint cartilage seem not to have nerve receptors.

Table 1.2 Comparison of mobility data, in degrees, for females and males (adapted from Staff, 1983; Houy, 1983)

		5th Percentile		50th Percentile		95th Percentile		Difference[1]
Joint	Movement	Female	Male	Female	Male	Female	Male	At 50th percentile
Neck	Ventral flexion	34.0	25.0	51.5	43.0	69.0	60.0	fem+8.5
	Dorsal flexion	47.5	38.0	70.5	56.5	93.5	74.0	fem+14.0
	Right rotation	67.0	56.0	81.0	74.0	95.0	85.0	fem+7.0
	Left rotation	64.0	67.5	77.0	77.0	90.0	85.0	none
Shoulder	Flexion	169.5	161.0	184.5	178.0	199.5	193.5	fem+6.5
	Extension	47.0	41.5	66.0	57.5	85.0	76.0	fem+8.5
	Adduction	37.5	36.0	52.5	50.5	67.5	63.0	NS
	Abduction	106.0	106.0	122.5	123.5	139.0	140.0	NS
	Medial rotation	94.0	68.5	110.5	95.0	127.0	114.0	fem+15.5
	Lateral rotation	19.5	16.0	37.0	31.5	54.5	46.0	fem+5.5
Elbow	Flexion	135.5	122.5	148.0	138.0	160.5	150.0	fem+10.0
Wrist	Supination	87.0	86.0	108.5	107.5	130.0	135.0	NS
	Pronation	63.0	42.5	81.0	65.0	99.0	86.5	fem+16.0
	Extension	56.5	47.0	72.0	62.0	87.5	76.0	fem+10.0
	Flexion	53.5	50.5	71.5	67.5	89.5	85.0	fem+4.0
	Adduction	16.5	14.0	26.5	22.0	36.5	30.0	fem+4.5
	Abduction	19.0	22.0	28.0	30.5	37.0	40.0	male+2.5
Hip	Flexion	103.0	95.0	125.0	109.5	147.0	130.0	fem+15.5
	Adduction	27.0	15.5	38.5	26.0	50.0	39.0	fem+12.5
	Abduction	47.0	38.0	66.0	59.0	85.0	81.0	fem+7.0
	Medial rotation (prone)	30.5	30.5	44.5	46.0	58.5	62.5	NS
	Lateral rotation (prone)	29.0	21.5	45.5	33.0	62.0	46.0	fem+12.5
	Medial rotation (sitting)	20.5	18.0	32.0	28.0	43.5	43.0	fem+4.0
	Lateral rotation (sitting)	20.5	18.0	33.0	26.5	45.5	37.0	fem+6.5
Knee	Flexion (standing)	99.5	87.0	113.5	103.5	127.5	122.0	fem+10.0
	Flexion (prone)	116.0	99.5	130.0	117.0	144.0	130.0	fem+13.0
	Medial rotation	18.5	14.5	31.5	23.0	44.5	35.0	fem+8.5
	Lateral rotation	28.5	21.0	43.5	33.5	58.5	48.0	fem+10.0
Ankle	Flexion	13.0	18.0	23.0	29.0	33.0	34.0	male+6.0
	Extension	30.5	21.0	41.0	35.5	51.5	51.5	fem+5.5
	Adduction	13.0	15.0	23.5	25.0	34.0	38.0	NS
	Abduction	11.5	11.0	24.0	19.0	36.5	30.0	fem+5.0

NS: not significant
[1]Differences are listed only if significant ($\alpha < 0.5$)

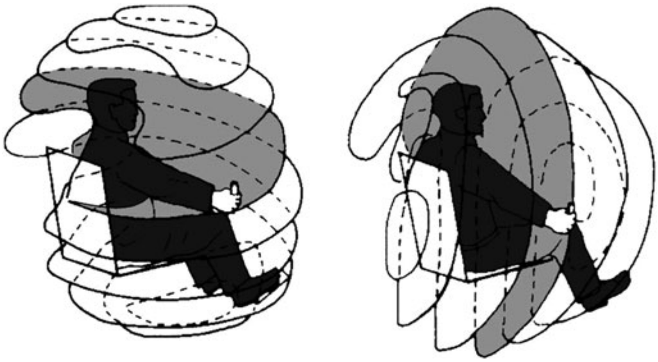

Fig. 1.5 Planes of horizontal and vertical hand reaches (adapted from Ignazi et al., 1982)

Artificial Joints

Natural body joints may fail because of disease, trauma, or long-term wear and tear. For the patient, joint failure is associated with motion limitations and usually with severe pain. Damage to bone and degeneration of joint cartilage may give cause for the replacement of the articulation with an artificial, manufactured joint if conservative medical treatments fail. Joint replacements in hips and knees as well as fingers have become routine: in the USA alone, current estimates are that, annually, nearly a million people receive joint implants, many of them elderly persons*.

This number is likely to increase with further improvements in technology: joint replacement usually restores function and mobility even for athletic activities* and, highly appreciated by the patient, eliminates or relieves pain.

Replacements for the ball-and-socket joint at the hip have been attempted for more than a century. One engineering aspect is the correct modeling of manufactured implants so that they can carry the mechanical loads and provide meaningful function*. The other technical task is the selection of proper materials. Routinely successful total hip replacement started in the 1960s* with the use of the metal-on-plastic articulations and the use of PMMA (poly methyl methacrylate) "cement" which serves as grout that mechanically links the prosthesis and the bone. More recent designs fix the metal implant surfaces directly to the bone, without cement. This can be done either with a press-fit or by encouraging bone in-growth: implant surfaces are coated with small beads or other three-dimensional surface geometries to create a pore sizes of less than 1 mm. To further encourage bone in-growth or on-growth, an osteoinductive or osteoconductive chemical coating may be sprayed on the "porous" surface of the implant.

If needed, the entire articulating surfaces are replaced: in the hip, the head of the femur (thigh bone) is removed and replaced by a spherical metallic or ceramic ball on a stem, and the acetabular cup is resurfaced with a plastic or ceramic liner. In the knee, which acts as a "sloppy" hinge, the articulating surfaces on the bottom of the femur are replaced with metal, and surfaces at the top of the tibia (shin bone) and on the patella (knee cap) are resurfaced with plastic.

Both hip and knee replacements have the same type of design for the major load-bearing components: the metallic component is convex and the plastic component is concave. The plastic generally used is an ultra-high molecular-weight polyethylene which allows for a low-friction articulation as the joint components move against each other.

Replacements of finger joints are usually a single-component molded plastic integral hinge. Use of this simple artificial joint is successful because of the low loads carried by the joints and the minimal debris generated by wear.

Less common, other joints can also be replaced, such as the ankle and the shoulder. Although commercial implants are available, these are less common due both to the complexity of the joint itself (and the required surgical technique to implant an artificial replacement), and because diseases of these joints have less of an impact on the daily activities: one can still walk with a fused ankle, but with an immobile hip or knee, even getting in or out of bed is difficult.

The design of joint replacements is constrained by biologic and mechanical considerations. Biologically, the device must be compatible with the body, both as a whole and as debris particles that are generated due to motion and subsequent wear. The corrosive and warm environment of the body places particular requirements regarding material toxicity, reactivity, mechanical strength, and wear. Of course, the device must be able to be implanted (in terms of size and complexity) and should yield near-normal range of motion and external appearance of the limb. Finally, the design of the device must consider the possibility of salvage: sufficient bone and soft tissue should remain to allow replacement of the device or fusion of the joint if needed.

When joint replacements fail, the symptoms to the patient usually are severe pain and newly restricted motion of the joint. Examination commonly shows that the device has become loose, which can result from post-surgical infection and from a biological response to particles. This is mostly a mechanical problem, frequently associated with debris from the metallic or plastic components or the cement. The wear particles may trigger a biologic reaction which leads to resorption of the bone and loss of implant support, as well as inflammation, reduced range of motion, and pain.

The Hand

The hand is a complicated structure whose sections have diverse mobilities. One of these, supination/pronation of the total hand (see Fig. 1.2), a rotation about the long axis of the forearm, actually takes place within the forearm, where the ulna and radius can twist slightly about each other because elastic fibers link these bones even though they do not touch.

The wrist joint consists of nearly flat surfaces at the distal ends of the bones of the forearm, radius and ulna, and of similarly flat opposing surfaces on the proximal carpal bones of the hand – see Fig. 1.6. These flat surfaces allow gliding motions between arm and hand, which achieve flexion/extension as well as ab- and adduction.

The bony structure of the hand is a complex composite of 27 bones. They form the solid structures of the wrist (carpus), the base of the hand (metacarpus) and its five digits, the thumb and four fingers. (Actually, there are two additional "loose" sesamoid bones in the thumb.)

Adjacent to the wrist joint, the base of the hand starts with two rows of carpal bones: in the proximal row, from radial to ulnar side, scaphoid, lunate, triquetrum,

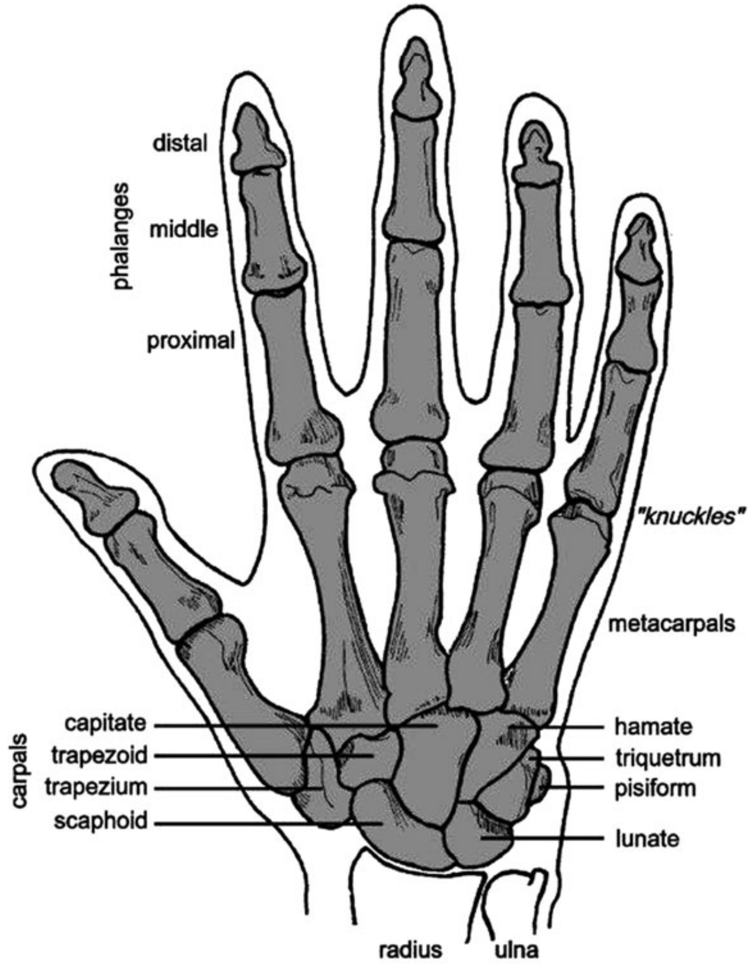

Fig. 1.6 The bones of the hand, dorsal view

pisiform; in the distal row, trapezium, trapezoid, capitate, hamate. The carpal bones are tied together by ligaments, so only little movement can take place; most displacement occurs in cupping the palm when the thumb touches the little finger.

Distal to the carpals, one metacarpal bone extends toward every one of the five digits. The carpo-metacarpal (CM) joints of the four fingers are of the hinge type with limited ranges; however, the joint of the shorter and sturdier metacarpal of the thumb has a saddle design that affords two degrees of freedom. The resulting ability of the thumb to oppose all four fingers allows a remarkable variety of manipulations.

The first digit, the thumb, has distally to its metacarpus only two phalanges, the proximal and the distal phalanx. In contrast, each of the other four digits posesses three phalanges distal to the proximal ends of their metacarpals. The metacarpophalangeal joints (MP joints, the "knuckles" of the fingers) provide primarily flexion/extension, as in making and releasing a fist, but also some adduction/abduction, for adjoining and spreading the fingers. All the interphalangeal joints (proximal PIP, distal DIP joints) are simple hinges.

The Spinal Column

The spinal column is a mechanically interesting, very complex structure. As shown in Fig. 1.7, it consists of a stack of 25 bones, the vertebrae. The topmost of the seven cervical vertebrae (C1–C7), the "atlas", carries the skull. The middle of the spine consists of 12 thoracic vertebrae (T1–T12). At the bottom are five lumbar vertebrae (L1–L5), resting on the sacrum, the "tailbone" (coccyx), which is a triangular fused group of rudimentary vertebrae*.

In the frontal view, a healthy spine is straight; yet, seen from the side it has a backward bend (kyphosis) at the thorax and forward bends (lordoses) at the neck and the lower back.

Figure 1.8 is a schematic of the lumbar section of the spinal column, showing particularly the articulations. The main bodies of the vertebrae rest upon each other on fibrocartilage disks: more about them below. Vertebrae also have two bone processes extending backwards-laterally; each of these articulation processes carries, on top, a rounded surface, facet, which fits into a corresponding cavity on the underside of the articulation process of the vertebra above. The facet joints, covered with synovial tissue, determine the ability to twist the spine, which mostly occurs in the cervical and thoracic sections.

Hence, the vertebrae rest upon each other in three joints of two different kinds: the cartilaginous cushion of the inter-vertebral disk (which is the articulation most often mentioned) and two bony synovial facet joints. About a hundred muscles and many ligaments (inside the foramen, between the protrusions of the vertebrae, and covering the whole spine) keep the complex spinal column in delicate balance.

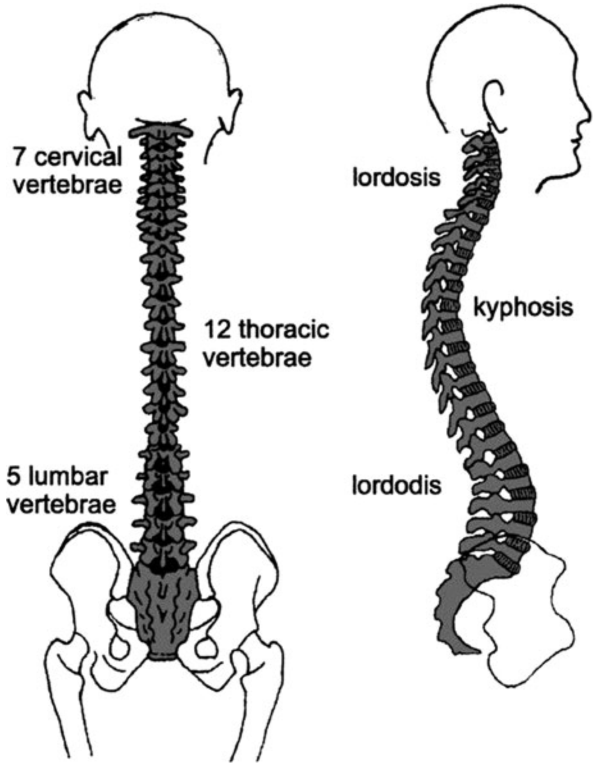

Fig. 1.7 Sketch of the human spinal column

Figure 1.9 sketches a 3D view of a typical vertebra: the front part, called the main (vertebral) body, provides two flat load-bearing surfaces, superior and inferior, for the intervertebral disks. The rear part is an arched structure: it curls around the intravertebral foramen, the opening through which the spinal cord passes. The stacked arcs of the vertebrae provide a protective tunnel for the spinal cord, which runs along the length of the spine. Each vertebral arch has five protrusions: the spinous (posterior) process, two transverse (lateral) processes and the two articulation processes that end in the four facet joints. That complex form of the vertebra provides attachment surfaces and leverage for muscles and ligaments.

The spine is capable of withstanding considerable loads, yet flexible enough to allow a large range of postures. There is, however, a trade-off between carried load and flexibility. If there is no external load on the spine, only its anatomical structures (bone form, joint geometry, capsules, ligaments and muscles) restrict its mobility. Loads acting on the spinal column reduce its mobility; under heavy loading, the range of possible postures is very limited.

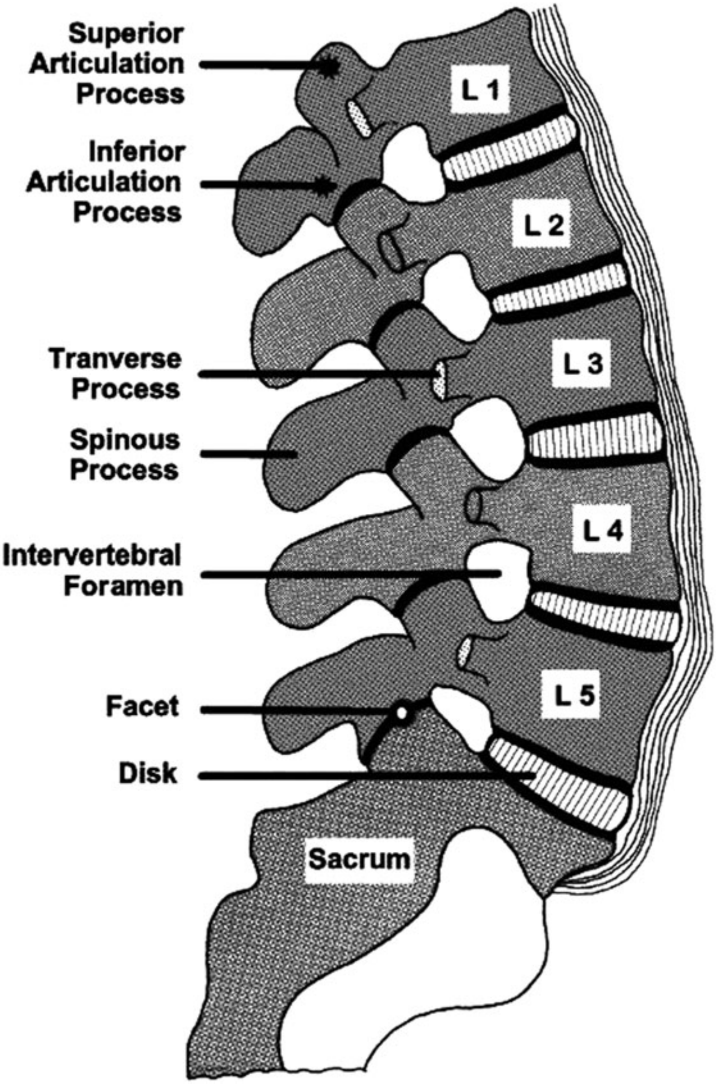

Fig. 1.8 Schematic of the lumbar section of the spinal column. *Heavy lines* indicate bearing surfaces

The spinal column is often the location of discomfort, pain, and injury because it transmits many internal and external strains. For example, when standing or sitting, the spine passes impacts and vibrations from the lower body on to the upper body. Conversely, forces and impacts experienced through the upper body, particularly when lifting or otherwise working with the hands are conveyed downward through

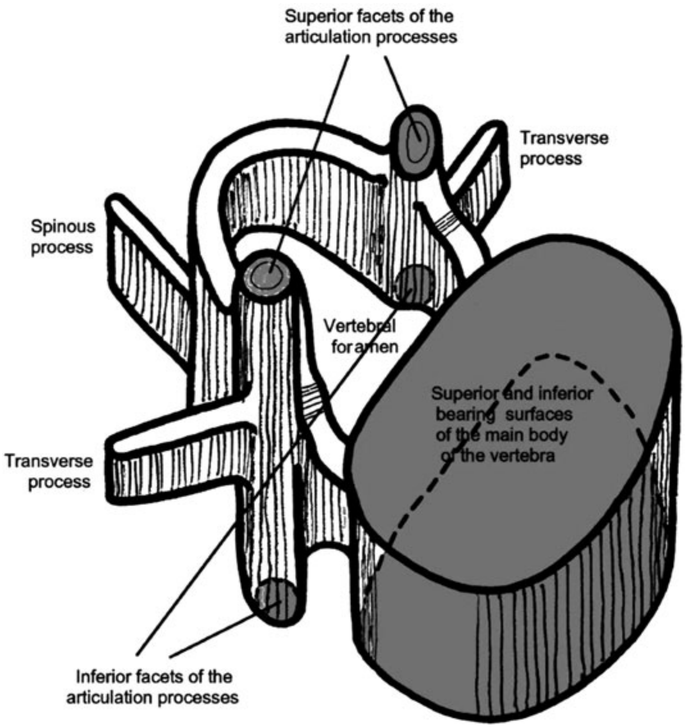

Fig. 1.9 Features of a typical vertebra: the main body, the arch with its processes and bearing surfaces on the main body, and the articulation processes

the spinal column to the floor or seat that support the body. Thus, the spinal column must absorb and dissipate much energy, whether it is transmitted to the body from the outside or generated inside by muscles.

Modeling the spine as a straight column, as depicted in the left side of Fig. 1.10, provides a simplification that allows a unique description of the relations between geometry and strain*. If the spinal column arches, shown in the center and on the right in Fig. 1.10, its load-bearing mechanism depends on the actual curvature. When the geometry of spinal arching is not fixed, no unique solution exists that describes its strain. Traditionally, force is thought to follow a straight line, called thrust line. For the arch is to be stable, the thrust line must lie within the cross section of all arch components. If at any point the thrust line falls outside the arch, either lateral force must reform the structure to be within its stable position range, or it buckles. Intra-abdominal pressure (IAP), which pushes in all directions within the trunk cavity, can have several beneficial effects: one of them is the ability to straighten the spinal curvature, as sketched on the right of Fig. 1.10, so that the thrust line stays within the spinal column. IAP may also reduce spinal compression by its axially directed component.

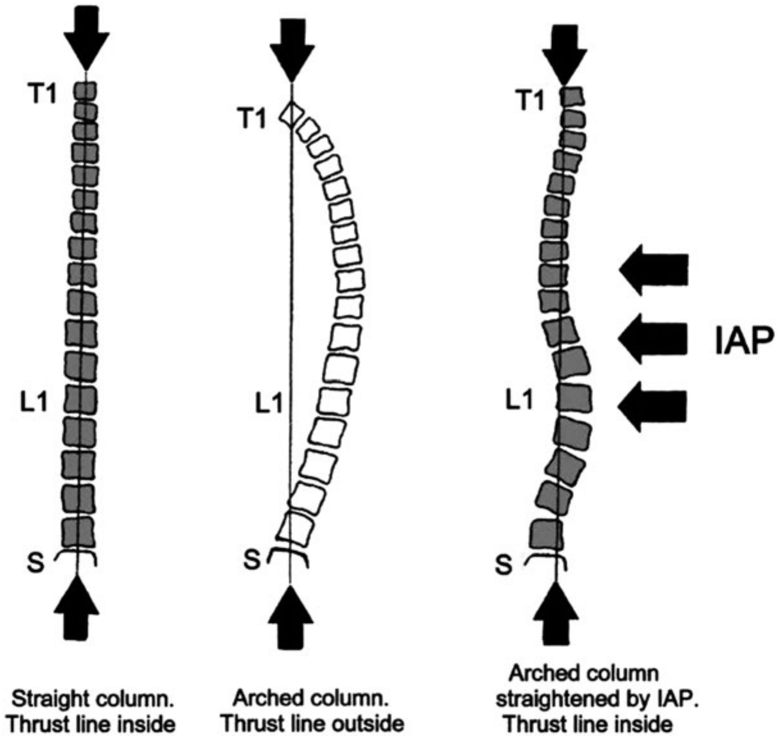

Fig. 1.10 Models of the spinal column under axial compression: see text (adapted from Aspden, 1988)

Compressing, shearing, bending and twisting constitute the major loadings of the spine, illustrated in Fig. 1.11. Spine compression force may result from the pull of axial trunk muscles, from external loads and from the masses of upper body segments masses. Owing mostly to the slanted arrangement of load-bearing surfaces at disks and facet joints, the spine is also subjected to shear. Furthermore, the spine must withstand both bending and twisting torques. The relations between actual loads (which vary greatly, depending on the task conditions) and load-bearing capabilities (which change as well) determine whether a person may be "overloaded" and hence become fatigued or even injured – a topic of occupational biomechanics, see Chap. 4. Designing tasks and equipment to consider human capabilities and preferences is in the domain of ergonomics/human factors engineering.

The Spinal Disk

The intervertebral disk is able to withstand compression and non-axial deformation because of its unique structure. At its core it consists of the nucleus pulposus, which resembles a gel-filled deformable ball: it carries most of the compressive loading transmitted along the spine and still allows the opposing surfaces of vertebral bodies

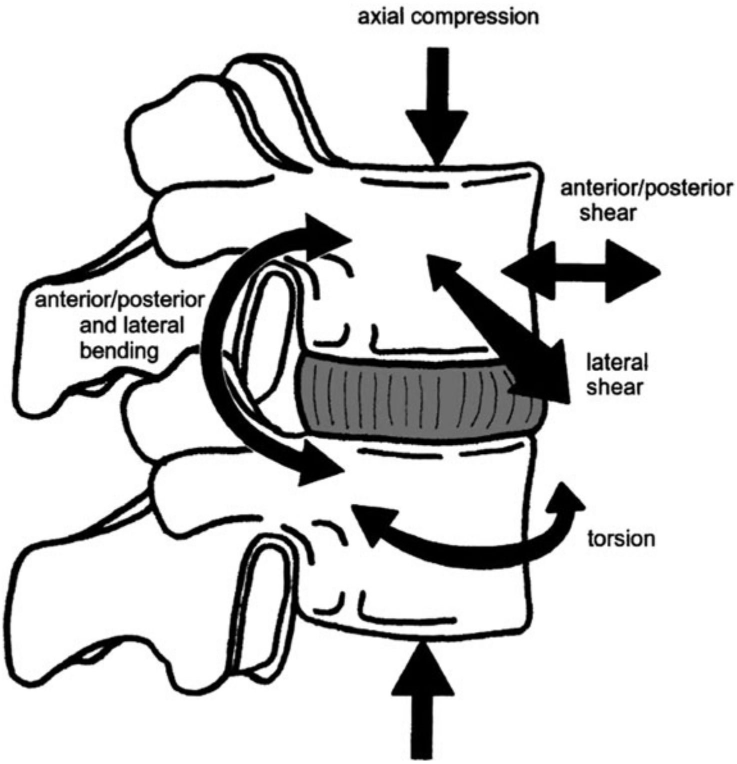

Fig. 1.11 Forces and torques acting on the spinal column (adapted from Marras, 2008)

to tilt with respect to each other. Laterally, the nucleus is held in position by the annulus fibrosus. It consists essentially of collagen fibers, arranged in several layers slanted against each other, which radially constrain the swelling pressure exerted by the nucleus during compression, slanting, bending and torsion of the paired vertebrae. The disk acts as a thick-walled pressure vessel, as a multi-directional articulation and as shock absorber.

The nucleus pulposus has no blood supply. It is nourished through the disk as a result of osmotic pressure, gravitational force, and the pumping effects of spine movement. It also does not have sensory nerves of its own, so pain due to damage arises in surrounding tissue.

If a disk does not function well, for instance due to deterioration (such as by aging) or damage (by an acute injury, for example), it cannot properly transmit loads and allow motions between adjacent vertebrae. Disk "herniation" occurs when parts of the annulus get weakened or even break so that components of the annulus become displaced from their proper location between adjacent vertebrae. If displaced matters protrude towards a spinal nerve, they can impinge on nerve tissue, which usually affects the transmission of nerve signals and causes pain – see Chap. 3.

Malfunction of the disk can bring about a combination of misalignment of vertebrae, strain of vertebral bone, of facet joints, and of connective tissues, muscles and ligaments. It often leads to restricted mobility, reduced ability to perform physical work, particularly to move loads such as in lifting. "Low back pain" is frequent, yet often difficult to diagnose and to treat. It is the result of an inherent structural weakness, of an injury, or of diseases that have been with humans since ancient times*.

Aging changes the spine, as it affects all skeletal components. Bone mass and structural strength increase with age in the young, then begin to decrease in mature adults. Children's spines are much more flexible than adult spines, depending on the load direction. Aging and growth commonly also increase the angulation of the cervical facets and increase cervical lordosis in adults. In the elderly, increased thoracic kyphosis and decreased lumbar lordosis are common; this is due at least in part to decreases in the height of the disk. Disk height changes stem from degeneration of the disk and changes in the curvature of the vertebral end plate, possibly from osteoporosis.

As already mentioned, the spinal column often is the site of overexertion. This may manifest itself by deformation, displacement, strains and sprains or damage to spinal disks, vertebrae, ligaments, cartilage, and muscle. Such injuries being a very frequent and very costly problem in businesses, much research has been directed at the causes and mechanisms involved. Since no detailed discussion of problems is possible here, it must suffice to state that uncoordinated pull of the muscles on the spinal column, particularly when associated with large and especially with asymmetric external loads may (directly or indirectly, acutely or cumulatively, often in unknown and not reconstructable ways) lead to various back overexertions and injuries. Ergonomic design of work place, equipment, and task can avoid some – but not all – risks. Even for persons with persistent back pains, work stations and procedures can be engineered to allow performance of suitable physical work*.

Notes

The text contains markers, *, to indicate specific references and comments, which follow.

Osteoporotic bones: Ostlere and Gold (1991).

Mobility is the difference between the smallest and largest angles enclosed by involved body segments: Often the actual arms of the rotation angle are not well defined: they may be the straight lines connecting the center of rotation of the enclosed articulation to the point of rotation of the next articulation (in the example of the knee joint, running distally to the ankle and proximally to the center of the hip joint); or they may be the estimated mid-axes of the adjacent body segments.

Joint replacement: Implants in 2003 in the USA, as per Roanoke Times of August 29, 2004:

- total hips: 165,000
- total knees: 326,000
- replacement eye lenses: 2,500,000
- coronary stents: 475,000
- cardiac pacemakers: 177,000
- artificial heart valve: 82,000
- cardiac defibrillators: 56,000.

Joint replacement usually restores function and mobility even for athletic activities: Healy et al. (2008).

Modeling of manufactured implants so that they can carry the mechanical loads and provide function: Elbert (1991).

Routinely successful total hip replacement started in the 1960s: Pioneered by Sir John Charnley (1911–1982).

Spine and vertebrae: Karpandji (1982), Panjabi et al. (1992) describe the geometry of vertebrae in detail. Hukins and Meakin (2000), Meakin et al. (1996), Chaffin et al. (2006), Marras (2008) and Vierra (2008) discuss the biomechanics of the spine.

Spinal geometry and strain: Aspden (1988), Meakin et al. (1996), Hukins and Meakin (2000) discuss Euler buckling of the spine.

Structural weakness of the spine: Low back problems have been diagnosed among Egyptians 5000 years ago and were discussed in 1713 by Bernadino Ramazzini (translation by Wright 1993). The problem is not confined to humans; dogs and other quadrupeds may suffer from low back pain as well.

Ergonomic design for persons with back problems: For more information, see among other publications those by Kroemer (1997), Violante et al. (2000), Chengular et al. (2003), Kroemer et al. (2003), Chaffin et al. (2006), Marras (2008), Vierra (2008).

Summary

The complex skeletal system with its bones, joints, and connective tissues allows a large range of motions, both forceful and well controlled, especially of the upper extremity. Its capabilities are highly variable; in general, they increase with use, which strengthens strained bones and lubricates loaded joints. However, damage by overloading is frequent: the spinal column, in particular, has been and continues to be the object of biomechanical and ergonomic studies. Many of its simpler components can be approximated by technical devices, such as finger, hip, and knee joints.

Glossary

Acetabulum Cup-shaped cavity at the base of the pelvis (hipbone) into which the ball-shaped head of the femur fits.

Anterior In front of the body; toward the front of the body; opposed to posterior.

Articulation Joint between bones.

Atlas The top cervical vertebra, supporting the skull.

Axis Center line of an object; midline about which rotation occurs.

Biceps brachii The large muscle on the anterior surface of the upper arm, connecting the scapula with the radius; flexor of the forearm.

Biceps ("Two heads") arm muscle reducing the elbow angle.

Biceps femoris A large posterior muscle of the thigh; flexor of the thigh.

Bending See moment.

Bone Hard dense porous material developed from connective tissue and forming the skeleton.

Brachialis Forearm muscle connecting the mid-humerus and the ulna.

Brachioradialis Forearm muscle connecting the humerus and the radius.

Cancellous Open, latticed, porous, as of bone.

Carpus The wrist.

Cartilage Tough, elastic, fibrous connective tissue.

Cervical Part of/pertaining to/ the cervix (neck), especially the seven vertebrae at the top of the spinal column.

Coccyx (or: sacrum) the tailbone, a triangular bone of fused rudimentary vertebrae at the lower end of the spine.

Collagen A protein forming the chief constituent of bone and connective tissue.

Compression The pressure (strain) generated in material caused by two opposing forces; opposite of tension.

Cortical Of/at the outside.

Degree(s) of freedom IN mechanics, the number of independent linear or rotational displacements which a body can execute.

Density Mass of material per unit volume.

Diaphysis Shaft of a long bone.

Digit The thumb and four fingers of the hand.

Distal Away from the center, peripheral; opposite of proximal.

Dominant The hand or foot exclusively or preferably used for certain actions.

Dorsal Toward the back or spine; also pertaining to the top of hand or foot, opposite of palmar, plantar, and ventral.

Elastic Spontaneous regaining of former shape after distortion; opposite of plastic.

Ergonomics The application of scientific principles, methods and data drawn from a variety of disciplines to the design of engineered systems in which people play significant roles.

Extend To move adjacent segments so that the angle between them is increased, as when the leg is straightened; opposite of flex.

External Away from the central long axis of the body; the outer portion of a body segment.

Facet Flat articulation surface at the upper (superior) and lower (inferior) parts of the articulation processes of a vertebra.

Fascia Layer of fibrous connective tissue enwrapping muscle, muscle bundles and bundles of fibers.

Femur The thigh bone.

Flex To move a joint in such a direction as to bring together the two parts which it connects, as when the elbow is bent; opposite of extend.

Flexibility Term occasionally used instead of mobility.

Foramen An opening in a bone, such as within a vertebra (the intravertebral foramen, part of the "spinal tunnel") or between two vertebrae (the intervertebral foramen, allowing the "spinal roots" to pass).

Glycoprotein (Or glucoprotein) protein containing carbohydrate.

Herniation Rupture; protusion of body (disk) material through an opening in its surrounding wall (annulus).

Humerus The bone of the upper arm.

Inferior Below, lower, in relation to another structure.

Internal Near the central long axis of the body; the inner portion of a body segment.

Knuckle The joint formed by the meeting of a finger bone (phalanx) with a palm bone (metacarpal).

Kyphosis Backward curvature of the spine; opposite of lordosis.

Lateral Lying near or toward the sides of the body; opposite of medial.

Ligament Band of firm fibrous tissue connecting bones.

Lordosis Forward curvature of the spine; opposite of kyphosis.

Lumbar Part of/pertaining to/the loin, the five vertebrae atop the sacrum.

Matrix Intercellular substance of tissue.

Medial Lying near or toward the midline of the body; opposite of lateral.

Meniscus A disk of crescent-shaped cartilage in the knee joint.

Metacarpal Pertaining to the long bones of the hand between the carpus and the phalanges.

Metacarpus The base of the hand (between the wrist and the digits).

Mobility The ability to move segments of the body.

Moment The product of force and its lever arm when trying to rotate and object about a fulcrum; the stress in material generated by two opposing forces that try to bend the material about and axis perpendicular to its long axis; see also torque.

Muscle Tissue composed of bundles of fibers that can contract.

Osmosis Diffusion of a fluid through a semi-permeable membrane.

Osteoporosis Bone becoming more porous and hollow, less dense and more brittle.

Palmar Pertaining to the palm (inside) of the hand; opposite of dorsal.

Patella The kneecap.

Pelvis The bones of the "pelvic girdle" consisting of illium, pubic arch and ischium which compose either half of the pelvis.

Phalanges The bones of the fingers and toes (singular, phalanx).

Physis The body as distinguished from the mind.

Plantar Pertaining to the sole of the foot.

Plastic Able to be distorted permanently into a different shape; opposite of elastic.

Popliteal Pertaining to the ligament behind the knee or to the part of the leg behind the knee.

Posterior Pertaining to the back of the body; opposite of anterior.

Protuberance Protruding part of a bone.

Proximal The (section of a) body segment nearest the head (or the center of the body); opposite of distal.

Radius The bone of the forearm on its thumb side.

Resorb To (again) break down and assimilate (something differentiated previously).

Sacrum (Or: coccyx) the tailbone, a triangular bone of fused rudimentary vertebrae at the lower end of the spine.

Scapula The shoulder blade.

Spine The column of vertebrae.

Spine (or spinal process) of a vertebra The posterior prominence.

Sternum The breastbone.

Sub A prefix designating below or under.

Superior Above, in relation to another structure; higher.

Supra Prefix designating above or on.

Tailbone (Or sacrum, coccyx) triangular bone of fused rudimentary vertebrae at the lower end of the spine.

Tarsus The collection of bones in the ankle joint.

Tendon Band of tough fibrous tissue connecting the end of a muscle to a bone.

Tension The strain in material generated by two opposing forces that try to stretch the material; opposite of compression.

Thoracic Part of/pertaining to/the thorax (chest), especially the 12 vertebrae in the middle of the spinal column.

Tibia The medial bone of the lower leg (shin bone).

Torsion The stress in material generated by two opposing forces that try to twist the material about its long axis; moment.

Transverse plane Horizontal plane through the body, orthogonal to the medial and frontal planes.

Triceps (“Three heads”) arm muscle increasing the elbow angle.

Tuberosity A (large) rounded prominence on a bone.

Ulna The bone of the forearm on its little-finger side. Ventral – pertaining to the anterior (abdominal) side of the trunk.

Vertebra A bone of the spine.

Volar Pertaining to the sole of the foot or the palm of the hand.

Wolff’s law “Use strengthens, disuse weakens”.

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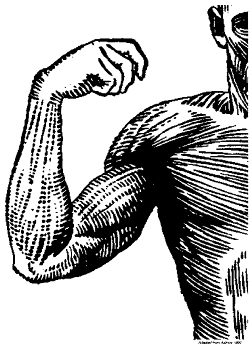
Chapter 2
Muscles



Overview

Skeletal muscles move body segments with respect to each other against internal and external resistances. Shortening is the only active function of the muscle. Nervous signals stimulate muscle components either to shorten dynamically, to statically retain their length or to allow being lengthened. Various methods and techniques are available for assessing muscular control and strength. The engineering application of data on available body strength requires the determination of whether minimal or maximal exertions, static or dynamic, are the critical design considerations.

The Model

In the human body, skeletal bones and connective tissues form an internal framework, moveable in its intermediate articulations. Skeletal muscles, which span one or two body joints, generate forces that pull on the bones that serve as lever arms.

The skeletal muscles are "linear motors" which, when triggered by nervous signals, contract within themselves, striving to shorten the distance between their attachments to bones. Muscles also may be stretched by external forces if these overcome the muscles' resistance.

Since muscles always exist in counteracting pairs around skeletal joints, their interplay determines forcefulness of the human body and controls its motions.

Introduction

Muscular efforts have been of special interest to physiological science; therefore, there is a long tradition of philosophical and experimental approaches and use of terminology.

K.H.E. Kroemer et al., *Engineering Physiology*, 4th ed.,
DOI 10.1007/978-3-642-12883-7_2, © Springer-Verlag Berlin Heidelberg 2010

Leonardo da Vinci (1452–1519) and Giovanni Alfonso Borelli (1608–1679) combined mechanical with anatomical and physiological explanations to describe the functioning of the human body. Borelli modeled the human body as consisting of long bones (links) that connect in the articulations (joints), powered by muscles that bridge the articulations. The knowledge developed by Gottfried Leibnitz (1646–1716) and Isaac Newton (1642–1727) explained the laws governing mechanics of the human body in terms of statics and dynamics.

Physiology books published until the middle of the twentieth century tended to divide muscle activities into two groups: one consisted of short bursts of contraction without motion of the involved body segments. This "isometric" condition received much research attention and, consequently, most published information on muscle strength applied to static efforts. The other group of physical activities of interest were dynamic efforts lasting minutes or hours; work, energy, and endurance were typical topics. These non-static activities of muscles were typically called "anisometric," even falsely labeled "isotonic" or "kinetic".

The glossary at the end of this chapter lists and defines terms that correctly describe muscular events.

Muscle Architecture

The human body has three types of muscle: smooth, cardiac and skeletal (striated). Smooth muscles control the opening (lumen) of and flow in blood vessels. Cardiac muscle in the heart pumps blood through the vascular system. Electrical stimulation and contraction mechanism are similar in smooth and cardiac muscle but anatomic and physiologic characteristics of cardiac muscle resemble those of skeletal muscle. Skeletal muscles (also called voluntary muscles) control body locomotion and posture. They usually connect two body members across their common joint; some muscles cross two joints.

In ergonomics, skeletal muscles are of primary interest since they move the segments of the human body and generate energy for exertion to outside objects. Knowledge about muscular characteristics is important for the design of work tasks, workplaces and equipment.

Agonist-Antagonist, Co-contraction

In the human body, the usual arrangement of muscles is in a "functional pair" where an opponent counteracts the contracting muscle. One muscle, or a group of synergistic muscles, flexes around an articulation while the other extends, as shown in Fig. 2.1. The active muscle is called agonist (or protagonist) and the opposing one antagonist. Co-contraction is the simultaneous contraction of two or more muscles, often of agonist and antagonist. Co-contraction serves to control the magnitude of a strength exertion or the speed of motion of limbs. Another kind of co-contraction

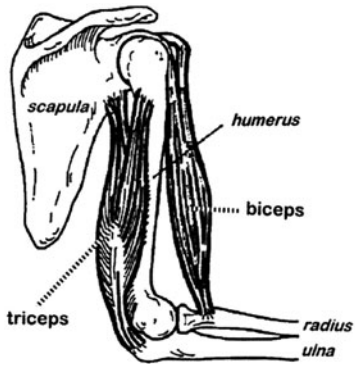


Fig. 2.1 Biceps and triceps muscles as antagonistic pair control elbow flexion and extension. Not shown are the brachialis muscle (attaching to humerus and ulna) and the brachioradialis muscle (connecting humerus with radius) which act together with the biceps as a synergistic flexor group

occurs when muscle activate that are not directly involved in a task. This happens, for example, when we tighten muscles in the left arm when those in the right arm execute a strong effort; this is called bilateral co-contraction.

Components of Muscle

There are several hundred skeletal muscles in the human body, known by their Latin names. (The often-used Greek prefix *myo* means muscle.) Many muscle are spindle-shaped (fusiform) with a wide "belly" and narrow ends where the wrapping tissue combines to form cable-like tendons, which attach to bones: "origin" is the proximal attachment, "insertion" the distal one. By weight, muscle consists of 75% water and 20% protein; the other 5% include fats, glucose and glycogen, pigments, enzymes, and salts.

Connective tissue, epimysium, wraps each muscle; it is called fascia when it is smooth and allows the muscle to slide against its surrounds. As sketched in Fig. 2.2, every muscle actually consists of bundles of muscles, fasciculi (fascicles), wrapped in connective tissue (perimisium). In turn, every fasciculum is made up of separate bundles of long muscle cells, called muscle fibers; again, connective tissue (endomysium) wraps each bundle of cells. A large number of fibers lie side-by-side. Some cells are as long as the fascicle; shorter fibers may be in series, head-to-head.

A complex membrane, the sarcolemma (also called plasmalemma) envelopes each muscle fiber. Inside that envelope are myofibrils (discussed in detail below) and a gelatin-like substance, sarcoplasm, which fills the spaces within and between the fibrils. The sarcoplasm contains dissolved proteins, minerals, glycogen, fats, and myoglobin.

Figure 2.3 shows the intricate network of small tubes, tubules, which run parallel to the myofibrils and also loop around them: this is the sarcoplasmic reticulum. Another network has interconnected transverse tubes, T-tubules. They start as indentations (invaginations) of the sarcolemma and then penetrate the muscle fiber

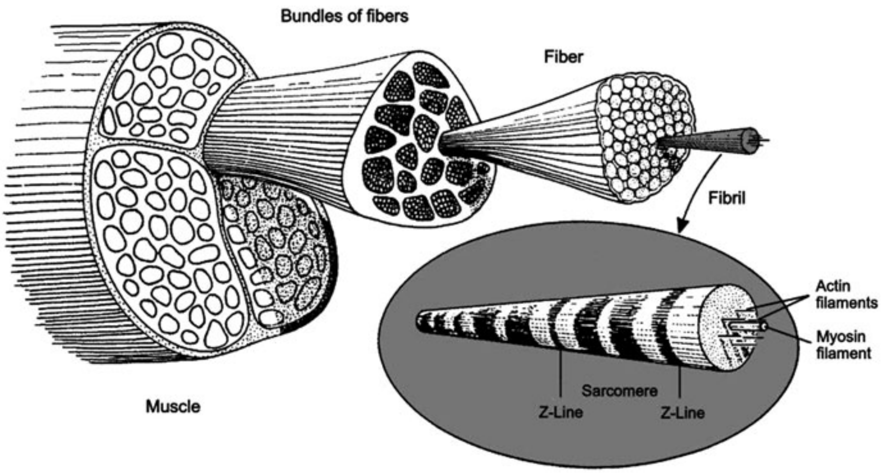


Fig. 2.2 Major components of muscle (adapted from Astrand et al., 2003; Wilmore et al., 2008)

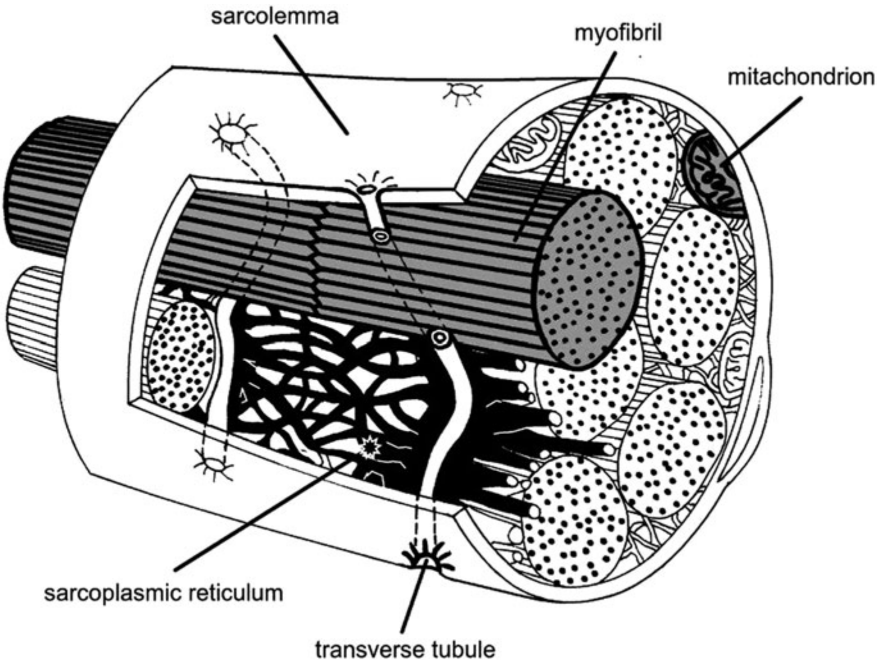


Fig. 2.3 Sketch of major components of muscle fiber (adapted from Astrand et al., 2003; Wilmore et al., 2008)

sideways. Thus, they are extensions of the sarcolemma and provide pathways for extracellular fluid.

The sarcolemma also contains mitochondria, organelles that are the “power sources of muscle”: they provide the energy that a muscle cell needs to contract. They do so by extracting energy from the breakdown of ATP, adenosine triphosphate, and converting glycogen and fats, dissolved in the sarcoplasm, to re-generate ATP – see Chaps. 7 and 8.

The networks of tubules of a muscle fiber connect with the wrapping around the bundles of fibers and its network; this connects with the membranes around the bundles of muscles; finally, there are connections to the sheathing of the total muscle. These joined networks fill the spaces within the muscle with a complex “plumbing and control” system. It allows fluid transport among the cells inside and outside the muscle; it provides influx of energy carriers and removal of metabolic byproducts and it transmits chemical and electrical messages.

Within each muscle fiber are thread-like myofibrils, generally parallel to each other by the hundreds or thousands. These fibrils, in turn, consist of bundles of filaments, protein rods that lie in huge numbers side-by-side and head-to-head. There are two primary types of myofilament, both elongated polymerized protein molecules: myosin and actin. These are the “movers” of muscular contraction because they can slide along each other – see below.

Figure 2.3 sketches major components of muscle fiber, Fig. 2.4 shows a schematic of the myofilaments myosin and actin forming a sarcomere; Table 2.1 lists approximate dimensions.

Seen via a microscope, skeletal muscle fibers appear striated (striped) because thin and thick, light and dark bands run across the fiber in the same repeated pattern along the length of the fiber. These striations indicate the locations of myosin and actin rods. One such dark stripe appears to cross the fiber like a thick membrane or

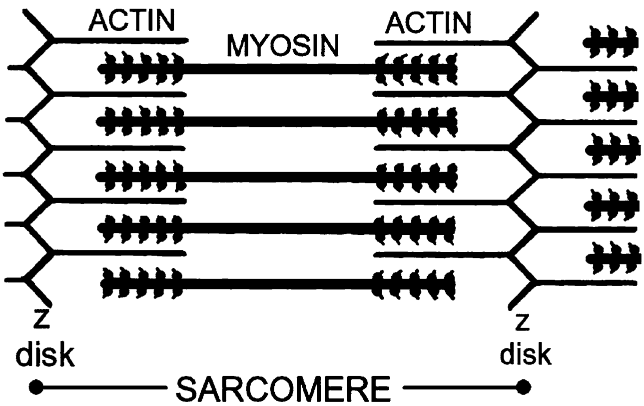


Fig. 2.4 Schematic of the myofilaments myosin and actin, and of a sarcomere

Table 2.1 Approximate dimensions of muscle components

Component	Diameter	Length
Fiber	5×10^5 to 10^6 Å	Up to 0.5 m
Myofibril (each contains up to 2,500 filaments)	10^4 to 5×10^4 Å	
Actin myofilament	50 to 70 Å	10^4 Å
Myosin myofilament	100 to 150 Å	2×10^4 Å

1 Å (Ångstrom) = 10^{-10} m

disk: this is the so-called z-disk (from the German *zwischen,* between), where actins originate on either side; see Fig. 2.4. The z-disk also carries much of the "plumbing and control" networks, just mentioned, through the muscle tissue.

The distance between two adjacent z-lines defines the sarcomere. Its length at rest is approximately 250 Å (1 Å = 10^{-10} m); accordingly, one millimeter of muscle fiber length can contain about 40,000 sarcomeres in series.

Each myofibril contains from 100 to 2,500 myosin filaments, lying side by side, and about twice as many actin fibrils. Small projections from the myosin filaments (resembling miniature golf clubs), called cross-bridges, protrude towards neighboring actin filaments. The actin filaments are twisted double-stranded protein molecules, wrapped in a double helix around the myosin molecules. In cross-section, six actin rods surround each myosin rod in a regular hexagonal array. That combination of actin and myosin is the contracting microstructure (also called the elastic element) of the muscle.

Muscle Contraction

Shortening is the only *active* action a muscle can do; external forces may stretch the muscle.

By convention, one distinguishes between the resting length of the muscle, its contracted (shortened) and its elongated (stretched) lengths. Figure 2.5 shows these three conditions. The sarcomere can shorten to about 60% in contraction or it may be stretched to about 160% of its rest length without damage. At around 200% stretch, muscle fibers, tendons, or tendon attachments are likely to break.

In a relaxed muscle, attractive forces between the actin and myosin filaments are chemically neutralized, but an incoming nervous signal (see Chap. 3) initiates filament activity. Cross-bridges are established and released as the actin "ratchets" along the myosin, sliding the opposing heads of actin rods towards each other*. This pulls the z-disks towards the tails of the myosin filaments: the sarcomere (and with it the muscle) shortens. After the contraction, the muscle returns to its resting length, primarily through a "recoiling" of its shortened filaments, fibrils, fibers and of other connective tissues.

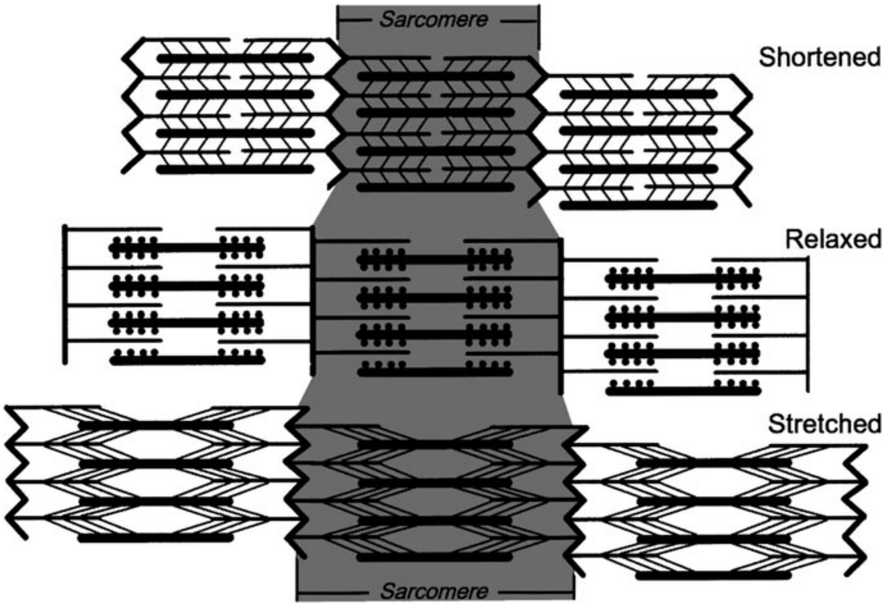


Fig. 2.5 Schematic of sarcomeres in contracted, relaxed and extended muscle

Careless use of the term "contraction" can lead to confusion:

"Contraction" literally means "pulling together", as in the sliding of actin on myosin filaments, which pulls the Z lines together and hence shortens the sarcomere.

Muscular shortening may occur either without resistance or against an opposing force; tension develops in the muscle only to the extent that resistance against the shortening exists. Therefore, the event of a "contraction" does not necessarily imply a forceful effort by the muscle.

During a "static contraction", the sarcomere length remains unchanged (isometric).

In an "eccentric contraction", the sarcomere is actually lengthened.

To avoid misleading implications and contradictions in terms, it is often better to use the terms activation, effort, or exertion, instead of contraction*.

Relation Between Muscle Length and Tension

Muscle can contract to about 60% of its resting length. In this condition, the actin proteins curl completely around the myosin rods and the z-lines are as close as possible. This is the shortest possible length of the sarcomere, at which the muscle can just barely develop any active contraction force; the muscle becomes more forceful as its length extends.

External force can stretch the muscle beyond its resting length. This slides actin and myosin fibrils along each other. When the muscle is extended to 120–130% of resting length, the cross-bridges between actin and myosin attain the best position to generate contact for contractile resistance. If the elongation continues even farther, the cross-bridge overlap diminishes; at about 160% of resting length, so little overlap remains that the muscle cannot develop any active resistance anymore. With further elongation, passive tissue resistance to stretch grows, like in a rubber band, until tissue snaps.

Below resting length, tension in the muscle results from only the active contraction effort of the muscle. Above resting length, the total tension in the muscle is the summation of active and passive strains. Accordingly, the curve of *active* contractile tension developed within a muscle is zero at approximately 60% resting length, about 0.9 at resting length, at unit value at about 120–130% of resting length, and then falls back to zero at about 160% resting length. (These values apply to an isometric twitch contraction, discussed below.) Figure 2.6 shows, schematically, the combination of active and passive tensions in a muscle.

The summation effect explains why we instinctively pre-stretch ("preload") muscles for a strong exertion, as in bringing the arm behind the shoulder before throwing a rock or ball forward.

In engineering terms, muscles exhibit "viscoelastic" qualities: "viscous" because their behavior depends both on the amount by which they deform and on the rate of deformation. They are "elastic" because, after deformation, they return to the original length and shape. These behaviors, however, are not pure in the muscle, because it is nonhomogeneous, anisotropic, and discontinuous in its mass. Nevertheless, nonlinear elastic theory and viscoelastic rules can describe major features of muscular performance.

Viscoelastic theory also helps to explain why the tension that can be developed isometrically ("statically", resisting eccentric stretch) is the highest possible, while in active shortening ("dynamically", during concentric movement) muscle tension

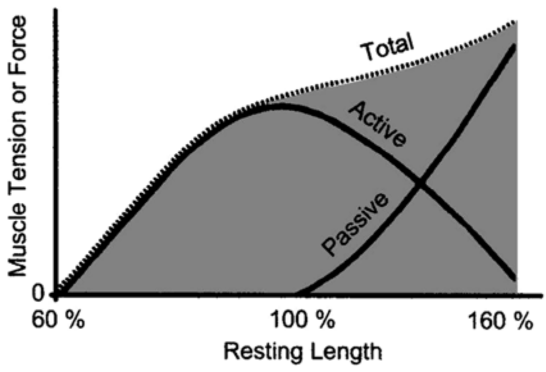


Fig. 2.6 Active, passive and total tension within a muscle at different lengths

is decidedly lower. The higher the velocity of muscle contraction, the faster actin and myosin filaments slide by each other and the less time is available for the cross-bridges to develop and hold. This principle of speed-related reduction in tension capability of the muscle holds true for both concentric and eccentric activities. In eccentric activities, however, the total tension resisting the stretch increases with larger length owing to the summing of active and passive tensions within the muscle, as just discussed.

The "Motor Unit"

The axon endings of nerve fibers, often hundreds or thousands of them, permeate muscles; they are the final branches of the efferent (motor) part of the peripheral nervous system (discussed in Chap. 3). The contact area of axon and sarcolemma of the muscle is called "motor endplate". Each nerve fiber innervates several, usually hundreds, even thousands of muscle fibers through as many motor endplates, sketched in Fig. 2.7. These fibers under common control are a "motor unit": the same signal stimulates them all. However, the muscle fibers of one motor unit lie usually not close to each other but are spread throughout the muscle. Thus, "firing" one motor unit does not cause a strong contraction at one specific location in a muscle but rather a weak contraction throughout the muscle.

The anecdotal "all-or-none principle" means that all muscle fibers of one motor unit are either fully relaxed or fully contracted. Yet, that statement does not describe the condition of a muscle in the initial phase of twitch buildup or during the return to the resting state.

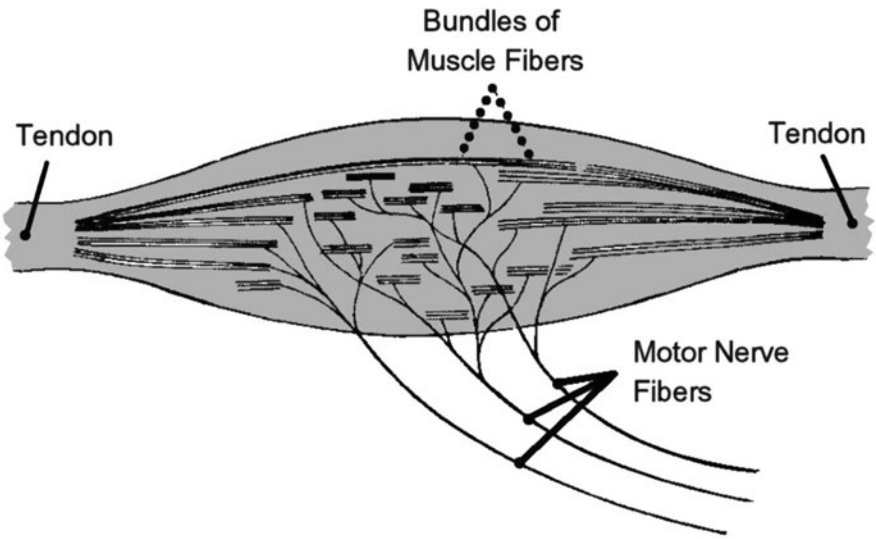


Fig. 2.7 Schematic of the motor endplates of three nerves (adapted from Guyton, 1979)

Muscle Twitch

Twitch is a single contraction of a motor unit; it starts upon receipt of a nervous stimulus and ends with complete relaxation. A twitch lasts up to 220 ms in skeletal muscle, yet only about 10 ms in ocular muscle. As Table 2.2 shows, twitches begin with a latent period; the phase of shortening follows, then comes a period of relaxation, and finally there is time for recovery – together about 130 ms for a typical fast twitch muscle fiber (see below for more information on fast and slow fibers).

When a fiber contraction is not yet completely released by the time the next stimulation signal arrives, summation (superposition) of twitches occurs. The new contraction builds on a level higher than if the fibers had been completely relaxed; consequently, the contraction achieves higher contractile tension in the muscle. Such "staircase" effect takes place when excitation impulses arrive at frequencies of 10 or more per second. When muscle stimulation is above a critical frequency, 30–40 stimuli/s, successive contractions fuse together to a maintained contraction, called tetanus. In superposition of twitches, the tension generated may be double or triple as large as in a single twitch; a full tetanus may have up five times the single-twitch tension.

Table 2.2 Single twitch of a fast-twitch muscle fiber

Period, duration	Muscle action	Energy metabolism (see Chap. 7)
Latent, about 10 ms	No reaction yet of the muscle fiber to the motor neuron stimulus	None
Shortening, about 40 ms	Cross-bridges between actin and myosin vibrate and "ratchet" the heads of the actin rods towards each other along the myosin	Energy for this process is freed from the ATP complex, mostly anaerobically
Relaxation, about 40 ms	Cross-bridges stop oscillating, bonds between myosin and actin break, the muscle returns to its original length	ATP is re-synthesized from ADP
Recovery, about 40 ms	None	Aerobic metabolism oxidizes glucose and glycogen, final regeneration of ATP and phosphocreatine

Muscle Fatigue

Muscular fatigue may be defined operationally and simply as "a state of reduced physical ability, which can be restored by rest". The feeling of fatigue indicates that the body is becoming unable to continue or repeat an effort. A benefit of the signals of fatigue is prevention of exhaustion and serious damage to muscles.

An everyday example is muscle fatigue that one painfully experiences when working with raised arms, such as adjusting a fixture overhead, depicted in Fig. 2.8.

Fig. 2.8 Fatiguing work overhead (adapted from Nordin et al., 1997)

After a short time, increasing discomfort, then pain, in the shoulder muscles, which keep the arms up or the neck muscles keeping the head bent backwards, make it impossible to go on with the work, even though nerve impulses still arrive at the neuromuscular junctions and the resulting action potentials continue to spread over the muscle fibers.

The reasons for fatigue are complex. They may relate to energy delivery in the muscle, to accumulation of metabolic byproducts such as lactate, to overexertion of muscular contraction mechanisms, even to events in the nervous system. Occurrence of fatigue depends on the type and intensity of the effort, on the fiber type of the involved muscles, on the person's fitness and training, and on the individual's motivation. Often, several of these factors combine to be causing fatigue. So-called central fatigue, associated with one's sense of effort and motivation, may occur also in the nervous control system; a strong emotional drive to perform, as in competition, can temporarily overcome muscular fatigue.

Sufficient supply of the muscle with arterial blood and unimpeded blood flow through the intricate pathways that penetrate muscle are crucial for muscle activities. Blood flow determines the ability of contractile and metabolic processes to continue because blood brings the needed energy carriers and oxygen and, equally important, it removes metabolic byproducts, particularly lactic acid and potassium as well as heat, carbon dioxide and water liberated during metabolism – see Chap. 6.

An artery enters the muscle usually at about its mid-length and branches there profusely. Some of the small arteries and their arterioles transverse muscle fibers while other blood vessels parallel the fibers; many crosswise linkages exist among them. This forms a complex network of blood vessels (the "capillary bed", see Chap. 5) permeating the muscle tissue. On the exit side, venules gather blood laden with metabolic wastes and channel it into veins. This capillary network is particularly well developed at the motor endplates.

The abundance of capillaries in the muscle provides good facilities for the supply of oxygen and nutrition to the muscle cells and for the removal of metabolic byproducts (see Chap. 7). However, a strongly contracting muscle generates strong pressure inside itself, as can be felt by touching a tightened biceps or calf muscle. By this pressure, the muscle compresses its own fine blood vessels. This impedes, may even shut off, the muscle's circulation in spite of a reflex increase in systolic blood

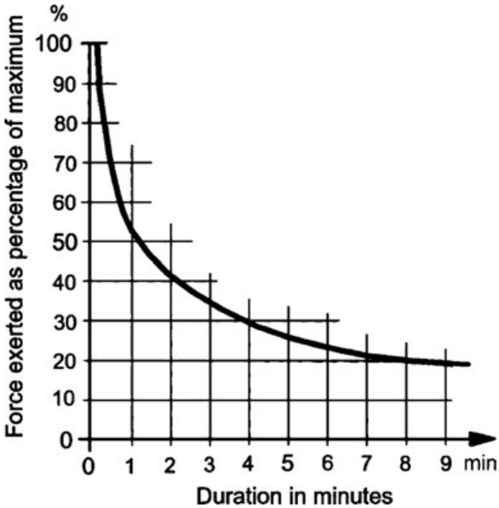


Fig. 2.9 Endurance of isometric muscle effort

pressure. Complete interruption of blood flow through a muscle leads to disabling muscle fatigue in a few seconds, forcing relaxation.

If repeated and/or strong efforts of the muscle severely diminish its flow of blood, lactic acid can remain as a byproduct of anaerobic glycolysis and potassium may accumulate. If so much lactate builds up that it blocks the breakdown of ATP, the muscle quickly loses its ability to function. These biochemical events perturb the coupling between nervous excitation and muscle contraction – the muscle experiences "fatigue" and must rest. Fortunately, simply taking a break, thus avoiding what caused the problem, leads to complete recovery.

The stronger the exertion of a muscle, the shorter the period during which this strength can be maintained. Figure 2.9 shows this relation between isometric strength exertion and endurance schematically: a maximal exertion can be maintained for just a few seconds; 50% of strength is available for about 1 min; but less than 20% can be applied for long periods.

Fatigue depends on the magnitude and duration of effort compared to the capability of the involved muscle; hence, physical training and skill development are subjective counteractions, effective to some extent. However, the proper ergonomic approach is to design out any work requirements that generate fatigue: the engineering solution is "fitting the task to the human".

Activities of Entire Muscles

Control of Muscle

Apparently, one cannot voluntarily contract more than two-thirds of all fibers of a muscle at once; this seems to be a safeguard against overstraining the muscle-tendon structure. However, contraction of all fibers at the same time can occur as a result of a reflex; this may strain the muscle or tendon to its total structural tensile capacity, and might even tear it.

The activities of a whole muscle, which comprises many motor units (discussed above), are controlled by "recruitment coding": it determines how many and which motor units turn on at any given instant. The cooperative effort of all participating motor units determines the tension in the whole muscle and hence the force that it transmits via tendons to the skeletal bones.

Exact control of the tension in a muscle depends on the number of muscle fibers innervated by one nerve axon (see Chap. 3): the smaller the number of fibers, the finer the muscle control. For example, in eye musculature, one nerve controls only seven muscle fibers, for an innervation ratio of 1:7, whereas the quadriceps femoris extending the knee has a ratio of approximately 1:1,000.

The nervous action potential spreads along the muscle at speeds of 1–5 m/s to initiate either recruitment or rate control: Rate control determines the number twitches per unit time.

Muscle Fiber Types

The proportion of fiber types in an individual seems to be genetically determined, but the total number of fibers, their size, contractile properties, and metabolic and fatigue characteristics can change with training or lack of use.

Muscle fibers may be of the slow-twitch type (also called Type I or red fiber). Relatively low-rate signals trigger them; therefore they often called low-threshold fibers. Slow fibers have small motor neurons and contract relatively leisurely, taking 80–100 ms until peak is reached. They produce comparatively low forces and are well suited for activities of light to moderate intensity even over extended time because they resist fatigue.

Other muscle fibers consist of fast-twitch fibers (also called Type II or white or high-threshold fibers), which have relatively short contraction times of about 40 ms. Fast fibers have large motor neurons and quick contraction relaxation speed. They exist in two main kinds: Fast fatigue-resistant FR fibers are capable of high force production. Fast fatigable FF fibers can produce the largest force and the greatest contraction–relaxation speed, but they fatigue easily.

Slow fibers are mostly recruited for finely controlled actions, while strong efforts generally involve fast fibers. For activities that require rapid, high force and/or high power, FR units are recruited first, followed by FF units.

Strength of Muscle and Body Segment

The term *strength* is often used in confusing ways: it may refer to the tension (force) *within* a muscle; or to the *internal transmission* of muscle tension (force) via limbs; or to the *external* exertion of force or torque via a body segment to an outside object.

Definition and proper use of the related terms avoid confusion:

Muscle strength is the maximal tension, or force, that muscle can develop voluntarily between its origin and insertion.

It would be advantageous to use "tension" (in N/mm^2 or N/cm^2) or "force" (in N) but the term strength is commonly used.

Internal transmission is the manner in which muscle tension, or force, transfers inside the body along links and across joint(s) as torque to the point of application to a resisting object.

If the internal transmission path of torque (in Nm) traverses several link-joint structures in series, each transfers the arriving torque (by the existent ratio of lever arms, m and h in Fig. 2.10) to the next link-joint until resistance is met, usually the point where the body interfaces with an outside object. This transfer of torques is more complicated under dynamic conditions than in the static case because of changes in muscle functions with motion and because of the effects of accelerations and decelerations on masses.

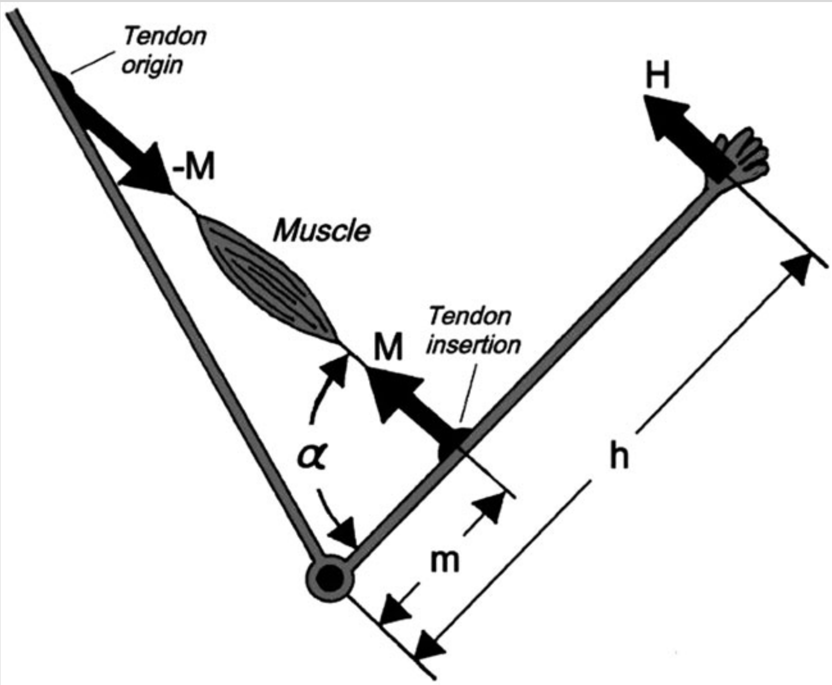


Fig. 2.10 The muscle-tendon unit exerting pull force M to bone links at origin and insertion

Body (segment) strength is the force or torque that a body segment can apply to an object external of the body.

The segment is usually hand, elbow, shoulder, back, or foot.

Muscle Strength

The "strength" of a muscle is properly described as the maximal tension, or force, that the muscle can develop voluntarily between its origin and insertion. It depends primarily on the number of muscle fibers in use, and on their thickness. Strength training increases the thickness of fibers, but probably not their number. Endurance training also increases capillary density and mitochondrial volume. Either kind of training also improves the overall coordination of motor unit activation in the central nervous system CNS (more in Chap. 3) because "muscles are the slaves of their motoneurons"*.

Within the muscle, filament contraction in the longitudinal direction of the muscle fiber generates tension, as discussed above. The tensions in each filament combine to a resultant tension of the muscle. Its magnitude is proportional to the cross-sectional thickness of the muscle. Maximal tensions measured in human skeletal muscle are within the range of 16–61 N/cm^2: 30 N/cm^2 is a typical value, often called "specific (human muscle) tension"*. So, if the muscle cross-section area is known (such as from cadaver measurements or from MRI scans), one can estimate a resultant muscle force. Yet, it is worth keeping in mind that this calculation relies on assumptions about cross-section and specific tension values – a technique to measure the muscle force directly in the living human is still missing.

Internal Transmission

The tension developed by a muscular contraction (whether concentric, isometric, or eccentric), tries to pull together two points: the *origin* of the muscle (that attachment closest to the center of the body) and the *insertion* at the opposite end of the muscle-tendon unit (away from the center of the body).

The origin (origins if the muscle has two "heads" such as the biceps, or three in the triceps) is commonly at the surface of a bone. From there, usually a short tendon runs to the muscle "belly" where most contractile elements are located. On the other side of the muscle, a tendon reaches outward toward the insertion. The tendon may be quite long; for example, the tendons that connect the muscles in the forearm with the digits of the hand are around 20 cm in length. The tendon insertion usually attaches to bone, but may also end in strong connective tissues, such as in some of the fingers. (More about the hand below.)

The long bones (representing the biomechanical "links" between articulations) are the lever arms at which muscle pulls to generate torque about a body joint. The torque developed depends, hence, not only on the strength of the muscle but also on its lever arm, and on the pull angle as well. Figure 2.10 shows this schematically – compare to Fig. 2.1.

The forearm link articulates in the elbow joint around the distal end of the upper arm link. The flexor muscle connects both links. It has its origin near the proximate end of the upper arm link* and it inserts on the forearm link at the relatively short distance *m* from the elbow. The flexor generates a muscle force *M*, which pulls on the forearm at the angle α (which depends on the existing elbow angle). Hence, $M \times \sin \alpha$ is the component of *M* that is perpendicular to the forearm; it generates a torque *T* about the elbow. The magnitude of T depends on force *M*, the lever arm *m* and the pull angle α. Accordingly,

$$T = m \times M \times \sin \alpha \tag{2.1}$$

Torque *T* transforms into hand force H, perpendicular to the forearm link at its lever arm *h*, according to lengths of the lever arms *m* and *h*:

$$T/m = H/h \tag{2.2}$$

Solving for hand force *H* yields

$$H = T/(m \times h) = (m \times M \times \sin \alpha)/h. \tag{2.3}$$

Since *m*, α, *h* and *H* are all measurable, one can compute the muscle force M:

$$M = (H \times h)/(m \times \sin \alpha). \tag{2.4}$$

(Check Chap. 4 for more detail and further use of biomechanical techniques.)

This simple model shows that the amount of force (H) available at the interface of the body with an external object depends on the

- Internal muscle force (M);
- Lever arms (m and h);
- Pull angle (α) which, in turn, depends on the angle between the two links.

By experience, we acquire the skill to position our body segments so as to achieve those lever arms and pull angles that permit the best use of our muscles to generate body strength needed to lift a heavy load, to push a big object, or to squeeze the handles of a hand tool.

Body (Segment) Strength

The original muscle pull (internally transmitted to the approximate body member, transformed in magnitude and direction during that transmission) results in a force or torque that the body can apply to an outside object:

- By hand to a tool, or to a handle on a box as in load lifting;
- By shoulder or back in pushing or carrying; or
- By the feet in operating pedals, or in walking or running.

The quality and quantity of the force or torque that the body can transmit to an outside object depends on mechanical and physical conditions, especially on the

- Body segment employed, for example, hand or foot.
- Type of body object attachment, such as a simple touch or a surrounding grasp.
- Coupling type, either by friction or with interlocking.
- Direction of force/torque vector.
- Needs for caution and control in task execution.
- Static or dynamic exertion, discussed below.

Consideration and proper selection of these conditions is a major task of the designer and ergonomist.

Exerting Strength with the Hand

The hands are our most-used work implements in daily life, able to exert large forces and to perform delicate manipulations as well. Anatomically, they are complex structure based on 27 bones, as shown in Chap. 1, Fig. 1.6. The set-up of muscles and tendons is a complicated example of internal transmission, discussed above.

Within the hand are the so-called intrinsic muscles. They mostly control the thumb (thenar muscles) and the little finger (hypopthenar muscles) and they execute adjustments of the metacarpals (interosseus muscles). However, major motions of the digits and the execution of large forces are primarily done by the extrinsic muscles, located in the forearm.

Since the extrinsic hand muscles are so far away from the digits, they possess long tendons, all of which must cross the narrow wrist. Each digit has two flexor tendons, one attaching to the distal phalanx and the other to a closer phalanx; the associated muscles are on the underside of the forearm. The extensor muscles are at the upper (dorsal) side of the forearm; they straighten the digits.

Figure 2.11 provides a simplified view of a cut across the proximal part of the hand: the carpal bones form a shallow channel, which the transverse carpal ligament covers, thus making it into a tunnel, the so-called carpal tunnel. This tight compartment must accommodate all the flexor tendons coming from the forearm, the median nerve and blood vessels.

On the other (dorsal) side of the carpal bones, the extensor tendons of the forearm muscles lie side by side. The thumb, the index and the little finger each have two extensors. After passing the wrist, several of the flexor tendons interconnect at the back of the hand.

Tendon sheaths envelope all the tendons, both flexors and extensors. These sheaths are flexible tunnels for the movement of the tendons, they provide guidance

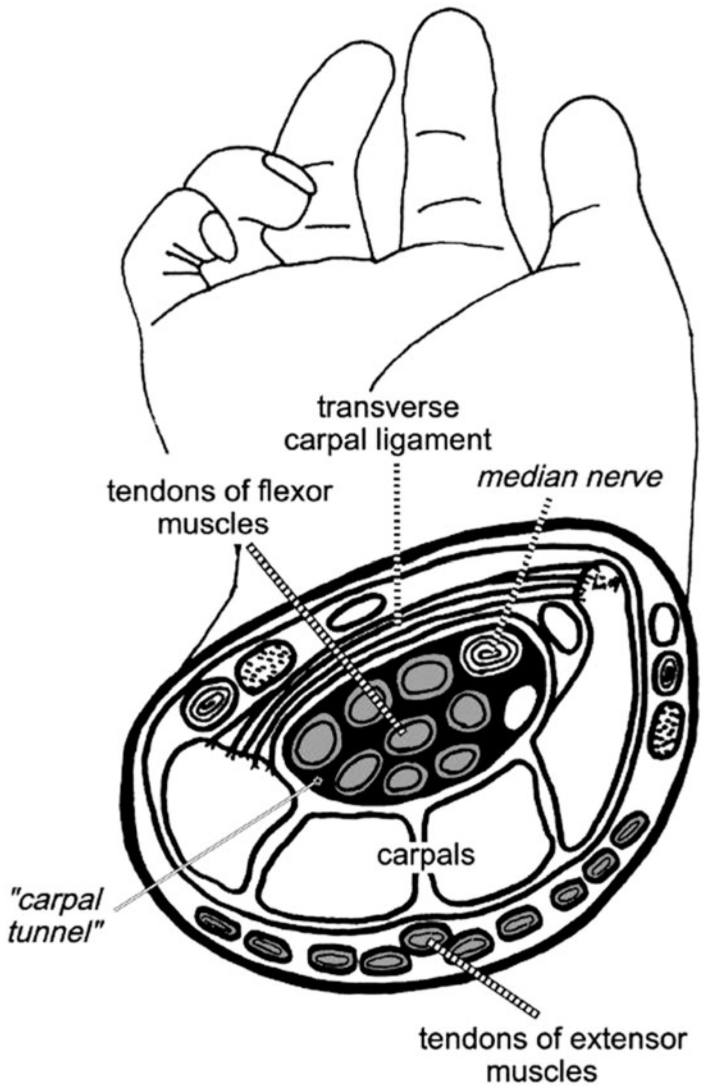


Fig. 2.11 Schematic view of the cross-section of a hand near the wrist, showing the flexor muscles in the carpal tunnel and the extensor muscles on the posterior side of the carpal bones (adapted from Kroemer and Kroemer, 2001)

for the tendons keeping them in place – see Figs. 2.12 and 2.13. That guidance is essential when tendons must change direction, such as when following a curved wrist or digit. Tough sheaths keep tendons from bow-stringing across bent joints by providing tubular loops and pulleys, reinforced by fibrous tissue structures that are ring-like (called annular) or crossed (cruciform).

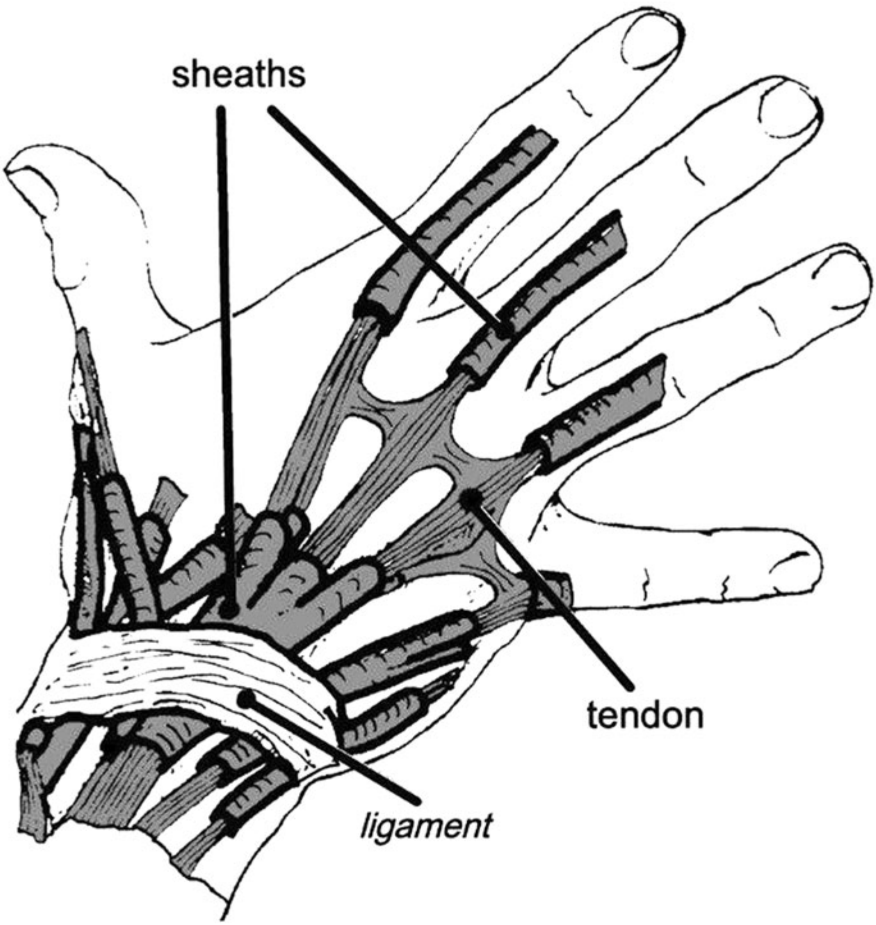


Fig. 2.12 Schematic of the extensor tendons and their sheaths in the back of the hand (adapted from Kroemer and Kroemer, 2001; Putz-Anderson, 1988)

The synovial layer of a sheath normally provides enough lubrication to ease the movements of the tendons within their enclosures; at the wrist, the displacement can amount to several centimeters. However, overuse can overload the lubricating capabilities; examples are forceful repeated hammering or rapid long-lasting keyboard operation*. Excessive friction between a tendon and its sheath may cause inflammation. This is critical especially in the carpal tunnel where inflammation and ensuing swelling of tissues increases pressure within that crowded compartment; compression of the median nerve can make it malfunction, resulting in the so-called carpal tunnel syndrome – see Chap. 3.

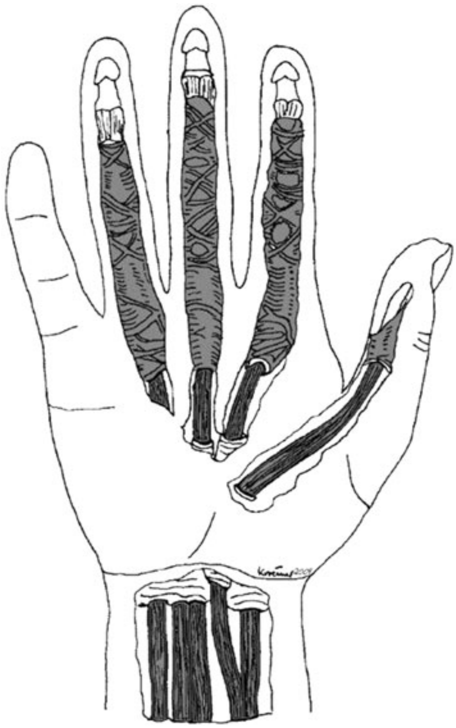


Fig. 2.13 Schematic of the flexor tendons and their sheaths in the palm side of the hand (adapted from Kroemer and Kroemer, 2001)

Static and Dynamic Exertions

In some muscle efforts, no movement and hence no perceptible changes in muscle length occur: in physiology terminology, this is an *isometric* exertion: from the Greek *iso*, meaning the same; and *metrein*, referring to the length of the muscle. (Yet, muscles, tendons, and other tissues have elasticity: thus, they stretch a bit under the inertial pull of a muscle. Accordingly, even in a so-called isometric effort, the muscle length may change by a small amount.)

Most efforts, however, are in motion, *variometric*: concentric when the muscle shortens, eccentric when the muscle becomes lengthened by an external force.

Static Strength

By definition, during an isometric effort, there is no change in muscle length (and therefore involved body segments do not move); all forces acting within the system are in equilibrium, as the first of Newton's Laws requires. Therefore, the physiological "isometric" case is equivalent to the "static" condition in physics.

> "Newton's Three Laws":
> The first law explains that unbalanced force acting on a mass changes its motion condition.
> The second law states that force equals mass multiplied by acceleration, $f = m \times a$.
> The third law makes it clear that force exertion requires the presence of an equally large counter force.

The static condition is theoretically simple and experimentally well controllable. It allows rather easy measurement of muscular effort; for that reason, most of the information currently available on "human strength" describes the outcomes of static (isometric) testing.

Besides the simple convenience of dealing with statics, measurement of isometric strength appears to yield a reasonable mid-range estimate of the maximally possible muscle exertion, as Fig. 2.14 illustrates. However, data on static strength are not related to eccentric motions and fast concentric motions, especially ballistic-impulse type exertions such as throwing.

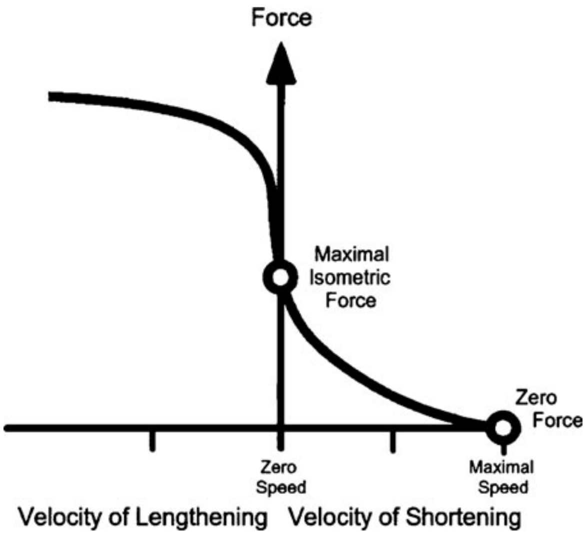


Fig. 2.14 Sketch of the assumed force-velocity relationship of muscle (schematic adapted from Winter, 1990; Herzog, 2008)

Dynamic Strength

A few more words on terminology in physiology and physics: as just mentioned, the physiologic *isometric* exertion generates, in mechanics terminology, a *static* condition. The terms *variometric* and the less descriptive *anisometric* indicate changing muscle length; this produces motion, a *dynamic* condition in mechanics terms. Within the physics field of dynamics, one speaks of *kinematics* when investigating motion; when considering the force that causes motion, the term is *kinetics*.

In dynamic activities, muscle length changes, and therefore involved body segments move. Body movement changes muscle configuration, muscle length, muscle force vector direction and leverage.

Given the arrangement of human skeletal muscles, especially their pull angles and lever arms (mechanical advantages), the displacement generally is small at the muscle but amplified at the point of exertion to the outside; Figs. 2.1 and 2.9 illustrate this for arm-hand travel.

The time derivatives of displacement (velocity, acceleration, and jerk) are of importance both for the muscular effort and the external effect: for example, acceleration (change in velocity) determines impact and force, as per Newton's Second Law.

Definition and experimental control of dynamic muscle exertions are much more complex tasks than the experimenter encounters in static testing. Many schemes for experimentation using various independent and dependent experimental variables can be developed*, but instead of following a planned comprehensive approach, most attempts to measure dynamic efforts address just particular aspects, such as:

Control of velocity as the independent test variable: If velocity is set to a constant value, one speaks of an *isokinematic* (*isovelocity*) measurement. (Note that occasionally this condition is mislabeled "isokinetic".) Mass properties usually are controlled in isokinematic tests whereas force and/or repetition are the chosen dependent test variables. The major problem in this approach is that the velocity is usually controlled at a handle or pedal, not at the muscle(s) of interest. In this case, the actual rate of muscle length change is not isokinematic.

Control of the amount of muscle tension (force) as the independent test variable: Usually, force is set to a constant value; in this *isotonic* test, mass properties and displacement (and its time derivatives) are likely to become controlled independent variables, and repetition a dependent variable. This *isoforce* condition is, for practical reasons, often combined with an *isometric* condition, such as in holding a load motionless. Without this combination, a major problem in this approach is that the tension (force, torque, resistance) is usually controlled at a handle or pedal, not at the muscle(s) of interest. This means that the actual tension of the muscle is not isotonic.

Controlling the external mass by keeping it constant is the mark of an *isoinertial* test. Repetition of moving such constant mass (as in lifting or lowering) may either be a controlled independent or a dependent variable. Also, displacement and its derivatives may become dependent outputs. Force (or torque) applied is liable to be a dependent value, according to Newton's Second Law. Obviously, choosing the amount of moving external mass per se does not control muscle tension.

This discussion highlights that, indeed, dynamic tests require more effort to describe and control than static (isometric) measurements. This complexity explains why, in the past, dynamic approaches have found few applications outside training and rehabilitation. Dynamic tests of muscle capabilities have not yet yielded many data applicable in ergonomics – with one exception: isoinertial testing has found wide use to set guidelines for "safe" lifting and lowering*. If one is allowed to perform as one pleases, such as in the "free dynamic tests" common in competitive sports, there is no appreciable experimental control over the actual use of muscles; however, the outcomes can be measured in distances thrown, heights jumped, or weights lifted.

The exertion-velocity curve in Fig. 2.14 provides general understanding of how the tension inside a muscle changes with the velocity of shortening or lengthening of that muscle. At no change in length, in the isometric condition, muscle tension is at a high level. In shortening, with increasing concentric velocity, less and less time remains to establish forceful cross bridges among actin and myosin filaments until, at the highest possible concentric speed, the force approaches zero. A similar effect occurs with increasing eccentric velocity; establishing cross bridges becomes more difficult with increasingly fast lengthening, but the passive resistance of muscle-tendon tissues to stretch elevates the overall level of internal muscle tension.

Very slow motions may be interpreted as a sequence of isometric exertions, done one-by-one at every point along the expected path of motion*. With this understanding, static measurements of muscle strength also reflect force/torque capabilities in slow motion. However, as the speed of motion increases, static data become increasingly less indicative of dynamic strength capabilities. Eccentric muscle efforts are usually rather slow; in this case, isometric measurements provide approximate information about eccentric muscle strength. In contrast, many concentric motions are quite fast, such as when running, throwing a ball, shoveling or hammering. In such rapid muscle contractions, the dynamic muscle output is likely to be rather different from statically generated muscle strength.

Regulation of Strength Exertion

The conceptual model in Fig. 2.15 helps to understand the factors involved in the exertion of voluntary strength. It shows a series of feedforward commands, arising in the central nervous system (CNS, see Chap. 3), to generate muscular activities aimed to execute a given task. Throughout the steps of ensuing activities in the body, several feedback loops report on the status of activities, so that new commands can adjust the actions in order to achieve the task efficiently and safely.

Feedforward

The control initiatives of the central nervous system start by calling up an "executive program" which, innate or learned, exists for all normal muscular activities, such as walking, hammering or lifting objects. "Subroutines" modify that general program to make it appropriate for the specific case, such as walking downstairs, hammering carefully, lifting with caution. Another modifier is motivation, which determines how much of the structurally possible strength a person will exert under the given conditions. Table 3.2 contains a listing of circumstances that may increase or decrease one's willingness to exert.

The results of these complex interactions are the excitation commands that the efferent nervous pathways transmit to the motor units involved where the signals

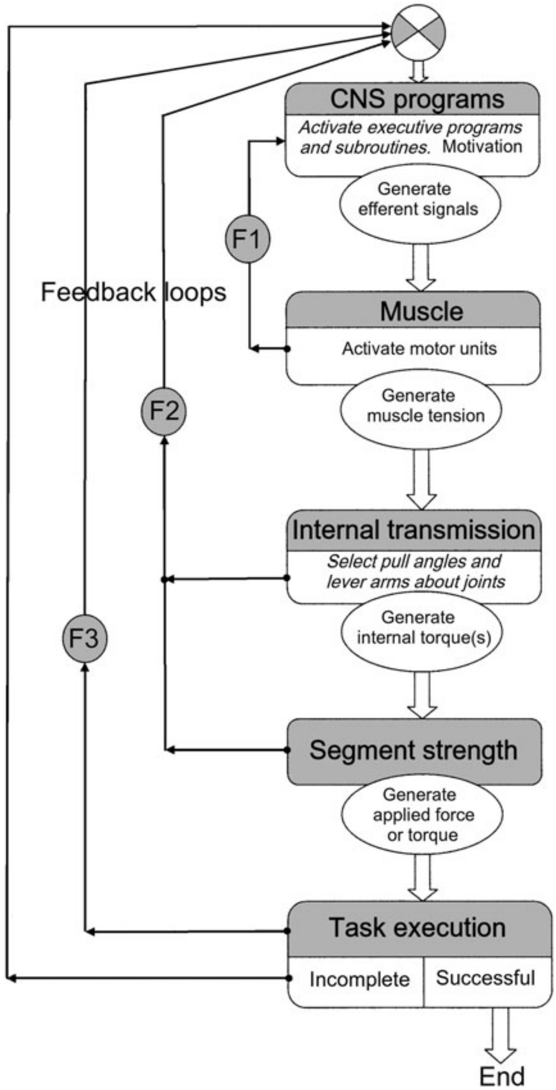


Fig. 2.15 Schematic of the generation and control of muscle effort

trigger muscle contractions. The actual tension developed in the muscle depends on the rate and frequency of the signals received, on the size of the muscle and the number of motor units involved.

The existing biomechanical conditions, especially lever arms and pull angles, modify the output of the muscle effort. These conditions are constant in a static effort but they change in the course of dynamic activities.

The following internal transmission of the torque(s) generated around body joints (for example from shoulder over elbow and wrist to the hand) alters the effects of muscle output until they arrive at the body segment that applies force to a tool or other object.

Feedback

Figure 2.15 also shows several feedback loops: they serve to monitor, control, and modify the muscular exertion and body segment positions and motions. The first feedback loop, F1, is primarily a reflex-like arc that originates at receptors (proprioceptors, see Chap. 3) in the joints signaling location, in the tendons indicating changes in muscle tension, and in muscles indicating their lengths. These receptors (interoceptors) and their signals are not under voluntary control and influence the signal generator in the spinal cord very quickly – but how they do it is not well understood.

Two further feedback loops, F2 and F3, originate at exteroceptors and pass their signals through a "comparator" and then reach the central nervous system. Loop F2 starts at receptors sending kinesthetic signals, reporting on events related to touch, pressure, and body position. When lifting an object, for example, body position and motion are monitored continuously along with the sensations of pressure in the hand and of the object rubbing against one's body.

Feedback loop F3 begins at exteroceptors and provides information on sounds and vision related to the effort to the comparator. For example, this may be the sounds or movements generated in equipment by the exertion of strength; it may be the pointer of an instrument that indicates the force applied; or it may be the experimenter or coach giving feedback and exhortation to the subject, depending on the status of the effort – see Table 2.3.

The comperator in the last two feedback loops compares the actual conditions reported by the body sensors to those conditions expected according to the feedforward signals. If actual and expected conditions differ, new commands are generated to eliminate the discrepancy.

Measuring Muscle Strength

The "Maximal Voluntary Effort"

People may not be subjected to tests that can damage their body, such as the muscle–tendon unit. Thus, tests of human body strength do not probe structural integrity; instead, the subject assesses what magnitude of effort is tolerable or suitable under the experimental conditions; that assessment determines the person's willingness to exercise that effort. This fact is expressed in the term "maximum voluntary contraction", MVC or, better, "maximal voluntary effort", MVE.

Accordingly, all human strength tests are self-controlled by the test subject. A person's maximal voluntary effort is not only dependent on skill, fitness and training status of the musculo-skeletal system: rather, the MVE is also the result of instructions, feedforward and feedback signals, and experimental conditions. Finally, MVE depends on individual/situational motivation – affected by the factors listed in Table 2.3.

Table 2.3 Factors likely to increase (+) or decrease (–) muscular performance

Circumstances	Likely effect
Feedback of results to subject	+
Instructions on how to exert	+
Arousal of ego involvement/aspiration	+
Drugs	+
Subject's outcry, startling noise	+
Hypnotic commands to perform strongly	+
Setting of goals, incentives	+
Competition, contest	?
Spectators	?
Fear of injury	–

The instructions given to the subject, and comments heard during the experiment, can have major impact on the magnitude of the MVE. The classical approach is the experimenter telling the subject to exert the maximal force possible either in a single maximal voluntary effort, or in repeated MVEs. Other instructions may ask explicitly for MVEs that follow the subject's self-assessment of suitability, safety, or avoidance of fatigue: typical for this approach are "psychophysical tests" regarding lifting or lowering loads where the subject receives the instruction to imagine that the task would have to be done continuously for hours*.

Measurement Opportunities

For the discussion of measurement techniques it is advantageous to separate the model shown in Fig. 2.15 into three sections: First, the *feedforward* part: the excitation signals, the contracting muscle and the internal transmission of muscle strength. The second part contains sensory *feedback*. The third part concerns the *output,* the force/torque/power that the hand (or other body segment) exerts to an external object, usually a work tool or measuring instrument. Each section provides opportunities to measure.

Measuring via Feedforward

When considering the feedforward section of the model, it becomes apparent that there are still no suitable means to measure the executive programs, the subroutines, or the effects of will or motivation on the excitation signals, which the central nervous system generates. In spite of decades of experience in recording electroencephalograms (EEGs), we still can glean only rather general and quantitative information from them.

However, techniques are at hand which allow observation and recording efferent excitation impulses that travel along the motor nerves to the motor endplates of the involved muscle. Implanted (intrusive) or surface electrodes can pick up these electric events, which are then recorded in electromyograms (EMGs). Their evaluation requires complex computer programs and skilled expertise*. Experimental techniques to measure the tensions within filaments, fibers, or muscles need more development to become practical*. Obviously, one can observe and record the positions and relative angles of body segments. That information allows some general estimation of mechanical advantages (lever arms) during the internal transmission of muscle exertion. However, the internal mechanical advantages are complex even in a static posture and change during motions: consider the varying lever arms of tendon attachments and the pull angles as sketched in Fig. 2.10. Further development of biomechanical models with fine details of the human body – see Chap. 4 – should lead to useful anthromechanical assessments.

Measuring via Feedback

In theory, the feedback loops in the nervous system offer some interesting possibilities for measurements. Yet, the afferent pathways from interoceptors are anatomically and functionally associated with the feedforward paths for the efferent impulses. Hence, it is practically impossible (with current technology) to distinguish the electric events associated with feedback signals from those associated with feedforward impulses. Until advanced measurement and interpretation techniques are available, the first two feedback loops (F1 and F2) remain not useful for strength measurements.

Yet, it is common to use the third feedback loop (F3), which starts at the subject's eyes and ears as exteroceptors, to control feedback by providing (or withholding) information about strength exertions*. Trainers and coaches routinely use such feedback manipulation to exhort enhanced performance.

Measuring Output

Evidently, the actually exerted body segment strength is the final result of a complicated chain of feedforward and feedback signals, controlled elements and modifying conditions. An instrument placed at the interface between the body and a solid structure records unambiguously the resultant output of all components in the loop. This leads to an operational definition: maximal voluntary body (segment) "strength is what is measured externally".

The resulting output of this complex system is simply defined and cleanly measured in amount and direction of the force (torque, impulse, power) vector applied, over time, to the measuring device. All external conditions are easily described: location of the interface between body and measuring device; design of the transmission device; position and support of the body; temperature, humidity, etc.

Granted, simply measuring the resulting output does not satisfy the desire to understand and control the complicated system that generates the result. However, there is one good reason for so proceeding: the measured strength output is exactly the practical information that the trainer, coach, physician, engineer and "owner" wants.

Strength Measurement Devices

Current devices to measure force or torque (moment) consist of several components. The first component is the *sensor*, the element that experiences the strain generated by force or torque application. The second component is the *converter*, the element which changes the strain into a measurable output. Both elements together are often called the *transducer*. A typical transducer consists of a deformable object, such as a metal beam, which is bent (usually only imperceptibly little) under the effort exerted on it. A strain gauge is commonly employed to convert the deformation into an electrical signal that is analog to the strain and deformation. No instruments are available, at this time, which are directly sensitive to force or torque; all rely on the sensor-converter technique.

The output of the transducer is usually fed through an amplifier so that the signal can be easily transmitted and used. The next element in the measurement device often is a display. This can be an analog indicator, usually a pointer displaced from its zero position according to the strength of the signal received from the amplifier; it may move over a stationary scale, or leave a permanent mark on a strip chart. Other indicators are digital; they may display the signal in discrete numbers. Usually, the system includes a data storage device, a computer/recorder, in series or parallel with the indicator. (In some recording systems, an indicator is not used: yet it is useful for observing the data flow so that obvious problems can be detected during the test.)

One important aspect is unfortunately occasionally overlooked: the measurement system must be calibrated so that it is assured that the same input results in the same known output in each test. It is discouraging to see in a laboratory a measurement device in use that has not been checked and calibrated for long periods of time.

The Strength Test Protocol

A carefully devised experimental protocol is essential for proper measurements. It specifies the selection of subjects, their protection and their information; the control of the experimental conditions; the use, calibration, and maintenance of the measurement devices; and other important facts, such as (the avoidance of) training and fatigue effects. The protocol must be so exact and comprehensive that, by following it, another experimenter can replicate the measurements.

Regarding the selection of subjects, care must be taken to ensure that the subjects participating in the tests are in fact a representative sample of the population of which data are to be gathered. Regarding the management of the experimental conditions, the control over motivational aspects is particularly difficult. Outside sports and medical testing it is widely accepted that the experimenter should not give exhortations and encouragements to the subject.

Table 2.4 is a listing of items in a test protocol; it contains the main features of the so-called Caldwell Regimen*. That was originally meant for isometric testing but minor amendments can adapt it to dynamic tests.

Table 2.4 Strength test protocol

The following items are those of primary importance. Others should be added as appropriate. Items with asterisks apply to both static and dynamic testing.

1. Description of the subjects:
   (a) Population and sample selection.
   (b) Current health and status: medical examination and questionnaire are recommended.
   (c) Gender.
   (d) Age.
   (e) Anthropometry (at least height and weight).
   (f) Training and experience related to the strength testing.
2. Information to the subjects about the test purpose and procedures.
   (a) Subjects shall avoid overexertion but give the best effort.
   (b) Instructions to the subject should be kept factual and not include emotional appeals.
   (c) Inform the subject during the test session about his/her general performance in qualitative, non-comparative, positive terms. Do not give instantaneous feedback during the exertion.
   (d) Rewards, goal setting, competition, spectators, fear, noise and the like can affect the subject's motivation and performance; therefore, should be avoided.
3. Static strength is measured according to the following conditions:
   (a) Static strength is assessed during a steady exertion sustained for 4 s.
   (b) The subject should be instructed to "increase to maximal exertion (without jerk) in about 1 s and maintain this effort during a 4 s count."
   (c) The transient periods of about 1 s each, before and after the steady exertion, are disregarded.
   (d) The strength datum is the mean score recorded during the first 3 s of the steady exertion. (The "peak" strength observed during the effort is up to one third larger than the average measure over an exertion period of 3 s.)
4. The minimal rest period between related efforts should be 2 min; more if symptoms of fatigue are apparent.
5. Description of the conditions existing during testing:
   (a) Body parts and muscles chiefly used.
   (b) Body position (body motion in dynamic testing) related to the effort.
   (c) Body support/reaction force available.
   (d) Coupling of the subject to the measuring device (to describe location of the strength vector).
   (e) Strength measuring and recording devices used.
6. Data reporting:
   (a) Mean (median, mode).
   (b) Standard deviation.
   (c) Skewness.
   (d) Minimum and maximum values.
   (e) Sample size.

Static (body segment) strength is defined as the capacity to produce torque or force in a maximal voluntary isometric effort. Similarly, dynamic (body segment strength) is the capacity to produce torque or force in motion, by a maximal voluntary variometric exertion. Strength has vector qualities and therefore should be described by magnitude and direction. Yet, other assessments are useful for specific purposes, such as the number of effort repetitions, or special exertions such as push-ups, curls, squats*.

Designing for Body Strength

The engineer or designer wanting to consider human strength faces a number of decisions. These include:

1. **Is the exertion static or dynamic?**
   Most available body segment strength data concern static (isometric) exertions. These data provide reasonable guidance also for slow motions, although they are probably too high for concentric motions and perhaps too low for eccentric motions. Of the little information available for dynamic strength exertions, most is limited to isokinematic (constant velocity) cases.
   For static exertions, information about isometric strength capabilities (such as listed below) is useful. In dynamic exertions, other considerations often apply, such as physical endurance (circulatory, respiratory, metabolic) capabilities of the operator, and prevailing environmental conditions*.
2. **Is the exertion by hand, by foot, or with other body segments?**
   If a choice of exertion modes is possible, the selection should rely on physiologic and ergonomic considerations to achieve the safest, least strenuous and most efficient performance. Foot motions consume more energy, are less accurate and slower but stronger than hand movements over the same distance. Specific design information is available for hand and foot exertions and for use of other body segments – see the examples below.
3. **What is the body posture and support during the strength exertion?**
   Exertion of strength does not depend only on the size of the muscle mass involved, but also on the reaction force stabilizing the body – as per Newton's "Third Law": force exertion requires the presence of an equal counterforce. The counterforce comes from support surfaces: the floor to stand upon, the seat to sit on, the backrest or wall to brace against. Strength transmission between the points of exertion and support depends on the positions and masses of involved body parts, which is especially important in dynamic tests.
4. **Is a maximal or a minimal strength exertion the critical design factor?**
   Maximal user output usually determines the structural strength of the object – even the strongest operator may not break a handle or a pedal, for example. Therefore the design value is, with a safety margin, above the highest perceivable strength application.

Minimal user output is that strength expected from the weakest operator which still yields the desired result. Hence, it sets the operational force or torque limits at which a handle or pedal can be successfully operated or a heavy object moved.

The minimal and maximal expected strength exertions establish the range of foreseen strength applications. “Average” user strength has usually no design value because half of the users are weaker and all others are stronger.

Proper Statistical Use of Strength Data

Measured strength data are commonly reported as averages (means) and standard deviations. This allows the use of common computational techniques to determine data points of special interest to the designer, as discussed in detail in Chap. 11. In reality, however, strength data often occur in a skewed dispersion rather than in a bell-shaped normal cluster. That statistical mishap is not of great concern, however, because usually the data points of design interest are in the extremes of the distributions: as just discussed, the data of concern are either the maximal forces or torques that the equipment must be able to bear without breaking, or the minimal exertions even “weak” persons are able to generate.

Minimal strengths can be specified as percentile values at the low end of the distribution: for weak exertions, often the fifth percentile is selected (as in Fig. 2.18, below). To represent the strongest expected exertions, it is best, in the interest of safety, to select a datum that lies well above the strongest measured exertion.

Even in well-controlled strength tests on the same subject, measurements may vary considerably: standard deviations may easily vary by 10 or more percent*.

Designing for Hand Strength

The human hand is able to perform a wide variety of activities, ranging from fine control to large forces:

- Fine manipulation of objects, requiring little displacement and force. Examples are writing by hand, assembly of small parts, adjustment of controls.
- Fast movements to an object, with moderate accuracy to reach the target but fairly small force exertion there. An example is the movement to a switch and its operation.
- Frequent movements between targets, usually with some accuracy but little force; such as in an assembly task, where parts must be taken from bins and assembled.
- Forceful activities with little or moderate displacement, such as with many assembly or repair activities, for example when turning a hand tool against resistance.
- Forceful activities with large displacements, for instance yielding a sledge hammer.

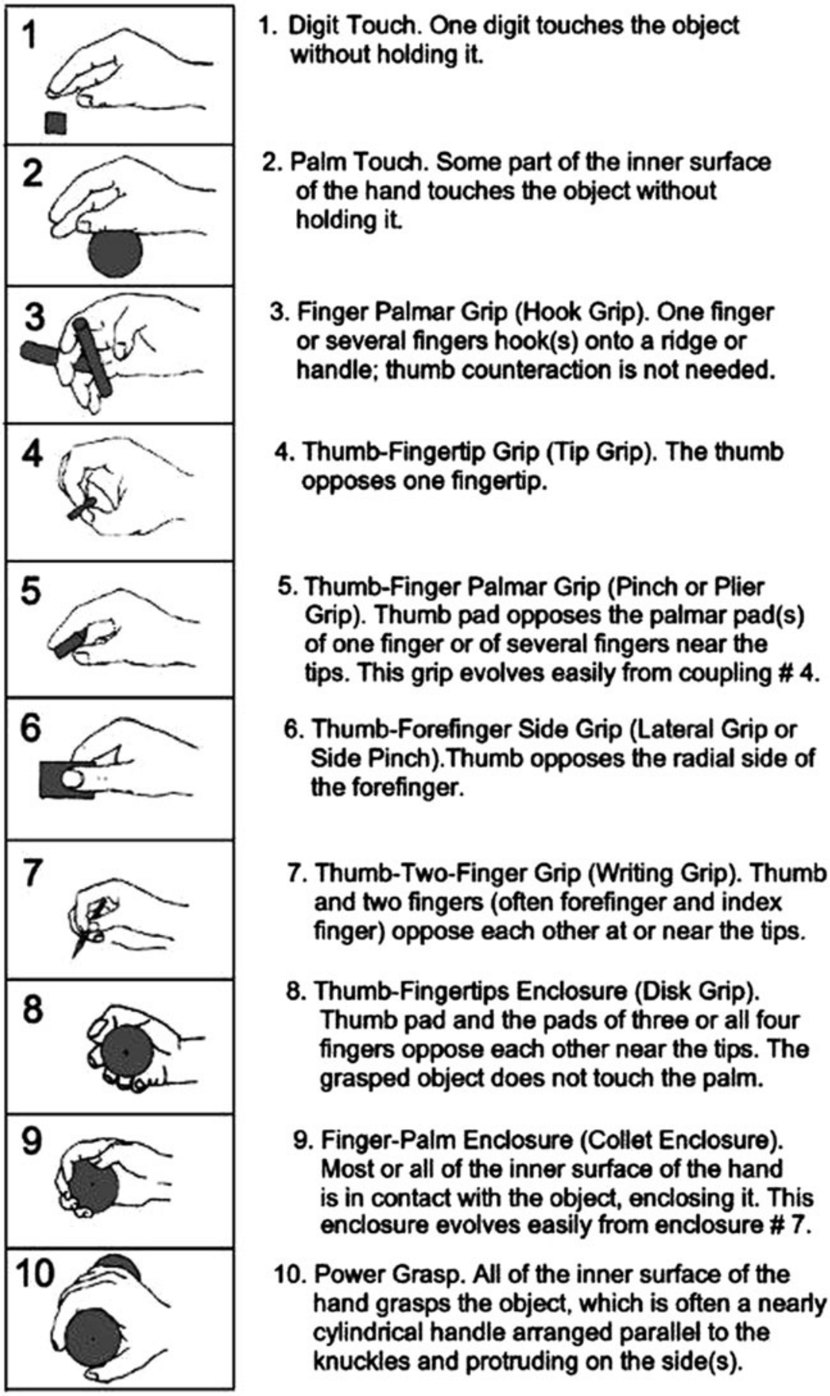


Fig. 2.16 Couplings between hand and handle (adapted from Kroemer, 1986)

Of the digits of the hand, the thumb is the strongest and the little finger the weakest. The whole hand, all digits in action combined with the palm, can exert large gripping and grasping strengths, but their execution depends on the coupling between the hand and the handle – see Fig. 2.16.

Muscles in the arm and shoulder can develop fairly large torques. Flexion strength about the elbow joint follows the distribution depicted in Fig. 2.17. Note that the data show the results of isolated isometric measurements, each done one after the other, not in one continuous sweep as the misleading common depiction as a curve suggests.

Examples of isometric hand forces at different arm positions are shown in Fig. 2.18. Whereas these forces are applied with the hand, they are generated by arm and shoulder muscles and therefore depend on arm posture and body support.

The flow of active and reactive strength vectors between the points of application and the body support depends on the positions of involved body segments, especially on their joint angles. Accordingly, the strength of all exertions, whether with the extremities, shoulder, backside or other site, is largely determined by the posture of the body and by the support of the body (which generates Newton's reaction force) by friction or bracing. An example: a person standing or walking receives all support from the floor. Slippery ground, as due to ice in the winter, may make it impossible to push a heavy object horizontally with hand or shoulder – Fig. 2.19 and Table 2.5 show typical cases.

The amount of strength available for exertion to an object outside the body depends on the weakest part in the chain of strength-transmitting body parts. Hand

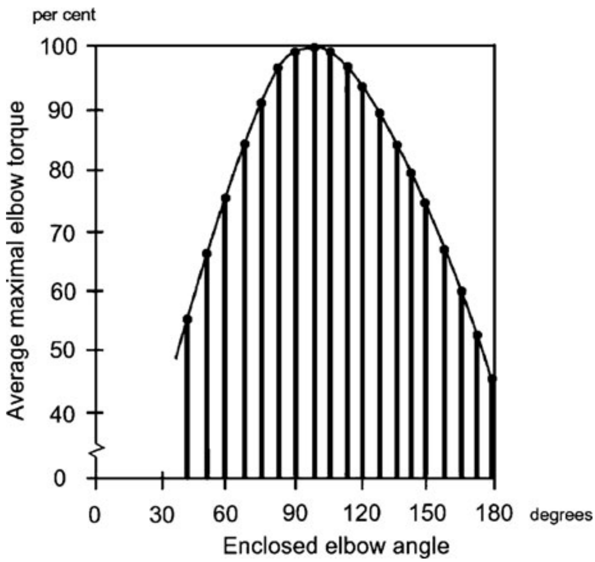
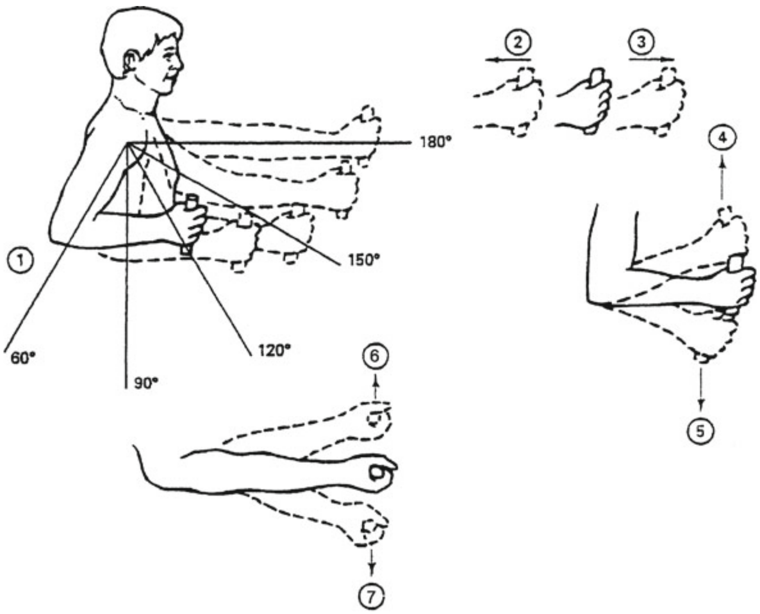


Fig. 2.17 Scheme of the relation between elbow angle and elbow flexion strength. The *curve* connects the results of single static tests



5th percentile Forces (N)

1 Elbow Angle (degrees)	2 Pull		3 Push		4 Up		5 Down		6 In		7 Out	
	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right	Left	Right
180	222	231	187	222	40	62	58	76	58	89	36	62
150	187	249	133	187	67	80	80	89	67	89	36	67
120	151	187	116	160	76	107	93	116	89	98	45	67
90	142	165	98	160	76	89	93	116	71	80	45	71
60	116	107	96	151	67	89	80	89	76	89	53	71

Fig. 2.18 Hand forces exerted by sitting men: Fifth-percentile values, in Newton (adapted from MIL HDBK 759, 1981)

force, for instance, may be limited by finger strength, or shoulder strength, or low back strength; and in every case, by the reaction force available to the body. Figure 2.19 helps in determining where the weak link is in the chain of strength transmission.

Using Tables of Exerted Torques and Forces

The literature contains many sources for data on body strengths – alas, nearly all of them for isometric efforts*. While these data indicate orders of magnitude of static forces and torques, the exact numbers should be viewed with great caution because they were measured on various subject groups, many of rather small numbers, under widely varying circumstances. For example: The information in Fig. 2.20

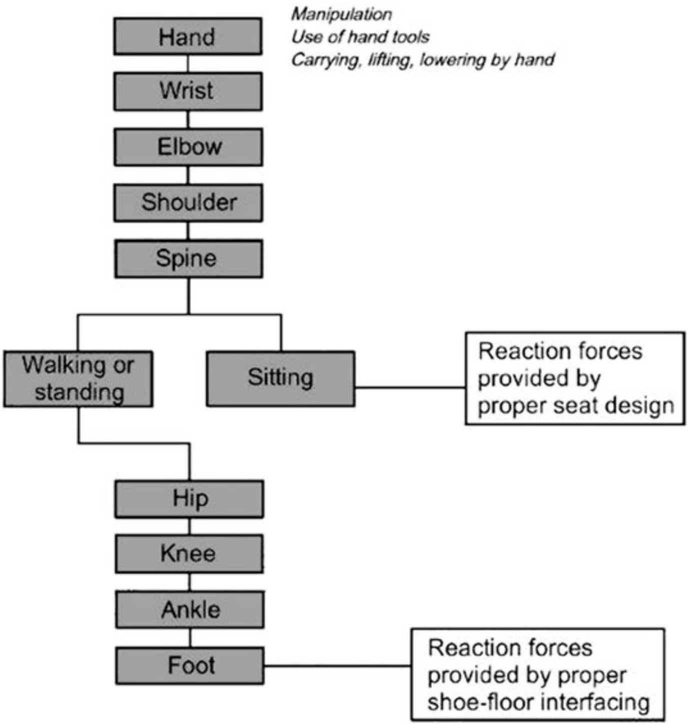


Fig. 2.19 Chain of critical body segments and body support for manipulating and other hand activities

and Table 2.5 derives from the same set of empirical data. They were extrapolated to show the effects of (a) location of the point of force exertion, (b) body posture, (c) body support and (d) friction at the feet on the horizontal push (and pull) forces, which male soldiers could exert. If the conditions or subjects are different, different strength values should be expected as well. To verify that a new design is operable, it is advisable to take body strength measurements on a sample of the intended user population, under conditions similar to actual use.

Designing for Foot Strength

If a person stands at work, operation of foot controls should not be required because, during these actions, the operator has to stand on the other leg. For a seated operator, such as in a vehicle, use of foot controls is much easier because the seat supports the body. This allows the feet to move more freely and, given suitable conditions, they can exert large forces and energies, for which the seat provides the needed reactions, as Figs. 2.21 and 2.22 indicate.

Table 2.5 Horizontal push and pull forces (in N), which male soldiers can exert intermittently or for short periods of time (adapted from MIL HDBK 759, 1981)

Horizontal force[1]; at least	Applied with[2]	Condition (μ: coefficient of friction at the floor)
100 N, push or pull	Both hands or one shoulder or the back	With low traction, $0.2 > \mu < 0.3$
200 N, push or pull	Both hands or one shoulder or the back	With medium traction, $\mu \sim 0.6$
250 N push	One hand	Braced against a vertical wall 51–150 cm from and parallel to the push plate. Or: Anchoring the feet on a perfectly nonslip ground
300 N, push or pull	Both hands or one shoulder or the back	With high traction, $\mu \sim 0.9$
500 N, push or pull	Both hands or one shoulder or the back	Braced against a vertical wall 51–180 cm from and parallel to the push plate. Or: Anchoring the feet on a perfectly nonslip ground
750 N push	The back	Braced against a vertical wall 90–110 cm from and parallel to the push plate. Or: Anchoring the feet on a perfectly nonslip ground

[1]Force may be nearly doubled for two operators, nearly tripled for three operators, pushing simultaneously.
[2]Figure 2.16 shows examples.

In the case of pedaling a bicycle, the legs transmit energy through the feet to the pedals. Normally, the location of the pedals is directly underneath the body, so that the body weight above them provides the reactive forces to the forces transmitted to the pedals. Placing the pedals more forward makes body weight less effective for generation of reaction force to the pedal effort; so, a recumbent bicycle provides a backrest against which the buttocks and low back press while the feet push forward on the pedal.

The feet can transmit small forces, such as for the operation of switches, in nearly all directions, with the downward or down-and-forward directions preferred. A sitting person can generate very large forces with nearly extended legs in the forward direction, helped by the support surfaces for buttocks and back and by inertia. In automobiles, operation of the brake or clutch pedal is normally easy to do while the angle at the knee is about 90°. But if the power-assist system fails, the feet

Fig. 2.20 (continued) Horizontal push forces (means and standard deviations, in N) exerted by male soldiers with their hands, the shoulder and the back. Legend: (1) Height of the center of the 20 cm high, 25 cm wide force plate; (2) Horizontal distance between the surfaces of the force plate and the opposing bracing structure; (*) Anthropometric definitions in Chap. 1 (adapted from AMRL-TR-70-114, 1971. Wright-Patterson AFB, Ohio: Aerospace Medical Research Laboratory; NASA-STD 3000, 1989)

	Height (1) of force plate	Distance (2)	Force, N *Mean*	SD
	Percent of shoulder height*		With both hands	
	50	80	664	177
	50	100	772	216
	50	120	780	165
	70	80	716	162
	70	100	731	233
	70	120	820	138
	90	80	625	147
	90	100	678	195
	90	120	863	141
	Percent of shoulder height*			
	60	70	761	172
	60	80	854	177
	60	90	792	141
	70	60	580	110
	70	70	698	124
	70	80	729	140
	80	60	521	130
	80	70	620	129
	80	80	636	133
	Percent of shoulder height*		With both hands	
	70	70	623	147
	70	80	688	154
	70	90	586	132
	80	70	545	127
	80	80	543	123
	80	90	533	81
	90	70	433	95
	90	80	448	93
	90	90	485	80
	100 percent of shoulder height*	Percent of thumb-tip reach*	With both hands	
		50	581	143
		60	667	160
		70	981	271
		80	1285	398
		90	980	302
		100	646	254
			With preferred hand	
		50	262	67
		60	298	71
		70	360	98
		80	520	142
		90	494	169
		100	427	173
	100 percent of shoulder height*	Percent of span*		
		50	367	136
		60	346	125
		70	519	164
		80	707	190
		90	325	132

Fig. 2.20

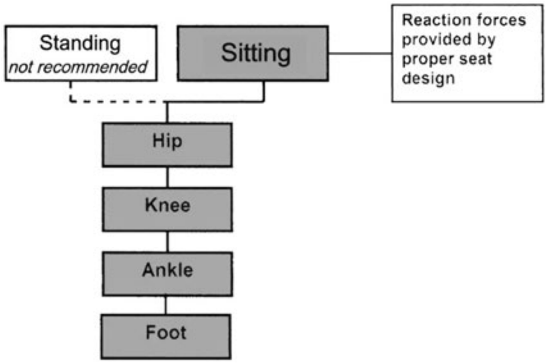


Fig. 2.21 Chain of critical body segments and body support for foot actions

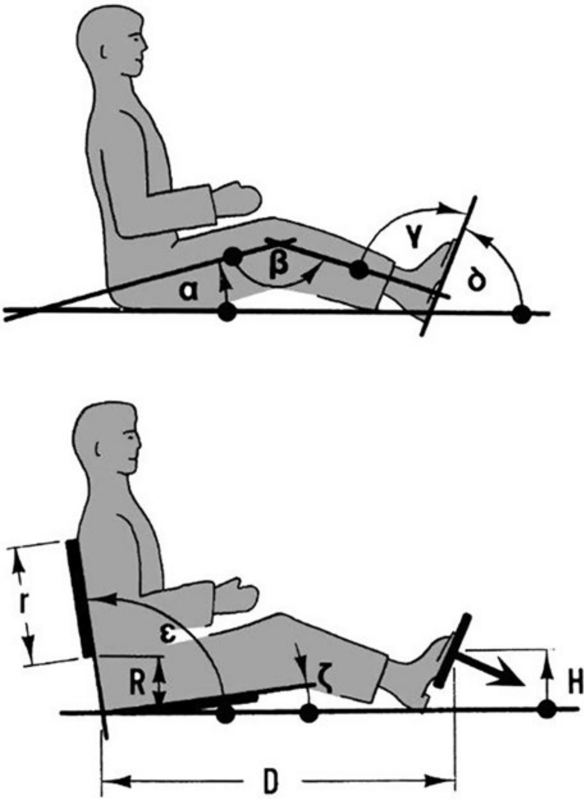
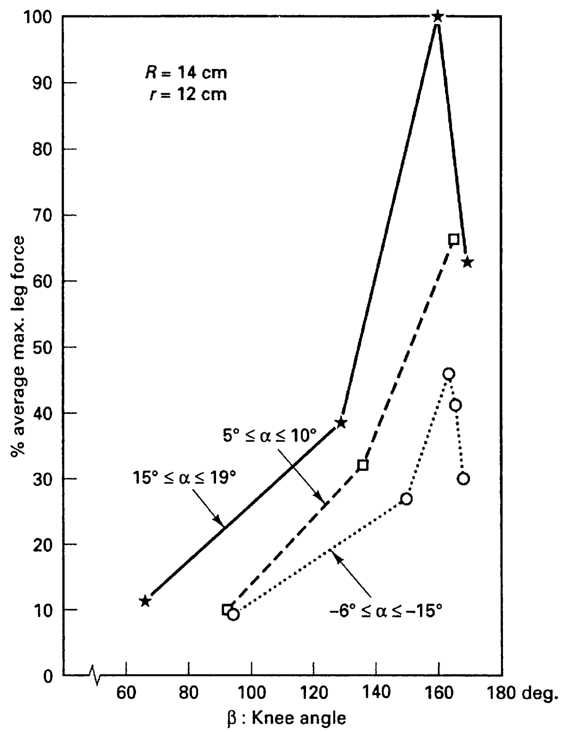


Fig. 2.22 Conditions affecting pedal force: body angles (upper illustration) and work space dimensions

must apply high brake forces: in this case, the operator thrusts the back against the backrest and extends the leg in order to generate the needed pedal force.

Figures 2.22, 2.23, 2.24, 2.25 and 2.26 provide information about the forces that the foot can apply to a pedal. Their magnitudes depend decidedly on body support and hip and knee angles. The largest forward thrust force can be exerted with the

Fig. 2.23 Effects of thigh angle α and knee angle β on pedal push force



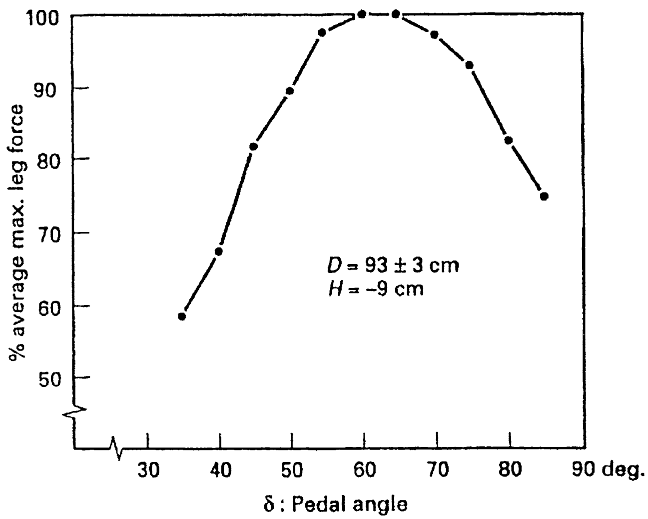


Fig. 2.24 Effects of ankle (pedal) angle δ on foot force generated by ankle rotation

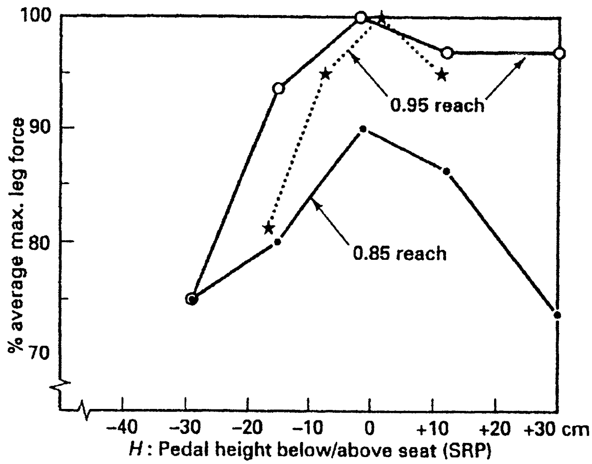


Fig. 2.25 Effects of pedal height H and leg extension on pedal push force

nearly extended leg: however, that allows only very little variation in pedal position and leg posture.

Figures 2.22 through 2.26 illustrate how the force that the foot can exert depends on the chain of strength transmission between seat and pedal. Bad seat design and adjustment; frail muscles; deficient joints at hip, knee or ankle; or low friction between foot (shoe) and pedal may all make for a "weak kick".

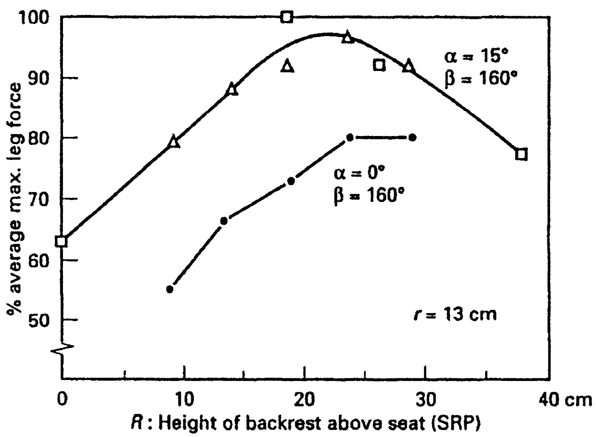


Fig. 2.26 Effects of backrest height R on pedal push force

Notes

The text contains markers, *, to indicate comments and references, which follow:

The actin "ratchets" along the myosin: Huxleys' "Sliding Filament" theory: see Herzog (2008).

The term contraction: Cavanagh (1988).

"Muscles are the slaves of their motoneurons": Basmajian and DeLuca (1985, p. 431).

"Specific human muscle tension": *Enoka* (1988).

The flexor muscle has its origin near the proximate end of the upper arm link: This is a simplification: in fact, the biceps has to two origins ("heads, as the name indicates") one of which crosses the shoulder joint.

Long-lasting keyboard operation: Kroemer (1989, 2001, 2009).

Strength tests using various independent and dependent experimental variables: Marras et al. (1993), Kumar (2004, 2008).

Isotonic: Note that the term *isotonic* often has been applied wrongly. Some older textbooks described lifting or lowering of a constant mass (weight) as typical for isotonics. This is physically false for two reasons. The first is that, according to Newton's Laws, changes in acceleration and deceleration of a mass require application of changing (not: constant) forces. The second fault lies in overlooking the changes that occur in the mechanical conditions (pull angles and lever arms) under which the muscle functions during the activity. (See Chap. 4 for more detail.) Hence, even if there were a constant force to be applied to a moving external object, the changes in mechanical advantages still would cause changes in muscle tension.

Guidelines for "safe" lifting and lowering: Snook (2005), Waters (2008).

A sequence of isometric exertions, done one-by-one at every point along the expected path of motion: The commonly chosen graphic style of displaying measurement connects the data points with an uninterrupted curve: this seems to imply a continuous motion, whereas in reality the strength measurements were done statically, point by point.

Psychophysical tests: Dempsey (2004), Snook (2005), Waters (2008).

Evaluations of electromyograms (EMGs): Basmajian and de Luca (1985), Merletti et al. (2004), Sommerich and Marras (2004), Kumar and Mital (1996).

Experimental techniques to measure the tensions within filaments, fibers, or muscles: Fukashiro et al. (1995), Komi et al. (1996), Schuind et al. (1992).

Control feedback: Kroemer and Marras (1980).

Caldwell Regimen: Caldwell et al. (1974), Dempsey (2004), Gallagher et al. (2004).

Strength assessments: Astrand et al. (2003), Wilmore et al. (2008).

Dynamic exertions and environmental conditions: Physiologic and ergonomic texts provide such information; for example by Astrand et al. (2003), Kroemer et al. (2003), Chengular et al. (2003), Gallagher et al. (2004), Winter (2004).

Standard deviations of static strength may easily vary by 10 or more percent: Astrand et al. (2003).

Literature on body strength: Compiled, for example in standards, by ISO, NASA and the Military; by Chengular et al. (2003), Kroemer et al. (2003), Kumar (2004, 2008), Marras and Karwowski (2006).

Summary

Muscle contraction is brought about by active shortening of muscle substructures. Elongation of the muscle is due to external forces.

Excitation signals from the central nervous system control muscle contraction. Each specific signal affects those fibers that form a motor unit, of which a muscle contains many.

An efferent stimulus causes a single twitch contraction of the motor unit. A rapid sequence of stimuli can lead to a superposition of muscle twitches, which may fuse together into a sustained contraction.

Prolonged strong contraction leads to muscular fatigue, which hinders and cuts short the muscle effort. Hence, a maximal voluntary contraction can last only a few seconds.

In isometric contraction, muscle length remains constant; this establishes a static condition for the affected body segments. In an isotonic effort, the muscle tension remains constant, which usually coincides with a static (isometric) effort.

Dynamic activities result from changes in muscle length, which bring about motion of body segments. In an isokinematic effort, speed remains unchanged. In an isoinertial test, the mass properties remain constant.

Maximal muscle tension depends on the motivation of the person exerting the effort as well as on the individual's muscle size and exertion skill.

Human body (segment) strength is measured routinely as the force (or torque) exerted to an instrument external to the body. It depends not only on muscle tension but also on body posture and on body support (supply of reaction force).

Measurement of strength requires carefully controlled experimental conditions.

Design of equipment and work tasks for human body segment strength capabilities requires

- *determining whether the exertion is static or dynamic*
- *establishing with what body part the force or torque is exerted*
- *arranging the best suitable body posture*
- *selecting the strength percentile (minimum and/or maximum) that is critical for the operation*

Glossary

Acceleration Second time-derivative of displacement.

Actin Muscle filament (see there) capable of sliding along myosin (see there).

Action Activation of muscle. See contraction.

Afferent Carrying inward, toward the cns.

Agonist The muscle performing an intended action – same as protagonist. See antagonist.

Anisometric Not isometric.

Antagonist The muscle opposing the action of an agonist.

Anthromechanics Biomechanics applied to the human body.

Arteriole Terminal branch of an artery, especially a small artery joining a larger artery to a capillary.

Artery A muscular elastic tube that carries blood away from the heart.

Body (segment) strength The ability to exert force (see there) or torque (see there) to an object that the body (segment) touches.

Capillary Minute blood vessel that connects arteriole and venule.

Capillary bed A network of capillaries in an organ.

Co-contraction Simultaneous contraction of two or more muscles.

Concentric (muscle effort) Shortening of a muscle against a resistance.

Contraction Literally, "pulling together" the z lines delineating the length of a sarcomere, caused by the sliding action of actin and myosin filaments. Contraction develops muscle tension only if the shortening is resisted. (Note that during an isometric "contraction" no change in sarcomere length occurs and that in an eccentric "contraction" the sarcomere is actually lengthened. To avoid such contradiction in terms, it is often better to use the terms activation, effort, or exertion.)

Dependent variable In experiments and tests, the variable whose value shows the effects, if any, of the controlled (independent) variable(s).

Displacement Distance moved (in a given time).

Distal Away from the center of the body.

Dynamics A subdivision of mechanics that deals with forces and bodies in motion.

Eccentric (muscle effort) Lengthening of a resisting muscle by external force.

Efferent Carrying outward, to an effector, usually a muscle.

Effort (of muscle) See contraction.

Electromyogram EMG, graphic record of the electric activity of a muscle.

EMG Electromyogram, see there.

Energy (the capacity to do) work. Proper units are the joule (J) and calorie (c).

Endomysium Connective tissue enwrapping a muscle fiber.

Epimysium Connective tissue enwrapping muscle.

Ergonomics The application of scientific principles, methods and data drawn from a variety of disciplines to the design of engineered systems in which people play significant roles.

Exertion (of muscle) See contraction.

Fascia Smooth connective tissue (epimysium) enwrapping muscle.

Fascicle Bundle of muscles, fascilulus.

Fast-twitch fiber Muscle fiber with relatively short contraction time (about 40 ms) and a large motoneuron. Also called type II or white or high-threshold fiber.

Fiber See muscle.

Fibril See muscle fibers.

Filament See muscle fibers.

Force A vector that can accelerate a mass. As per Newton's third law, the product of mass and acceleration; the proper unit is the Newton, with $1\ \text{N} = 1\ \text{kg m s}^{-2}$. On earth, one kg applies a (weight) force of 9.81 N (1 lb exerts 4.44 N) to its support. Muscular force often is described as tension multiplied with the transmitting cross-sectional area.

Free dynamic In this context, an experimental condition in which neither displacement and its time derivatives, nor force are manipulated as independent variables.

Independent variable In experiments and tests, the variable whose value is intentionally manipulated to show effects, if any, on the observed (dependent) variable(s).

In situ In the original position/place.

In vivo Within the living organism/body.

Isoacceleration A condition in which the acceleration is kept constant.

Isoforce A condition in which the muscular force (tension) is constant, isokinetic. This term is equivalent to isotonic.

Isoinertial A condition in which muscle moves a constant mass.

Isojerk A condition in which the time derivative of acceleration, jerk, is kept constant.

Isokinetic A condition in which muscle tension (force) is kept constant. See isoforce and isotonic; compare with isokinematic.

Isokinematic A condition in which the velocity of muscle shortening (or lengthening) is constant. (Depending on the given biomechanical conditions, this may or may not coincide with a constant angular speed of a body segment about its articulation.) Compare with isokinetic.

Isometric A condition in which the length of the muscle remains constant.

Isotonic A condition in which muscle tension (force) is kept constant – see isoforce. (In the past, this term occasionally was falsely applied to any condition other than isometric.)

Jerk Third time-derivative of displacement.

Kinematics A subdivision of dynamics that deals with the motions of bodies, but not the causing forces.

Kinetics A subdivision of dynamics that deals with forces applied to masses.

Lever arm One component of the formula for moment (or torque): m = force × lever arm.

Mechanical advantage In this context, the lever arm (moment arm, leverage) at which a muscle works around a bony articulation.

Mechanics The branch of physics that deals with forces applied to bodies and their ensuing motions.

Mitochondrium Organelle in a (muscle) cell, able to produce ATP.

Moment The product of force (see there) and the length of the (perpendicular) lever arm at which it acts. Physically the same as torque (see there).

Motor endplate Contact area of axon and sarcolemma of the muscle.

Motor unit All muscle filaments under the control of one efferent nerve axon.

Muscle A bundle of fibers, able to contract or be lengthened. In this context, striated (skeletal) muscle that moves body segments about each other under voluntary control.

Muscle contraction The result of contractions of motor units distributed through a muscle so that the muscle length is shortened.

Muscle fiber Element of muscle, containing fibrils which consist of filaments.

Muscle fibril Element of muscle fiber, containing filaments.

Muscle filaments Muscle fibril elements (actin and myosin, polymerized protein molecules) capable of sliding along each other, thus shortening the muscle and, if doing so against resistance, generating tension.

Muscle force The product of tension within a muscle multiplied with the transmitting muscle cross-section.

Muscle strength The ability of a muscle to generate and transmit tension in the direction of its fibers. See body strength.

Muscle tension The pull within a muscle expressed as force divided by transmitting cross-section.

Myo Prefix referring to muscle (greek mys, muscle).

Myosin Muscle filament (see there) along which actin (see there) can slide.

Mys Prefix referring to muscle (greek mys, muscle).

Perimysium Connective tissue enwrapping bundles of muscle fibers.

Plasmalemma Membrane of a muscle cell, also called sarcolemma.

Power Work (done) per unit time.

Protagonist The muscle performing an intended action – same as agonist. See antagonist.

Proximal Toward the center of the body.

Rate coding The time sequence in which efferent signals arrive at a specific motor unit and cause it to contract.

Recruitment coding The time sequence in which efferent signals arrive at different motor units and cause them to contract.

Repetition Performing the same activity more than once. (One repetition indicates two exertions.)

Rhythmic The same action repeated in regular intervals.

Sarcolemma Membrane of a muscle cell, also called plasmalemma.

Sarcoplasmic reticulum The "plumbing and control" system of the muscle.

Slow-twitch fiber Muscle fiber triggered by relatively low-rate signals; therefore often called a low-threshold fiber. It has a leisurely contracting time (80–100 ms) and small motoneurons. Also called type I or red fiber.

Statics A subdivision of mechanics that deals with bodies at rest.

Strength See body strength and muscle strength.

Tension Force divided by the cross-sectional area through which it is transmitted.

Torque The product of force (see there) and the length of the (perpendicular) lever arm. Physically the same as moment (see there) but commonly used with twisting or turning.

Type I fiber Slow-twitch muscle fiber, see there.

Type II fiber Fast-twitch muscle fiber, see there.

Variometric Of differing length.

Venule A small vein joining a capillary to a larger vein.

Velocity First time-derivative of displacement.

Work The product (integral) of force and distance moved.

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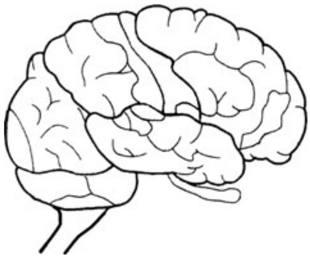
Chapter 3
Neuromuscular Control



Overview

The central nervous system is one of the control and regulation networks of the body. It collects inputs from various sensors that respond to internal and external stimuli. Its integration and regulation functions concerning motor activities are mainly in the cerebrum, the cerebellum, and the spinal cord. The pathways for incoming and outgoing signals are the neurons, which possess the ability to inhibit or facilitate the transmission of impulses.

The Model

The nervous system transmits information about events inside and outside the body from various sensors along its afferent pathways to the brain. Here, decisions about appropriate actions and reactions are made, feedforward signals generated and sent along the efferent pathways to the muscles.

Introduction

The overall purpose of the human regulatory and control systems is to maintain equilibrium (homeostasis) on the cellular level and throughout the body despite changing demands on the body generated by varying external environments and task requirements. Temporary, often instantaneous action signals must be generated in response to acute demands on the body.

The human body is under the control of two corresponding organizations: the endocrine system and the nervous system. Endocrine glands produce hormones, which circulate with the blood stream to carry chemical messages to those cells programmed to receive them. For example: one set of hormones (norepinephrine) stimulates smooth muscle in some organs, but in others inhibits the muscular contractions; another hormone (acetylcholine) has just the opposite effect on the same

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smooth muscles. The response time to hormonal messages is slow in comparison with the reaction to electrical impulses, which the nervous system directs at specific receptors, for example in finger flexor muscles.

The following text concentrates on the nervous system, particularly as it affects functions of skeletal muscle.

Organization of the Nervous System

Figure 3.1 sketches the organization of the human nervous system.

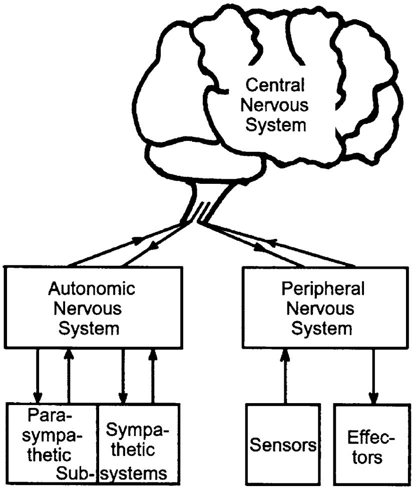

Fig. 3.1 Organization of the human nervous system

By Function

Functionally, there are two major subdivisions of the nervous system: the autonomic (visceral) system and the somatic system. The *autonomic* subdivision generates instinctive attitudes ("fright, flight or fight") and it regulates involuntary functions such as cardiac and smooth muscle, blood flow, digestion, or glucose release in the liver. It is subdivided into the sympathetic and the parasympathetic subsystems, which control unconscious actions, among them heart rate. The *somatic* (from the Greek *soma*, body; or *somesthetic*) nervous system regulates mental activities, skeletal muscle, and conscious actions.

By Location

Anatomically, the nervous system has three major subdivisions; one is the *autonomic* nervous system just described. The second, the *peripheral* nervous system, PNS, includes the cranial and spinal nerves; it has no control functions but transmits signals to and from the brain. The third is the *central* nervous system, CNS, which includes brain and spinal cord; it has primarily control functions.

The Central Nervous System

Figure 3.2 shows the customary division of the brain into several sections. Its left and right halves, called hemispheres, appear generally similar, but they have their special functions. With respect to the neuromuscular control system, the forebrain's *cerebrum* is of particular importance: it consists of the two (left and right) cerebral hemispheres, each divided into four lobes. The cerebrum manages sensory experience and consciousness; its frontal lobes control skilled behavior including speech, mood, thought, planning; the parietal lobes interpret sensory input and control body movements; the occipital lobes are in charge of vision; the temporal lobes generate memory and emotions.

The *cortex,* the many-folded top layer of the cerebrum, holds the "motor cortex" that controls voluntary movements of the skeletal muscles, whereas the "sensory cortex" interprets sensory inputs. At the base of cerebrum are thalamus, hypothalamus and the basal ganglia; the ganglia control semivoluntary complex activities such as walking. Part of the hindbrain is the *cerebellum*, which distributes and integrates impulses from the cerebral association centers to the motor neurons in the spinal cord. The *brain stem* controls the functions of such vital organs as the heart and lungs.

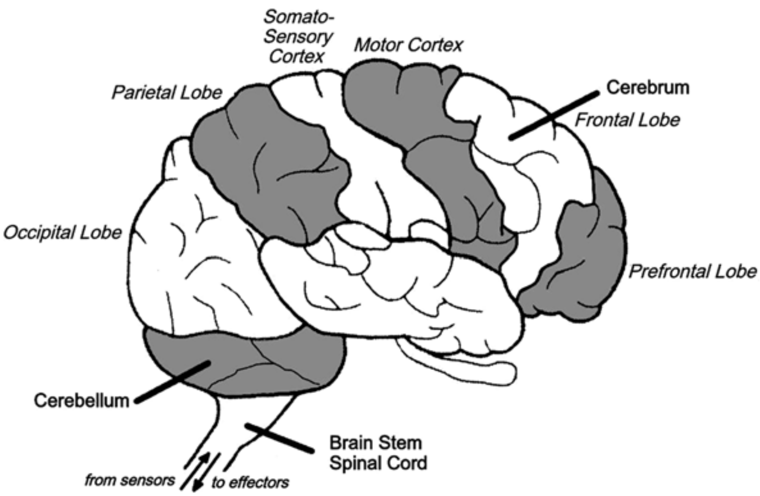

Fig. 3.2 The human brain seen from the right side

The brain of an adult human weighs between 1,200 and 1,400 g and has approximately 100 billion nerve cells.

The *spinal cord* is an extension of the brain: it coordinates fast actions, particularly reflex limb movements: an example is the “knee jerk”. A reflex begins with a stimulation of a peripheral sensory receptor, which triggers an afferent signal to the spinal cord. There, it evokes an immediate response and efferent impulse to the appropriate muscles. Since no time-consuming higher brain functions are involved, an effector can execute a reactive action just a few milliseconds after the stimulus. All reflex effectors are either muscle fibers or gland cells; hence the result of a reflex is either a muscular contraction or a gland secretion.

The spinal cord provides the nerves that serve as pathways for incoming and outgoing information by which the brain communicates with the rest of the body. Enclosed within the spinal vertebrae, as described below, the spinal cord extends down from the brain stem. At the top, twelve pairs of cranial nerves emanate laterally from the upper section of the spinal cord; below, thirty-one pairs of spinal nerves radiate to their specific sectors of the body. Down at the second lumbar vertebra, L2, the last nerves of the spinal cord emerge from the protection of the vertebrae and extend farther downward. The name of this final diverging bundle of spinal nerves is cauda equina because it resembles a horse tail.

Sensors and Effectors of the Peripheral Nervous System

The central nervous system, CNS, receives information arising from body sensors via the sensory part of the peripheral nervous system, PNS. (This branch is also called the afferent or feedback section of the PNS.) It carries signals concerning the outside from *external* receptors (exteroceptors), and from *internal* receptors (interoceptors) reporting on changes within the body. Since all of these sensations come from various parts of the body, external and internal receptors together are also called somatic sensors (Greek *soma*, body).

Internal receptors include the *proprioceptors* (Latin *proprius,* “one’s own”). Among these are the muscle spindles, nerve filaments wrapped around muscle fibers; they detect the amount of stretch of the muscle. Golgi organs are associated with muscle tendons and detect their tension, hence report to the central nervous system information about the strength of contraction of the muscle. Ruffini organs are kinesthetic receptors located in the capsules of articulations. They respond to the degree of angulation of the joints (joint position), to sustained strain and to slow changes.

The sensors in the *vestibulum* (see Fig. 3.3) of the inner ear are also proprioceptors: they detect and report the position of the head in space and respond to sudden changes in its attitude. This is done by sensors in the three semi-circular canals, each located in another orthogonal plane. Signals from proprioceptors in the neck, triggered by displacements between trunk and head, allow to relate the position of the trunk to that of the head.

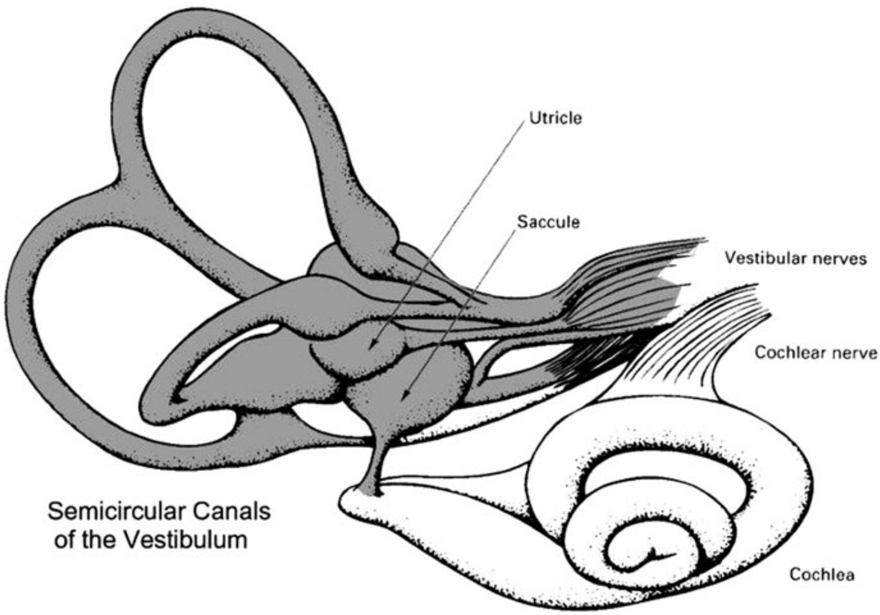

Fig. 3.3 The vestibulum (adapted from Kroemer et al., 2003)

Another set of interoceptors, called *visceroceptors*, reports on the events within the visceral (internal) structures of the body, such as organs of the abdomen and chest, as well as on events in the head and other deep structures. The usual modalities of visceral sensations are pain, burning sensations, and pressure. Similar sensations may also come from external receptors; since the pathways of visceral and external receptors are closely related, information about the body is often integrated with information about the outside.

External receptors provide information about the interaction between the body and the outside: sight (vision), sound (audition), taste (gustation), smell (olfaction), temperature, chemical agents, and touch (taction). Several of these are of particular importance for the control of muscular activities: especially the sensations of touch, pressure, and pain can be used as feedback to the body regarding the direction and intensity of muscular activities transmitted to an outside object.

Figure 3.4 sketches the location of common receptors at the body surface: Krause's end bulbs react to cold; Ruffini, Meissner's and Pacinian corpuscles respond to warmth, touch and pressure, respectively. Merkel's endings are mechanoreceptors, responding to touch. Furthermore, free nerve endings abound throughout the skin of the body; they respond to light and heavy touch, to heat and cold, and probably are chiefly responsible for reporting pain sensations.

The types of receptors, and their densities, vary throughout the body; tongue, lips, fingers and feet are the most sensitive regions of the body. Since nerve pathways interconnect extensively, the sensations reported are not always specific to

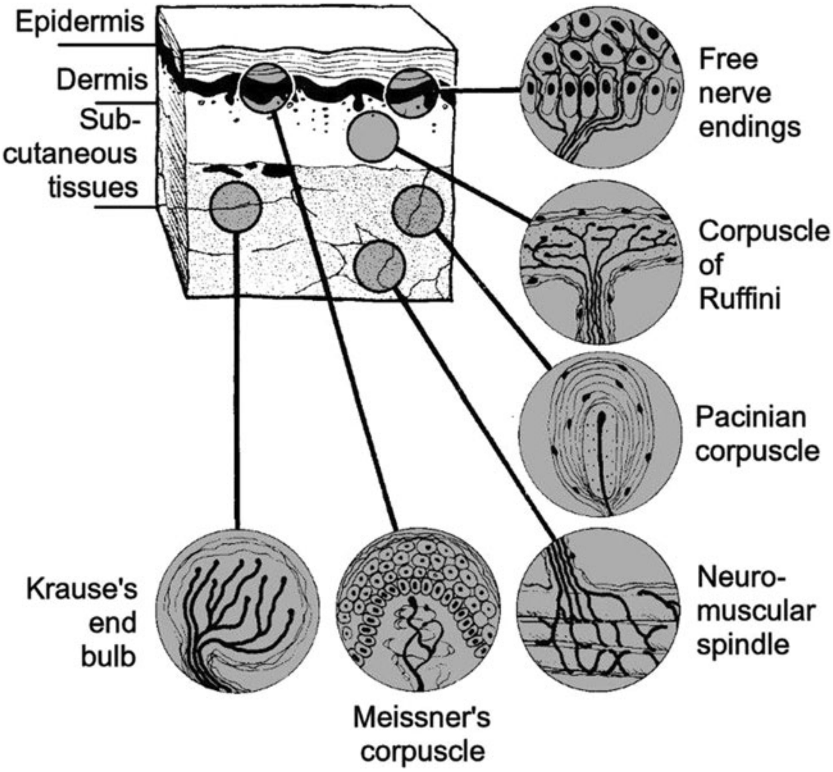

Fig. 3.4 Location of common receptors near the body surface (adapted from Langley and Cheraskin, 1958)

a modality; for example, very hot or cold sensations can be associated with pain, which may also be caused by hard pressure on the skin.

Almost all sensors respond vigorously to a change in the stimulus but then report less and less during the next seconds or minutes if the load stays constant. This adaptation makes it possible to live with, for example, the continued pressure of clothing; the speed of adaptation is specific to sensors. Furthermore, the speeds with which the sensations are transmitted to the central nervous system are quite different for different sensors: light and sound, for example, cause the fastest reactions whereas pain transmission is usually the slowest.

Many decisions made in the central nervous system, CNS, based on the evaluation of incoming signals, result in action signals carried along the feedforward part of the peripheral nervous system, PNS, to "effector" muscles. (Hence, this branch is called efferent, motor or motoric section of the PNS.) Their main effects (pertaining to this book) are signals that make muscle motor units contract – already discussed in Chap. 2.

The Nervous Pathways

The spinal cord runs from the brain stem down to the second lumbar vertebra, staying within the *intra*-vertebral foramens: these stacks of bone arches of the vertebrae (see Fig. 1.9 in Chap. 1) form a protective tunnel (occasionally called a channel) for the soft fragile cord. Between adjacent vertebrae, two nerve bundles emerge from the cord to the left and the right, as depicted in Figs. 3.5 and 3.6; each passes through an *inter*-vertebral foramen, a lateral opening between adjacent vertebrae. These lateral nerve bundles are often called nerves roots (because that's how they look as they

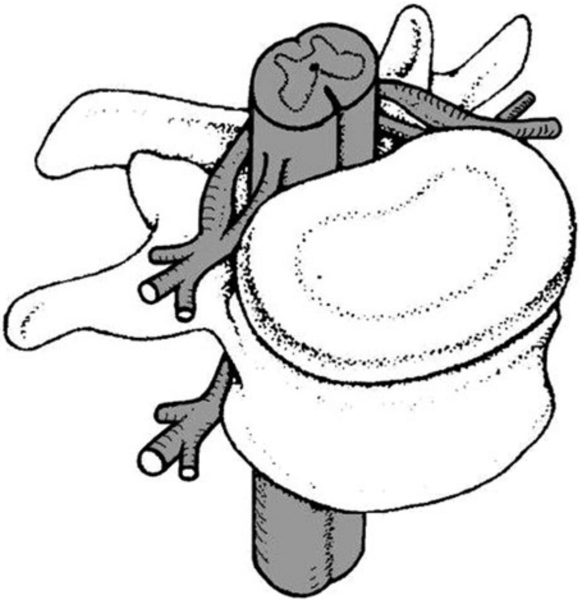

Fig. 3.5 Spinal cord and nerve roots passing through the vertebral foramina (adapted from Kroemer, 2009)

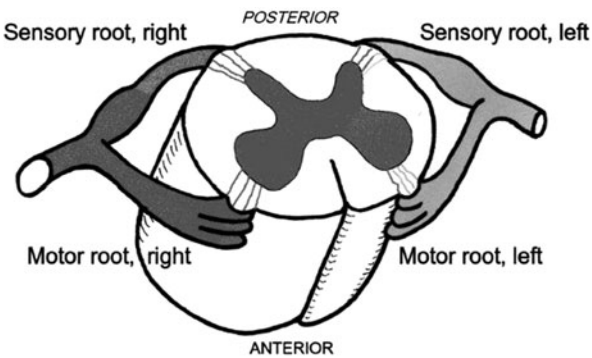

Fig. 3.6 Sensory and motor roots (adapted from Kroemer, 2009)

emerge from the stem). The nerves contain the fibers of both the motor and sensory tracts; they are the pathways by which the brain and spinal cord communicate with the rest of the body.

The uppermost section of the spinal cord contains twelve pairs of *cranial* nerves, which serve structures in the head and neck as well as the lungs, heart, pharynx and larynx, and many abdominal organs. They control eye, tongue, and facial movements, and the secretion of tears and saliva. The main inputs are from the eyes, the taste buds in the mouth, the nasal olfactory receptors, and touch, pain, heat, and cold receptors of the head.

Below the neck, thirty-one pairs of *spinal* nerves emanate between the thoracic and lumbar vertebrae and serve defined sectors of the rest of the body. Figure 3.7 shows specific areas of the skin (dermatomes) innervated by distinct nerves and lists where their roots start in the spinal column.

Injury to the spinal column and the spinal cord, or disk material protruding towards the spinal cord or the nerve roots emanating from it, can impinge on nerve tissue or damage it and severely affect the transmission of signals and hence the nervous control of a specific body part. The brain may interpret this as a disorder of the body segment itself and feel pain in the part which the nerve supplies. Typical of this is sciatica, pain felt along the sciatic nerve that traverses hip and thigh, usually caused by a herniated disk of the lumbar spine.

The Neuron

The basic functional unit of the nervous transmission system is the *neuron*, also called a nerve cell. There are about 12 billion neurons in the brain, most in the cerebral cortex, and in the spinal cord. Neurons transmit signals from one to another through their filamentous nerve fibers, which serve as a communication system throughout the body. In the brain, neurons are also responsible for memory, for patterns of thinking and motor responses, and so forth. Neurons connect in *synapses.* This junction between two neurons has a switching ability; it can or may not transmit signals.

Figure 3.8 sketches a typical neuron combining the main features of motor neurons, sensory neurons, and interneurons. It consists of three major parts: the main body (soma), and its processes: either the axon, a long extension, or short branching dendrites. Figure 3.9 illustrates the connection between two neurons via a myelinated axon and a synapse.

Each motor neuron has only one axon, which serves to transmit signals from the cell body. At a distance from the soma, the axon branches out into terminal fibrils that connect with other neurons. Axon lengths range from only a few millimeters to a meter or longer. The neuron has up to several hundred dendrites, projections of usually only a few millimeters. They receive signals from the axons of other neurons and transmit these to their own neuron cell body. The lower left corner of Fig. 3.7 shows the synapse endpoints of (usually hundreds of) fibrils coming

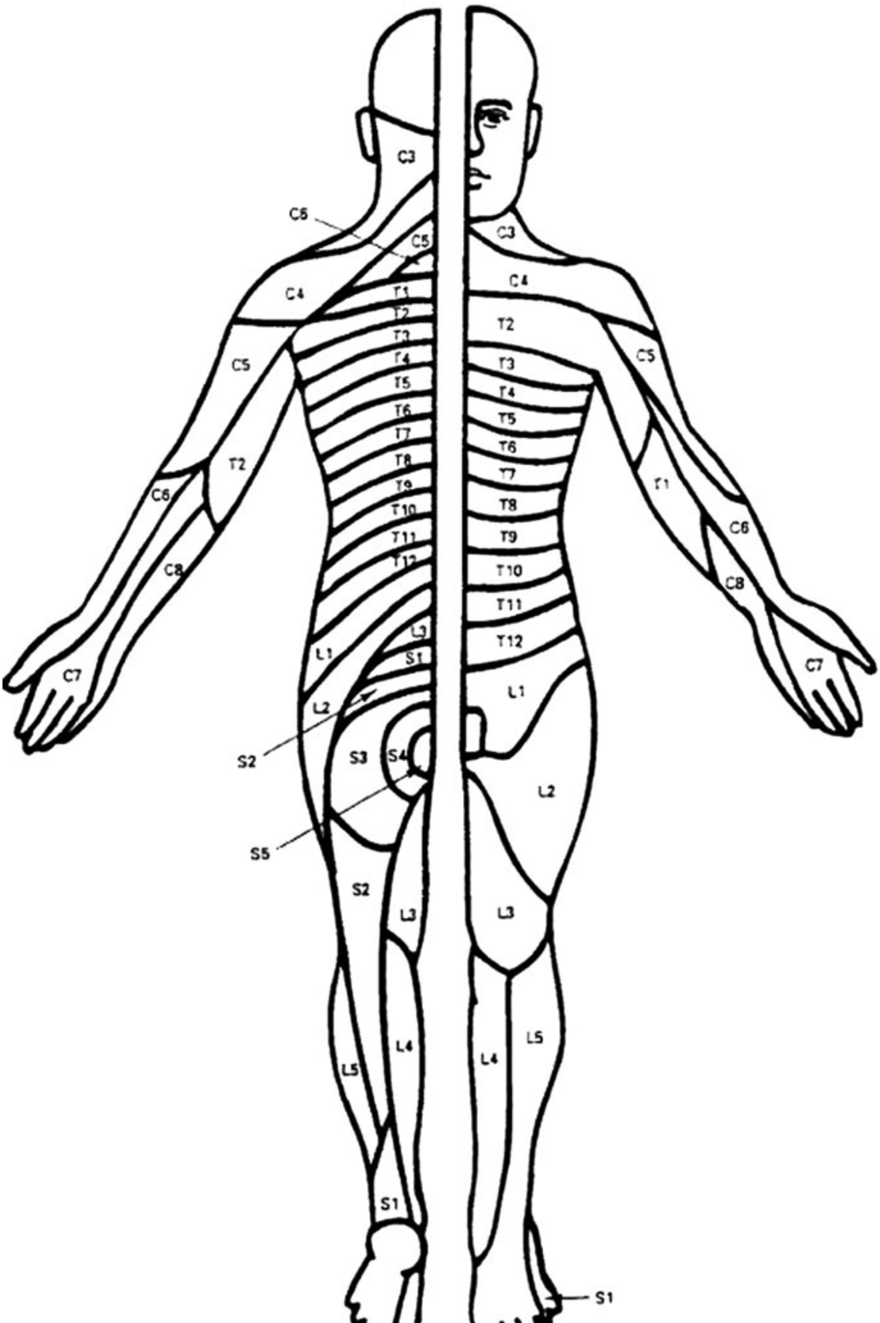

Fig. 3.7 Sensory dermatomes with their spinal nerve roots: C stands for cervical, T for thoracic, L for lumbar, S for sacral

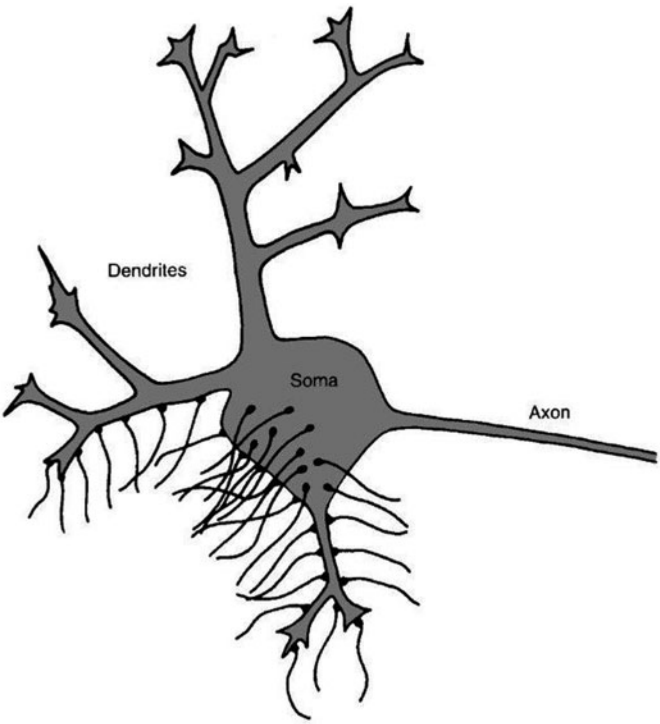

Fig. 3.8 Typical neuron components: soma, dendrites, axon. Synapses are sketched only in the *lower left part* of the figure

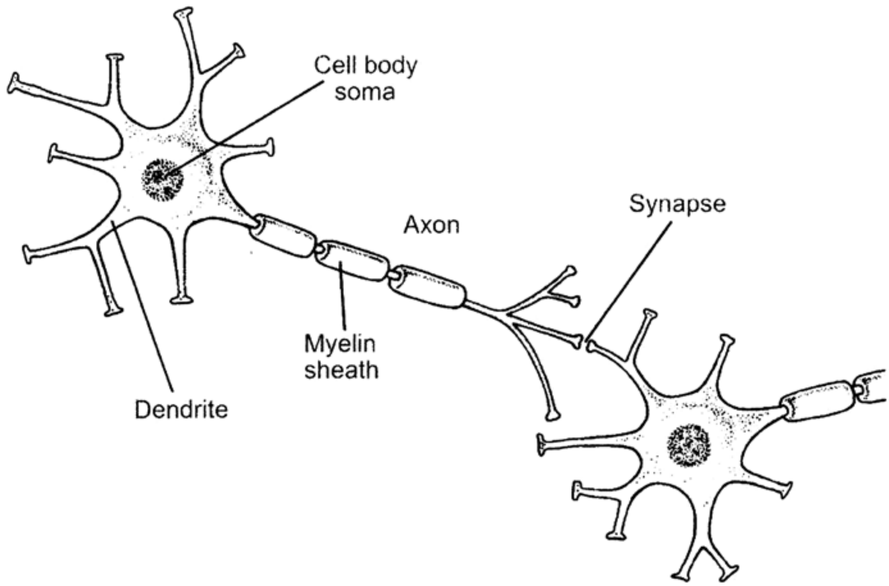

Fig. 3.9 Two motor neurons connected by axon and synapse

from axons of other neurons. Synapses are formed like knobs, bulbs, clubs, or feet. Each synaptic body has numerous vesicles which contain transmitter substance. The synaptic membrane is separated from the opposing subsynaptic membrane of the neuron by a synaptic cleft, a space of about 2 Å.

Transmission of Nerve Signals

Some axon terminals secrete an excitatory transmitter substance, others carry an inhibitory neurohumor; hence, some terminals excite the neuron and others inhibit it. Among the excitatory neurohumors is norepinephrine, while one of the inhibitory secretions is dopamine. Certain chemical agents (such as some anesthetics and curare) can prevent the secretion of excitatory neurohumor thus inhibiting the transmission of signals, possibly causing paralysis of the musculature.

Excretion of an excitatory transmitter increases the permeability of the subsynaptic membrane beneath the synaptic knob, which allows sodium ions to flow rapidly to the inside of the cell. Since sodium ions carry positive charges, the result is an increase in positive charge inside the cell, bringing about an excitatory post-synaptic potential. This sets up an electrical current throughout the cell body and its membrane surfaces, including the base of the axon. If this potential spikes high enough, it initiates an action potential in the axon. If the potential does not exceed a threshold value, no action impulse will be transmitted along the axon. Usually, a summation of inputs succeeds in getting over the threshold, as in Fig. 3.10. Such summation can either result from simultaneous firing of several synapses or from rapid repeated firing of the same synapse. If the threshold is exceeded, the axon carries repeated action impulses as long as the potential remains high enough. The higher the post-synaptic potential rises, the more rapidly the axon fires.

Depending on their type and size, some neurons are able to transmit as many as a 1,000 impulses/s along their axons, while others cannot transmit more than 25 signals/s.

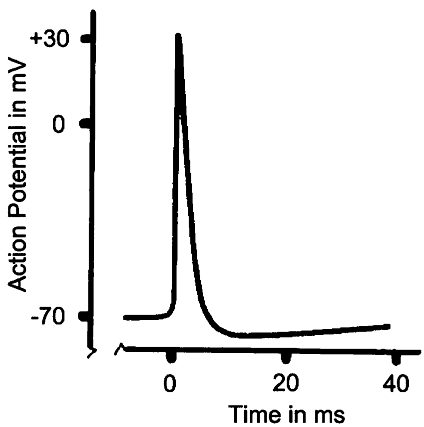

Fig. 3.10 A typical nerve action spike

Inhibitory transmitters have an opposite effect on the synapse: they create a negative potential called the inhibitory post-synaptic potential. This reduces the actual synaptic potential, which may result in a value below the threshold of the neuron: different neurons have different thresholds. Thus, the inhibitory synaptic knobs may stop or prevent neuron discharge.

Most nervous impulses are not carried by a single neuron from receptor to destination but follow a chain of linked neurons. (The transmission may stop if it comes to a neuron with a particularly high threshold.) Once developed, the action potential propagates itself point by point along a nerve fiber, not needing further stimulation. At each successive point along the fiber, the action potential rises to a maximum and then rapidly declines. Because of this shape, the action potential is occasionally called a spike potential. The height of the spike, its strength, does not vary with the strength of the stimulus, nor does it weaken as it progresses along the axon. The stimulus is either strong enough to elicit a response, or there is no potential; this is an all-or-none phenomenon similar to the one discussed in the contraction of skeletal muscle.

While nerve fibers hardly fatigue, synapses do; some very rapidly, some rather slowly.

The velocity of the nerve impulse is a constant for each nerve fiber, ranging from 0.5 m/s to about 150 m/s. The particular speed does not change along a specific fiber; it correlates with the diameter of the fiber, being faster in a thick fiber than in a thin strand. In the peripheral parts of the nervous systems, axons and dendrites are sheathed along their length. The envelope consists of myelin, a white material composed of protein and phospholipid. The presence of a myelin sheath allows a larger speed of conduction. Skeletal muscles are served by thick myelinated axons terminating at the motor endplates, while pain fibers are the thinnest and not myelinated.

Control of Muscle

Reflexes can take place without involvement of higher brain centers, but most complex voluntary muscular activities need fine regulation through efferent feedforward and afferent feedback control, sketched in Fig. 3.11. Muscle actions differ, so they require variable involvement of the higher brain centers, such as the cerebral cortex, the basal ganglia and the cerebellum. Apparently, the motor cortex controls mostly very fine discrete muscle movements, whereas everyday gross movements, such as walking, running or posture control are tasks done in the basal ganglia with their large pools of neurons. This may be the locus for "executive programs" mentioned in Chap. 2.

Activation of a muscle follows this sequence:

- Step 1: An excitation signal travels along the efferent nervous pathways to the axon of the signal-carrying motor nerve, which terminates at a "motor endplate" located in a z-disk: this is the myoneural junction for the "motor unit" (discussed in Chap. 2)

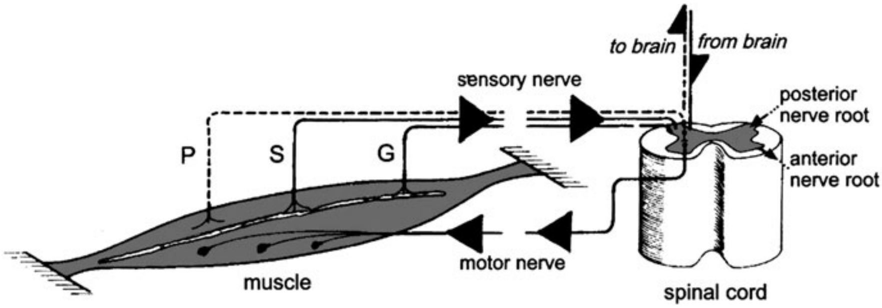

Fig. 3.11 Motor and sensory nerves controlling muscle action: P, pain signal; S, from muscle spindle; G, from Golgi organ (adapted from Kroemer, 2009)

- Step 2: The excitation signal (observable in an electromyogram, EMG) stimulates a de-polarizing action of the muscle cell membrane. This allows spread of the action potential along the sarcoplasmic reticulum.
- Step 3: The potential triggers the release of calcium ions into the sarcoplasmic matrix surrounding the filaments of the motor unit.
- Step 4: This removes tropomyosin, the hindrance for interactions between actin and myosin filaments through chemical, mechanical, and electrostatic actions.
- Step 5: Opposing heads of actin rods move towards each other, sliding along the myosin filaments: their heads may meet, bunch up, even overlap. This reduction of the length of the sarcomere is called "contraction". The shortening of many fibrils at the same time shortens the whole muscle. (Note that a muscle can attempt to contract but, instead, may become lengthened by an overwhelming stretching force – see Chap. 2.)
- Step 6: Rebounding of calcium ions in the sarcoplasmic reticulum switches the contraction activity off, which allows the filaments to relax.

A common way to record the occurrence of efferent signals is to implant a wire or needle electrode, or to attach a surface electrode to the skin, near the motor endplates of the innervated motor unit of the muscle of interest – see Chap. 2 – and to record the electrical activities in an electromyogram, EMG*.

Ergonomic Engineering to Facilitate Control Actions

Among the major tasks of human factors engineering is to design tasks and gear so that they "fit the human" by facilitating good outcomes of operator effort and by protecting the individual*.

Events and conditions exist that humans cannot detect because they are outside their sensory capabilities; examples are cosmic radiation that endangers space travelers, x-rays that can hurt lab technicians, carbon monoxide that may kill silently. Engineers can select instruments which are sensitive to such humanly undetectable distant stimuli and then convert their output to signals which are in the sensory domain of the human: for instance, an audible sound and a visible light can warn operators effectively about harmful radiation and poisonous gas. That technical conversion may concern distal stimuli that are fully incompatible with human sensors or stimuli which are not conspicuous enough to be perceived securely. Figure 3.12 illustrates the principle of transforming imperceptible distal signals into proximal stimuli which humans can process.

A similar task is to convert human physical output as needed to control complex machinery, such as automobiles, ships, airplanes and spacecraft. One of the technical issues concerns insufficient human strength: various ways to augment muscular capabilities are currently used, such as "power(ed) steering" and "power(ed) brakes" in many vehicles. One of the allied tasks is to provide appropriate sensory feedback so that, in spite of the converting device, the operator retains "feel for the behavior" of the machinery.

A related task is the prediction of the future response of a compound system following current control inputs; examples are the course that a large ship will travel depending on a current rudder setting, or the future trajectory of a plane or spacecraft in response to present control actions. Generating immediate feedback regarding future system performance – see Fig. 3.13 – requires not only knowledge of

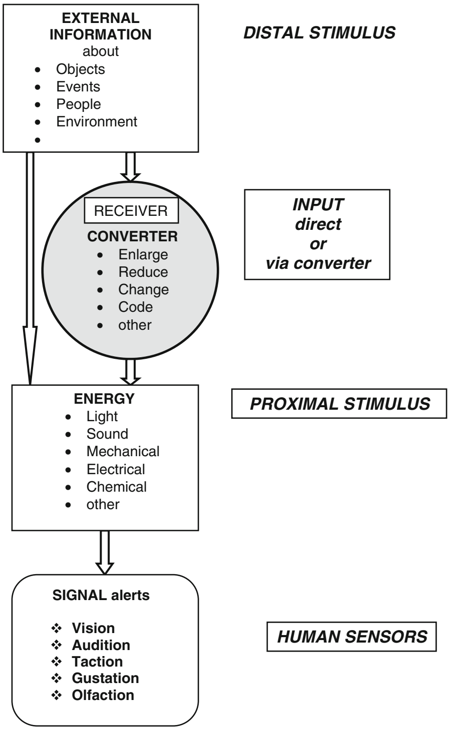

Fig. 3.12 Converting distal signals into proximal stimuli that can serve as inputs to the human processor (adapted from Kroemer, 2006)

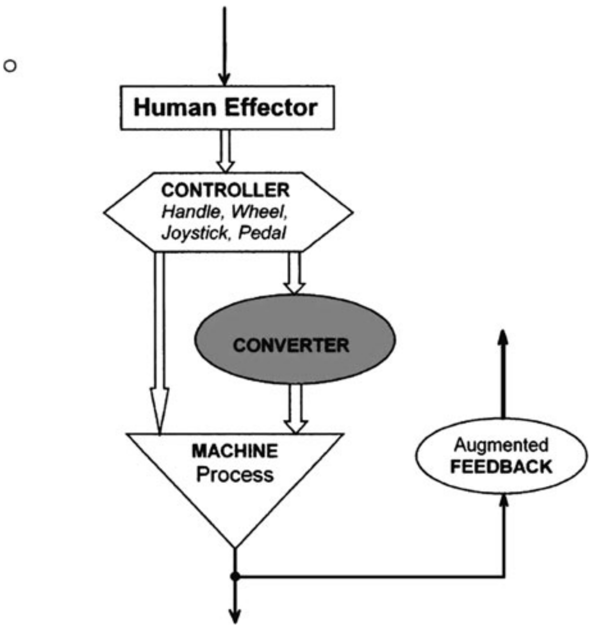

Fig. 3.13 Transforming human effector output (adapted from Kroemer, 2006)

the converters used to transmit human inputs to the system, but also of the dynamic properties and future behavior of the system: often, appropriately programmed computers provide that information.

Injury to an efferent nerve reduces the ability to transmit signals to innervated muscle motor units and hence impedes the control of activities of muscles, for instance to organize and regulate specific force or torque for application to tools, equipment, and work objects. Likewise, impairment of afferent nerves reduces the information that sensors can relay to the central nervous system. Sensory feedback is very important for many activities because it contains information about force and pressure applied, position assumed, and motion experienced.

Sensory nerve impairment usually brings about sensations of numbness, tingling, or pain in the associated body part. Impairment of an autonomic nerve reduces the ability to control such functions as sweat production in the skin. Common signs of reduced autonomic function are dryness and shininess of skin areas controlled by that nerve.

Spinal cord injuries often cause severe impairment of nervous pathways. Horse riding and automobile accidents, for example, may cause sudden displacement of the head with respect to the trunk. Too often, this results in dislocation or breakage of vertebrae which, in turn, damages the spinal cord passing through the vertebral foramen (as mentioned above). Damage to the cord may render it incapable to transmit feedforward signals to body areas innervated by nerves below the injury point, and also make it unable to conduct feedback signals from these body parts to the brain. As a result, the victim has no control over the innervated body segments and no sensation in them.

To the engineer, these events pose the task of – best – preventing such accidents, or at least to design protective devices: so far, little success has been achieved for horse riders, whereas persons in vehicles have benefitted from improved protective shells around them and from shock-protecting devices inside the cabin, such as air bags, head rests and body restraints, which can prevent whiplash and impact on car structures.

Acute trauma can affect nerve functioning, but so can the cumulative effects of often repeated light trauma, even if each event by itself is not harmful. A typical case is the "carpal tunnel syndrome" in the hand: it is the final episode in a chain of events. The common root causes are overly repetitive finger motions, such as can occur in long-lasting in piano playing, keyboarding, knitting, gardening and many hand activities at work or leisure.

Carpal tunnel syndrome (CTS) is among the best known cumulative trauma disorders. Apparently, it was observed to occur in the middle and late nineteenth century, initially called palsy, spasm, or cramp in the medical literature, later often myalgia and tenosynovitis. In 1959, Tanzer described several CTS cases: Two of his patients had recently started to milk cows on a dairy farm, three worked in a shop in which objects were handled on a conveyor belt, two had done gardening with considerable hand weeding, and one had been using a spray gun with a finger trigger. Two patients had been working in a large kitchen where they stirred and ladled soup twice daily for about 600 students.

In 1966 and 1972, Phalen described the typical gradual onset of numbness in the thumb and the first two and a half fingers of the hand. In 1975, Birkbeck and Beer described the results of a survey they made of the work and hobby activities of 658 patients who suffered from CTS. Four out of five patients were employed in work that required light yet highly repetitive movements of the wrists and fingers. In 1976, Posch and Marcotte analyzed 1,201 cases of CTS*.

Excessive repetition of finger flexor tendons motions in their sheaths causes increasing friction and, often, inflammation of these tissues. The associated swelling leads to pressure inside the narrow space between the carpal bones of the hand and the transverse carpal ligament, the "carpal tunnel" shown in Fig. 2.11 of Chap. 2. Continuing the repetitive actions worsens inflammation, swelling and pressure. That strain compresses the tendons in their sheaths, blood vessels and the median nerve, which all pass through the carpal tunnel. The median nerve supplies the thumb, the index and middle fingers and the near side of the ring finger. (The little finger and the outside of the ring finger are under control of the ulnar nerve.) Excessive pressure on the median nerve impairs all its functions, autonomic, sensory and motor; usually, the victim first has the feelings of tingling and numbness in the innervated digits, then pain and reduced control of finger motions. The medical diagnosis often relies on the measurement of reduced conduction velocity in the afflicted median nerve.

The solutions are obvious: to resolve the medical condition, a surgeon cuts (partly) the restricting transverse carpal ligament; this relieves the pressure and gives the tissues space to heal. Of course, it is best to avoid the problem by not performing excessive repetitions of finger flexions. Accordingly, the fundamental solutions are in the hands of engineers who can design equipment and work tasks to suit human capabilities. Since the nineteenth century, overuse of the Morse telegraph key, of the keyboard of the piano, and of Sholes' 1878 QWERTY typewriter keyboard all have been known to lead to cumulative repetition trauma*, yet only the Morse key has fallen by the wayside.

Technology seemingly at the brink of practical use, especially nanotechnology, may provide means to pick up nervous signals and transmit these to effectors, and to provide feedback to the CNS. Such bioengineering achievement would mean immeasurable help to persons whose natural body control system has been damaged.

Notes

The text contains markers, *, to indicate specific references and comments, which follow.

Electromyogram: Kumar and Mital (1996), Sommerich and Marras (2004), Marras and Karwowski (2006), Marras (2008).

Design tasks and gear so that they "fit the human": See, for example, Kroemer (2006, 2009), Kroemer and Kroemer (2001), Kroemer et al. (2003).

Carpal tunnel syndrome: See Pfeffer et al. (1988), Arndt and Putz-Anderson (2001), Kroemer (2001) for reviews.

Keyboards and keys causing cumulative repetition trauma: Kroemer and Kroemer (2001), Kroemer (2009).

Summary

The body must continuously control muscle functions according to information about conditions and events reported from its many and varied sensors. The information feedback to the central nervous system (where decisions are made and actions initiated) and the feedforward signals to the muscles flow along the peripheral nervous system.

Afferent and efferent signals are transmitted along neurons, consisting of soma, dendrites, and axon. At the neuron, nerve fibrils (from other neurons) end in synapses which serve as selective switches. Depending on the strength

of the incoming signal, it is either transmitted or not transmitted across the synaptic membrane.

With many sensors reacting to the same stimulus, and many afferent pathways transmitting the signals at different intensities and speeds, the peripheral nervous system serves as a filter or selector for the central nervous system.

Damage to efferent and afferent nerve usually results in loss of motor control and of sensory feedback.

Glossary

Action Activation of muscle. see contraction

Acute trauma Severe sudden damage.

Adaptation Responsive adjustment, here diminished reaction.

Afferent Carrying inward, toward the CNS.

Autonomic (visceral) system Part of the nervous system that regulates involuntary actions; has the sympathetic and the parasympathetic subsystems.

Axon Long process of a nerve fiber, conducting impulses away from the nerve soma.

Carpal tunnel syndrome (CTS) An impairment of the median nerve.

Central nervous system (CNS) Brain and spinal cord together.

Cerebellum (Latin, small brain) Part of the cerebrum, regulates complex voluntary muscle actions, maintains body posture and balance.

Cerebrum Largest portion of the brain, controls and integrates motor and sensory functions as well as higher functions such as thought, reason, memory and emotions.

CNS Central nervous system, see there.

Contraction Literally, "pulling together" the z lines delineating the length of a sarcomere, caused by the sliding action of actin and myosin filaments. Contraction develops muscle tension only if the shortening is resisted. (Note that during an isometric "contraction" no change in sarcomere length occurs and that in an eccentric "contraction" the sarcomere is actually lengthened. To avoid such contradiction in terms, it is often better to use the terms activation, effort, or exertion.)

Cortex The outer layer of grey matter of the brain covering the cerebral hemisphere.

Cranial nerve Nerve that serves structures in the head, neck, lungs, heart, pharynx, larynx, and many abdominal organs.

CTS Carpal tunnel syndrome, see there.

Cumulative trauma Damage that increases by successive addition of small injuries.

Dendrite Short process of a nerve fiber that conducts impulses inward to the nerve soma.

Dermatome Skin area innervated by the sensory fibers of a single spinal nerve.

Distal stimulus Stimulus (see there) outside the body

Dynamics A subdivision of mechanics that deals with forces and bodies in motion.

Effector A muscle, gland or organ, that acts in response to a nerve impulse.

Efferent Carrying outward, to an effector, usually a muscle.

Effort (of muscle) See contraction.

Electromyogram (EMG) Graphic record of the electric activity of a muscle.

EMG Electromyogram, see there.

Energy (The capacity to do) work. Proper units are the joule (J) and calorie (cal).

Ergonomics The application of scientific principles, methods and data drawn from a variety of disciplines to the design of engineered systems in which people play significant roles.

Exertion (of muscle) See contraction.

External receptors Receptors that respond to signals outside the body; same as exteroceptors.

Exteroceptors See external receptors.

Feedback Information carried inward, toward the central nervous system.

Feedforward Information carried outward from the central nervous system to an effector.

Foramen Opening in a vertebra.

Force A vector that can accelerate a mass. As per Newton's third law, the product of mass and acceleration; the proper unit is the Newton, with $1\ N = 1\ kg\ m/s^2$. On earth, one kg applies a (weight) force of 9.81 N (1 lb exerts 4.44 N) to its support. Muscular force often is described as tension multiplied by transmitting cross-sectional area.

Homeostasis The state of equilibrium.

In situ In the original position/place.

In vivo Within the living organism/body.

Innervate To supply a body part with nerves.

Internal receptors Receptors that respond to signals inside the body; same as interoceptors.

Interoceptors See internal receptors.

Kinesthesia Sense that detects body position, and movements of joints, muscle, tendons.

Kinesthetic See kinesthesia.

Kinetics A subdivision of dynamics that deals with forces applied to masses.

Mechanics The branch of physics that deals with forces applied to bodies and their ensuing motions.

Motor endplate Contact area of axon and sarcolemma of the muscle.

Motor unit All muscle filaments under the control of one efferent nerve axon.

Muscle A bundle of fibers, able to contract or be lengthened. In this context, striated (skeletal) muscle that moves body segments about each other under voluntary control, see Chap. 2.

Muscle contraction The result of contractions of motor units distributed through a muscle so that the muscle length is shortened, see Chap. 2.

Myelin An envelope that consists of protein and phospholipid, around an axon.

Myo Prefix referring to muscle (greek mys, muscle).

Mys Prefix referring to muscle (greek mys, muscle).

Nerve root Nerve bundle that emanates laterally from the spinal cord.

Neuron A nerve cell.

Parasympathetic system The part of the autonomic nervous system that opposes the physiological effect of the sympathetic system.

Peripheral nervous system (PNS) The nerves outside the Central Nervous System, see there.

Plasmalemma Membrane of a muscle cell, also called sarcolemma.

PNS Peripheral nervous system, see there.

Power Work (done) per unit time.

Pressure Force distributed over an area.

Proprioceptors Sensors that report on the status of the body (latin proprius, "one's own").

Proximal stimulus Stimulus (see there) signal that arrives at a body sensor.

Rate coding The time sequence in which efferent signals arrive at a specific motor unit and cause it to contract.

Recruitment coding The time sequence in which efferent signals arrive at different motor units and cause them to contract.

Reflex Involuntary action produced automatically in response to a stimulus.

Repetition Performing the same activity more than once. (One repetition indicates two exertions.)

Root See nerve root.

Sarcolemma Membrane of a muscle cell, also called plasmalemma.

Sciatica Pain felt along the sciatic nerve that traverses hip and thigh.

Soma Body, such as of a cell (from the Greek soma, body).

Somatic Of, relating to, or affecting the body.

Somesthetic Sensing the body.

Spinal cord Strand of nerve tissues extending from the medulla down through the foraminae of the spinal column.

Spinal nerves Bundles of nerve that emanate between the thoracic and lumbar vertebrae and serve defined sectors of the rest of the body, see nerve roots.

Statics A subdivision of mechanics that deals with bodies at rest.

Stimulus Agent, action or condition that elicits (or should elicit) a physiological or psychological response.

Strain (In engineering terms) the experienced physical or psychological demand ("pressure") resulting from stress.

Strength See body strength and muscle strength.

Stress (In engineering terms) a condition that generates physical or psychological strain ("demand, pressure") on material or a human.

Sympathetic system The part of the autonomic nervous system that opposes the physiological effect of the parasympathetic system.

Synapse Junction between two neurons.

Tension Force divided by the cross-sectional area through which it is transmitted.

Twitch A single contraction of a motor unit.

Velocity First time-derivative of displacement.

Work The product (integral) of force and distance moved.

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Chapter 4
Anthromechanics

Overview

Anthromechanics is the discipline of biomechanics applied to the human: biomechanics explain characteristics, actions and responses of a biological system in mechanical terms. That discipline incorporates methods and techniques from physics, especially mechanics; mathematics, including computer sciences; anatomy, particularly anthropometry; and, of course, biology and physiology. In this chapter, anthromechanical considerations explore and explain the action of muscles bridging body joints, the assessment of mass properties of the human body, and the transmission of forces and torques along a chain of body segments.

The Model

The body, consisting of solid, flexible and fluid components, possesses mass and other material properties that obey physical laws. The body is built on and around a solid skeleton of links (the long bones) with sections that articulate in joints. Muscles are the "engines" that power the body. Therefore, mechanical terms and computational techniques can describe many functions of the human body.

Introduction

Anthromechanics is not a new science. Leonardo da Vinci (1452–1519) and Giovanni Alfonso Borelli (1608–1679) combined the then existing knowledge of physics, anatomy and physiology. In his book *De Motu Animalium (The Motion of Animals)*, Borelli developed a model of the human skeleton consisting of a series of links (long bones) joined at their articulations and powered by muscles bridging the articulations. This "stick person" approach still underlies many current biomechanical models of the human body.

K.H.E. Kroemer et al., *Engineering Physiology*, 4th ed.,
DOI 10.1007/978-3-642-12883-7_4, © Springer-Verlag Berlin Heidelberg 2010

The knowledge developed by Gottfried Leibnitz (1646–1716) and Isaac Newton (1642–1727) explained the physical relationships between force, mass, and motion. Of particular importance are "Newton's Laws":

– the first explains that unbalanced force acting on a mass changes its motion condition;
– the second states that force equals mass multiplied by acceleration;
– the third makes it clear that force exertion requires the presence of an equally large counter force.

Development of anthromechanics achieved a first high point in the late 1800s when researchers determined the masses of body segments, investigated the interactions between mass distribution and external impulses applied to the human body, and discussed statics and mechanics of the human body*.

Since then, biomechanical research has addressed, among other topics, the response of the body to vibrations and impacts; human strength and motion of the whole body and its components; functions of the spinal column; hemodynamics and the cardiovascular system; and prosthetic devices*.

Treating the human body solely as a mechanical system means to make many and gross simplifications, for example, disregarding mental functions. Furthermore, mechanical analogies also simplify realty, such as:

- Anthropometric Data: dimensions obtained from statistical manipulation of data measured on groups of people.
- Articulation Linings: lubricants, joint structures.
- Articulations: joints and bearing surfaces, often considered frictionless.
- Bones: lever arms, central axes, structural members.
- Contours: surfaces of geometric bodies.
- Flesh: volumes, masses.
- Muscles: motors, dampers or locks.
- Nerves: control and feedback circuits.
- Organs: generators or consumers of energy.
- Tendon Sheaths: pulleys and sliding surfaces, often considered frictionless.
- Tendons: cables transmitting muscle forces.
- Tissue: elastic load-bearing surfaces, springs, contours.

Stress and Strain

In engineering terms, strain is the result or effect of stress: stress is the input, strain the output. One example: the weight of the upper body stresses the spine and its supports, generating strain in these structures. Stress often is a measure of the force applied over a unit area, and has units of pressure (N/mm^2). Strain is a relative deformation corresponding to the applied stress, and has units of change in length divided by gage length; stated in mm/mm, or sometimes %. (Detailed discussions of stress analysis are beyond the scope of this text. However, there are many basic mechanics books available for further information.)

In the 1930s, the psychologist Hans Selye introduced his concept of stress (and distress) being caused by stressors. He was borrowing an engineering term to describe a psychologic condition – unfortunately, the use of the term "stress" as either being cause (in engineering) or result (in psychology) can create much confusion: What is, for example, "job stress"? To avoid ambiguity, the engineering terminology will be used in this text: stress produces strain.

Mechanical Bases

Mechanics is the study of forces and of their effects on masses. *Statics* considers masses that are at rest or in equilibrium because balanced forces act on them. *Dynamics* concerns the motions of masses; motion results from the action of unbalanced external force on mass.

Dynamics, also called kinesiology when applied to the human body, subdivides into two fields. *Kinematics* considers the motions (displacements and their time derivatives velocity, acceleration, jerk) but not the forces that bring these about; in contrast, *kinetics* is concerned with just these forces.

"Newton's Laws', already listed, are basic to biomechanics. The second law sheds light on one important factor in biomechanics: force. Force is defined by its ability to change the velocity of a mass by generating acceleration: a force can cause a mass to speed up or slow down, and change its direction of motion. Force is a vector, having magnitude and direction.

Force is not a basic unit of the international metric measuring system but a derived one, calculated from the acceleration of a mass. (Acceleration is the first time-derivative of velocity.) Relatedly, no device exists that measures force directly. All devices for measuring force (or torque) rely on other physical phenomena, usually either displacement (such as bending of a metal beam) or acceleration experienced by a mass.

The correct unit for force measurement is the Newton (N). One Newton of force accelerates 1 kg of mass by 1 m/s^2: $1\ \text{N} = 1\ \text{kg} \times 1\ \text{m/s}^2$. On earth, 1 kg has a weight (weight is a force!) of 9.81 N*.

Torque (also called moment) is a vector that can change the angular velocity of a mass by generating an angular acceleration. Torque is calculated as the product of force and its lever arm (distance) to the articulation about which it acts. By definition, the lever arm is at a right angle to the direction of the force; in kinesiology, the lever arm often is called the mechanical advantage.

To calculate the forces or moments that act on an object of interest, we establish a space around it; within these fictional boundaries, we enforce Newton's Laws. If there is no motion, or no change in motion, then the object is in static equilibrium: *static* since there is no new motion and *equilibrium* because the forces and moments are balanced. When balanced, the sum of the forces, and the sum of the moments, must be zero:

$$\sum \text{forces} = 0 \tag{4.1a}$$

$$\sum \text{moments} = 0 \tag{4.1b}$$

Example: Establish a space around a person standing on a weight scale. Within that space, all forces (and moments) sum up to zero. Accordingly, the force with which the scale is pushing up on the person's feet must balance the downward force, the weight, due to the mass of the person. The weight (mass × acceleration, Newton's 2nd Law) equals the reaction force (Newton's 3rd Law).

Because the fictional boundaries around the object of interest seem to cut it free from its surroundings, it is called a "free body": that may be the entire person pushing on a scale, or is can be just the arm of a person holding a load.

Static Equilibrium

Figure 4.1 illustrates how forces and moments produced by muscle change with arm position. Biceps brachii, the primary flexing muscle, exerts a force M' on the forearm. The biceps force M' has a lever arm *m* around the elbow joint. The lever arm is perpendicular to the action line of M'.

The torque T about the elbow joint is:

$$\mathrm{T} = m \times \mathrm{M'} \tag{4.2}$$

The length of *m* changes with the elbow angle: it is longest at a right angle between forearm and upper arm; the lever arm *m* gets smaller the more the arm is flexed or extended.

Figure 4.2 represents the same condition in a more detailed and realistic sketch. The actual direction of the muscle force vector M usually is not at a right angle to the lever arm m; thus, it differs from the vector P (which is perpendicular, as was M' in Fig. 4.1). With the angle ß between P and M, the relationship between the two vectors is

$$\mathrm{P} = \mathrm{M} \cos ß \tag{4.3}$$

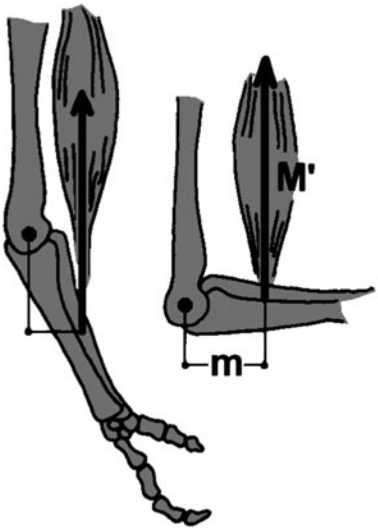

Fig. 4.1 Changing lever arm of the force vector M' with varying elbow angle

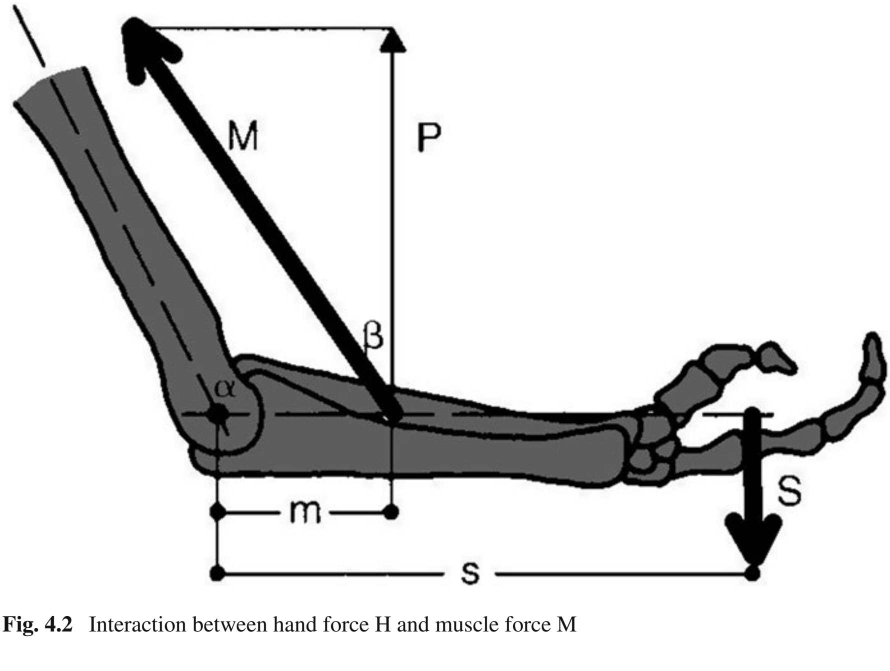

Fig. 4.2 Interaction between hand force H and muscle force M

The angle ß itself varies with the elbow angle α, hence ß is a function of α:

$$ß = f(\alpha) \quad (4.4)$$

Muscle force M generates a torque T around the elbow joint:

$$T = m \times P \quad (4.5)$$

If there is no acceleration, all forces and torques are in balance: in every direction, the sum of the forces and the sum of the torques must be zero. This requires counteraction to the torque T by an equally large but opposing torque which may be generated by a force vector S (parallel to P) pulling down on the hand. With its perpendicular lever arm *s*, S establishes static equilibrium if

$$s\,S = m \times P = m \times M\,\cos ß \quad (4.6)$$

This yields an equation for calculating the muscle force vector M:

$$M = (S/\cos ß) \times (s/m) \quad (4.7)$$

This equation confirms that, to generate a hand force vector S, muscle force M varies with the ratio between the lever arms (*s/m*) and with the elbow angle ß. Measuring the external force S, the angle ß and the lever arms *s* and *m,* provides all values needed to determine the magnitude of the muscle force vector M.

Note that in this example the arm was considered massless. However, real-life conditions are a bit more complex. It can be rather difficult to determine the insertion point of the biceps muscle force vector M on the radius bone because encapsulating ligaments restrain the muscle in a groove on the humerus bone to near the elbow bend. This makes the angle ß steeper than assumed in Fig. 4.2. Furthermore, the biceps muscle has two heads, which split along the upper part of the humerus and attach in different locations to the shoulder blade. Moreover, the brachialis muscle helps in flexing the elbow; it originates at about half the length of the humerus on its anterior side and inserts on the ulna. In some arm positions, the brachioradialis muscle, connecting radius and ulna, can also contribute to elbow flexion.

Figure 4.3 illustrates the elbow flexor conditions more realistically than before. M is again the contractile force vector of the biceps, (90°–ß) is its pull angle with respect to the long axis of the forearm, and P = M cosß its torque-generating force about the elbow joint at the lever arm m. A similar analysis for the brachialis force vector N shows its component force Q perpendicular to the lever arm n. Angle γ (which changes with the elbow angle α) is the difference between the directions of N and Q, hence Q = N cosγ. Taking into account the external torque T = *s* × S as well (assuming a right angle between force S and its lever arm *s*: if this were not the case, a vector analysis of S determines its angular components), the conditions for static equilibrium are as follows:

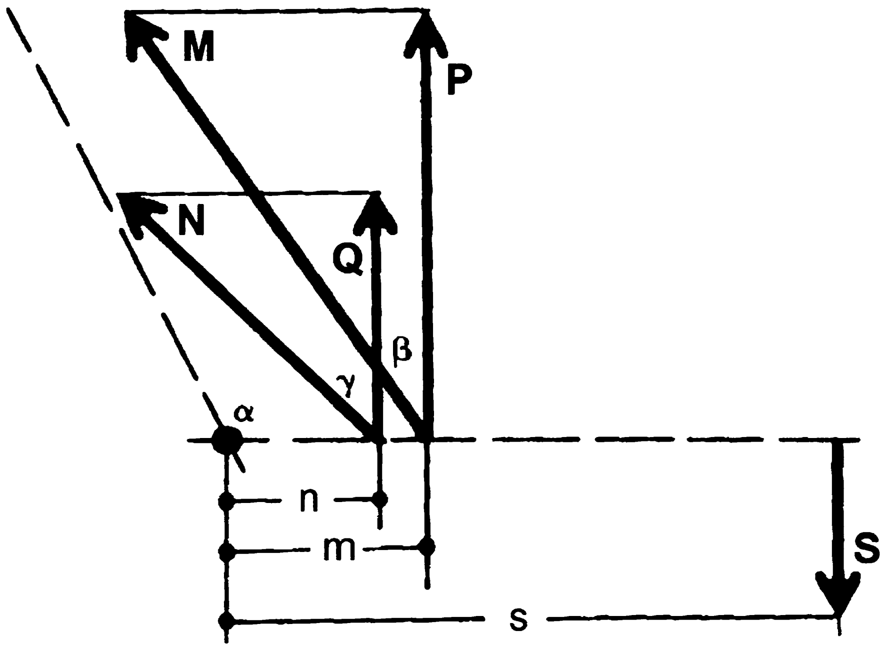

Fig. 4.3 Interactions between two muscles and an external force; gravity disregarded

There must be a horizontal joint reaction force H present to counteract the horizontal components of M (namely M sinß) and of N (N sinγ), which otherwise would push the forearm sideways. The insertion of a horizontal force H into Eq. (4.8) recognizes that need*. (Force H may be generated by shoulder muscles acting on the upper arm or by resting the elbow against a vertical surface.)

All forces in the horizontal direction sum to zero:

$$\mathrm{M}\ \sin\beta + \mathrm{N}\ \sin\gamma + \mathrm{H} = 0 \tag{4.8}$$

Insertion of a joint reaction force V into Eq. (4.9) prevents elevation or lowering of the forearm; this done, all forces in the vertical direction sum to zero:

$$\mathrm{P} + \mathrm{Q} - \mathrm{S} + \mathrm{V} = 0 \tag{4.9}$$

Inserting a joint-reaction torque T into Eq. (4.10) assures that the elbow angle α does not change. All torques about the elbow joint sum to zero:

$$m \times \mathrm{P} + n \times \mathrm{Q} - s \times \mathrm{S} + \mathrm{T} = 0 \tag{4.10}$$

If the last three equations are satisfied, then the forearm is at rest with respect to the upper arm.

This example illustrates the importance of properly considering all the forces and torques that act within and upon the system. A proximal boundary was established at the elbow joint for a "free body" analysis of the hand-forearm segment. It was necessary to introduce a reaction force H at the elbow boundary to provide horizontal restraint. Similar insertion of other joint reactions, vertical force V and torque T, assured static equilibrium.

The next step, a free-body analysis of the upper arm, proximally crosses the free-body boundary at the elbow. For this new analysis, the joint reaction forces H and V and the torque T are transferred (in their opposite directions) to the distal end of the upper arm's free-body diagram*. Then the analysis proceeds in similar fashion as done for the forearm-hand section.

This discussion shows that it is fairly easy to measure the resultant output of all concurring muscular forces – here the hand force S – but that overall output does not indicate which muscles contribute how much. Furthermore, muscles may be active which were not considered in the analysis. For instance, the triceps muscle also may be involved for control and regulation at the elbow; it would add to the torque generated by S and counteract the biceps and brachialis muscles, forcing them to increase their efforts. Obviously, the anthromechanical approach, as used here, calculates only "minimal net results": the smallest total of forces and moments needed to achieve the desired effect. The actual efforts of individual muscles may be much higher than the equations indicate, especially if antagonistic groups of muscles counteract each other.

Dynamic Analyses

Biomechanical analyses can identify physical efforts of everyday activities such as when lifting loads; they are useful for the evaluation of assist devices for walking (canes, crutches or walkers); they can determine the strains in body joints (data needed for the design of artificial joints) and the efficacy of external protective equipment such as back belts for use during lifting or of knee braces for support and protection during strenuous activities.

Traditional dynamic analyses follow the same approach as used in the static example above: Chose the analysis space; construct the appropriate free-body diagram; identify forces and torques crossing the free-body boundaries; solve the equations to determine the unknown values. However, dynamic equilibrium must incorporate the effects of changes in velocities (accelerations) as per Newton's 2nd Law. Accordingly, dynamic forces derive from "(mass) × (acceleration)" and dynamic moments from "(mass moment of inertia) × (angular acceleration)". With these embellishments, the equations for equilibrium Eqs. (4.1a) and (4.1b) remain valid. Yet, determining the mass properties of all components and their linear or rotational accelerations (such as centrifugal, tangential and Coriolis – all changing over time) can become daunting tasks. New computerized analyses can use efficient paradigms and procedures in anthromechanics*.

Anthropometric Inputs

Anthromechanics rely much on anthropometric data, often adapted and simplified to fit the mechanical approach. Figure 11.1 in Chap. 11 identifies the reference planes used originally in anthropometry and subsequently in anthromechanics: the medial (mid-sagittal) plane divides the body into right and left halves; the frontal (coronal) plane establishes anterior and posterior sections of the body; the transverse (horizontal) plane cuts the body in superior and inferior parts. Their common intersection establishes the origin of a xyz axis system. However, anatomy defines only the location of the medial plane while the frontal and transverse planes need to be fixed by consensus. When the human stands upright in the so-called anatomical position, convention is to assume that the three planes meet in the center of mass (CM) of the body, which is in the pelvic region. If the posture is different, one may decide either to retain the anatomical fixation of the coordinate system in the pelvic CM or to establish a new origin depending on the given conditions*.

Links and Joints

Simplifying the human skeletal system into a relatively small number of straight-line links (representing long bones) and joints (representing major articulations) can make treatment and computation simple. Figure 4.4 shows a typical link-joint system. In this example, hands and feet are not subdivided into their components, and the spinal column consists of only three links. Clearly, such simplification does not represent the true design of the human body-yet, depending on the desired application, it may suffice to stand in for certain mechanical properties.

Determination of the location of joint centers of rotation is relatively easy for simple articulations, such as the hinge-type joints in fingers, elbows, and knees. However, this is much more difficult for complex joints with several degrees of freedom, such as in the hip and, even more difficult, in the shoulder. Approximations may suffice: in Fig. 4.4, the shoulder joint consists of two articulations with an intermediate scapular link. In many cases, carefully simplifying location and properties of a joint can be adequate to meet modeling requirements; yet, it may be critical to consider that model joint characteristics may reflect the true body articulation only partially or merely within a limited range of motion.

Once joints are established, the straight-line distance between adjacent joint centers is the link length. Tables 4.1 and 4.2 list definitions of the joint centers and of the links connecting them. General estimates of links lengths for the 1985 US population appear in Table 4.3.

Unfortunately, anthropometric measurements do not run from joint to joint but usually between externally discernible landmarks, such as bony protrusions on the skeleton – see Chap. 11. Hence, one task in developing a model depicting the human body is to establish the numerical relationships between standard anthropometric measures and link lengths. Simply expressing segment lengths as proportions of

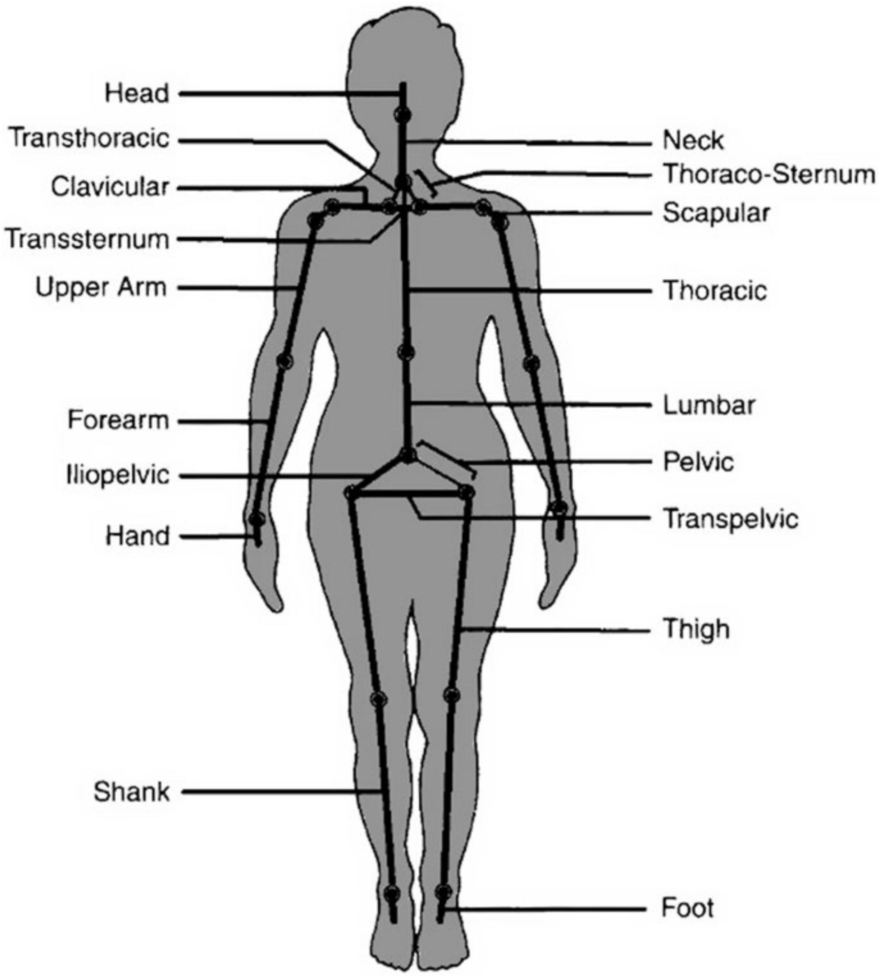

Fig. 4.4 Typical link-joint system (adapted from NASA/Webb, 1978)

stature (a procedure occasionally – and falsely – propagated) is usually not suitable: stature is highly related only to a few height measures but shows very low correlations with most measures of the human body (see the list of correlation coefficients in Table 11.4). However, if data on bone lengths are available, ratios or regression equations* allow calculation of link lengths, as listed in Tables 4.4 and 4.5.

Body Volumes

Measurement of whole body or of segment volume is often necessary for the calculation of inertial properties or for design of close-fitting garments. Use of the

Table 4.1 Definitions of joint centers (adapted from NASA/Webb, 1978)

Head and neck	
Head-neck	Midpoint of the interspace between the occipital condyle and first cervical vertebra
Neck-thorax	Midpoint of the interspace between the 7th cervical vertebra and the first thoracic vertebra
Trunk	
Thorax-lumbar	Midpoint of the interspace between the 12th cervical vertebra and the first lumbar vertebra
Lumbar-sacral	Midpoint of the interspace between the 5th lumbar vertebra and the first sacral vertebra
Leg	
Hip	The lateral point at the tip of the femoral trochanter 10 mm anterior to the most laterally projecting part
Knee	Midpoint of a line between the centers of the posterior convexities of the femoral condyles
Ankle	Level of a line between the tip of the; lateral malleolus of the fibula and a point 5 mm distal to the tibial malleolus
Arm	
Thoraco-sternal	Midpoint position of the palpable junction between the proximal end of the clavicle and the upper border (jugular notch) of the sternum
Clavi-scapular	Midpoint of a line between the coracoid tuberosity of the clavicle (at the posterior border of the bone) and the acromial-clavicular articulation (or the tubercle at the lateral end of the clavicle): the point should be visualized as on the underside of the clavicle
Gleno-humeral (Shoulders)	Midregion of the palpable bony mass of the head and tuberosities of the humerus; with the arm abducted about 45° relative to the vertebral margin of the scapula, a line approximately bisects the joint when dropped perpendicularly to the to the long axis of the arm from the outermost margin of the acromion
Elbow	Midpoint on a line between the lowest palpable point, the medial epicondyle, of the humerus, and a point 8 mm above the radiale (radio-humeral junction)

Archimedes principle provides the body volume: immersing the body in a container filled with water, then measuring the volume of the displaced water yields the volume of the immersed body. The technique works well for obtaining volumes of limbs and, if changes due to respiration can be controlled, of the whole body. The immersion technique works with living persons and cadavers; yet, the used segmentations differ, as Fig. 4.5 shows.

One of the indirect methods for obtaining volume is to assume that geometric forms can represent body segments. Sphere, cylinder, or truncated cone are shapes with easily calculated volumes. Another approach is to use information about the cross-section contours, which can be obtained by CAT scans or by dissection. If these cross-section contours are taken at sufficiently close separations so that the

Table 4.2 Definition of body links (adapted from NASA/Webb, 1978)

Head and neck	
Head	This straight line between the occipital condyle/C1 interspace center and the center of mass of the head
Neck	The straight line between the occipital condyle/C1 and C7/T1 vertebral interspace joint centers
Trunk	
Torso (total)	The straight-line distance from the occipital condyle/C1 interspace joint center to the midpoint of a line passing through the right and left hip joint centers
Thorax (sublinks)	• *Thoraco-sternum*: a closed linkage system composed of three links. The right and left transthoraxes are straight-line distances from the C7/T1 interpace to the right and left sterno-clavicular joint centers. The transsternum link is a straight-nine distance between the right and left sterno-clavicular joint centers • *Clavicular*: straight-nine distance between the right and left sterno-clavicular and the claviscapular joint centers • *Scapular*: straight line between the claviscapular and the gleno-humeral joint centers • *Thoracic*: The straight line between the C7/T1 and the T12/L1 vertebral interspace joint centers
Lumbar	The straight line between the T12/L1 and L5/S1 vertebral interspace joint centers
Pelvis	A linkage system composed of three links. The right and left ileo-pelvic links are straight lines between the L5/S1 interspace joint center and a hip joint center. The transpelvic link is a straight line between the right and left hip joint centers
Leg	
Thigh	The straight line between the hip and knee joint centers of rotation
Shank	The straight line between the knee and ankle joint centers of rotation
Foot	The straight line between the ankle joint center and the center of mass of the foot
Arm	
Upper arm	The straight line between the gleno-humeral and elbow joint centers of rotation
Forearm	The straight line between the elbow and wrist joint centers of rotation
Hand	The straight line between the wrist joint center of rotation and the center of mass of the hand

Table 4.3 Ratio (in %) of link length to bone length (adapted from NASA/Webb, 1978; Dempster, 1964)

Segment	Mean (%)	Standard deviation (%)
Thigh link/Femur length	93.3	0.9
Shank link/Tibia length	107.8	1.8
Upper arm link/Humerus length	89.4	1.6
Forearm link/Ulna length	98.7	2.7
Forearm link/Radius length	107.1	3.5

Table 4.4 Regression equations for estimating link lengths (in cm) from bone lengths (adapted from NASA/Webb, 1978; Dempster, 1964)

Empirical equation	Standard error of estimate	Correlation coefficient
Thigh link length = 132.8253 + 0.8172 tibia length	16.57	0.73
Thigh link length = 92.0397 + 0.8699 fibula length	10.34	0.87
Shank link length = 8.2184 + 1.0904 fibula length	5.95	0.97
Shank link length = 1.0776 tibia length	nda	nda
Arm link length = 66.2621 + 0.8665 ulna length	9.90	0.94
Arm link length = 58.0752 + 0.9646 radius length	8.92	0.94
Forearm link length = 1.0709 radius length	nda	nda
Forearm link length = 0.9870 ulna length	nda	nda

nda: no data available

Table 4.5 Estimated link lengths (in cm) for the 1985 US population (adapted from NASA/Webb, 1978)

	Female			Male		
	5th	50th	95th	5th	50th	95th
Thigh link	36.9	39.5	42.1	40.4	43.2	46.1
Shank link	34.7	37.4	40.0	38.9	42.1	45.3
Upper arm link	26.1	27.8	29.5	28.6	30.5	32.3
Forearm link (ulna)	22.7	24.1	25.5	25.6	27.1	28.7
Forearm link (radius)	22.7	24.1	25.5	25.9	27.5	29.2

changes between cross-sections can be assumed linear with distance, the volume V is the sum of the cross-section areas A_i multiplied with their distances d_i from each other:

$$\mathrm{V} = \sum (A_i \, d_i) \tag{4.11}$$

Often, the distance d between cross-section costs is kept constant and adjacent cross-sectional areas are averaged:

$$\bar{A}_i = \sum [(A_{i-1} + A_i)/2] \tag{4.12}$$

Other approximations rely on the assumption that the cross-sections resemble regular geometric figures. For example, if the body cross-section is elliptical, then its area results from

$$A_i = \pi a_i b_i \tag{4.13}$$

where a_i is the semimajor axis and b_i is the semiminor axis of a section i; Eq. (4.11) yields the volume.

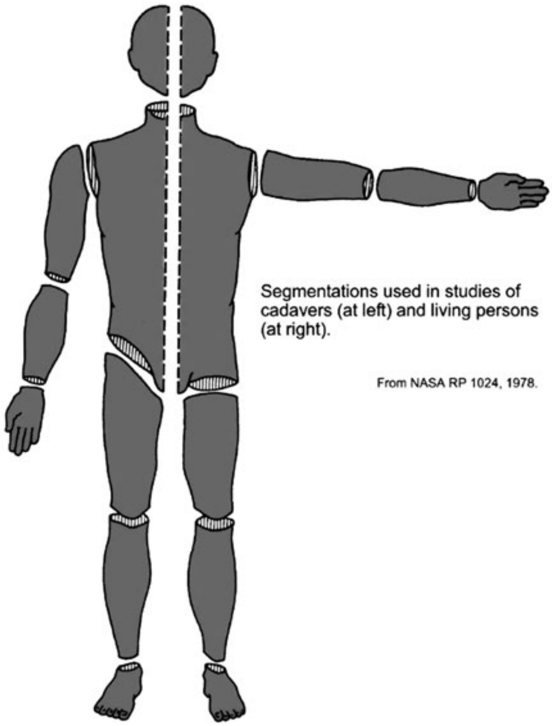

Fig. 4.5. Defining body segments on living persons and cadaver bodies

Inertial Properties

Knowledge of mass properties of the total body and its portions is important for establishing static and dynamic properties of the human body. Into the 1960s, measurements on cadavers provided basic benchmark data. More recent combinations of classic and 3D measurements taken on the body's surface, and of deep body scans (such as by x-rays and magnetic resonance imaging MRI) provided detailed information about mass distribution characteristics and the composition of the body's interior: presence and extent of adipose and of connective tissues, especially muscles, and of skeletal bone with the locations of body joints. Regression equations and other statistical predictors describe the volumes, masses and moments of inertia of the whole body and its segments, including composite volumes, centers of volume, intersegment cut centroids and principal inertial axes*. Computerized mathematical models serve to describe the geometry and the internal composition of the body, using information derived from tomography, magnetic resonance imaging, and dual energy x-ray absorptiometry*.

According to Newton's Second Law, weight W is a force depending on body mass m and the gravitational acceleration g, according to

$$W = m\ g \tag{4.14}$$

Weight is easily determined with a variety of scales; when measured in air, there is a slight error due to buoyancy. Table 4.6 lists equations to estimate body segment weight from total body weight W, based on cadaver measurements.

Density D is the mass per unit volume V:

$$D = W/(g\ V) \tag{4.15}$$

Mass is

$$m = D\ V \tag{4.16}$$

The specific density D_s is the ratio of D to the density of water, D_w

$$D_s = D/D_w \tag{4.17}$$

The human body is not homogeneous throughout; its density varies depending on tissue cavities, water content, fat tissue, bone components. Still, in many cases it is sufficient to assume that either the body segment in question or even the whole body is of constant (average) density.

Information about the relations of body segment weight to total body weight, compiled in Table 4.7, provides some insight into mass and density distributions.

Table 4.6 Prediction equations to estimate segment mass (in kg) from total body weight W (in kg) (adapted from NASA/Webb, 1978)

Segment	Empirical equation	Standard error of estimate	Correlation coefficient
Head	$0.0306W + 2.46$	0.43	0.626
Head and neck	$0.0534W + 2.33$	0.60	0.726
Neck	$0.0146W + 0.60$	0.21	0.666
Head, neck and torso	$0.5940W - 2.20$	2.01	0.949
Neck and torso	$0.5582W - 4.26$	1.72	0.959
Total arm	$0.0505W + 0.01$	0.35	0.829
Upper arm	$0.0274W - 0.01$	0.19	0.826
Forearm and hand	$0.0233W - 0.01$	0.20	0.762
Forearm	$0.0189W - 0.16$	0.15	0.783
Hand	$0.0055W + 0.07$	0.07	0.605
Total leg	$0.1582W + 0.05$	1.02	0.847
Thigh	$0.1159W - 1.02$	0.71	0.859
Shank and foot	$0.0452W + 0.82$	0.41	0.750
Shank	$0.0375W + 0.38$	0.33	0.763
Foot	$0.0069W + 0.47$	0.11	0.552

Table 4.7 Relative weights of body segments in % of body weight (adapted from NASA/Webb, 1978)

Groups of segments: total body weight (%)	Single segment: segment group (%)
Head and neck: 8.4	Head: 73.8 Neck: 26.2
Torso: 50.0	Thorax: 43.8 Lumbar: 29.4 Pelvis: 26.8
Total leg: 15.7	Thigh: 63.7 Shank: 27.4 Foot: 8.9
Total arm: 5.1	Upper arm: 54.9 Forearm: 33.3 Hand: 11.8

Detailed density data obtained from weight and volume measurements of dissected cadavers are in Tables 4.8 and 4.9. However, the use of cadaver material causes some problems, such as loss of fluids and chemical changes in tissue. Studies on living subjects relied on stereophotometry and used immersion and weighing techniques to determine density*.

Table 4.8 Segment mass ratios (in %) derived from cadaver studies (adapted from Roebuck et al., 1975)

	Harless (1860)	Braune and Fischer (1889)	Fischer (1906)	Dempster[1] (1955)	Clauser et al. (1969)	
Segment	2 specimen	3 specimen	1 specimen	8 specimen	13 specimen	Average
Head	7.6	7.0	8.8	8.1	7.3	7.8
Trunk	44.2	46.1	45.2	49.7	50.7	47.2
Total arm	5.7	6.2	5.4	5.0	4.9	5.4
Upper arm	3.2	3.3	2.8	2.8	2.6	2.9
Forearm and hand	2.6	2.9	2.6	2.2	2.3	2.5
Forearm	1.7	2.1	–	1.6	1.6	1.8
Hand	0.9	0.8	–	0.6	0.7	0.8
Total leg	18.4	17.2	17.6	16.1	16.1	17.1
Thigh	11.9	10.7	11.0	9.9	10.3	10.8
Shank and foot	6.6	6.5	6.6	6.1	5.8	6.3
Shank	4.6	4.8	4.5	4.6	4.3	4.6
Foot	2.0	1.7	2.1	1.4	1.5	1.7
Total Body[2]	100.0	100.0	100.0	100.0	100.0	100.0

[1]Dempster's values adjusted by Clauser et al. (1969).
[2]Calculated from head + trunk + 2 (total leg + total arm).

Table 4.9 Body densities from cadaver studies (adapted from McConville et al., 1980)

	Harless (1860)	Dempster[1] (1955)		Clauser et al. (1969)	
Segment	Mean	Mean	SD	Mean	SD
Head	–	–	–	1.071	–
Head + neck	11.1	11.1	0.012	–	–
Neck + torso	–	–	–	1.023	0.032
Thorax	–	0.92	0.056	–	–
Abdomino-pelvic	–	1.01	0.014	–	–
Torso + limbs	–	1.07	0.016	–	–
Thigh	1.07	1.05	0.008	1.045	
Lower leg	1.10	–	–	–	–
Shank	–	1.09	0.015	1.085	0.014
Foot	1.09	1.10	0.056	1.085	0.014
Total arm	–	1.07	0.027	1.058	0.025
Upper arm	1.08	–	–	–	–
Forearm	1.10	1.13	0.037	1.099	0.018
Hand	1.11	1.16	0.110	1.108	0.010
Total Body	–	–	–	1.042	0.018

[1]Dempster's values adjusted by Clauser et al. (1969).

Table 4.10 Locations of the centers of mass of body segments, measured (in %) from their proximal ends (adapted from Roebuck et al., 1975, based on data from Clauser et al., 1969)

	Harless (1860)	Braune and Fischer (1889)	Fischer (1906)	Dempster (1955)	Clauser et al. (1969)
Segment	2 specimen	3 specimen	1 specimen	8 specimen	13 specimen
Head[1]	36.2[1]	–	–	43.3[1]	46.6[1]
Trunk[nc]	44.88[nc]	–	–	–	38.0[nc]
Total arm	–	–	44.6	–	41.3
Upper arm	–	47.0%	45.0	43.6	51.3
Forearm and hand	–	47.2	46.2	67.7	62.6
Forearm[nc]	42.0[nc]	42.1[nc]	–	43.0[nc]	39.0[nc]
Hand[nc]	39.7[nc]	–	–	49.4[nc]	18.0[nc]
Total leg[nc]	–	–	41.2[nc]	43.3[nc]	38.2[nc]
Thigh[nc]	48.9[nc]	44.0[nc]	43.6[nc]	43.3[nc]	37.2[nc]
Shank and foot	–	52.4	53.7	43.7	47.5
Shank	43.3	42.0	43.3	43.3	37.1
Foot	44.4	44.4	–	42.9	44.9
Total body[2]	58.6[2]	–	–	–	58.8[2]

[1]Percent of head length, measured from the crown down.
[2]Percent of stature, measured from the floor up.
[nc]The values on these lines are not comparable because the investigators used differing definitions for segment lengths.

Lean Body Mass

Another useful concept to distinguish between the compositions of different bodies is that of the Lean Body Mass (or Lean Body Weight). The usual underlying assumption that basic structural body components such as skin, muscle and bone are relatively constant in percentage composition from individual to individual; yet, the fat component varies throughout the body and among different persons. Accordingly, total body weight W is

$$W = \text{lean body weight} + \text{fat weight} \tag{4.18}$$

There are several techniques to determine body fat. Many use skinfold measures: in selected areas of the body the fold thickness of loose skin is measured with a special caliper. Unfortunately, measurement of skinfold thickness is a rather difficult and not very reliable procedure since skinfolds may be grasped and compressed in different manners, they can slip from the instrument and the pressure applied by the instrument over its measuring surfaces might vary.

Locating the Center of Mass

For many computations, the body mass may be considered concentrated at one point in the body where its physical characteristics respond in the same way as if distributed throughout the body. This becomes particularly important for analyses of gait and other motions. The measurement of the location of the mass center of living persons is a bit complicated because respiration causes shifts in the mass distribution, as do muscular contractions, shifting body fluids, and food or fluid ingestion or excretion. Of course, there are major shifts in the location in the center of mass with different body positions and in particular with body movements.

For the body at rest, various methods exist to determine the location of the center of mass, CM. Most rely on the principle of finding the one location where a single support would keep the body balanced. Another simple technique is to place the body on a platform which is supported by two scales at precisely known support points. The two forces at the support points counteract the body weight. Figure 4.6 shows this procedure and the calculations proceed as follows:

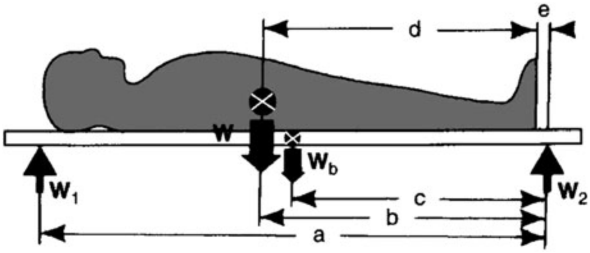

Fig. 4.6 Finding the center of mass of the body placed on a known board and on two scales

The sum of the vertical components of force and the sum of the moments about W_2 are both zero, since the body is at rest:

$$W_1 - W - W_b + W_2 = 0 \tag{4.19}$$

$$a \times W_1 - b \times W - c \times W_b = 0 \tag{4.20}$$

W_1 is the force at scale 1; a is the distance between scales 1 and 2; W is the weight of the body at its center of mass CM; W_b is the weight of the board at its CM, and c its distance from W_2; d is the distance between the CM of the body and the soles of the feet, and e their distance from W_2.

Geometrically,

$$b = d + e. \tag{4.21}$$

Rearranging and inserting known force and distance values provide the value for the location of the center of mass, CM:

$$d = (a \times W_1 - c \times W_b)/(W_1 + W_2 - W_b) - e. \tag{4.22}$$

Note that the actual weight W of the subject does not appear in the equation for d.

Table 4.10 contains the results of several studies to determine mass center locations; three of the studies took place well over a 100 years ago.

Moments of Inertia

To assess the mechanics of linear motions, information about the mass of involved body segments is necessary. For the modeling of rotations, one needs to know the moments of inertia.

Three approaches to determine the principal moments of inertia of the body and its segments are common. The first is to use geometric models whose selected shapes (often spheres or cylinders) represent the actual body form; their densities must be constant and known. The second approach to predict the principal moments of inertia is to use regression equations based on body weight, segment weight, or segment volume*. The third technique uses the mechanical construct of the "radius of gyration", K, expressed as a portion of segment (or link) length, L. This length L is multiplied by K, such as listed in Table 4.11. The resulting product is multiplied by the appropriate segment mass to obtain an estimate of the moment of inertia.

Kinematic Chain Models

Figure 4.7 shows a "stick" model of the human body build on and around a simplified skeleton consisting of straight links between adjacent joints.

Table 4.11 Radius of gyration K in % of segment length L. The principal axes are x, forward; y, to the right; and z, down (adapted from NASA/Webb, 1978)

Name	Link L	Axis	K (%)
Head	Head length	x	31.6
		y	30.9
		z	34.2
Torso	Torso length: trochanterion height to suprasternale height	x	43.0
		y	35.2
		z	20.8
Thigh	Fibular height to trochanterion height	x	27.9
		y	28.4
		z	12.2
Shank	Fibular height	x	28.2
		y	28.2
		z	7.6
Foot	Foot length	x	26.1
		y	24.9
		z	12.2
Upper arm	Radiale to acromion length	x	26.1
		y	25.4
		z	10.4
Forearm	Stylion to radiale length	x	29.6
		y	29.2
		z	10.8
Hand	Hand breadth	x	50.4
		y	45.6
		z	26.6

Forces exerted with the hand (H_x, H_y, or H_z) to an outside object or the torques generated in the hand (T_H) are transmitted along the links. First, the force exerted with the right hand, modified by the existing mechanical advantages, must be transmitted across the right elbow (E). (Also, at the elbow additional force or torque must be generated to support the mass of the forearm. However, for the moment, the model will be considered massless.) Similarly, the shoulder (S) must transmit the same efforts, again modified by existing mechanical conditions. In this manner, all subsequent joints transmit the effort exerted with the hands throughout the trunk, hips, and legs and finally from the foot to the floor. Here, one foot standing on a plane inclined by the angle α counteracts all the hand efforts. At this point, the orthogonal force and torque vectors can be separated again, similarly to the vector analysis at the hand. In a massless body, the same sum of vectors must exist at the feet as started at the hand.

Of course, the assumption of zero body mass is unrealistic. This can be rectified by incorporating information about mass properties of the human body segments, as detailed above. Body motions (accelerations), instead of the static posture assumed here, would further complicate the model. Moreover, considering only the efforts visible at the interfaces between the body and the environment disregards the fact

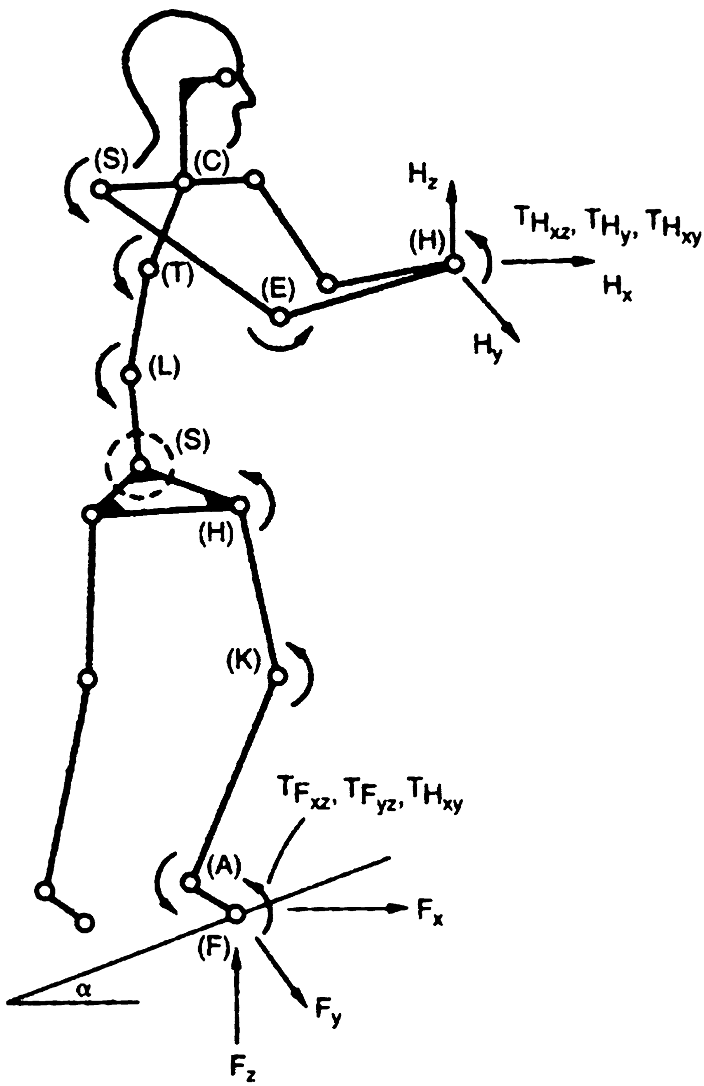

Fig. 4.7 Free-body diagram of the link-joint model of the human body, indicating the chain of forces (F) or torques (T) transmitted from the hand through arm, trunk and leg to the foot on the floor

that, at all body joints, antagonistic muscle groups exist which usually counteract each other for control and stabilization. Their possibly high individual efforts may nullify each other to the outside observer.

Nevertheless, for this simple model a set of equations allows its computational analysis. These equations follow from the standard procedure for a body at rest (a similar equilibrium example was discussed earlier in this chapter). Setting the sum of forces in all directions to zero, and likewise the sums of all torques, yields

$$\mathrm{H}_x + \mathrm{F}_x = 0 \tag{4.23}$$

$$\mathrm{H}_y + \mathrm{F}_y = 0 \tag{4.24}$$

$$\mathrm{H}_z + \mathrm{F}_z = 0 \tag{4.25}$$

$$\mathrm{T}_{\mathrm{H}xz} + \mathrm{T}_{\mathrm{F}x} = 0 \tag{4.26}$$

$$\mathrm{T}_{\mathrm{H}y} + \mathrm{T}_{\mathrm{F}yz} = 0 \tag{4.27}$$

$$\mathrm{T}_{\mathrm{H}x} + \mathrm{T}_{\mathrm{F}xy} = 0 \tag{4.28}$$

Such procedures are basic to even rather complex mechanical models of the human body*.

Notes

The text contains markers, *, to indicate specific references and comments, which follow.

Interactions between mass distribution and external impulses: See Kroemer et al. (1988) for more details.

Biomechanical research: King (1984), Chaffin and Andersson (1984), Marras and Radwin (2006), Chaffin (2008), Kumar (2008).

New computerized analyses can use efficient paradigms and procedures in anthromechanics. Reviews by Marras and Radwin (2006) and by Chaffin (2008) describe the state of the science in the early 2000s.

Unit for force measurement is the Newton (N): Some older tables of forces use the units “kg” or “kgf” or “kp,” or “lb” or “lbf”; they all can be translated into Newton because the kilogram-“force”-unit equals 9.81 N; the pound-“force”-unit converts to 4.44 N.

Joint reaction force: It is routine to insert joint reactions initially into free-body analysis equations; experimental measurements, model assumptions or mathematically solving the equations will make it clear whether these joint forces or torques actually exist.

Free-body diagram: At the boundaries, a free body diagram must account for all forces and moments by which the body interacts with connected bodies and the environment, such as gravity: see mechanics texts for details of that procedure; Oezkaya and Nordin (1999), Chaffin et al. (2006) present worked examples.

Center of mass of the body: See Roebuck et al. (1975), NASA/Webb (1978), Roebuck (1995).

Calculation of link lengths: Chaffin et al. (2006) discuss other means to estimate length links and the location of joint centers in relation to surface landmarks.

Regression equations and other statistical predictors describe the volumes, masses and moments of inertia: Harless (1860), Braune and Fischer (1889), Fischer (1906), Dempster (1955), Clauser et al. (1969), Chandler et al. (1975), Herron et al. (1976), McConville et al. (1980), Young et al. (1983), Kaleps et al. (1984), Zehner (1984) provide historically interesting reviews and data sets. Hay (1973), NASA (1989), NASA/Webb (1978), Roebuck et al. (1975), Chaffin and Andersson (1984) and Roebuck (1995) compiled data. Kroemer (2008) published a summary.

Summary

Biomechanical modeling of the human body, or of its parts, in general requires simplification of actual (physiologic, anatomic, anthropometric) characteristics to fit the methods and techniques derived from mechanics. While this establishes limitations regarding the completeness, reliability, and validity of the anthromechanical procedures, it also allows research and conclusions with unique insights which would not have been possible if using traditional (physiologic, anatomic, anthropometric) approaches. However, one has to be keenly aware of the limitations imposed by the underlying simplifications.

An important application of biomechanics is in the calculation of torques or forces that can be developed by muscles about body joints. In reversing this procedure, one can assess the strain on muscles, bones, and tissues generated by external loads on the body in various positions.

Body segment dimensions, their volumes and mass properties can be calculated from anthropometric data.

Kinematic chain models of linked body segments allow the prediction of total-body capability (such as lifting) from the consideration of body segment capabilities.

A taxonomy for position and motion of the body exists which describes these both mathematically and verbally.

Although much information is at hand, anthromechanics is still a developing scientific and engineering field with a wide variety of focus points, research methods, and measurement techniques for producing new theoretical and practical results. While using the substantial data and knowledge *base that exist, the practicing engineer must studiously follow the progress reported in the scientific and engineering literature in order to stay abreast of developments so that the most appropriate information can be applied to the design and management of human/machine systems.*

Glossary

Acceleration Second time-derivative of displacement.

Action Activation of muscle. See contraction

Agonist The muscle performing an intended action – same as protagonist. See also antagonist

Antagonist The muscle opposing the action of an agonist.

Anthromechanics Biomechanics (see there) applied to the human.

Biomechanics The study of the mechanics of a living body, especially of the forces exerted by muscles and gravity on the skeletal structure; also, the mechanics of a part or function of a living body such as of the heart or of locomotion.

Co-contraction Simultaneous contraction of two or more muscles.

Concentric (muscle effort) Shortening of a muscle against a resistance.

Contraction Literally, "pulling together" the z lines delineating the length of a sarcomere, caused by the sliding action of actin and myosin filaments. Contraction develops muscle tension only if the shortening is resisted. (note that during an isometric "contraction" no change in sarcomere length occurs and that in an eccentric "contraction" the sarcomere is actually lengthened. To avoid such contradiction in terms, it is often better to use the terms activation, effort, or exertion.)

Displacement Distance moved (in a given time).

Distal Away from the center of the body.

Dynamics A subdivision of mechanics that deals with forces and bodies in motion.

Eccentric (muscle effort) Lengthening of a resisting muscle by external force.

Effort (of muscle) See contraction.

Energy (The capacity to do) work. Proper units are the joule (J) and calorie (c).

Ergonomics The application of scientific principles, methods and data drawn from a variety of disciplines to the design of engineered systems in which people play significant roles.

Exertion (of muscle) See contraction.

Force A vector that can accelerate a mass. As per newton's third law, the product of mass and acceleration; the proper unit is the Newton, with 1 N = 1 kg m/s^2. On earth, one kg applies a (weight) force of 9.81 N (1 lb exerts 4.44 N) to its support. Muscular force often is described as tension multiplied by transmitting cross-sectional area.

Free dynamic In this context, an experimental condition in which neither displacement and its time derivatives, nor force are manipulated as independent variables.

In situ In the original position/place.

In vivo Within the living organism/body.

Isoacceleration A condition in which the acceleration is kept constant.

Isoforce A condition in which the muscular force (tension) is constant, isokinetic. This term is equivalent to isotonic.

Isoinertial A condition in which muscle moves a constant mass.

Isojerk A condition in which the time derivative of acceleration, jerk, is kept constant.

Isokinetic A condition in which muscle tension (force) is kept constant. See isoforce and isotonic; compare with isokinematic

Isokinematic A condition in which the velocity of muscle shortening (or lengthening) is constant. (Depending on the given biomechanical conditions, this may or may not coincide with a constant angular speed of a body segment about its articulation.) Compare with isokinetic.

Isometric A condition in which the length of the muscle remains constant.

Isotonic A condition in which muscle tension (force) is kept constant – See isoforce. (In the past, this term occasionally was falsely applied to any condition other than isometric.)

Jerk Third time-derivative of displacement.

Kinematics A subdivision of dynamics that deals with the motions of bodies, but not the causing forces and torques.

Kinetics A subdivision of dynamics that deals with forces and torques applied to masses.

Lever arm One component of the formula for moment (or torque): m = force × lever arm.

Mechanical advantage In this context, the lever arm (moment arm, leverage) at which a muscle works around a bony articulation.

Mechanics The branch of physics that deals with forces applied to bodies and their ensuing motions.

Moment The product of force and the length of the (perpendicular) lever arm at which it acts. Physically the same as torque (See there).

Moment of inertia Measure (in kg·m^2) of the resistance of an object to change in its rotation rate. Also called mass moment of inertia, rotational inertia, angular mass.

Muscle force The product of tension within a muscle multiplied with the transmitting muscle cross-section.

Muscle strength The ability of a muscle to generate and transmit tension in the direction of its fibers. See also body strength.

Muscle tension The pull within a muscle expressed as force divided by transmitting cross-section.

"**Newton's Laws**": 1. Mass remains at uniform motion (which includes being at rest) until acted upon by unbalanced external forces. 2. Force is proportional to the acceleration of a mass. 3. Action is opposed by reaction.

Physics The science of matter or energy and their interactions.

Physiology The biological study of the functions of living organisms and their parts.

Power Work (done) per unit time.

Protagonist The muscle performing an intended action – same as agonist. See also antagonist

Proximal Toward the center of the body.

Repetition Performing the same activity more than once. (One repetition indicates two exertions.)

Statics A subdivision of mechanics that deals with bodies at rest.

Tension Force divided by the cross-sectional area through which it is transmitted.

Torque The product of force and the length of the (perpendicular) lever arm. Physically the same as moment (see there) but commonly used with twisting or turning.

Velocity First time-derivative of displacement.

Work The product (integral) of force and distance moved.

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Human Factors
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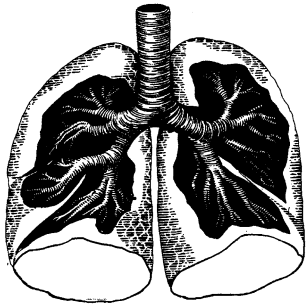
Chapter 5
Respiration



Overview

The respiratory system provides oxygen for energy metabolism and dissipates metabolic byproducts, especially carbon dioxide. In the lungs, oxygen is absorbed into the blood. Blood circulation transports oxygen (and nutrients) throughout the body, particularly to the working muscles. It removes metabolic byproducts either to the skin (where water and heat are dissipated) or to the lungs. There, carbon dioxide as well as water and heat are dispelled while more oxygen is absorbed.

The Model

The human respiratory system primarily is a two-way gas exchanger. Its main tasks are, first, to absorb oxygen from the inhaled air into the lungs and to dissipate that oxygen to circulating blood; second, to extract carbon dioxide from the blood and to dispel it into the air to be exhaled. Both functions, though in opposite directions, require diffusion of gas through the membranes that separate the air space within the lungs from blood in arteries and veins; they also require a pumping action of the lungs to generate air flow that fills and empties the lungs.

The ribcage contains the lungs. Muscles expand and then shrink the cage: this opens the lungs to incoming air and then pushes air out. The airways between lungs and throat and nose are not merely pathways but they also serve to condition the air inhaled from the human's surroundings.

Introduction

The respiratory system moves air into and out of the lungs. Here, part of the oxygen contained in the inhaled air is absorbed and transferred to the blood flowing in the pulmonary arteries. (Blood circulation is a topic of the following Chap. 6). The

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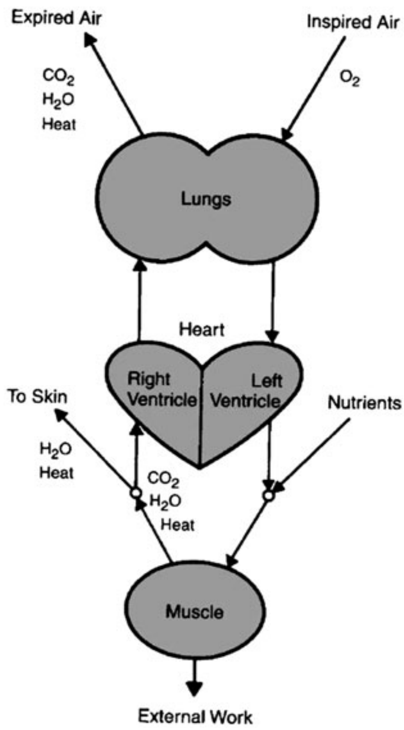

Fig. 5.1 The interrelated functions of the respiratory and circulatory systems

lungs also remove carbon dioxide, water, and heat (all byproducts of the metabolic processes, described in Chap. 7) from blood that arrives in the pulmonary veins and transfers them into the air to be exhaled. The absorption of oxygen and the expulsion of metabolites take place at sponge-like surfaces in the lungs. Obviously, there is close interaction between the respiratory system and the circulatory system which provides the transport of oxygen, carbon dioxide, water and heat – see Fig. 5.1.

Architecture

Figure 5.2 depicts the respiratory system. Air enters the body through the nose and mouth and passes through the throat (pharynx), voice box (larynx), and the windpipe (trachea) into the so-called bronchial tree, a series of two-way divisions. The first branching is into the left and right bronchus. In each lung, the airways branch repeatedly into ever smaller ducts, bronchi into bronchioles, until they terminate in the saclike alveoli of the lungs.

The adult respiratory tract has 23 successive paired branchings. The first sixteen branches merely conduct the air with little or no gas exchange. The next three branches are respiratory bronchioles (diameter of about 1 mm) with some gas exchange. The final four generations of branches form the alveolar ducts which

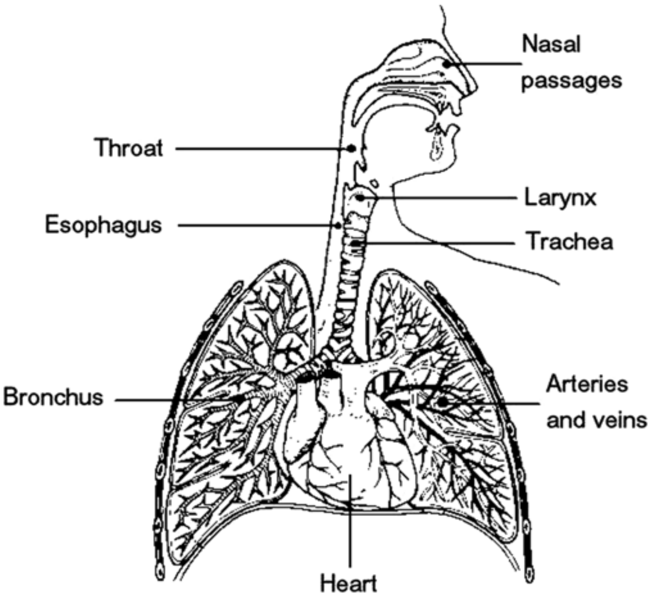

Fig. 5.2 Main structures of the respiratory system

terminate in the alveoli. These are small air sacs with diameters of about 400 μm with thin membranes between capillaries and other subcellular structures allowing the exchange of oxygen (O_2) and carbon dioxide (CO_2) between blood and air. Figure 5.3 shows the scheme of the respiratory tree. Altogether, between 200 and 600 million alveoli provide a grown person with 70–100 m^2 of exchange surface.

Air flow is the result of the pumping action of the thorax. The diaphragm, which separates the chest cavity from the abdomen, descends about 10 cm when the abdominal muscles relax (which brings about a protrusion of the abdomen). Furthermore, inspiratory muscles connecting the ribs contract and, by their anatomical and mechanical arrangements, raise the ribs. Hence, the dimensions of the rib cage and of its included thoracic cavity increase both towards the outside and in the direction of the abdomen: this sucks air into the lungs.

When the inspiratory muscles relax, elastic recoil in lung tissue, in the thoracic wall and the abdomen restores their resting positions without involvement of expiratory muscles: this expels air from the lungs. However, if heavy work creates ventilation needs above those at rest, the recoil effects are augmented by actions of the respiratory muscles. The internal intercostal and the abdominal muscles reduce the chest and lung cavity; the external intercostal muscles and downward movement of the diaphragm enlarge the thoracic cavity.

Thus, inspiratory and expiratory muscles are activated reciprocally, and both overcome the resistance provided by the elastic properties of the chest wall and of airways and pulmonary tissue. By far most of that resistance is in the airways because the air flow in the trachea and the main bronchi is turbulent, particularly

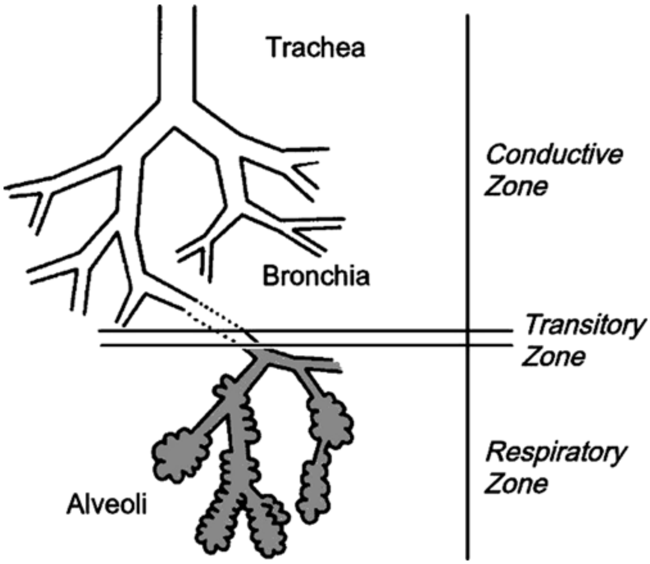

Fig. 5.3 Scheme of the respiratory tree

so at the high flow velocities required by heavy exercise. However, in the finest air tubes air flow is slow and laminar. Altogether, the energy required for breathing is relatively small, amounting to only about 2% of the total oxygen uptake of the body at rest and increasing to not more than 10% at heavy exercise.

Functions

The primary tasks of the respiratory system are to absorb oxygen from air and provide it to the body, and to dispel carbon dioxide, heat, and water; this *external respiration* is the topic of this chapter. Chapter 7 in this book deals with *internal respiration*, the utilization of oxygen and the production of carbon dioxide and other metabolites by the cells, hence also called *cellular* respiration.

The specific task of breathing is to move air into, through, and out of the lungs. This includes conditioning the inspired air: adjusting the temperature of the inward flowing air, moistening or drying it. The temperature regulation is so efficient that the inspired air is at about body core temperature, 37°C, when it reaches the end of the pharynx, whether inspiration is through the mouth or through the nose.

The passageways clean the incoming air from particles of foreign matter. Cleansing mostly takes place at mucus-covered surfaces of the nasal passages, which trap particles larger than about 10 μm in their small hairs and moist membranes. Smaller particles settle in the walls of the trachea, the bronchi, and the bronchioles. An occasional sneeze or cough (with air movements at approximately the speed of sound in the deeper parts of the respiratory system) helps to expel foreign particles. Thus, the deep lungs are kept nearly sterile.

In a normal climate, about 10% of the total heat loss of the body, whether at rest or work, occurs in the respiratory tract. This percentage increases to about 25% at outside temperatures of –30°C. In a cold environment, heating and humidifying the inspired air cools the mucosa; during expiration, some of the water condenses out of the warm humid air – hence the "runny nose" in the cold.

Respiratory Volumes

The volume of air exchanged in the lungs depends much on the activation of respiratory muscles. When they remain relaxed, there is of course still air left in the lungs; a forced maximal expiration reduces this volume of air in the lungs to the so-called *residual capacity*, see Fig. 5.4. A maximal inspiration adds the volume called *vital capacity*. Both volumes together are the *total lung capacity*. During rest or submaximal work, only the so-called *tidal volume* is moved, leaving both an inspiratory and an expiratory reserve volume within the vital capacity.

Dead volume, or dead space, is the volume – about 150 mL – of the conductive zone of the human airways where inhaled air does not come in contact with alveoli and, therefore, does not contribute to gas exchange. Accordingly, of a normal inspiration of 500 mL, only 350 mL reach the alveoli.

Vital capacity and other respiratory volumes are usually measured with a spirometer. The results depend on the age, training, sex, body size, and body position of the subject. Total lung volume for highly trained tall young males is between 7 and 8 L and their vital capacity up to 6 L. On average, women have lung volumes that are about 10% smaller than those of men. Untrained persons have volumes of about 60–80% of their athletic peers.

Pulmonary ventilation is the movement of gas in and out of the lungs. The pulmonary ventilation is calculated by multiplying the frequency of breathing by the expired tidal volume. This is called the (respiratory, expired) *minute volume*. At rest, one breathes around 12 times/min. In light exercise, primarily the tidal volume increases. With heavier work the respiratory frequency also quickly increases up to about 45 breaths/min. (Children breathe much faster at maximal effort; 5-year olds

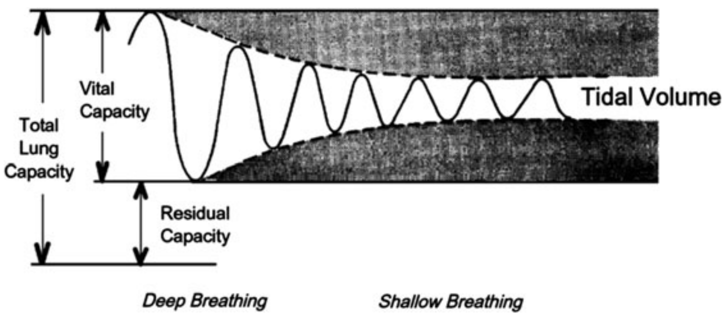

Fig. 5.4 Respiratory volumes

do so about 70 times/min, about 55 times/min at 12 years of age). This indicates that breathing frequency, which is easy to measure, is not a very reliable indicator of the demands of work performed.

Alveolar ventilation, the volume of fresh air that enters the alveoli each minute, is a suitable measure of an individual's respiratory effectiveness. If 350 mL normally reach the alveoli with each breath, the common alveolar ventilation is around 4.2 L/min with 12 breaths/min. In a maximal effort, alveolar ventilation can be as high as 100 L/min; at the opposite extreme, a person can stay alive with as little as 1.2 L/min.

Measurement Opportunities

Following the demands of work, the human respiratory system is able to increase its moved air volumes and absorbed oxygen by large multiples from those at rest. The minute volume can increase from about 5 to 100 L or more per minute; that is a boost by a factor of 20. Though not exactly linearly related to it, the oxygen consumption shows a similar increase.

Observing the changes in pulmonary functions allows assessing a person's strain while performing physical work: breathing rate, tidal volume and minute volume are of particular interest. Of these, breathing rate is easily recorded with a plethysmograph; the use of an air flow meter is feasible as well. Yet, in general these measurements provide less useful information than recordings of circulatory events (especially heart rate, see Chap. 6) and of metabolic functions (especially oxygen consumption, see Chap. 7).

Summary

The respiratory system moves air into and out of the lungs where oxygen contained in the inhaled air is absorbed and transferred to the blood flowing in the pulmonary arteries. The lungs also remove carbon dioxide from blood that arrives in the pulmonary veins and transfer it into the air to be exhaled.

Air entering the respiratory tree is conditioned so that gas exchange at the alveoli is facilitated: oxygen is absorbed into the blood, and carbon dioxide, heat, and water are dispelled into the air to be exhaled.

Normally, only a part (the tidal volume) of the available volume (vital capacity) of the respiratory passages is utilized for respiratory exchange.

At rest, the breathing frequency is less than 20/min. With light work, the frequency remains near resting level, but the tidal volume gets larger. In heavy work, both breathing rate and tidal volume increase.

In response to physically demanding work, the respiratory system can easily increase its moved air volume by a factor of 20 over resting conditions, accompanied by a similar increase in oxygen intake.

Glossary

Ergonomics The application of scientific principles, methods and data drawn from a variety of disciplines to the design of engineered systems in which people play significant roles.

Plethysmograph Instrument to record variations in the size of parts of the body, such as of the chest circumference with breathing.

Respiration The process of breathing, inhaling and exhaling, which moves air into and out of the lungs and provides oxygen for energy metabolism and dissipates metabolic byproducts, especially carbon dioxide. This chapter does not cover "internal" or "cellular respiration", the utilization of oxygen and the production of carbon dioxide and other metabolites by cells, which is discussed in Chap. 7.

Spirometer Instrument to measure the flow of air into and out of the lungs.

References and Further Reading

There is an abundance of books on human physiology and respiration, among them

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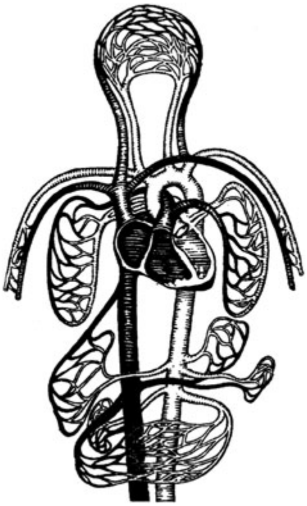
Chapter 6
Circulation



Overview

Two transport systems transfer materials between body cells and tissues: the blood circulation and the lymphatic circuit. They move nutritional materials from the digestive tract to cells for catabolism, synthesis, and deposit. The blood takes oxygen from the lungs to the consuming cells; it carries carbon dioxide to the lungs to be expelled, lactic acid to the liver and kidneys for processing, and it takes heated body fluid, water, to the skin and lungs for heat dissipation. The blood stream also is part of the body control system by carrying hormones from endocrine glands to receptive cells.

The Model

The human blood circulation is a closed loop with two fluid pumps in series: the right and left heart halves. After passing through a pump, the blood flows within ever branching and narrower arteries until it slowly moves through a delicate network of fine vessels in an organ. Here, as needed, oxygen, hormones and other materials are exchanged with the surrounding tissues; also, heat and other byproducts of metabolic processes are gathered or dispersed. This accomplished, the blood drains into small vessels which combine to a vein that ends in the atrium of the next half of the heart. The circulatory system of the blood, with the lymphatic system as an accessory, is able of adapting to serve many different target locations throughout the body, with often changing demands.

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Introduction

Blood circulation is essential for providing nutrients and oxygen to body organs, such as muscles; and to remove metabolic by-products. The flow is accomplished by the pumping heart, whose beat rate is often taken as the indicator of the work load of the total body. The lymphatic circuit, separate from the blood vessels, collects excess fluid from body tissues and returns it the blood; in this respect, the lymphatic system is an accessory to the blood flow system.

Body Fluids

Water is the largest weight component of the body: about 60% of body weight in men, about 50% in women. In slim individuals, the percentage of total water is higher than in obese persons since adipose tissue contains very little water. The relation between water and lean (fat-free) body mass is about 72% in healthy adults. Of the total body water (say, 40 L in an adult) about 70% (25 L) is intracellular fluid, within body cells. The other 30% (about 15 L) surround the cells: this extracellular fluid has an ionic composition similar to sea water. The concentrations of various electrolytes are different in the extra- and intra-cellular fluids. The cell membrane, which separates those two fluids, acts as a barrier for positively charged ions (cations).

Of the extracellular fluid, some is contained within blood vessels (intravascular) while the rest is between the blood vessels and the cell membrane (interstitial fluid); the cells "bathe" in interstitial fluid. Substance exchange between the intravascular and interstitial fluids takes place primarily through the walls of the capillaries; however, plasma and blood corpuscles cannot pass through these walls.

Blood

Approximately 10% of the total fluid volume of the human body consists of blood. The volume of blood is variable, however, depending on age, gender, and training. Volumes of 4 to 4.5 L of blood for women and 5 to 6 L for men are normal. About 2/3 of the total volume are usually located in the venous system, the other third is in the arterial vessels. When the body is at rest, the total volume of blood in the body circulates through it in about one minute.

Per gram, blood can carry 3.85 J (0.92 cal); this is called the specific heat of blood.

Blood consists of two portions: one is the fluid plasma, the other suspended cells, called formed elements. By volume, blood is half water and nearly as much, 45%, red cells. Plasma solids (chiefly proteins) constitute about 4% and 1% consists of white blood cell and platelets.

The red cell volume in the total blood volume is called hematocrit. Red cells, looking like donuts without holes, have a large surface to carry gases, especially oxygen and carbon dioxide. They are red because of the hemoglobin that they carry.

Some white cells (lymphocytes, monocytes) have their origin in lymph system tissues. Bone marrow produces blood cells (erythrocytes), white blood cells (leukocytes, granulocytes), and platelets (thrombocytes); about 300,000 cells and platelets are in 1 mm^3 of blood.

Loss of less than 10% of the total blood volume is not critical for a healthy person. If the loss approaches 20%, blood pressure diminishes and changes in pulse and breathing set in. At a blood loss of 40% or more death is imminent if blood and fluids are not infused.

Blood Groups

According to the content of certain antigens and antibodies, blood is classified into four groups: A, B, AB, 0. These classifications reflect incompatibility reactions in blood transfusions. However, there are other subdivisions: the one by the rhesus (Rh) factor can point to an obstetrical problem which may occur when a pregnant rhesus-negative woman carries the child of a rhesus-positive father.

Functions

The plasma carries dissolved materials to the cells, particularly oxygen and nutritive materials (monosaccharides, neutral fats, amino acids – see Chap. 7) as well as enzymes, salts, vitamins and hormones. It removes waste products, particularly dissolved carbon dioxide and heat.

The red blood cells perform the oxygen transport. Oxygen attaches to hemoglobin, an iron-containing protein molecule in the red blood cell. Each molecule of hemoglobin contains four atoms of iron which combine loosely and reversibly with four molecules of oxygen. Hemoglobin has a strong affinity to carbon monoxide, which takes up spaces otherwise filled by oxygen; this explains the high toxicity of CO.

Carbon dioxide molecules can bind to amino acids of the hemoglobin protein; since these are different binding sites, hemoglobin molecules can react simultaneously with oxygen and carbon dioxide.

Each gram of hemoglobin can combine with 1.34 mL of oxygen, at most. With 150 g hemoglobin per litre of blood, a fully O_2-saturated liter of blood can carry 0.20 L of oxygen. In addition, a small amount of oxygen, about 0.003 L, is dissolved in the plasma.

The Lymphatic System

The lymphatic system is separate from the blood vessels yet an accessory to the blood flow system. One of its tasks is to collect excess interstitial and extracelluar fluid from body tissues and carry it the blood system.

Endings of lymphatic capillaries exist in most tissue spaces, close to blood capillaries. The lymphatic capillaries are thin-walled and permeable so that even large particles and protein molecules can pass directly into them. Hence, the fluid in the lymphatic system is really an overflow from tissue spaces; lymph is much the same as interstitial fluid. The lymphatic capillaries have one–way flap valves to direct the flow toward larger ducts, called lymphatics. At intervals, they pass through lymph nodes: these filter out foreign materials including invading micro-organisms. Finally, lymphatics lead to the neck where they empty into the blood circulation at the juncture of the left internal jugular and left subclavian veins.

The flow of lymph within its tubing system depends on the interstitial fluid pressure: the higher the pressure, the larger the lymph flow. Another factor affecting lymph flow is the so-called lymphatic pump: excess lymph stretches the lymph vessel which then automatically contracts. This contraction pushes the lymph past its one-way valves. The contractions occur periodically, one at every 6 to 10 s. Motion of tissues surrounding the lymph vessels, such as by the contraction of skeletal muscle surrounding a vessel, can also pump lymph.

These lymph-pumping mechanisms generate a partial vacuum in the tissues so that they can collect excess fluid. Lymph flow is highly variable, on the average 1 to 2 mL/min; usually, enough to drain excess fluid and especially excess protein that otherwise would accumulate in the tissue spaces. Swelling of the feet and lower legs in the course of long sitting with little motion (for example, during long airplane rides) is a common example of the collection of fluids, particularly in the lymphatic system.

The Circulatory System of the Blood

Working muscles and other organs require generous blood flow to supply them with oxygen and nutrients, to remove metabolites, and for hormonal control. The blood consumers are located throughout the body, and their needs of supply often change. Hence, varying and huge demands are placed on the transport system, the circulatory system of the blood.

Architecture of the Circulatory System

It is convenient, and anatomically and functionally correct, to model the human blood circulation as a closed loop with two fluid pumps in series: the right and left heart halves. After passing a pump, the blood flows within ever branching and narrower arteries until it moves slowly through a delicate network of fine vessels, the “vascular bed” (see below) of an organ. Here, oxygen and other carried goods are exchanged with the surrounding tissues. This accomplished, the blood drains into small vessels that combine to form veins, ending in the atrium of the next half of the heart.

The left half of the heart powers the *systemic* subsystem. It carries oxygen-rich blood to the capillary beds, which transverse organs such as the skeletal muscles. There, it releases oxygen and energy carriers such as glucose and glycogen, while it picks up metabolic by-products, especially carbon dioxide, water and heat. The vascular bed drains into the venules of the *pulmonary* subsystem, powered by the right heart. After passing through that pump, the blood reaches the capillary beds of the lungs, where it releases metabolic byproducts and picks up oxygen, to be brought to the next consumer.

The total circulatory system consists of a large number of parallel or serial, often interconnected sections which supply individual organs. It interacts closely with the respiratory systems, as shown earlier in Fig. 1.1 of Chap. 5

The Heart as Pump

The heart is in essence a hollow muscle which produces, via contraction and with the aid of valves, blood flow through it. Each of the halves of the heart has an antechamber (atrium) which opens into the chamber (ventricle), the pump proper. The blood flows from the main vein into the atrium; it then moves through an open valve into the ventricle. Musculature surrounding the ventricle compresses it after its valves closed; this is the systole. When the internal pressure is equal to the pressure in the aorta, the exit valve opens so that the ventricle can expel the pressurized blood into the aorta, the main artery: the left side of the heart pushes blood into the systemic system, the right heart side into the pulmonary system. During the following diastole, the heart relaxes; then another systole follows. The events in the heart halves are similar, but the right sides generates only about 1/5 the pressure in the pulmonary arteries that the left heart produces in its systemic arteries.

The mechanisms for excitation and contraction of the heart muscle are similar to those of skeletal muscle; however, specialized cardiac cells (the sinoatrial nodes) in the atrium serve as “pacemakers” which do not need external nervous impulses to function. They determine the frequency of contractions by propagating stimuli to other cells in the ventricle, especially the Purkinje fibers, which make the ventricular muscles contract.

The heart’s own intrinsic control system operates, without external influences, at rest with (individually different) 50 to 70 beats/min. Changes in heart action stem from the central nervous system via the autonomic system (see Chap. 3). Stimulation to augment heart action comes through the sympathetic system, mostly by increasing the heart rate, the strength of cardiac contraction, and the blood flow through the coronary blood vessels supplying the heart muscle. The parasympathetic system causes a decrease of heart activities, particularly a reduced heart rate through weakened contraction of the atrial muscle, slowed conduction of impulses (lengthening the delay between atrial and ventricular contraction), and decreased blood flow through the coronary blood vessels. The parasympathetic system is dominant during rest periods. (The coordinated actions of the sympathetic and parasympathetic nervous systems are another example of control by two opposing systems such as exercised by the agonist/antagonist setup of skeletal muscle).

The electrokardiogram (EKG, also spelled electrocardiogram and abbreviated ECG) records myocardial action potentials. Letters mark certain events in the EKG: P names the wave associated with electrical stimulation of the atrium while the Q, R, S, and T waves identify ventricular events. The EKG mostly serves for clinical diagnoses; however, with appropriate apparatus it can be used for counting the heart rate. Figure 6.1 shows the electrical, pressure, and sound events during a contraction-relaxation cycle of the heart.

As already mentioned, the blood flow from the ventricle depends on the strength of contraction during systole: since the volume of blood cannot escape as fast from the aorta as the heart expels into it, continuing contraction of the heart increases blood pressure further. Part of the excess volume is kept in the aorta and its large branches which act as an elastic pressure vessel (German *windkessel*). After the aortic valve closes at the beginning of the relaxation (diastole) of the heart, the elastic properties of the aortic walls propel the stored blood into the ever branching arterial system where the elastic blood vessels smooth out the waves of blood volume. In the smallest branchings of the arterial tree, the blood flow is even and slow – see Fig. 6.2.

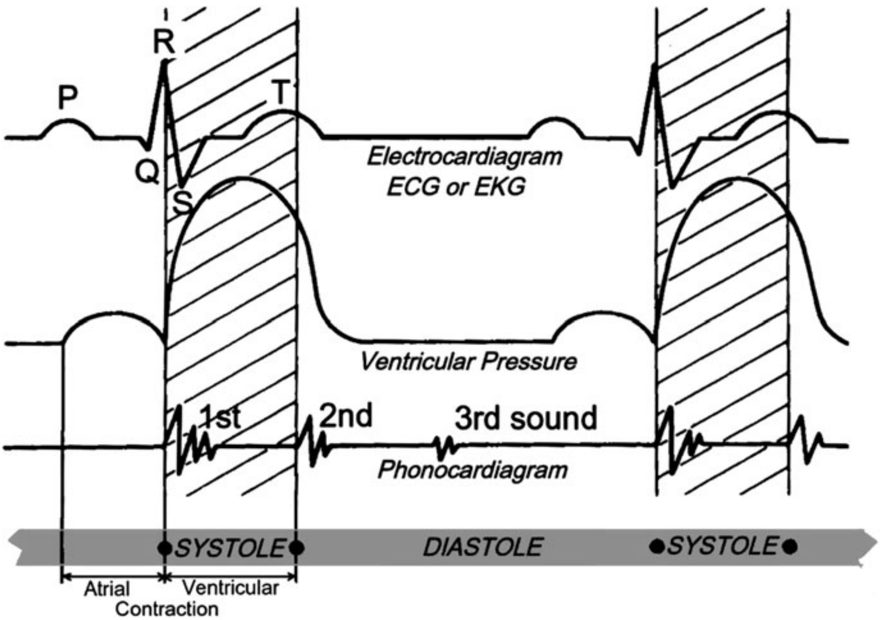

Fig. 6.1 Electrocardiogram, pressure fluctuation, and phonogram of the heart

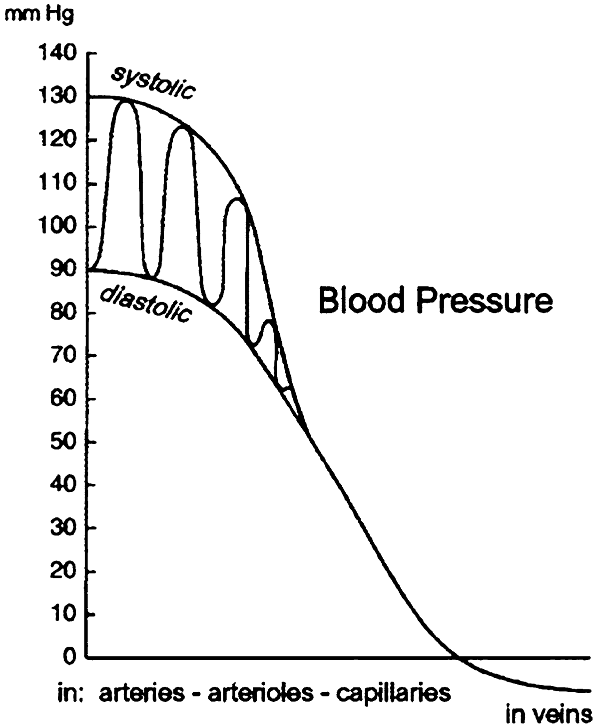

Fig. 6.2 Scheme of the smoothing and reduction of blood pressure along the circulatory pathways

At rest, about half the volume in the ventricle is ejected (stroke volume) while the other half remains in the heart (residual volume). Under exercise load, the heart ejects a larger portion of the contained volume. When the heart strains to supply much blood, such as during very strenuous physical work with small muscle groups or during maintained isometric contractions, the heart rate can become very high.

At a heart rate of 75 beats/min, the diastole takes less than 0.5 s and the systole just over 0.3 s. At a heart rate of 150 beats/min, the periods are close to 0.2 s each: an increase in heart rate occurs mainly by shortening the duration of the diastole.

Cardiac Output

The cardiac output mainly depends on two factors: the pressure generated by each contraction in the blood, and the frequency of contraction, the heart rate. Both determine the so-called (cardiac) minute volume. (The available blood volume in the body does not vary). The cardiac output of an adult at rest is around 5 L/min. When performing strenuous exercise, this volume can increase five-fold to about 25 L/min; a well-trained athlete may reach up to 35 L/min. Table 6.1 shows the needs of organs for blood supply at rest and during heavy exercise.

Table 6.1 Blood supply for organs during rest and work

Consumer	At rest[1] (%)	At heavy work[1] (%)
Muscle	15	75
Heart	5	5
Digestive tract	20	3
Liver	15	3
Kidneys	20	3
Skin	5	5
Bone	5	1
Fatty tissues	10	1
Brain	5	5

[1]Estimated cardiac output is about 5 L/min at rest, 25 L/min at heavy work

The ability of the heart to adjust its minute output volume to the requirements of the activity depends on two factors: on the effectiveness of the heart as a pump, and on the ease with which blood can flow through the circulatory system and return to the heart. A healthy heart can pump much more blood through the body than usually needed. Hence, an output limitation is more likely to lie in the transporting capability of the vascular portions of the circulatory system than in the heart itself. In the vascular system, the arterial section (before the metabolizing organ) has relatively strong elastic walls which act as a pressure vessel transmitting pressure waves far into the body, though with much loss of pressure along the way. At the arterioles of the consumer organ, the blood pressure is reduced to approximately one-third its value at the heart's aorta. Figure 6.2 shows the smoothing of pressure waves and reduction of pressure along the blood pathway schematically. As blood seeps through the consuming organ (such as a muscle) via capillaries, flow becomes slow and pressure drops. The pressure differential (positive on the arterial side, negative on the venous side) helps to maintain blood transport through the "capillary bed".

The Capillary Bed

The architectural patterns of the blood vessels that penetrate the tissues of the lungs or other organs in need of blood supply are quite similar – see Fig. 6.3. In the direction of the blood flow, the blood vessels branch so prolifically from arteries into arterioles into capillaries (altogether, there are about 10^9 capillaries in the human body) that their total available volume increases even as each cross-section area decreases. (An example: Oxygen enters the blood stream in the pulmonary capillaries with an operational area of about 90 m^2 and is delivered in the systemic capillaries through a surface more than double as large). This slows the blood flow in the so-called capillary bed; the slow movement allows diffusion through the large area of thin cell walls. On the exit side of the vascular bed, the small venules combine to form fewer but larger vessels, veins.

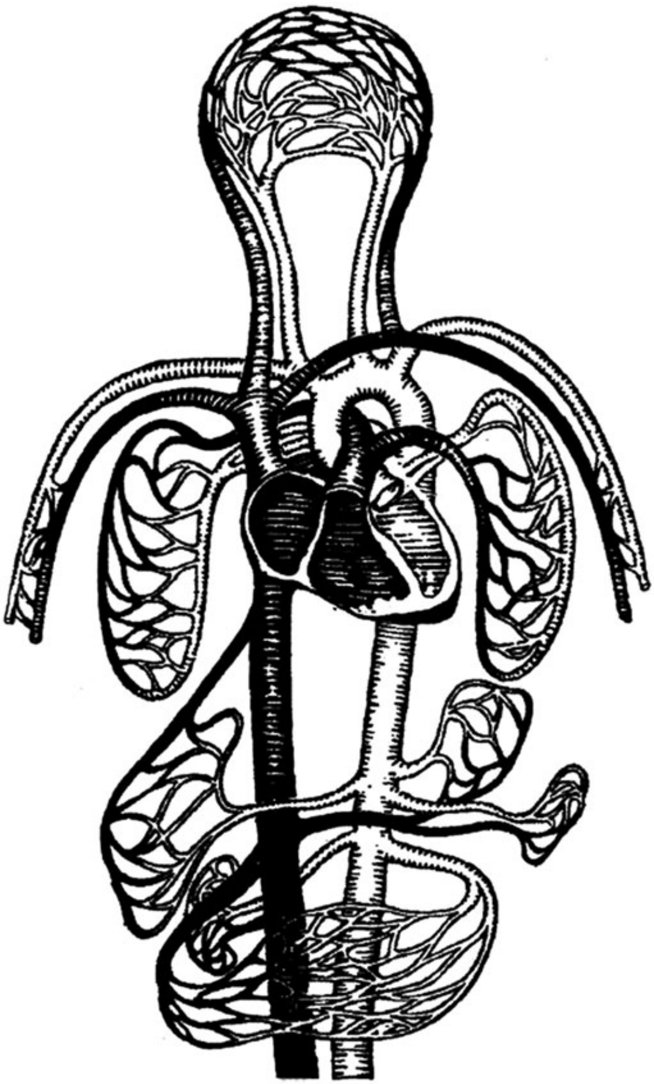

Fig. 6.3 Sketch of the circulatory system (adapted from Asimov, 1963)

The diagram of the capillary bed in Fig. 6.4 shows blood entering through the arteriole, which is surrounded by smooth muscles. These muscles control the opening (lumen) of the blood vessel by contracting or relaxing in response to stimuli from the sympathetic nervous system and to local accumulation of metabolites. The following metarteriole has fewer enclosing muscle fibers; other ring-like muscles, the pre-capillary sphincters control the entrance to the capillaries. The metarteriolic and the pre-capillary muscles primarily respond to local tissue conditions.

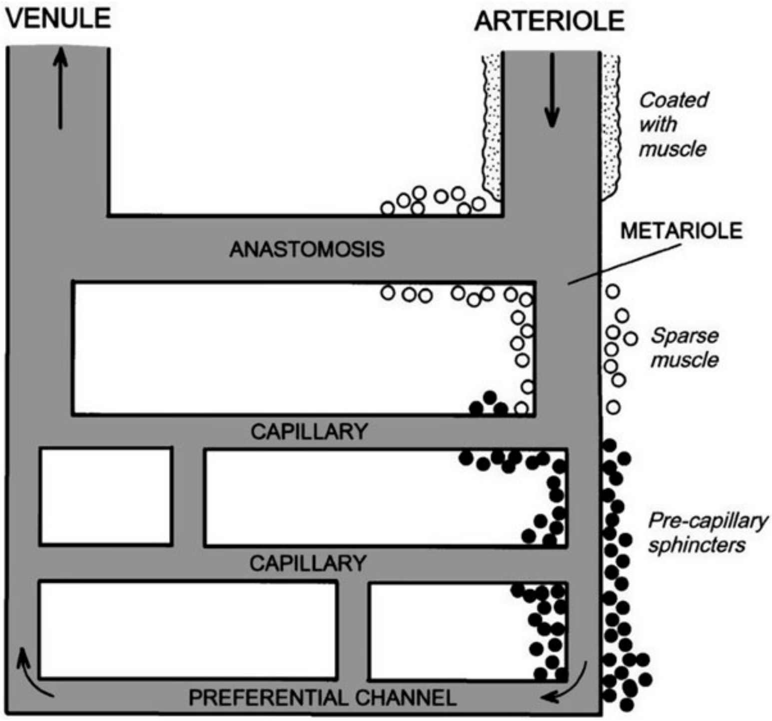

Fig. 6.4 Diagram of the capillary bed

Contraction or relaxation of the flow-controlling muscles change the flow resistance and hence the blood pressure. If lack of oxygen, or accumulation of metabolites, requires high blood flow, the muscles allow the pathways to remain open; blood may even use a shortcut, anastomosis, a shunt from arteriole to venule. Relatively large cross-sectional openings in the capillary bed reduce blood flow velocity and blood pressure, allowing nutrients and oxygen to enter the extracellular space of the tissue, and permitting the blood to accept metabolic byproducts from the tissue. (However, if contraction of striated muscle compresses the fine blood vessels, flow may be hindered or shut off. This is of particular consequence in sustained strong isometric contraction – see Chap. 2). Constriction of the capillary bed reduces local blood flow so that other organs in more need of blood may receive more of it.

The venous portion of the systemic system has a large lumen with little flow resistance; only about one-tenth of the total loss in blood pressure occurs here. (This low pressure system may be called a *capacitance* system in contrast to the arterial *resistance* system). Valves are built into the venous system, allowing blood flow only toward the right ventricle.

The pulmonary circulation is designed similarly to the systemic circulation, but has less vessel constriction or shunting.

Hemodynamics

As in the physics of classical fluid dynamics, the important factors in the dynamics of the blood flow (hemodynamics) are the capacity of the pump (the heart) to do the work; the physical properties of the fluid (blood) to be pumped, particularly its viscosity ("internal friction"); and the properties of the transport pipes (blood vessels) in regard to the required flow rates (volume per unit time) and flow velocities.

The difference in internal pressure between the start and the end of the flow pathway is the main determiner of flow rate and flow velocity; it depends on the resistance to flow. They are related by the equation for the pressure gradient:

$$\Delta p = Q \times R \tag{6.1}$$

with p the pressure gradient $\Delta(p_{start} - p_{end})$, Q the flow rate, and R the peripheral resistance.

Since at any point in a fluid the pressure is equal in all directions, it can be measured as the pressure against the lateral walls of the containing vessel. Thus, the usual measure of "blood pressure" (commonly with a cuff around the left upper arm) reflects the lateral pressure, but the elastic properties of the containing blood vessel and other intervening tissues modify that reading.

The flow resistance of a blood vessel is quite different from the formula used for rigid manufactured pipes but still depends in essence on the diameter of the vessel, the length of the vessel, and on the viscosity of the blood. Blood viscosity is about 3 to 4 times greater than that of water, determined primarily by number, dimensions, and shapes of the blood cells, and is dependent on the protein content of the plasma; the more hematocrit, the higher the resistance to flow.

The flow of blood is often not streamlined (laminar) but turbulent. Turbulence occurs when the outer layers of the blood stream are in physical contact with the inner walls of the blood vessels and, therefore, move more slowly than the more central sections of the blood flow. Turbulence increases the energy loss within the moving fluid, therefore (at a given pressure gradient) the average flow is slower than in a laminar stream.

The static pressure in a column of fluid depends on the height of that column (Pascal's Law). However, the hydrostatic blood pressure in, for example, the feet of a standing person is not as large as expected from physics since the valves in the veins of the extremities modify the value: in a standing person, the arterial pressure in the feet may be only about 100 mmHg higher than in the head. Nevertheless, blood, water, and lymph in the lower extremities can pool there, particularly when one stands (or sits) still for a long enough time, swelling the volume of the lower extremities.

Blood Vessels

Of the blood vessels, the capillaries and to some extent also the post-capillary venules provide semi-permeable membranes to the surrounding tissue so that nutrients and gases can be exchanged. All other blood vessels, the arteries, arterioles and veins serve only as transport channels. The walls of these vessels consist (in different compositions) of elastic fibers, collagen fibers, and smooth muscles. The walls are thick in the big arteries and thin in the big veins. Blood flow at each point in these blood vessels is primarily determined by the pressure head of the blood wave and the diameter of the vessel at this point. Size and architecture of different vessels influence blood flow, blood distribution, and vascular resistance.

As already mentioned, the arteries serve as pressure tanks during the ejection of the blood from the heart. Their elastic tissues stretch under the systolic impact, store this energy and then release it during diastole, thus smoothing an intermittent flow to a more continuous stream. Still, the ejection of the blood from the left ventricle causes a pressure wave to travel along the blood vessels at speeds of 10 to 20 times the velocity of the blood in the aorta (which is about 0.5 m/s when the body is at rest). Since the pressure waves distort blood vessels even at some distance from the heart, such as in the fingers, measuring how frequently these pulses occur (such as with a plethysmographic instrument attached to a finger) reveals the heart rate. Far away from the heart, in the capillaries, venules and veins there is no appreciable pressure variation associated with the heart's systolic and diastolic phases.

The flow resistance in the large arteries and veins is small, since the diameter of these vessels is large, and the flow velocity is high. In contrast, the peripheral resistance in the arterioles, metarterioles, and capillaries is substantial; that causes a significant reduction in blood pressure, even though the velocity of the (turbulent) blood flow is still high. The diameter of the vessels, generally below 0.1 mm, can be further reduced by smooth muscle fibers that wrap around the vessel. Contraction of these muscles constricts the vessels, which recoil to their normal size when the muscle relaxes. Thus, contracting these smooth muscles around the blood vessels (and possibly the pressure generated by contraction of nearby striated muscle) can change the flow characteristics and achieve reduction or complete shut-off of circulation to organs where blood supply is not so urgent, hence allowing better supply to those organs in need of it. To avoid a decrease in arterial blood pressure, any increase in vessel diameter by vasodilation (opening blood vessels beyond their lumen at regular vasomotor tone) must be compensated by vessel constriction in other areas and/or by an increase in cardiac output.

The collecting venules have an external coating of connective tissue and smooth muscle rings, which is only intermittently spaced near the arterial bed but develops into a complete layer in their distal parts, toward the larger veins. Thus, alternately contracting and relaxing muscles act as a pump which moves venous blood towards the right heart because valves in the veins of extremities prevent backflow of the blood; this is of importance because the blood pressure in the veins is very low, near zero just before the heart.

The venous system usually carries about $^3/_4$ of the total blood volume while arteries contain about 20 and capillaries 5% of the blood volume.

Regulation of Circulation

If organs such as muscles need increased blood flow, flow regulation takes place primarily at two sites: at the heart and in the organ to be supplied.

The blood pressure in the aorta depends on cardiac output, on peripheral resistance, elasticity of the main arteries, viscosity of the blood, and on the blood volume. The local flow is mainly determined by the pressure head and the diameter of the vessel through which it passes. The smooth muscles encompassing the arterioles and veins continuously receive nerve impulses that keep the opening (lumen) of the vessels more or less constricted. This local vasomotor tone is controlled by vasoconstricting fibers driven from the medulla; alterations of the tone keep the systemic arterial blood pressure on a level suitable for the actual requirements of all vital organs. (Changes in heart function and in circulation are initiated at brain levels above the medullary centers, probably at the cerebral cortex).

If at a particular site metabolite concentrations rise above an acceptable level, this local condition directly causes nearby metarteriolic and sphincter muscles to relax, allowing more blood flow. When skeletal muscles work hard and therefore require more blood flow, signals from the motorcortex can activate vasodilation of precapillary vessels in the muscles and simultaneously trigger a vasoconstriction of the vessels supplying the abdominal organs. This leads to a remarkable and very quick redistribution of the blood supply favoring skeletal muscles over the digestive system – the so-called “muscles-over-digestion” principle.

However, even in heavy exercise the systemic blood flow is controlled in such a way that the arterial blood pressure provides adequate blood supply to brain, heart, and other vital organs. For this purpose, neural vasoconstrictive commands can override local dilatory control. For example, the temperature-regulating center in the hypothalamus can affect vasodilation in the skin if this is needed to maintain a suitable body temperature, even if this means a reduction of blood flow to the working muscles – the “skin-over-muscles” principle (see Chap. 8).

Thus, on the arterial side, circulation at the organ/consumer level is regulated both by local control and by impulses from the central nervous system, the latter having overriding power. Vasodilation in organs needing increased blood flow, together with vasoconstriction where blood is not so necessary, regulate local blood supply. At the same time, the heart increases its output by higher heart beat frequency and higher blood pressure.

At the venous side of circulation, constriction of veins, combined with pumping actions of dynamically working muscles and forced respiratory movements, facilitate return of blood to the heart. This makes increased cardiac output possible, because the heart cannot pump more blood than it receives.

Heart rate generally follows oxygen consumption and hence energy production of the dynamically working muscle in a linear fashion from moderate to heavy work (see the section on “indirect calorimetry” in Chap. 7). However, the heart rate at a given oxygen intake is higher when the work is performed with the arms than with the legs. This reflects the use of different muscles and muscle masses with different lever arms to perform the work. Smaller muscles doing the same external work as larger muscles experience more strain and require more oxygen.

Static (isometric) muscle contraction increases the heart rate, apparently because the body tries to bring blood to the tensed muscles. However, it is difficult to compare this effect in terms of efficiency (like in "beats per effort") with the increase in heart rate during dynamic efforts because, in the isometric contraction, a muscle does not "work" (in the physical sense: there is force but no displacement) whereas in the dynamic case, work is done.

Physical work done in a hot environment causes a higher heart rate than in moderate climate, as explained in Chap. 9. Finally, emotions, nervousness, apprehension, and fear can affect the heart rate especially at rest and during light work.

Measurement Opportunities

Given current technology, it is impractical to measure the changes in blood supply at the working muscle, although this would be of special interest because the local supply determines largely whether the muscle can perform its job. Yet, without using invasive techniques, available instrumentation makes it easy to assess functions of the heart, even when the person is at rest or work: heart (pulse) rate can be recorded by electrical and volume (pressure) changes and the sound can be heard easily even without a stethoscope. With heart beat frequency so closely related to body effort and its observation so convenient, measuring heart rate is a very important tool for medical and ergonomic purposes.

Summary

In the human body, two transport systems transfer materials between body cells and tissues: the blood and the lymphatic system. They move nutritional materials from the digestive tract to cells for catabolism, synthesis, and deposit; and they transport oxygen and metabolic byproducts.

The blood circulation system is a closed loop with two fluid pumps in series: the right and left heart halves. After passing through a pump, the blood flows within branching and narrowing arteries until it slowly moves through a delicate network of fine vessels in an organ. Here, as needed, oxygen and other materials as well as heat are exchanged with the surrounding tissues. This accomplished, the blood drains into small vessels that combine to a vein that ends in the atrium of the next half of the heart. The circulatory system of the blood, with the lymphatic system as an accessory, is able of adapting to serve many different target locations throughout the body, with often changing demands.

Blood plasma carries dissolved materials to the cells, particularly oxygen and nutritive materials as well as enzymes, salts, vitamins and hormones. It

removes waste products, particularly dissolved carbon dioxide and heat. The red blood cells perform the oxygen transport. Both oxygen and carbon dioxide attach to hemoglobin, an iron-containing protein molecule in the red blood cell.

Working muscles and other organs require generous blood flow to supply them with oxygen and nutrients, to remove metabolites, and for control through the hormonal system. These consumers are located throughout the body, and their supply needs change. Hence, very different and huge demands are placed on the transport system, the circulatory system of the blood.

Flow through the arterial and following venous subsystems is determined by the organs selected by the body for their need of blood and by local conditions of muscle contraction. The volume of blood pumped per minute is about 5 L at rest and can increase up to seven fold at strenuous work. This increase is brought about mostly by changes in heart rate and in blood pressure.

Heart rate (pulse rate) is the number of ventricular contractions per minute; it creates pressure waves in the arteries. Its range is usually 60 to 70 beats/min at rest and increases about three-fold at strenuous exercise.

Stroke volume is the volume of blood ejected from the left heart into the main artery during each ventricular contraction. It is usually 40 to 60 mL at rest and may increase three-fold with hard work.

Cardiac output, also called (cardiac) minute volume, equals stroke volume multiplied with heart rate. This volume of blood injected into the main artery per minute can increase five- to seven-fold over resting values.

Blood pressure (BP) is the internal pressure in the arteries near the heart; at rest it is about 70 mmHg during diastole and 120 during systole. These values may double with heavy exercise.

The flow in the circulatory system is accomplished by the pumping heart, whose beat rate is often taken as the indicator of the work load of the total body.

Glossary

Absorption Here, passing through cell walls.

Anastomosis A shunt (shortcut) from arteriole to venule.

Arteriole Terminal branch of an artery, especially a small artery joining a larger artery to a capillary.

Artery A muscular elastic tube that carries blood away from the heart.

Assimilation Transformation of digested nutriment into a part of the organism.

Blood groups Classification of blood (into four groups: A, B, AB, 0) according to the content of certain antigens and antibodies.

Blood pressure The internal pressure in the arteries near heart.

Cardiac minute volume Heart stroke volume multiplied with heart rate: the volume of blood injected into the main artery per minute.

Cardiac output Heart stroke volume multiplied with heart rate: the volume of blood injected into the main artery per minute.

Catabolism Metabolic breakdown of complex molecules into simpler ones, often with release of energy.

Diastole Relaxiation of the heart ventricle.

Diffusion Here, permeation of cell walls.

ECG Electrocardiogram, See there.

EKG Electrokardiogram, See there.

Electrocardiogram (ECG, also spelled electrocardiogram, EKG) The electrical events associated with the heart beat.

Electrokardiogram (EKG, also spelled electrocardiogram, ECG) The electrical events associated with the heart beat.

Erythrocytes Red blood cells.

Granulocytes White blood cells.

Heart rate (same as pulse rate) Number of ventricular contractions per minute.

Hematocrit The percentage of red cell volume in the total blood volume.

Hemoglobin An iron-containing protein molecule in the red blood cell.

Leukocytes White blood cells.

Lumen The open cross-section of a blood vessel.

Plasma (of blood) The fluid portion of blood.

Platelets Thrombocytes.

Plethysmograph Instrument to record variations in the size of parts of the body, such as of the finger circumference with blood pressure pulses.

Pressure Force per surface unit.

Pulmonary system The portion of the blood circulation supplied by the right side of the heart.

Pulse rate (same as heart rate) Number of ventricular contractions per minute.

Red blood cells Erythrocytes.

Sinoatrial nodes The natural "pacemakers" of the heart.

Specific heat The amount of heat required to raise the temperature of a mass unit by 1°; as compared to the amount of heat required to raise the temperature of a gram of water by 1°.

Stroke volume The volume of blood ejected from the heart into the main artery during each ventricular contraction.

Synthesis Formation of a compound from simpler compounds or elements.

Systemic system The portion of the blood circulation supplied by the left side of the heart.

Systole Compression of the heart ventricle.

Thrombocytes Platelets.

Vasoconstriction Reducing the lumen of a blood vessel below its lumen at regular vasomotor tone.

Vasodilation Opening of a blood vessel beyond its lumen at regular vasomotor tone. Must be compensated by vessel constriction.

Vein A large membranous tube that carries blood to the heart.

Venule A small vein joining a capillary to a larger vein.

Viscosity Resistance to flow, "internal friction" of a fluid.

White blood cells Leukocytes, granulocytes.

References and Further Reading

There is an abundance of books on human physiology and circulation, among them

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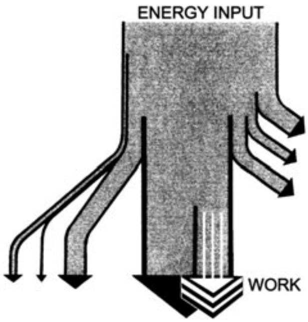
Chapter 7
Metabolism



Overview

Over time, the healthy human body maintains a balance between energy input and output. Nutrients determine the input from which the body's metabolic processes liberate chemically stored energy. By converting energy from that supply, the body keeps itself running, produces heat and physical work. Work is measured in terms of physical energy transmitted to objects outside the body.

The Model: The "Human Energy Machine"

The metabolism of the human body functions similarly to a gas/electric hybrid automobile: The "human motor" runs on energy drawn from an "ATP battery", which is continually re-charged by a generator powered by a metabolic "combustion engine".

In the cylinders of the automobile engine, an explosive combustion of a fuel–air mixture transforms chemically stored energy into physical kinetic energy. That energy moves the pistons of the engine, which drives a generator that charges the battery. The battery powers an electric motor which, through gears, turns the wheels of the car. Cooling the engine is necessary to prevent overheating; waste products need removal.

The "human motor" runs on the energy drawn from the breakdown of ATP to ADP. Continual rebuilding of ATP from ADP is necessary to keep the process running. This rebuilding needs energy, which derives from the "combustive" breakdown of glucose, glycogen and triglycerides in the presence of oxygen. In the "human machine" muscle fibers are both cylinders and pistons: bones and joints are the gears. The working muscles produce metabolic byproducts, including heat, which need removal.

K.H.E. Kroemer et al., *Engineering Physiology*, 4th ed.,
DOI 10.1007/978-3-642-12883-7_7, © Springer-Verlag Berlin Heidelberg 2010

Introduction

This chapter provides an overview of human metabolism, primarily as it concerns energy use by muscles. The text first covers the assimilation of chemical energy and then discusses the process of energy liberation to meet the requirements of physical work*.

Human Metabolism and Work

The first law of thermodynamics, the law of energy conservation, says that all real-world processes involve transformations of energy which conserve the total amount of energy. Since energy can neither be created nor destroyed, the energy consumed by an animal or human has a definite course, as sketched in Fig. 7.1. The digestive tract does not absorb all of the ingested food with its energy but lets a bit pass through and purges it as feces (F). In some animals, especially cattle, noteworthy quantities of energy may also be eliminated as methane. Furthermore, some byproducts of the metabolic processes in the body are energetically useless, such as urea and water, which get removed in the urine (U). Subtracting these losses from the initial consumption results in the assimilated (digested, absorbed) energy, the net energy input (I).

The body uses the net input energy (I) in different ways. First, some digested materials serve as building blocks (B) for synthesizing more complex components, especially during growth and as replacements cells. Secondly, some energy gets stored in cells for later use (S). Finally, there are secretions, such as saliva and sweat.

The largest portion of the energy input is used for respiration, the process of consuming oxygen and generating CO_2 and heat when the body performs a biochemical activity which requires energy. That energy becomes available from the breakage of

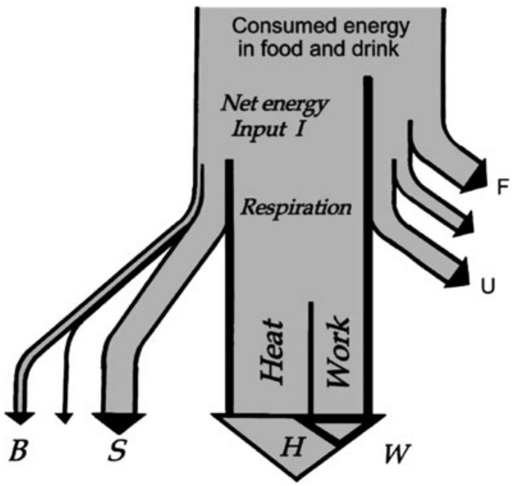


Fig. 7.1 Hypothetical flow of energy from intake to expenditure (adapted from Speakman, 1997)

bonds in the high-energy molecule ATP. The freed energy makes muscle contraction possible, such as in performing work (W) on an object outside the body.

In the human body, the balance between energy input I and outputs follows, somewhat simplified, this equation:

$$I = M = H + W + S. \tag{7.1}$$

M is the metabolic energy generated; it divides into the heat H (which the body must dispel to the outside), the work (or exercise) W performed, and the energy storage S in the body: positive if it increases, negative if it decreases.

The measuring units for energy (work) are Joules (J) or calories (cal) with 4.19 J = 1 cal. (Exactly: 1 J = 1 Nm = 0.2389 cal = 10^7 ergs = 0.948×10^{-3} BTU = 0.7376 ft lb.) Often one uses the metric kilojoule (1 kJ = 1,000 J) or the kilocalorie (1 Cal = 1 kcal = 1,000 cal) to measure the energy content of foodstuffs. The units for power are the Watt (1 W = 1 J/s) or the kcal/h (1 kcal/h = 1.163 W).

Assuming that there is no change in energy storage and that no net heat is gained from the environment or lost to it (see the following Chaps. 8 and 9 for details about actual heat exchanges), allows simplifying the energy balance equation to

$$I = H + W. \tag{7.2}$$

Human energy efficiency (work efficiency) is the ratio between work performed and energy input:

$$e\ (\text{in}\ \%\ ) = 100\,W/I = 100\,W/M. \tag{7.3}$$

In everyday activities, only about 5% or less of the energy input converts into work, which is the energy usefully transmitted to outside objects; highly trained athletes may attain, under favorable circumstances 25%, perhaps more*. Obviously, the body converts by far most of its energy input into heat, usually at the end of a long chain of internal metabolic processes.

Skeletal muscles (see Chap. 2) are able to convert chemical energy into physical energy – the following Chap. 8 discusses physical work. From resting, muscle can increase its energy generation up to 50-fold. Such enormous variation in metabolic rate not only requires quickly adapting supplies of energy and oxygen to the muscle but also generates large amounts of waste products (mostly heat, carbon dioxide and water) which need removal. Thus, while performing physical work, the body's ability to maintain an internal equilibrium (homeostasis) largely depends on coordinated functioning of the circulatory and respiratory systems to serve the involved muscles by supply of energy carriers and oxygen and by removal of wastes and heat. Figure 7.2 shows schematically the interactions among energy inputs, metabolism, and outputs.

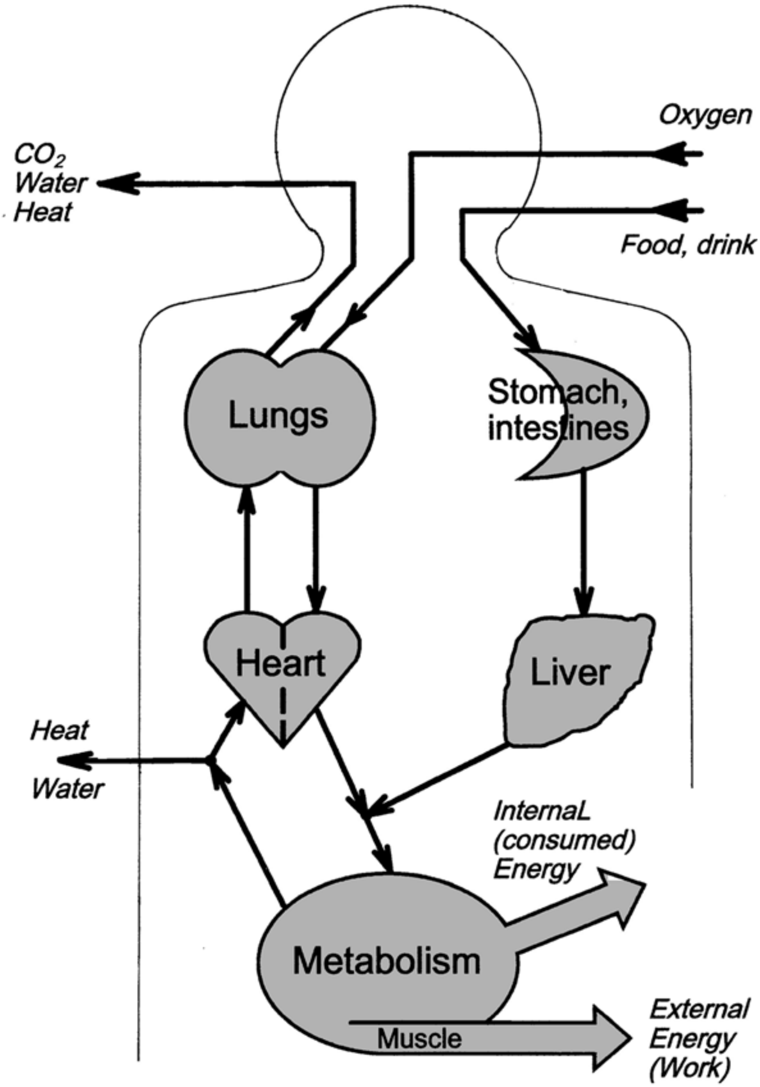


Fig. 7.2 Interactions among energy inputs, metabolism, and outputs of the human body

Energy Liberation in the Body

Food and drink, entering the body through the mouth, introduce their energy into the body. The main energy carriers are carbohydrates and fats, and possibly proteins. After passing through the stomach, the small intestines absorb the nutrients into blood and lymph. The following chemical conversion assimilates the absorbed nutrients for energy storage as tissue-building fat, and as glycogen or as glucose for imminent use. However, if cellular activity needs immediate supply, these chemical bonds are too slow in disbanding their energy. ATP, adenosine tri-phosphate, provides instantly and easily accessible energy while it degrades to ADP, adenosine di-phosphate. Yet, the energy supply in ATP lasts only for a short time; converting ADP into ATP rebuilds the energy store. The conversion of ADP into ATP requires energy which is taken from the body's main energy stores, glucose, glycogen and fats.

The chemically stored energy in ATP is released at the mitochondria of muscles; it enables muscular contractile work which generates kinetic (mechanical) energy.

Energetic Reactions

Energy transformation in living organisms involves particularly two chemical reactions:

- Anabolism, the formation of bonds, requires energy input: these reactions are called endergonic (or endothermic).
- Catabolism, the breakage of molecular bonds, liberates energy: such reactions are called exergonic (or exothermic).

Depending on the molecular combinations, bond breakages yield different amounts of released energies. Often, reactions do not go simply from the most complex to the most broken-down state, but progress in steps with intermediate and temporarily incomplete stages.

The Pathways of Digestion

Figure 7.3 shows the path of digestion in a schematic sketch. Energy enters the body through the mouth in food or drink (ingestion). Chewing breaks the food into small particles and saliva starts its chemical breakdown. Saliva in the mouth is 99.5% water and contains salt, enzymes and other chemicals including mucus. Mixing the food particles with saliva (mastication) makes them stick together in a size (bolus) convenient for swallowing and lubricates it for passage (deglutition) down to the stomach. The enzyme lysozyme destroys bacteria which otherwise would attack the mucous membranes and teeth.

During swallowing, breathing stops for a couple of seconds and the epiglottis closes so that the bolus does not get into the windpipe (trachea) but can slide down the gullet (esophagus). The slide takes up to 8 seconds for a bolus of formerly solid food but just about a single second for liquids.

Churning movements, 2 to 4/min, inside the stomach help the gastric juice to break up the bolus until it is fully liquefied (chyme). In the stomach, absorption quickly transfers alcohol into the bloodstream. The enzyme pepsin and hydrochloric

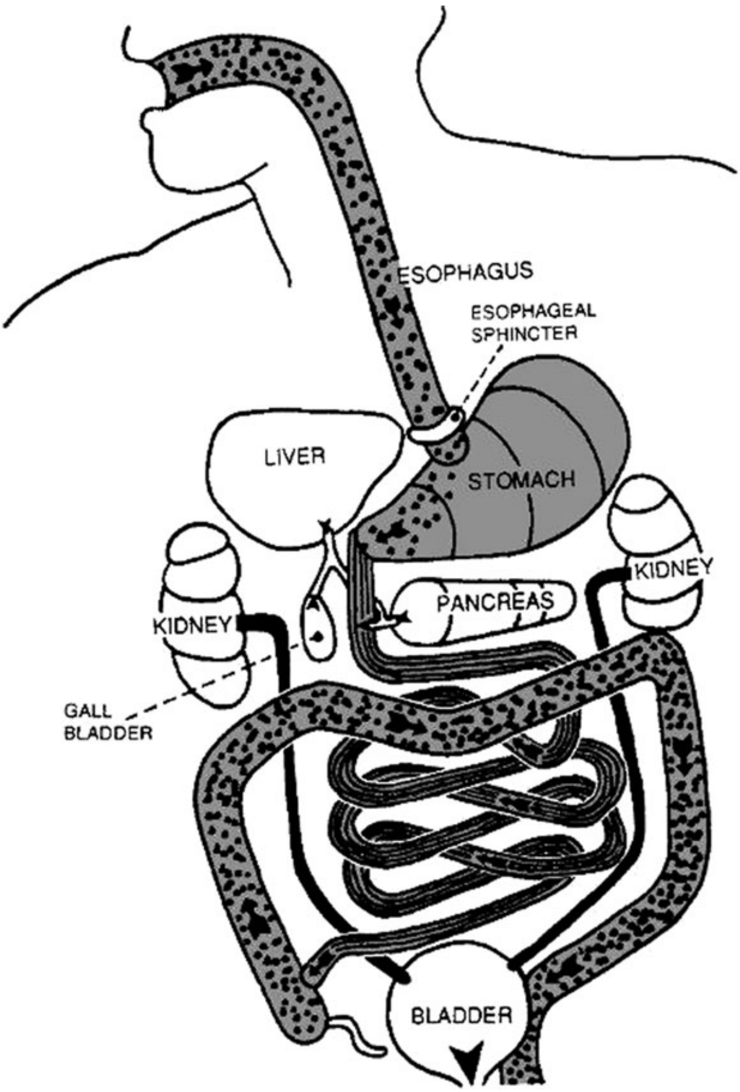


Fig. 7.3 The pathways of digestion

acid initiate digestion by breaking down proteins in the stomach, but there is little effect on the molecules of fats and carbohydrates. Fatty food stays in the stomach for up to 6 h; protein-rich materials pass through more quickly, while carbohydrates leave within 2 h.

Most of the chemical digestion of foods takes place in the duodenum, about the first 25 cm of the small intestine (which at 3 cm has a smaller diameter than the large intestine but at 7 m length is about five times longer). Circular muscles mix its content, while longitudinal muscles contract in waves and propel the content downstream. The inner surface of the small intestine has many finger-like projections (villi) which increase the contact area. The surfaces embed blood and lymph capillaries, which absorb digested foods. The pancreas adds digestive enzymes and hormones. The liver and gall bladder add bile, a salt-rich fluid that helps to emulsify and absorb fats. During the 3 to 5 h the foodstuffs stay in the small intestine, it extracts about 90% of all nutrients.

The final removal of nutrients takes place in the large intestine, which has a diameter of about 5 cm and a length of approximately 1.5 m. The first section, the cecum, mostly does chemical digestion; the following colon absorbs water and electrolytes. Again, circular muscles mix and longitudinal muscles of the intestine propel its content. Finally, the intestine shapes solid wastes and undigested food components into a soft paste (feces) for egestion (defecation). The blood transports nitrogenous wastes to the kidneys, which excrete them into the urine.

Thus, digestion begins in the stomach but mostly occurs in the small intestines. Digestion changes foodstuff chemically by breaking large complex molecules into components suitable to be transported through membranes of body cells and then absorbed. The large variety of chemical reactions that ensue on the digested and absorbed foodstuffs is called "assimilation": a re-assembly into molecules that either can be easily degraded to release their energy content, or stored as energy reserves, or used as raw materials for body growth and repair. All together, it takes 5 to 12 hours after eating to extract the nutrients and energy from food.

Energy Content of Nutrients

Our food consists of various mixtures of organic compounds (foodstuffs) and water, salts and minerals, vitamins and other items and of fibrous organic material (primarily cellulose). The fibrous roughage, or bulk, improves mechanical digestion by stretching the walls of the intestines but does not release energy.

A bomb calorimeter serves to measure the energy value of foodstuffs: it burns food material electrically so that it is completely reduced to carbon dioxide ($C0_2$), water (H_2O), and nitrogen oxides. The developed heat is the measure of the energy content*.

The basic foodstuffs are carbohydrates, fats, and proteins. Their nutritionally usable energy contents per gram are, on average:

- Carbohydrate, 18 kJ (4.2 kcal).
- Protein, 19 kJ (4.5 kcal).
- Fat, 40 kJ (9.5 kcal).
- Alcohol, 30 kJ (7 kcal).

The energy content of our daily food (and drink) depends on the mixture of the basic foodstuffs therein; examples are listed in Table 7.1. Protein oxidized in the

Table 7.1 Approximate energy content of foods and drinks

	kcal/100 g (kcal/100 mL)	kJ/100 g (kJ/100 mL)
Meat, poultry, fish		
Bacon, fried	585	2,440
Chicken, fried	265–285	110–1,190
Chicken, skinless, roasted	190	795
Halibut	170	710
Hamburger beef, cooked	265	1,100
Hot dog, beef	320	1,135
Red snapper	95	390
Roast beef, lean	170	700
Salmon	185	760
Shrimp	95	380
Steak, cooked	210	880
Tuna, canned in oil	210	880
Tuna, canned in water	110	460
Turkey, white meat	185	655
Bread	220–280	925–1,175
Butter	720	3,025
Honey	300	1,260
Jam	275	1,150
Olive oil	850	3,570
Sugar	385	1,610
“**Fast Foods**”		
French fries	300	1,255
Hamburger, “Deluxe, Double, Big Mac, Whopper” and the like	575	2,415
Hamburger, “Single”	260–300	1,090–1,160
Pizza, “Super, Supreme” and the like	390	1,650
Pizza, cheese, regular	230	970
Sandwich	215–330	900–1,380
Snacks		
Brownies	405	1,700
Candy, hard	390	1,630
Cookies, chocolate chip	460	1,925
Cookies, oatmeal with raisins	470	1,965
Cupcakes, chocolate icing	360	1,510
Peanuts, roasted	585	2,445
Potato chips	575	2,400
Pretzels	400	1,655
Beverages		
Beer, light	30–40	110–160
Beer, regular	40–50	170–190
Coffee	2	8
Hot chocolate, hot cacao	85	365
Juice, orange, apple	45	190

Table 7.1 (continued)

	kcal/100 g (kcal/100 mL)	kJ/100 g (kJ/100 mL)
Liquor, bourbon, scotch, gin, vodka and others,		
Alcohol 40 Vol% (80 proof)	225	980
45 Vol% (90 proof)	260	1,085
Milk, low fat	50	205
Milk, whole	65	265
Milkshake	130	545
"Soft drinks", Cola, Sprint, Fanta and others	40	170
Tea	0	0
Wine, red, white	80	325

1,000 cal = 1 kcal = 1 Cal
1,000 J = 1 kJ

body yields 19 kJ/g, which is only about 75% of the energy freed in the calorimeter: energy liberation from protein in the body is less efficient than the yield from fats and carbohydrates. However, that fact is not of great practical importance because the body prefers to use protein to build new body components rather than to burn it up for energy liberation.

The energy in our food exists essentially in the molecular bonds of carbon, hydrogen, and oxygen; and of nitrogen in proteins.

Carbohydrates come in small to rather large molecules; most consist of only the three chemical elements carbon, oxygen, and hydrogen. (The ratio of H to O usually is 2 to 1, just as in water: hence the name carbohydrate, meaning watered carbon). Carbohydrates exist as simple sugars (monosaccharides), double sugars (disaccharides) and in form of a large number of monosaccharides joined into chains (polysaccharides). The most common natural polysaccharides are plant starch, glycogen, and cellulose.

All carbohydrates are ultimately converted to glucose, a monosaccharide which the blood transports to all body tissues. Carbohydrate digestion starts by breaking the bonds between saccharides so that the compounds reduce to simple sugars. The monosaccharides produced in the digestion process are principally glucose (80%), fructose and galactose; the latter two eventually also convert to glucose. For storage, the body keeps it in form of glycogen in the liver and also in muscles. When needed, the glycogen in the liver is his converted to glucose and then transported to active tissues, where it is metabolized.

Fat is a triglyceride: a fat molecule of one glycerol nucleus joined to three fatty acid radicals. Unsaturated fat has double bonds between adjacent carbon atoms in one or more of the fatty acid chains; hence, the compound is not saturated with all the hydrogen atoms it could accommodate. Some of the available bonds are in fact not occupied by hydrogen atoms, but increase the number of linkages between carbon atoms themselves. The more unsaturated a fat is, the more it is a liquid, oil.

Most plant fats are polyunsaturated while most animal fats are saturated and hence solid. (A diet with a high content of saturated fat is medically suspect since it is linked with high blood pressure.)

Digestion of fat takes place in the small intestine; chemically, it is the breakage of bonds linking the glycerol residue to the three fatty acid residues. Glycerol and fatty acid molecules are small enough to cross cell membranes and hence can be absorbed. The bloodstream can transport only water-soluble materials such as glycerol. Many fatty acids are water repellent: these are absorbed into the lymph vessel system (see Chap. 6). Most fat is stored subcutaneously and in the viscera, and a small portion is stored within muscles.

Fats can provide a large portion of the energy during prolonged but moderately intense exercise. For cellular metabolism it must first be reduced from its complex triglyceride form to its basic components, glycerol and free fatty acids, FFAs. Only FFAs are used to form ATP.

Proteins are chains of amino acids joined together by peptide bonds. Many such different bonds exist, and thus proteins come in a large variety of types and sizes. Digestion, which occurs partially in the stomach but mostly in the small intestine, breaks the bonded protein into amino acids, which are then absorbed into the bloodstream. The blood carries them to the liver, which disperses cells throughout the body to be rebuilt into new proteins. Other amino acids become enzymes, organic catalysts that control chemical reactions between other molecules without being consumed themselves. Still other amino acids become hemoglobin, the oxygen carrier in the blood, or hormones, or collagen. Obviously, the body has many important uses for proteins, beyond using them as a source of energy.

Absorption and Assimilation

The stomach absorbs primarily water, salts, and certain drugs, among them alcohol; yet, as already mentioned, most of the absorption and assimilation of the other foodstuffs takes place in the small intestine. Here, digested foodstuffs enter the blood capillaries or, especially fatty acids, the lymphatic system. The blood capillaries drain eventually into the hepatic portal vein. This vein also receives inputs from the stomach, pancreas, gall bladder, and spleen. Lymph flows from the intestinal walls through the thoracic duct to the left subclavian vein. Here, the lymph enters the blood stream and becomes part of the blood plasma. The liver receives blood from the portal vein and also from the hepatic artery.

Liver cells remove digestion products from the blood and store or metabolize them. The liver also generates glycogen $(C_6H_{10}O_5)_x$, the storage form of carbohydrate, from glucose $(C_6H_{12}O_6)$. (Muscle mitochondra can do that as well.) The liver also synthesizes neutral fat (triglyrides) from glucose (hence, one can “get fat” without eating any), fatty acids, and possibly amino acids derived from proteins. Thus, the liver controls much of the fat utilization of the body. Fat serves as the body’s main energy storage.

Energy Release

After digestion, absorption and assimilation, the principal energy carriers are in the body in form of

- glucose and its storage form, the closely related glycogen,
- triglycerides (neutral fat), and
- amino acids in protein.

Of these, glucose is the most easily used energy carrier. Glucose is present at the mitochondria of muscles, more is easily available from the blood stream. Its catabolism can occur with the use of oxygen, aerobically; or without it, anaerobically.

Aerobic Metabolism of Glucose

Oxidation of glucose follows the stoichiometric formula:

$$C_6H_{12}O_6 + 6O_2 = 6CO_2 + 6H_2O + 37 \text{ (up to 39) ATP.} \tag{7.4}$$

This means that one molecule of glucose combines with six molecules of oxygen, imported to the process from the outside; this generates six molecules each of carbon dioxide and water, while energy (up to 2,891 kJ/mol, 39 ATP) is released. Note that equal volumes of water, carbohydrate and of oxygen take part in that conversion. Based on this fact, the measurement of the amounts of oxygen uptake and of water and carbohydrate produced allows the assessment of the actual energy use in the body, especially with respect to the Respiratory Quotient, discussed in the next chapter.

Chemically, oxidation is a loss of electrons from an atom or a molecule (conversely, reduction is a gain of electrons). In such reactions, electrons appear in the form of hydrogen atoms and the oxidized compound is de-hydrogenated. In human metabolism, organic fuels (glucose, fats, and occasionally amino acids) constitute the major electron donors, while oxygen is the final electron acceptor (oxidant) of the fuel.

Anaerobic Metabolism of Glucose

Another method of oxidation is breaking glucose and glycogen molecules into several fragments and letting these fragments oxidize each other. This means energy yield under "anaerobic" conditions, since no external oxygen is imported; the processes are called glycolysis and glycogenolysis, respectively (*lysis* means breakdown). Their energy yields are 2 mol of ATP per 1 mol of glucose but 3 mol of ATP for 1 mol of glycogen.

Glucose catabolism (and fat catabolism as well) takes place in sequential biochemical reactions, which produce intermediary metabolites. The first phase is anaerobic: the 6-carbon compound glucose breaks into two 3-carbon molecular fragments, each of which naturally becomes a 3-carbon compound pyruvic acid molecule. This can become lactic acid if not oxidized: lactic acid is a normal metabolic intermediate of some importance for "muscle fatigue", mentioned earlier in Chap. 3 and discussed in more detail in Chap. 8. This process releases some energy; in stoichiometric terms,

$$C_6H_{12}O_6 + 1\ \text{ATP} = 2\ \text{Lactic Acids} + 3\ \text{ATP}. \tag{7.5}$$

The second phase starts out to be anaerobic: pyruvic acid splits into carbon dioxide and hydrogen in a series of self-renewing reactions known as the Krebs cycle (also called citric acid cycle or tricarboxylic cycle) shown in Fig. 7.4. Here, hydrogen atoms separate in pairs from the intermediary metabolites, the first of which is pyruvic acid. (The removal of hydrogen atoms from the intermediary metabolites, called dehydrogenation, is particular to the Krebs cycle). As oxygen becomes available, hydrogen reacts with it to form water. Now, glucose completely metabolizes and produces six CO_2 molecules and six H_2O molecules, as per Eq. (7.4).

Metabolism of Carbohydrate

The oxidation of carbohydrates employs three processes: aerobic glycolysis, Krebs cycle, and electron transport chain, as shown in Fig. 7.4. The oxidation of carbohydrates generates 37–39 mol of ATP from 1 mol of muscle glycogen; if glucose is used, the maximal gain is 38 ATP moles.

Metabolism of Fat and Protein

The use of fat relies on lipolysis of its triglycerides (neutral fat) to free fatty acids: in turn, the FFAs become metabolized by the removal of hydrogen and associated electrons. Their oxidation yields 129 molecules of ATP per 1 mol of FFA. In this way, fat supplies a large amount of ATP energy.

Oxidation of amino acids, components of protein, is used only in emergency situations; so, metabolism of protein is usually negligible.

While fat accounts for most of the energy reserves in the body, already existing glucose and glycogen are the most easily and first used sources of energy at the cell level, both in the central nervous system and by muscles.

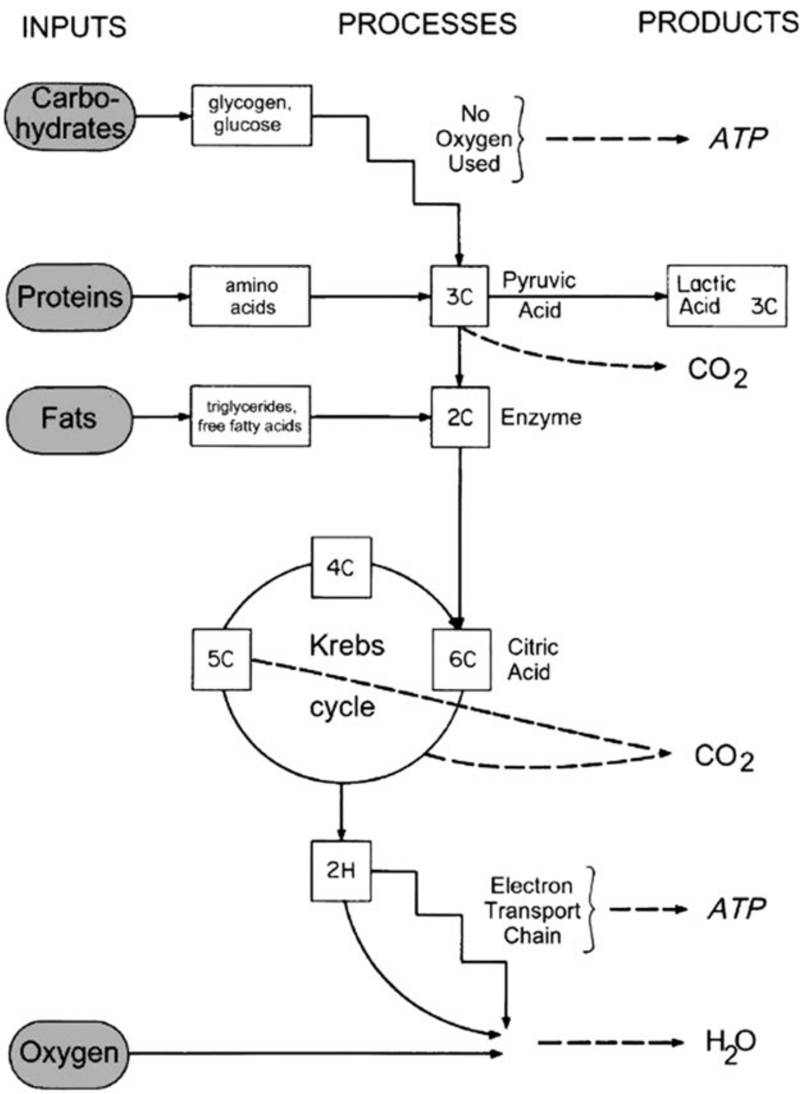


Fig. 7.4 Breakdown of foodstuffs, Krebs cycle. The number of carbon and hydrogen atoms is marked in the squares of each step

Energy Storage

Fat provides by far the most stored energy in the body. On average, in a young man, fat makes for about 16% of body weight, increasing to 22% by middle age and more if he "is fat". Young women average about 22% of body weight in form of fat, which usually rises to 34% or more by middle age. Athletes generally have lower percentages, about 15% in men and 20% in women. A (low) value of 15% fat in a 60 kg person results in 9 kg of body fat. Twenty-five percent of a 100 kg person, or 34% of a 75 kg person, mean approximately 25 kg of body fat. These values amount to energy storage in form of fat of about 360,000 kJ (85,500 Cal) in a skinny, lightweight person, and to more than 10^6 kJ (nearly 240,000 Cal) in a heavy person.

The energy yield of fat per volume is approximately 9,805 kJ/mol (2,340 kcal/mol), nearly 3.5 times that of the carbohydrate derivatives glucose and glycogen – but the conversion of fat to usable energy takes more time to get started.

Glycogen provides much less stored energy. Most humans have about 400 g of glycogen stored near the muscles, about 100 g in the liver, and some in the bloodstream. This means that only about 9,200 kJ (2,200 Cal) of energy are available from glycogen. About the same amount is present in the form of glucose.

Under normal circumstances, the body does not use protein amino acids for energy since their catabolism usually involves the death of cells, protein being part of the protoplasm of living cells. Catabolism of proteins does occur, however, in fasting, malnutrition, starvation, certain illnesses, and in all-out physical efforts.

Energy for Muscle Work

In muscle, the mitochondria cells store "quick-release" energy in form of the molecular compound adenosine triphosphate, ATP. This "intracellular vehicle of chemical energy" transfers its energy by donating its high-energy phosphate group to the process of muscle contraction, which requires energy.

Hydrolysis can break the ATP phosphate bonds easily and quickly to provide the energy for muscle contraction:

$$\text{ATP} + \text{H}_2\text{O} = \text{ADP} + \text{energy (released)}. \tag{7.5a}$$

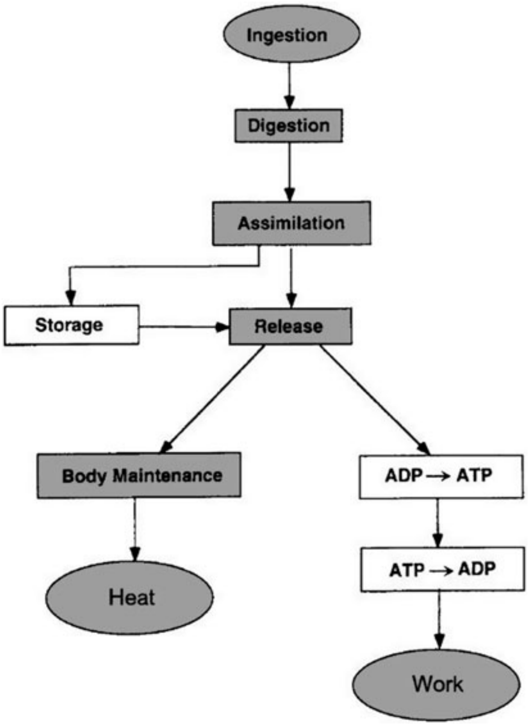
However, most energy demands consume the small available ATP supply rapidly; therefore, ATP needs to be replenished constantly. Creatine phosphate, CP, (also called PCr, for phosphocreatine) achieves this by transferring a phosphate molecule to adenosine diphosphate, ADP. However, this reaction requires energy:

$$\text{ADP} + \text{CP} + \text{energy (required input)} = \text{ATP} + \text{H}_2\text{O}. \tag{7.5b}$$

The cycle of converting ATP into ADP (releasing energy) and then re-converting ADP into ATP (requiring energy) is anaerobic. The ATP-ADP-ATP conversion acts immediately but is not fully efficient because the amount of energy gained during the breakdown is less than the energy required to re-build ATP from ADP.

Because ATP provides quick energy for only a few seconds, its resynthesis from ADP is necessary for continuous operation. The required energy derives from the breakdown of glucose, glycogen, fat, and possibly protein: breaking their complex molecules to simpler ones, ultimately to CO_2 and H_2O, provides the ultimate

Fig. 7.5 Schematic overview of the energy flow from ingestion via metabolism to output



energy source for the rebuilding of ATP from ADP. Figure 7.5 provides a schematic overview of the energy conversion from ingestion to output as heat or work.

Release of Energy During a Strong Muscular Effort

Muscle Twitch

As discussed in Chaps. 2 and 3, a nervous signal causes a muscle twitch contraction. A twitch consists of four periods, see Table 7.2: The *latent* period, typically lasting about 10 ms, shows no reaction yet of the muscle fiber to the motor neuron stimulus. *Shortening* takes place usually within 40 ms for a fast-twitch fiber. Released heat energy causes the cross-bridges between actin and myosin to undergo a thermal vibration, which creates in a kind of "ratchet" action causing the heads of the actin rods to slide towards each other along the myosin filaments. At the end of this period, the muscle element has reached its shortest length and usually developed tension. During the *relaxation* period, also commonly about 40 ms in a fast-twitch fiber, the bridges stop oscillating, the bonds between myosin and actin break, and the muscle is pulled back to its original length either by the action of antagonistic muscle or by an external load. During the *recovery* period, again taking about

Table 7.2 Energy metabolism in a single twitch of a fast-twitch fiber

Period, duration	Energy metabolism	Muscle action (see Chap. 2)
Latent, about 10 ms	None	No reaction yet of the muscle fiber to the motor neuron stimulus
Shortening, about 40 ms	Energy for this process is freed from the ATP complex, mostly anaerobically	Cross-bridges between actin and myosin vibrate and "ratchet" the heads of the actin rods towards each other along the myosin
Relaxation, about 40 ms	ATP is re-synthesized from ADP	Cross-bridges stop oscillating, bonds between myosin and actin break, the muscle returns to its original length
Recovery, about 40 ms	Aerobic metabolism oxidizes glucose and glycogen, final regeneration of ATP and phosphocreatine	None

40 ms, the metabolism of the muscle is aerobic, with glucose and stored glycogen being directly oxidized for the final regeneration of ATP and phosphocreatine.

The First Few Seconds of Muscular Effort

At the very beginning of intensive muscle work, breaking the phosphate bonds of ATP releases the "quick energy" for muscular contraction. However, the contracting muscle consumes its local supply of ATP in about two seconds.

The First Ten Seconds of Effort

The next source of immediate energy is creatine phosphate, CP. It transfers a phosphate molecule to the just created molecule of ADP and thus turns it back into ATP. Skeletal muscle contains enough CP to synthesize ATP for 8 to 12 seconds of intensive muscle activity.

Effort Longer than Ten Seconds

After about 10 seconds of ATP–ADP–ATP reactions, the CP supply is exhausted. However, the muscle can continue to do moderately high muscular work by producing ATP through glycolysis, the breakdown of glucose and, if not enough is available, of glycogen through glycogenolysis. The energy yield of these processes is 2 mol of ATP per 1 mol of glucose, 3 mol of ATP for 1 mol of glycogen.

Muscular Work Lasting Minutes to Hours

If the physical activity has to continue, it must be at a level where the oxygen supply suffices to keep the energy conversion processes going; hence, extended muscular work is necessarily at a lower level of energy than a quick burst of maximal effort can generate. In enduring work, the oxygen supply at the mitochondria must allow continual aerobic energy conversion. Without oxygen, a molecule of glucose yields three molecules of ATP; with oxygen, the glucose energy yield is 39 molecules of ATP.

When muscular work lasts from several minutes to hours, this provides time for pyruvate, a product of glycolysis or glycogenolysis, to enter the mitochondria. There, its conversion in the Krebs cycle produces additional energy for ATP resynthesis.

Fat is rich in energy. The use of fat relies on lipolysis of its triglycerides to free fatty acids: in turn, the FFAs become metabolized by the removal of hydrogen and associated electrons. Their oxidation yields 129 molecules of ATP per 1 mol of FFA. In this way, fat supplies a large amount of ATP energy. Use of fat for energy takes time to start, yet it is highly effective and entirely aerobic.

Oxidation of amino acids, components of protein, is used only in emergency situations; so, metabolism of protein is usually negligible.

Aerobic and Anaerobic Work

As just discussed, after the start of intense muscular effort, energy liberation can proceed without use of oxygen: during the initial 10 s, ATP and CP provide energy for very high performance; then, anaerobic glycolysis supplies energy for a few minutes of strenuous muscular work. However, for longer lasting work, even when of lower intensity, only aerobic energy conversion can provide the necessary energy.

In aerobic conditions, energy yield is so efficient that one can keep up fairly high energy expenditure as long as ATP is reformed as quickly as it is used up. The conversion of glucose and glycogen is simple, but the utilization of fats (glycerol and fatty acids) requires a more complex process: they convert to intermediary metabolites and enter the Krebs cycle. Their final energy yield is approximately 9,805 kJ/mol, more than threefold that from glucose.

Still, if very heavy expenditure is required over long time, such as in a marathon run, the interacting metabolic system and the oxygen-supplying circulatory system might become overtaxed. A runner who "hits the wall" most likely has used up the body's glycogen supply and also went into "oxygen debt" – more in the next Chap. 8.

However, in our every-day activities we regulate our energy output to match the body's ability to develop energy with a sufficient supply of oxygen. If needed, we simply take a break during which our body resynthesizes accumulated metabolic byproducts and returns the metabolic, circulatory and respiratory systems to their normal states.

Overall, work of a sustainable intensity is aerobic, even if many of the single intermediate steps in the metabolic reactions are in fact anaerobic. For example, glucose breakdown is first anaerobic, followed by an aerobic phase: oxygen is required

Table 7.3 Anaerobic and aerobic energy liberation during maximal efforts (adapted from Astrand and Rodahl, 1977/1986)

	Duration of the greatest possible effort				
Energy released	10 s	1 to 10 min		1 to 2 h	
By anaerobic processes					
in kJ	100	170	150	80	65
in %	85	65–70	10–15	2	1
By aerobic processes					
in kJ	20	80	1,000	5,500	10,000
in %	15	30–35	80–90	98	99
Total in kJ	120	250	1,150	5,580	10,065
Primary energy source	ATP splitting	CP	Glucose, glycolysis	Glycogen and fatty acids, Krebs Cycle	
Type of process	Anaerobic	Mixed	Mixed	Aerobic	

for the complete metabolism of glucose. Glycogen stores near muscles deplete much more quickly when the muscles must work anaerobically than when able to work aerobically. The combustion of all fat derivatives is strictly aerobic.

Usually, at rest and during moderate work, the oxygen supply is sufficient and, hence, the energy metabolism is essentially aerobic. This leads to high ATP and low ADP concentration. To meet intermediate work (energy) demands, the breakdown of glucose speeds up. Above a critical intensity of labor, the oxygen-transporting system cannot provide enough oxygen to the cells and pyruvate transforms into lactic acid instead of going through the Krebs Cycle. During continued intermediate work, the lactate developed may reconvert to glycogen in the liver; this can take place even at the muscle, if aerobic conditions exist. With increasingly higher work intensity, more phases of the metabolic processes become anaerobic which may eventually require cessation of the muscular work.

Table 7.3 shows schematically the contributions of aerobic and anaerobic energy liberation during short and long maximal efforts. During maximal work of short duration, up to 1 min or so, the energy available depends on ATP splitting. If hard work lasts up to about 10 min, the fuel conversion is complex: at the start, anaerobic utilization of ATP and phosphocreatine predominates. Then, anaerobic conversion of glucose to lactate takes over increasingly. In prolonged heavy work, lasting an hour or more, the maximal work output depends on the oxidation of glycogen and fatty acids.

Energy Use and Body Weight

At the beginning of this chapter, Eq. (7.1) described the balance between energy input, energy output, and energy storage. If the input exceeds the output, energy storage in form of body mass ("weight") increases; conversely, mass decreases if the input is smaller than the output. A change of one kilogram in body weight is the result of an increase or a reduction of about 29,000 to 34,000 kJ (7,000 to 8,000 kcal) in energy input.

Apparently, the body tries to maintain a given energy storage. This means that normally a person's body weight (which mostly derives from the weight of water, bones and tissues, and from the mass of fat as stored energy) stays at the present level. Changing that "set point" requires definite changes in health, in nutritional habits (reduction or increase of energy in food and drink supply) and in energy expenditures (such as vigorous and repeated exercising, or reduction of physical activities). As long as the body keeps the set point, body weight remains constant. For example, if one reduces food intake slightly, the body tries to extract enough energy from the remaining intake to preserve the old body weight. A continued starvation diet lowers fat storage, hence, body weight. However, returning to the previous eating habits after having achieved a lowered body weight allows the body to re-attain its previous weight, unless the set point has been lowered. Changing the set point usually requires that one stays an extended time at that new level of nutrition and exercise.

Notes

The text contains markers, *, to indicate specific references and comments, which follow.

Assimilation of chemical energy and energy liberation: There are many textbooks that explain biological and chemical physiology in general; other books focus on special fields such as medical physiology, for example by Guyton and Hall (2000); on work and exercise, for instance by Astrand et al. (2003); or on sports, such as by Wilmore et al. (2008).

Human energy efficiency (work efficiency): Astrand et al. (2003); Wilmore et al. (2008).

Energy content of foodstuffs: Webb (1985); McLean and Tobin (1987).

Summary

The metabolic breakdown of foodstuffs releases energy. Most of that energy transforms into heat, only a small portion can be transmitted as "work" (mechanical energy) to an outside object.

When the body performs physical work, the muscular efforts require energy. This energy is provided by a biochemical process called respiration, which consumes oxygen and generates carbon dioxide, water and heat. The energy becomes available from the breakage of bonds in the high-energy molecule ATP.

ATP is stored at the mitochondria of muscles. The initial synthesis of ATP requires energy. When the muscle needs energy, the existing ATP is degraded to ADP; this liberates energy anaerobically. The conversion acts immediately but is not fully efficient because the amount of energy gained during the breakdown of ATP is less than the energy required to re-build ATP from ADP.

The ATP supply in the muscle is so small that it can sustain only a few seconds of muscle contraction effort. However, skeletal muscle contains enough CP to synthesize ATP for about 10 s of muscle activity.

The muscle can continue to contract beyond that time by using other energy resources that transfer their energy to replenish the depleted ATP stores.

If moderately high muscular work continues, glucose and glycogen are used to produce ATP through glycolysis, the breakdown of glucose and, if not enough is available, of glycogen through glycogenolysis.

When muscle work extends over minutes or hours, pyruvate, a product of glycolysis or glycogenolysis, can enter the mitochondria. Furthermore, carbohydrates and fats can be utilized in the slow yet efficient way of aerobic cellular respiration for ATP production.

The oxidation of carbohydrates employs three processes: aerobic glycolysis, Krebs cycle, and electron transport chain. The oxidation of carbohydrates generates 37 to 39 mol of ATP from 1 mol of muscle glycogen; if glucose is used, the maximal gain is 38 ATP moles.

The use of fat relies on lipolysis of its triglycerides to FFAs (free fatty acids): in turn, they become metabolized by the removal of hydrogen and associated electrons. Their oxidation yields 129 molecules of ATP per 1 mol of FFA. In this way, fat supplies a large amount of ATP energy.

Oxidation of amino acids, components of protein, is used only in emergency situations; so, metabolism of protein is usually negligible.

Glossary

Absorption Here, passing through cell walls.

Anabolism Formation of bonds, which requires energy input: endergonic (or endothermic) reactions.

Assimilation Transformation of a digested nutriment into a part of the organism.

Catabolism Breakage of molecular bonds, which liberates energy: exergonic (or exothermic) reactions.

Digestion The act of changing food chemically into components suitable for assimilation (see there) into the body.

Endergonic (same as endothermic) reaction Chemical reaction requiring energy input.

Endothermic See endergonic.

Ergonomics The application of scientific principles, methods and data drawn from a variety of disciplines to the design of engineered systems in which people play significant roles.

Exergonic (same as exothermic) reaction Chemical reaction yielding energy, usually as heat.

Exothermic See exergonic.

Metabolism Chemical processes in the living body; in a narrower sense, the energy-yielding processes.

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Chapter 8
Exercise and Work

Overview

Performing the same intensity of exercise or work strains individuals differently, in accordance with their physique and training. In order to match the physical requirements of a task with a person's capacity for this effort, one needs to know both the individual's energetic capacity, and how much of this capacity a given job demands.

The following text first deals with assessing a person's capacity, then addresses job demands.

The Model

For matching work and person it is necessary to know both the individual's energetic capacity and how much of this capacity a given job demands.

Having a person perform calibrated exercise allows to measure the person's related capacities. Conversely, measuring the physiological reactions of "standard" persons when they work permits to categorize the physical demands of their task.

Introduction

The measurement units of exercise (such as at sports) and of work (in manufacture, commerce, agriculture, transportation, for example) as well as their physical demands, which they pose on the human body, of course are those of energy, the same as posted in Chap. 7.

K.H.E. Kroemer et al., *Engineering Physiology*, 4th ed.,
DOI 10.1007/978-3-642-12883-7_8, © Springer-Verlag Berlin Heidelberg 2010

The measuring units for energy (exercise, work) are Joules (J) or calories (cal) with 4.19 J = 1 cal. (Exactly: 1 J = 1 Nm = 0.2389 cal = 10^7 ergs = 0.948×10^{-3} BTU = 0.7376 ft lb). For convenience, one often uses the metric kilojoule, 1 kJ = 1,000 J or the kilocalorie, 1 Cal = 1 kcal = 1,000 cal. The unit for power is the Watt, 1 W = 1 J/s.

Capacity for Physical Exercise and Work

The capability of the human body for work or exercise depends on its ability to generate varying energy levels over various time periods. These capabilities are determined by the individual's capacity for energy output (especially physique, health, skill); by the muscular and neuromuscular function characteristics (such as muscle strength, coordination of motion, and the like); by psychological factors (such as motivation, not a topic of this text); and by the thermal environment, which is the topic of Chap. 9. Figure 8.1 sketches these relations.

Among the currently used procedures to assess internal metabolic capacities, four techniques predominate:

1. Diet and weight observation;
2. Direct calorimetry;
3. Indirect calorimetry; and
4. Subjective rating of perceived strain.

Diet and Weight Observation

To maintain the body's homeostasis, "energy balance", all energy that enters the body in form of nutrients, solid or fluid, must lastly leave the body, mostly in terms of energy internally consumed to maintain the body (finally converted to heat) or as external exercise or work performed – see Fig. 8.1. This balance assumption means that there is neither energy storage (when the person gets fatter, more voluminous and heavier) nor use of stored energies (the person getting slimmer). Accordingly, diet and weight observation provides a means for assessment of internal energetic processes, but requires rather lengthy observation periods, usually weeks or months.

If such balance exists, then measurement of the energy content in food and drink intake provides information about the energy output related to external work. However, strict and complete control of energy input is feasible in a laboratory setting but rather difficult in everyday circumstances where usually the subject simply records the intake.

Assessment of the amount of total body fat, or conversely of lean body mass, usually relies on measuring skinfold thickness and inserting the results into one of several prediction equations, which should yield values for body fat or lean mass;

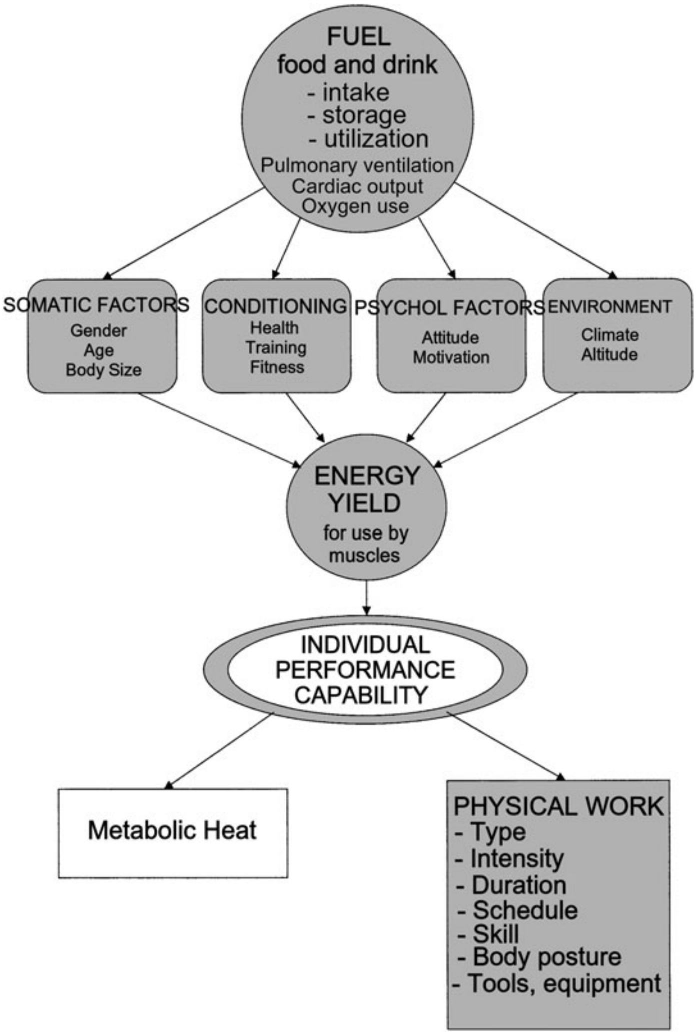

Fig. 8.1 Main determiners of individual physical work capacity (adapted from Kroemer et al., 2003)

all in all, this is not a very accurate procedure. Another approach is to calculate the so-called Body Mass Index, BMI, from weight and stature; however, this is not much of an improvement over comparing waist and hip circumferences*.

Direct Calorimetry

Since all of the body's energy intake finally transforms into heat (if no external work is done and no energy stored), the amount of heat output from the body provides a direct measure of the person's metabolic rate. For the measurement, one can enclose the body with an energy-tight chamber which allows measurement of all heat generated by the body and then transmitted outside by conduction, convection, radiation, and evaporation. There are several requirements for this procedure: the room must be small, which limits activities; energy exchange with air, equipment, and walls must be controlled. Hence, direct calorimetry is feasible only in special laboratories and is not of much practical interest.

Indirect Calorimetry

For indirect calorimetry, a variety of measurement techniques is at hand:

Assessment by Oxygen Consumption

When the body performs work, oxygen consumption (and CO_2 release) is a measure of the associated metabolic energy production. Oxygen intake ("uptake") is the volume of oxygen (at defined atmospheric conditions) absorbed per minute from the inspired air. At rest, this volume is about 0.2 L/min; it can increase with strenuous exercise 30-fold, as discussed in Chap. 7. Several measurement techniques rely on the principle that differences in O_2 (or CO_2) content between the exhaled and inhaled air indicate the quantity of oxygen absorbed (or carbon dioxide released) in the lungs. Knowing the "caloric value" of oxygen (on average, about 5 kcal per liter of O_2), the volume of oxygen consumed for an activity allows calculating the energy that the body converts. (Brief descriptions of techniques to measure oxygen uptake are in Appendix 1 to this chapter)

The "respiratory exchange quotient" RQ (or Respiratory Exchange Rate, RER) compares the volumes of carbon dioxide expired to oxygen consumed. Metabolizing 1 g of carbohydrate requires 0.83 L of oxygen and releases the same volume of carbon dioxide (see Eq. 7.4). Hence, for carbohydrate, the RQ is one (unit). The energy released is 18 kJ/g of O_2, 21.2 kJ/L O_2. Table 8.1 shows the RQs for carbohydrate, fat and protein conversion. Thus, measuring the volumes of CO_2 and O_2 during work indicates which energy carrier is metabolized, and how much energy is consumed.

Table 8.1 Oxygen needed, RQ, and energy released in nutrient metabolism

		Carbohydrate	Fat	Protein	Average[1]
O_2 consumed, L/g		0.83	2.02	0.79	na
RQ, RER		1.00	0.71	0.80	na
Energy yield	kJ/g	18	40	19	na
	kJ/LO_2	21.2	19.7	18.9	21
	kcal/LO_2	5.05	4.69	4.49	5

[1] Assumes the construct of a "normal" adult on a "normal" diet doing "normal" work

Assessment by Heart Rate

There is close interaction between the metabolic processes and their support systems: for proper functioning, the working muscles or other metabolizing organs must be supplied with nutrients and oxygen, and metabolic byproducts must be removed. That transport system, blood circulation, is powered by the heart. Therefore, heart rate HR (a primary indicator of circulatory functions) and oxygen consumption (representing the metabolic conversion) have a linear and reliable relationship in the range between light and heavy work, as sketched in Fig. 8.2. Given this relation, one often can simply substitute heart rate measurements for measurement of metabolic processes, particularly O_2 assessment. This is a very attractive shortcut since heart rate counts are easier to do than oxygen measurements.

The simplest techniques of counting the heart rate are to palpate an artery, often in the wrist or perhaps in the neck, or to listen to the sound of the beating heart – see Chap. 6, Fig. 6.1. All the measurer has to do is count the number of heartbeats over a given period of time (such as 15 s) and from this calculate an average heart rate per minute. More refined techniques utilize various plethysmographic methods, which rely on tissue deformations due to changes in filling of the imbedded blood vessels. These methods range from measuring mechanically the change in volume of tissues, for example in a finger, to using photoelectric techniques that react to changes in transmissibility of light depending on the blood filling, such as of the ear lobule. Other techniques rely on electric signals associated with the pumping actions of the heart, usually sensed by electrodes placed on the chest.

Measurement of heart rate has another major advantage over oxygen consumption as indicator of metabolic processes: heart rate responds more quickly to changes

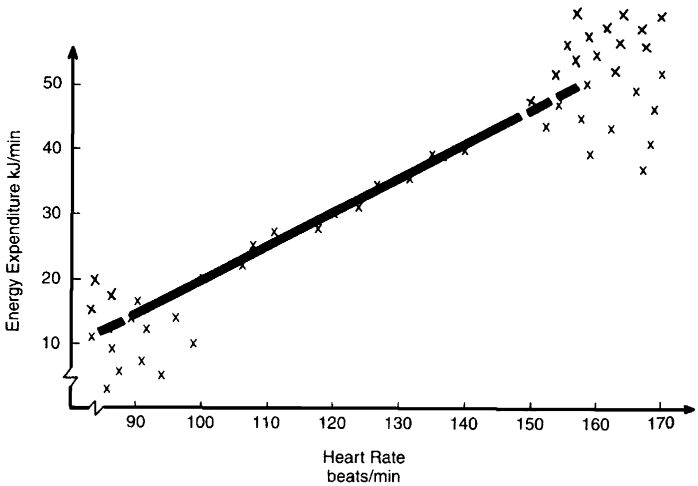

Fig. 8.2 Scheme of the relationships between oxygen uptake (expressed as energy expenditure) and heart rate

in work demands, hence indicates more easily quick changes in body functions due to changes in work requirements.

The reliability of these techniques is limited primarily by the intra- and inter-individual relationships between circulatory and metabolic functions. Statistically speaking, the regression line (shown in Fig. 8.2), which associates heart rate with oxygen uptake (energy production), differs in slope and intersect from person to person and from task to task, and may change with training or disconditioning of a person.

In addition, the scatter of the data around the regression line, indicated by the coefficient of correlation, is also variable. The correlation is low at very light exercise where the heart rate is barely elevated but can be influenced easily by psychological events (such as excitement, startling noise or fear) which may be completely unrelated to the task proper. At very heavy work, the O_2/HR relation may also fall apart, for example when cardiovascular capacities may be exhausted before metabolic or muscular limits are reached. Presence of heat load (see Chap. 9) also influences the O_2/HR relationship.

Assessment by Subjective Rating of Perceived Effort

Humans are able to perceive the strain that a given work task generates in their bodies and they can judge this perceived effort in absolute and relative terms. Certainly, assessing and rating the relationship between the physical stimulus (the work performed) and its perceived sensation have been used as long as people have expressed their preference of one type of work over another.

Since the 1960s, formal techniques for "rating the perceived exertion" (RPE) associated with different kinds of efforts have been at hand*. A common procedure is to appraise the effort on a nominal scale from "light" to "hard." Such a verbally anchored scale also allows to "measure" the strain subjectively perceived while performing standardized work.

Examples of rating scales are printed in Appendix 2 to this chapter.

Standardized Tests

Most current medical and physiological assessments of human work capacities rely on measuring oxygen consumption and heart rate. To assess and compare persons' capacities, several tests with standardized external work are in common use. They typically employ bicycle ergometers, treadmills, or steps located in a laboratory on which the subject performs controlled exercises.

Bicycle, Treadmill and Step Tests

Exercising on bicycles, treadmills, and steps stresses certain body parts and body functions: bicycling requires predominantly use of the leg muscles. Since the legs constitute both in their mass and their musculature large components of the human body, their extensive exercising in a bicycle test also strains pulmonary, circulatory, and metabolic functions of the body. However, a person who is particularly strong in the upper body but not well trained in the use of legs would show different strain reactions in bicycle ergometry than, say, a trained bicycle racer.

The treadmill also stresses primarily lower body capabilities, but in contrast to bicycling while sitting the whole body weight must be supported and propelled by the feet and legs. If the treadmill is inclined, the body must also be lifted. Hence, this test strains the body in a somewhat more complete manner than bicycling but still lets trunk and arm capabilities out of consideration. Furthermore, it requires somewhat more bulky equipment than a stationary bicycle.

Another method of standardizing test technique is to have the subject step up onto a raised platform and then step down again, repeated for the duration of the test. This "step test" technique requires only simple equipment; it stresses body functions in a fashion somewhat similar to running on a treadmill, however by primarily making the subject elevate the total body weight instead of moving it forward. A person heavier in weight and with shorter legs than another subject would show larger energy consumption. As in the other tests, muscular capabilities of the upper body are not tested at all.

Challenges

Test selection often relies on availability of equipment and ease of use rather than on theoretical considerations. Obviously, the bicycle, treadmill, and steps test techniques do not reproduce the requirements of regular work. They exercise almost exclusively the lower extremities, not trunk or upper body functions. Consequently, various improvements on test equipment and procedures have been proposed. Two examples: a ladder-mill on which one climbs using both arms and legs; a bicycle ergometer on which the testee simultaneously operates hand-operated cranks.

In spite of their shortcomings, the current test techniques (especially those using bicycle or treadmill) have become standard procedures to measure a persons' capabilities for exercising at known intensity, judged by oxygen consumption and/or heart rate and/or by subjective ratings.

The probably most often employed assessment of a person's capacity for physical work measures the ability of the respiratory system to absorb oxygen into the blood and the related ability of the circulatory system to deliver this oxygen to the consumers (usual muscles) in need of it. These interrelated capabilities are described by the maximal volume of oxygen which a person can consume during intense exercise, at sea level. The "VO_2max" ranges from 2.5 to 4.5 L/min in well-trained women, and is between 3 and 6 L/min in athletic men. Instead of using such absolute numbers, relative values consider body size; these result from dividing the maximal volume of oxygen (in milliliters) by body mass (in kilograms). The "relative VO_2max" is likely to be near 20 mL/min/kg in untrained persons and may go up to 80 mL/min/kg in a champion athlete.

Persons so "calibrated" may then be sent to work at an assembly line, on a construction site or on the moon; their reactions allow to assess how straining their work procedures are. This is the rationale by which tables were established that describe energy expenditures or heart rates associated with certain jobs or occupations (see below). Unfortunately, there is little or no assurance that the published field data describing the demands ("heaviness") of jobs indeed stem from measurements on "calibrated" subjects under "controlled" conditions. Furthermore, tasks and conditions of work may vary even if called the same. Consequently, there is wide diversity in published data.

In many jobs, exertion levels do not remain constant but vary over time. To take that variation into consideration, one can assess the operator's effort by frequent sampling or by a measurement extended over a sufficiently long time, so that peaks and lows in energy intake, conversion, and output "average out". For example, in Chap. 7, Eqs. (7.2) and (7.3) excluded energy storage. However, imbalances between energy intake and output of hundreds of kilojoules over a day are common; accordingly, in fact there can be significant changes in energy storage.

Most of the energy store in a healthy adult is in the form of adipose tissue, amounting to about 400,000 kJ, as discussed in Chap. 7. A substantial change in storage should result in a change in body weight. (Data on energy consumption often relate to body weight). However, body water disturbs the seemingly simple relationship between weight and energy storage, because water is a large and rather labile component of body weight but contributes nothing to the energy stores.

A further challenge is to avoid that measuring processes influence the measurement results. For example, putting on and carrying apparatus to monitor oxygen consumption often hinder the subject's motions and breathing, and even just being observed can lead to task performance that differs from the normal procedures. In these cases, energetic and circulatory processes diverge from those at "no-test circumstances" of regular work.

To judge and use data measured during physical work, a reliable "baseline" is needed. A subject's basal metabolism is a solid reference for energetic processes. However, is quite difficult for a subject to achieve a true, reliable basal condition with its stringent requirements (see below); therefore, it is often replaced by measurements on a resting subject, where conditions and measurements are more variable. Uncertainty about the baseline is of particular concern for light efforts that elevate body functions only slightly. (This may explain some of the percent-wise large variations found in different texts concerning the energy requirements of light work).

Energy Requirements at Work

While the foregoing discussion concerned the body's energetic capabilities, the following text concentrates on the demands that different activities impose on the human body.

Procedures to Catalogue Metabolic Requirements

Using "calibrated" subjects (see above) allows to measure the metabolic demands of work tasks and to group the results into convenient categories. For the measurements one assumes, as usual, no change in energy storage in the body. Either basal or resting metabolism establishes a baseline.

Basal Metabolism

A minimal amount of energy is necessary to keep the body functioning even if it does no activities. This basic metabolism is measured under strict conditions: usually after fasting for 12 hours, with protein intake restriction for at least 2 days; and during complete physical rest in a neutral ambient temperature. Under these conditions, the basal metabolic values depend primarily on age, gender, height, and weight, with the last two variables occasionally replaced by body surface area. In healthy adults there is little inter-individual variation, hence a commonly accepted value is 1 kcal (4.2 kJ)/kg/h; equivalent to 4.9 kJ/min for a person of 70 kg.

Resting Metabolism

The highly controlled conditions needed to measure basal metabolism are rather difficult to accomplish. Thus, one usually measures the metabolism (and the heart rate) before the working day, with the subject at rest as well as possible. Depending on the given conditions, resting metabolism is around 10–15% higher than basal metabolism.

Work Metabolism

The increase in metabolism from resting to working is called work metabolism: it represents the amount of energy needed to perform the work.

As Fig. 8.3 shows schematically, at the start of physical work, the actual oxygen uptake lags behind the demand: during the first 45–90 seconds of working at an intensity near 50% of the maximum possible, the energy metabolism is almost completely anaerobic because the oxygen supply needs time to meet the demand. Thus, during the first minutes of physical work, a discrepancy exists between required oxygen and available oxygen. After that slow onset, oxygen intake rises rapidly and finally approaches the level at which it fulfills the oxygen demands of the work. The initial oxygen deficit must be repaid at some time, usually during the following work if it is not overly demanding, or during a rest period.

When the demands of work stay below approximately 50% of the worker's capacities for maximal oxygen uptake, then heart rate and cardiac output increase so that they can finally achieve the required supply level. When they maintain this supply level, then the body is at "steady state"*.

When work ends, the oxygen demand falls back to its resting level, quickly at first and then leveling off. During this recovery time, depleted ATP stores are refilled, and

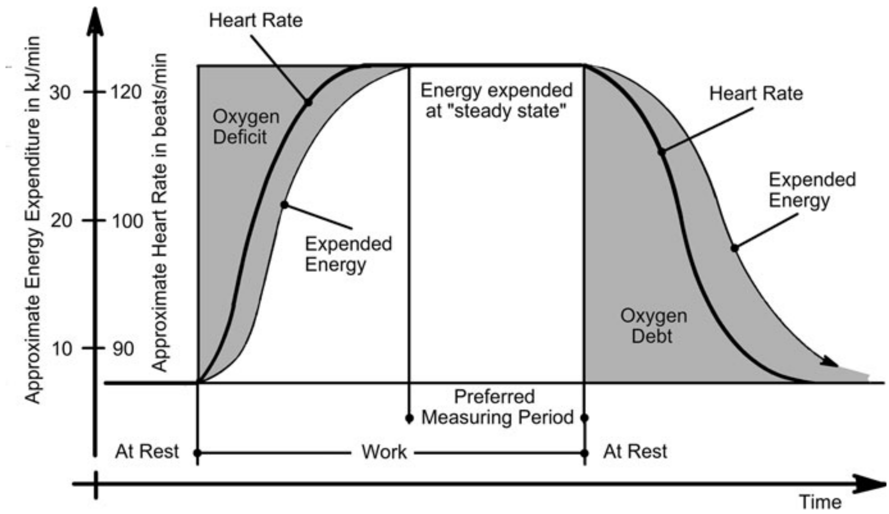

Fig. 8.3 Schematic illustration of energy liberation, energy expenditure, and heart rate at steady state work

myoglobin and hemoglobin are refurbished with oxygen. Still elevated tissue temperature and epinephrine concentration, augmented cardiac and respiratory functions, reconversion of lactate to glycogen and other phenomena cause that, as a rule, the oxygen debt repaid is approximately twice as large as the oxygen deficit incurred*.

Given the close interaction between the circulatory and metabolic systems, heart rate reacts similarly; yet, it increases faster at the start of work than oxygen uptake and it also falls back more quickly to its resting level.

If the workload overtaxes the worker's metabolic (circulatory, respiratory, muscular) capacities, the person will have to stop the effort. Yet, when the body can supply what the workload demands in oxygen uptake, heart rate, cardiac output, ventilation, circulation, and other functions and can stay on this level – see Figs. 8.4 and 8.5 – then steady state is achieved. Obviously, a well-trained person can attain this equilibrium between demand and supply at a rather high workload, whereas an unfit person would be unable to attain a steady state at this requirement level but could be in equilibrium at lower demand. Measurement of a person's maximal oxygen uptake assesses the individual capacity for hard exercise and labor.

If the energetic work demands exceed about half the person's maximal O_2 uptake capacity, anaerobic energy-yielding metabolic processes play increasing roles. Onset of the feeling of "fatigue" (see below) usually coincides with depletion of glycogen deposits in the working muscles, drop in blood glucose, and increase in blood lactate. However, the associated physiological and motivational processes are still not fully understood: highly motivated persons (such as in competitions, especially in sports) may continue to perform such demanding effort for some time in spite of the physiological obstacles.

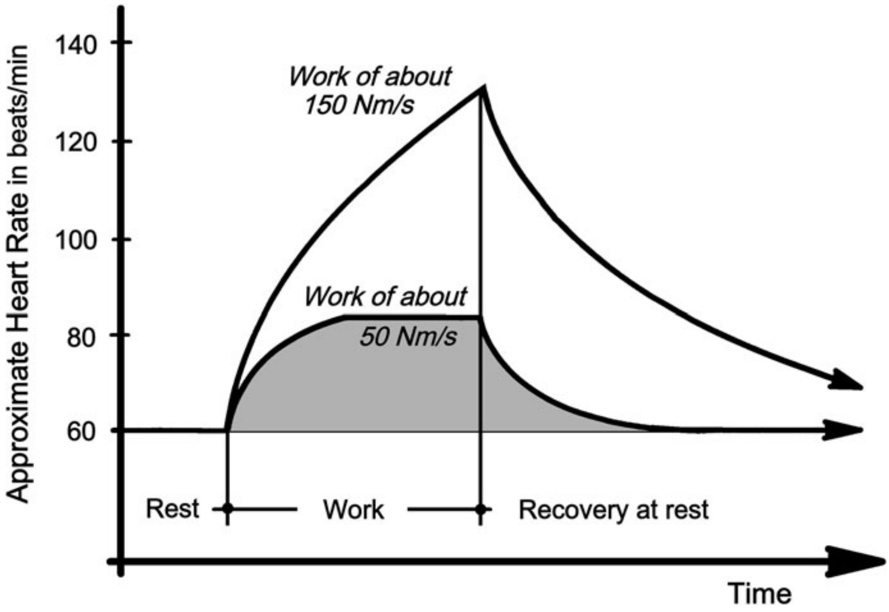

Fig. 8.4 Heart rate at exhausting work and at steady state work

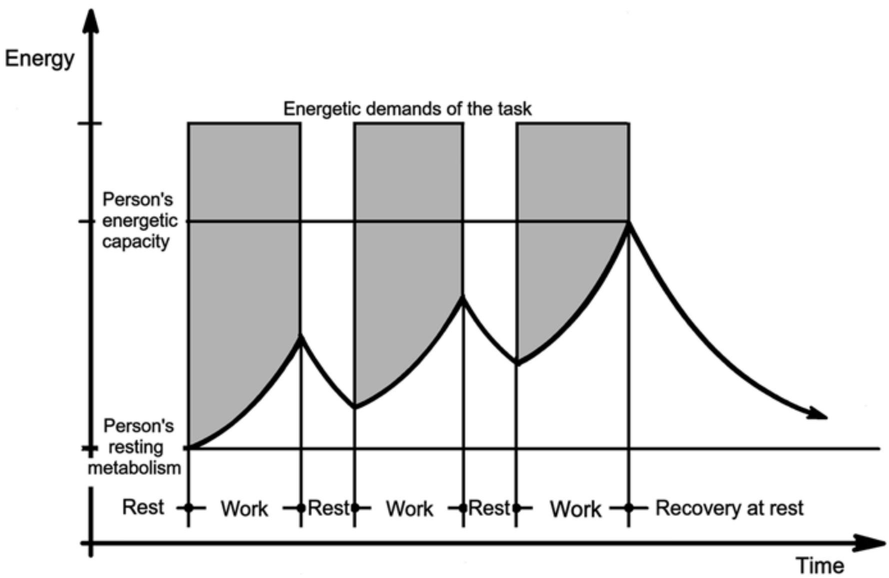

Fig. 8.5 Metabolic reactions to the attempt of doing work that exceeds one's capacity even with interspersed rest periods

When vigorous activity causes incapacitating oxygen deficit, unacceptably high lactate content of the blood and circulatory strain, a “steady state” balance between demands and supply cannot be achieved and the body must stop working – as sketched in Fig. 8.5. Rest periods can counteract impending exhaustion. Given the same ratio of “total resting time” to “total working time,” many short rest periods have more recovery value than a few long rest periods.

Taken during steady state work, measurements of oxygen intake and heart rate dependably indicate the metabolic and circulatory demand-and-supply functions in the body. Oxygen and HR measurements done during the first few minutes of work do not reflect the long-time work demands on the body because of the slow responses of oxygen uptake and heart activity. These slow responses to sudden changes in work demand make it doubtful that O_2 consumption and HR can reliably reflect the effects of physical work that contains rapid increases and decreases in effort. Measurements taken after the cessation of the work could be indicators of the severity of the preceding work but are difficult to interpret, partly because it is usually uncertain how long the recovery period actually is*.

Techniques to Estimate Energy Requirements

Besides actual measurements, two other means are often employed to obtain information on the energetic requirement of enduring physical effort: using tabulated data or calculating energy requirements.

Using Tables

In the 1950s and 1960s, physiologists measured energy expenditures in many jobs and occupations and compiled the data into tables: Table 8.2 is an excerpt. Of course, professions and jobs change over time even if some basic task elements remain the same. Table 8.3 presents information on energy expended in elementary body positions and activities. Table 8.4 contains data on energy consumption in various recreational sports. The data in both tables are estimates for the prototypical healthy young man of 75 kg; the numbers are 10–15% lower for the typical woman. Of course, care is necessary when using these tables: first, the actual conditions may not be typical; second, the table data can be in different units: for example, Table 8.2 contains information on *total energy cost per day,* Table 8.3 describes *work metabolism*, and the data in Table 8.4 refer to *kg units of body weight*.

Calculating

Synthetic tables (such as Table 8.2) contain measurements taken when many jobs or activities were quite different from what they are today: housewives now seldom wash and wring by hand, secretaries no longer pound on mechanical typewriters, lumbermen don’t usually cut down trees with hand saw and ax, few farmers walk

Table 8.2 Total energy expenditure, in kcal per day, in various professions and employments (adapted from Astrand and Rodahl, 1977). The physical demands are likely to be different now from what they were in the 1960s and '70s

	Energy expenditure, kcal/day		
	Minimum	Mean	Maximum
Men			
Coal miners	2,970	3,660	4,560
Elderly industrial workers	2,180	2,820	3,710
Elderly Swiss peasants	2,210	3,530	5,000
Farmers	2,450	3,550	4,670
Forestry workers	2,860	3,670	4,600
Laboratory technicians	2,240	2,840	3,820
Steelworkers	2,600	3,280	3,960
University students	2,270	2,930	4,410
Women			
Elderly housewives	1,490	1,990	2,410
Middle-aged housewives	1,760	2,090	2,320
Elderly Swiss peasants	2,200	2,890	3,860
Factory workers	1,970	2,320	2,980
Laboratory technicians	1,340	2,130	2,540
University students	2,090	2,290	2,500

Table 8.3 Energy consumption (to be added to basal metabolism) at various activities (adapted from Astrand and Rodahl, 1977/1986; Guyton, 1979; Rohmert and Rutenfranz, 1983; Stegemann, 1984)

	kJ/min
Lying down, sitting, standing	
Resting while lying down	0.2
Resting when sitting	0.4
Sitting with light work	2.5
Standing still and relaxed	2.0
Standing with light work	4.0
Walking without load	
Walking on horizontal smooth surface at 2 km/h	7.6
Walking on horizontal smooth surface at 3 km/h	10.8
Walking on horizontal smooth surface at 4 km/h	14.1
Walking on horizontal smooth surface at 5 km/h	18.0
Walking on horizontal smooth surface at 6 km/h	23.9
Walking on horizontal smooth surface at 7 km/h	31.9
Walking on grass at 4 km/h	14.9
Walking in pine forest, smooth surface, at 4 km/h	18 to 20
Walking on plowed heavy soil at 4 km/h	28.4
Walking and carrying on smooth solid horizontal ground	
1 kg on the back at 4 km/h	15.1
30 kg on the back at 4 km/h	23.4

Table 8.3 (continued)

	kJ/min
50 kg on the back at 4 km/h	31.0
100 kg on the back at 3 km/h	63.0
Walking downhill on smooth solid ground at 5 km/h	
5° decline	8.1
10° decline	9.9
20° decline	13.1
30° decline	17.1
Walking uphill on smooth solid ground at 2.5 km/h	
10° incline, gaining altitude at 7.2 m/min	
No load	20.6
20 kg on back	25.6
50 kg on back	38.6
16° incline, gaining altitude at 12 m/min	
No load	34.9
20 kg on back	44.1
50 kg on back	67.2
25° incline, gaining altitude at 19.5 m/min	
No load	55.9
20 kg on back	72.2
50 kg on back	113.8
Climbing stairs or ladder	
Climbing stairs, 35° incline, steps 17.2 cm high	
100 steps/min, gaining altitude at 17.2 m/min, no load	57.5
Climbing ladder, 70° incline, rungs 17 cm apart	
66 steps/min, gaining altitude at 11.2 m/min, no load	33.6

While Rohmert and Rutenfranz claim that, for the same activity, intra- and inter-individual differences in energy consumption are within 10%, a comparison of data presented in various texts shows a much higher percentage of variation, particularly at low activity levels.

Table 8.4 Total energy expenditure per kg body weight at various sports

	Energy expenditure kJ/kg/h
Badminton	53
Bicycling, 9 km/h	15
Bicycling, 16 km/h	27
Bicycling, 21 km/h	40
Cross-country skiing, 9 km/h	38
Cross-country skiing, 15 km/h	80
Ice skating, 21 km/h	41
Jogging, 9 km/h	40
Running, 12 km/h	45
Running, 16 km/h	68
Swimming, breaststroke, 3 km/h	45
Walking, 4 km/h	13
Walking, 7 km/h	25

behind their plow pulled by oxen or horses. Furthermore, these older data may have been "averaged" over unknown subjects or attained with only a few subjects.

An "analytic" approach avoids related problems: one can compose the total energetic cost of job or task activities by adding up the energetic cost of the work elements which, combined, make up this activity. This approach follows industrial engineering practices, especially job analysis*.

If one knows the time spent in a given activity element and its metabolic cost per time unit, one can simply calculate the energy requirements of this element by multiplying its unit metabolic cost with its duration time. Repeating this for all other work elements, and adding all results up, provides an estimate of the total energetic job effort.

For example:
For a person resting (sleeping) 8 h/day, at an energetic cost of 5.1 kJ/min, the total energy cost is 2,448 kJ (5.1 kJ/min × 60 min/h × 8 h). If the person then does 6 h of light work while sitting, at 7.4 kJ/min, this adds another 2,664 kJ to the energy expenditure. With an additional 6 h of light work done standing, at 8.9 kJ/min, and further with 4 h of walking at 11.0 kJ/min, the total expenditure during the full 24-h day comes to 10,956 kJ (approximately 2,610 kcal).

As this example shows, the energetic requirements of given activities, per hour, day, week, or year can be computed from tables of metabolic requirements of job elements. When using these, one has to be careful to check whether or not they include the basal or resting rates: Table 8.3 does not contain the baseline values but Tables 8.2 and 8.4 do. In developed countries, daily expenditures range from about 6,000–20,000 kJ/day, with observed median values of about 10,000 kJ (2,400 Cal) for women and about 14,000 kJ (3,300 Cal) for men.

Light or Heavy Jobs?

With a linear relationship between heart rate and energy uptake, one can generally use heart rate to establish the "heaviness" of work. Of course, descriptive labels as "light" or "easy" or "heavy" reflect individual judgments that rely very much on the current socio-economic concept of what is permissible, acceptable, comfortable, or hard. Depending on the circumstances, there may be a diversity of opinions about how physically demanding a given job is. Table 8.5 lists ratings of job severity according to energetic and circulatory demands. This is a unisex table: most men would find the work lighter, and most women feel the effort to be heavier than labeled.

Light work is associated with rather small energy expenditure (about 10 kJ/min including the basal rate) and a heart rate of approximately 90 beats/min. At this level of work, the oxygen available in the blood and from glycogen at the muscle

Table 8.5 Classification of work (performed over an entire work shift) from “light” to “extremely heavy” according to energy expenditure and heart rate

	Total energy expenditure		Heart rate
Classification	kJ/min	kcal/min	Beats/min
Light work	10	2.5	90 or less
Medium work	20	5	100
Heavy work	30	7.5	120
Very heavy work	40	10	140
Extremely heavy work	50	12.5	160 or more

suffices to meet the needs of the working muscles. At *medium* work, with about 20 kJ and 100 bpm, the oxygen requirement at the working muscles is still covered, and initially developed lactic acid is resynthesized to glycogen during the activity. In *heavy* work, with about 30 kJ and 120 bpm, enough oxygen is still available if the person is physically fit and trained for such work. However, the lactic acid concentration incurred during the initial minutes of the work is not reduced but remains until the end of the work period, to be brought back to normal levels after cessation of the work.

In light, medium and even in heavy work, metabolic and other physiological functions can attain a steady-state condition throughout the work period, provided the person is capable and trained. This is not the case anymore with *very heavy* work, where energy expenditures are in the neighborhood of 40 kJ, and heart rate is around 140 bpm. Here, the original oxygen deficit increases throughout the duration of work, making intermittent rest periods necessary or even forcing the person to stop working altogether. At even higher energy expenditures, such as 50 kJ/min, associated with heart rates of 160 bpm or higher, oxygen deficit and accumulation of byproducts of the biochemical processes are of such magnitudes that frequent rest periods are needed; even highly trained and capable persons may be unable to perform this job throughout a full work shift.

Another rule of thumb for assessing the magnitude of effort uses an individual’s maximal oxygen uptake: work that requires 30–40% of the person’s maximal uptake can be done for 8 h; but if the job requires 50% or more, exhaustion is likely to occur*.

Overall Changes in Body Functions in Response to Work Loads

As stated at the beginning of this chapter, there is close interdependency among respiration, circulation, and metabolic functions. The least capable of them sets the limit for an individual’s physical performance. Of course, other specific capabilities may also cap the possible output: muscular strength frequently limits performance. Furthermore, changes in health, fitness, skill or motivation affect performance abilities.

Table 8.6 Changes in physiological functions from rest to maximal effort

	Change from rest to maximal effort	
Energy consumption	From 1 to 20 kcal/min	× 20
Oxygen uptake	From 0.2 to 4 L	× 20
Cardiac action	Heart rate: from 60 to 180 beats/min	× 3
	Stroke volume: from 50 to 150 mL	× 3
	Cardiac output = minute volume × heart rate: from 5 to 35 L/min	× 7
	Blood pressure, systolic: from 90 to 270 mmHg	× 3
Respiration	Breathing rate: from 10 to 50 breaths/min	× 5
	Minute volume = tidal volume × breathing rate: from 5 to 100 L/min	× 20

Table 8.6 lists the main changes in physiological functions, from rest to maximal work, for energy and oxygen consumption, heart actions and respiration. Any and all of these variables are useful for assessing a person's response to a given work load, or for judging the demands imposed by the task. However, measures of ventilation or metabolic responses are suitable only for assessing "dynamic" work. "Static" efforts, in which muscles are contracted and kept so, hinder or completely cut off the blood supply by compression of the capillary bed; so, relatively little additional energy is consumed. Therefore, techniques relying on respiratory or metabolic functions cannot well assess static efforts even although they may be fatiguing.

Fatigue

The term "fatigue" is used in this text as an operational description of a temporary state of reduced ability to continue muscular contraction or physical work. This phenomenon is best researched for maintained static (isometric) muscle contraction. As described in Chap. 2, when an effort exceeds about 15% of the maximal voluntary contraction (MVC) capability of a muscle, blood flow through the muscle becomes reduced due to the pressure build-up within the muscle; in a maximal effort, the muscle may compress its blood vessels completely, in spite of a reflex increase in systolic blood pressure. Insufficient blood flow brings about an accumulation of potassium ions in the extracellular fluid and depletion of extracellular sodium. Combined with intracellular accumulation of phosphate (from the degradation of ATP), these biochemical events perturb the coupling between nervous excitation and muscle fiber contraction. Depletion of ATP or creatine phosphate as energy carriers, and the accumulation of lactate (which was long believed to be the main reason for fatigue), do occur as well. In addition, the increase of positive hydrogen ions, resulting from anaerobic metabolism, causes a drop in intramuscular pH, in turn inhibiting enzymatic reactions, notably those in the ATP breakdown*.

Discomfort, pain and de-coupling of central nervous system (CNS) control and muscle action signal the onset of fatigue. However, persons with high motivation to overcome the feeling of fatigue or exhaustion are able to continue their physical effort for considerable time whereas others stop shortly after fatigue begins.

Fatigue can be avoided by reducing or stopping the effort that causes fatigue. During a rest period, accrued metabolic byproducts can be metabolized, the respiratory and circulatory systems recover, and the will to continue may be restored. As Figs. 8.3, 8.4 and 8.5 demonstrate, the recovery benefits are largest immediately after stopping work but much less beneficial later during the rest intermission. Therefore, as already stated, many short rest pauses have more value in avoiding or overcoming fatigue than fewer but longer stops. In the case of heavy physical work, for example, this means that one should not ”push through” and then rest, more or less exhausted; rather, the manager should encourage laborers to take frequent but short breaks.

Human Engineering/Ergonomics

Calorimetric information is especially useful

- To assess individual energetic functions in response to standardized activities: this is a measurement of individual metabolic work capacity.
- To assess the energetic requirements of a given activity as reflected by the energetic response of a "standard person", or of a specifically selected and trained individual, to that work.

It can be argued that, in the interest of standardization, test activities should be kept neutral, not resembling actual job tasks. However, the current standard tests (bicycle, treadmill, steps) primarily involve the use of leg muscles, not of the upper body and arms; however, arm and upper body muscles are primarily used in most everyday jobs. Development of new standard tests therefore seems in order to better determine job-related capabilities.

Much of the currently used equipment to measure metabolic reactions to work tasks is awkward to wear and requires that a physician or physiologist performs the testing, often in a laboratory instead of at a regular workplace. Development of test instrumentation that is less cumbersome and invasive than current equipment would make testing easier and more realistic. Even if some of the present techniques should be maintained, it would be useful to determine categories of work tasks in which simple assessments, such as by heart rate or by subjective judgment, would suffice.

Managers and engineers establish the required task and how it shall be done, and often have control over the external environment. They must adjust the work to be performed (and the work environment) to suit the operator's physiologic capabilities – which includes the encouragement, not just tolerance, of freely taking frequent rest periods during heavy work, as just mentioned.

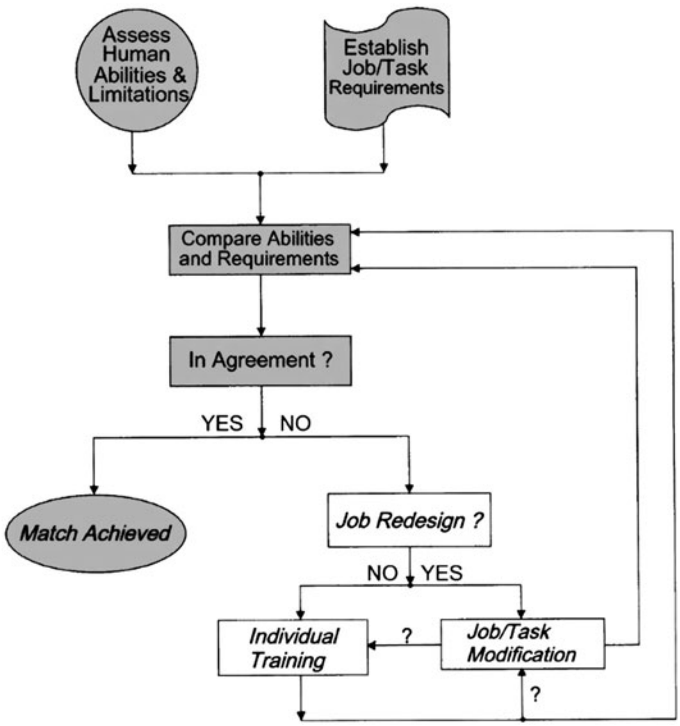

Fig. 8.6 Matching task demands with human abilities

Managers and engineers must also understand the physiologic (and psychologic) procedures to determine performance limits, and how to interpret this information (which currently mostly stems from laboratory tests that do not resemble actual work tasks) and apply it to a real-world jobs. If job demands exceed human capabilities, it is necessary to re-design the work by changing tasks, tools, and environment as appropriate and needed*; training of the operator in procedure and fitness may also be advisable. This approach of matching requirements with abilities is shown in Fig. 8.6.

Notes

The text contains markers, *, to indicate specific references and comments, which follow.

Body Mass Index, BMI: Centers for Disease Control, http://www.cdc.gov/nchs

Techniques for "rating the perceived exertion": Borg (1962, 1982, 2001, 2005), Pandolph (1983).

The body is at "steady state": In reality, however, even in a so-called steady-state situation, heart rate, cardiac output, pulmonary ventilation can still increase gradually, which may be a consequence of increasing body temperature or due to an increasing use of fatty acids as substrate.

The oxygen debt repaid is approximately twice as large as the oxygen deficit incurred: "The body must pay 100% interest on the oxygen borrowed from the anaerobic bank"; Astrand and Rodahl (1977/1986).

Measurements taken after the cessation of the work during the recovery period: Lehmann (1952/1962), Brouha (1960).

Industrial engineering practices, job analysis: Bernard and Joseph (1994).

Re-design the work by changing tasks, tools, and environment as appropriate and needed; Kroemer et al. (2003).

Use of instantaneously reacting oxygen sensors allows breath-by-breath analysis: McLean and Tobin (1987), Webb (1985).

The Doubly Labelled Water isotope technique: Lifson et al. described the DLW method first in 1955; Speakman (1997) provides more information.

Reliability and validity of rating scales: Borg (2001, 2005). Check Wilson and Corlett (2005) for other rating scales.

Summary

Among the techniques to assess metabolic processes, measurements of oxygen uptake and of heart rate are practical and reliable; equipment is commercially available. Subjective ratings of perceived effort require no hardware at all.

The measuring techniques assess an individual's metabolic and circulatory capabilities in response to standardized exercise, which is usually performed on bicycle ergometers or treadmills. Reversing that process, observation of workers' metabolic and circulatory efforts while performing work, allows categorizing work requirements.

Energy requirements depend on the activity level of the body: "basal" metabolism suffices to keep the body alive while no effort is done, "resting" metabolism keeps the body functioning while at rest, and "work" metabolism maintains the body at work.

At the start of work, both oxygen consumption and heart rate increase sluggishly but heart rate does so more quickly. If the demand level is suitable, these body functions finally achieve a steady state. After cessation of the effort, oxygen intake and heart rate fall back to their resting levels, HR again more quickly than O_2 uptake.

Measurement of oxygen consumption or heart rate as indicators of the physical task requirements should be performed during the steady-state phase of the exercise. In this case, ranges of energy and heart rate requirements allow general classifications of task "heaviness".

In some cases, energy requirements can be taken from tabulated listings. However, the given conditions (for example pertaining to work details, the individual worker or the climate) may not be reliably the same as assumed for the table values.

Often, one can calculate the energy requirement of a job by breaking it into elemental subtasks for which the (average) energy requirements are known: the total energy need is the sum of the energy needs for each subtask.

If the physical demands are too high for the individual, no steady rate can be achieved, and the work must be interrupted for rest and recovery. Such finding gives reason to redesign the task.

Appendix 1: Techniques of Indirect Calorimetry

Measuring the oxygen consumed over a sufficiently long period of time is a practical way to assess the metabolic processes. (A physician or physiologist should perform this test). As discussed earlier, one liter of oxygen consumed releases about five kcal of energy in the metabolic processes. This assumes a normal diet, a healthy body oxidizing primarily carbohydrates and fats under conditions of light to moderate work, and suitable climatic conditions. (The "normality" of the metabolic conditions can be judged, to some degree, by the respiratory exchange quotient, RQ, mentioned earlier).

Classically, indirect calorimetry has been performed by collecting all exhaled air during the observation period in airtight (Douglas) bags. The volume of the exhaled air is then measured and analyzed for oxygen and carbon dioxide as needed for the determination of the RQ. From these data one can calculate the amount of oxygen, and hence energy, used during the collection period. This requires a rather complex air collecting system, including nose clip and a mouthpiece with intake and exhaust valves. This apparatus can become quite uncomfortable for the subject and hinders speaking, which limits this procedure mostly to the laboratory. A major improvement was done by diverting only a known percentage of the exhaled air into a small collection bag. This 1950s procedure is still in use since the subject must carry only a relatively small device, which does not affect most daily activities much.

Use of instantaneously reacting oxygen sensors brought significant progress because their placement into the air flow of the exhaled air allows breath-by-breath analysis*. Since the volume of exhaled air can also be measured by suitable sensors, "open" face masks draw a stream of air across the face of the subject who simply inhales from this air flow and exhales into it. This allows free breathing, speaking and drinking; it even cools the face (which might in fact improve the working capacity to a small extent). Another technical variation employs a hood-like enclosure of the head. The differences in oxygen measured with either equipment are usually less than 15%; therefore, for most field observations, the accuracy of bagless procedures is quite sufficient.

Another technique uses isotopes. It relies on so-called doubly-labelled water, DLW, in which both the hydrogen and the oxygen have been partly or completely replaced with uncommon heavy isotopes of these elements, usually deuterium and oxygen-18. The depletion of these isotopes indicates the generation of water in the body which parallels the metabolizing process – see Eq. (7.4). A dose of water with these isotopes is injected or drunk by the subject, animal or human. Samples of saliva, urine, or blood allow measurements of the isotope concentrations and their elimination rates. At least two such samples are needed: the first one after the isotopes have reached equilibrium in the body, and a second sample some time later. The measuring period maybe as short as 24 h in small animals and as long as 14 days in adult humans. The DLW isotope technique is particularly useful for measuring an average metabolic rate ("field metabolic rate") over days or weeks when direct or indirect calorimetry would be impractical*.

Appendix 2: Rating the Perceived Effort

Early in the nineteenth century, models of the relationships between a physical stimulus and one's perceptual sensation of that stimulus (its psychophysical correlate) were developed. In 1834, Weber suggested that the "just noticeable difference" ΔI depends on the absolute magnitude of the physical stimulus I:

$$\Delta I = a \times I \tag{8.1}$$

where a is constant.

In 1860, Fechner related the magnitude of the "perceived sensation P" to the magnitude of the stimulus I:

$$P = b + c \log I \tag{8.2}$$

where b and c are constants.

In the 1950s, Stevens and Ekman introduced ratio scales (with a zero point and equidistant scale values), to describe the relationships between the perceived intensity I and the physically measured intensity P of a stimulus:

$$P = d \times I^n \tag{8.3}$$

where d is a constant and n ranges from 0.5 to 4, depending on the modality.

Since the 1960s, Borg and collaborators have modified these relationships to take into account deviations from previous assumptions (such as zero point and equidistance), and to describe the perception of different kinds of physical efforts. Borg's "General Function" is:

$$P = e + f\,(I - g)^n. \tag{8.4}$$

The constant e represents "the basic conceptual noise" (normally below 10% of I) and the constant f indicates the starting point of the curve; g is a conversion factor that depends on the type of effort.

Ratio scales indicate only proportions between percepts, but do not indicate absolute intensity levels. They neither allow intermodal comparisons nor comparisons between intensities perceived by different individuals. Borg has tried to overcome this problem by assuming that the subjective range and intensity level are about the same for each subject at the level of maximum intensity. In 1960, this led to the development of a "category scale" for the Rating of Perceived Exertion (RPE). The scale ranges from 6 to 20 (to match heart rates from 60 to 200 bpm) with equidistant steps. Every second number is verbally anchored:

Borg RPE Scale

- 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)

In 1980, Borg proposed the CR-10 Scale, a category scale with steps in constant ratios, said to retain the same correlation (of about 0.88) with heart rate as the RPE scale, particularly if large muscles were involved in the effort.

Borg CR-10 Scale

- 0 – nothing at all
- 0.5 – extremely weak, just noticeable
- 1 – very weak
- 2 – weak, light
- 3 – moderate
- 4 – somewhat strong
- 5 – strong, heavy
- 6
- 7 – very strong
- 8
- 9
- 10 – extremely strong, almost maximal
- 11 or higher – The individual's absolute maximum, highest possible.

(Note: The terms "weak" and "strong" may be replaced by "light," or "hard," or "heavy," respectively).

Just as any other psychophysical measurements, Borg scales need rigidly controlled procedures to yield credible results. For example, put the CR 10 Scale in front of the person who will rate the perceived intensity of work, with these instructions:

> *You do not have to specify your feelings, but do select the number that most correctly reflects your perception of the job demands. If you feel no loading, you should answer zero, nothing at all. If you start to feel something just noticeable, your answer is 0.5, extremely weak. If you have an extremely strong impression, your answer will be 10. So, the more you feel, the higher the number you are choosing. Keep in mind that there are no wrong numbers; be honest, do not overestimate or underestimate your ratings.*

Borg claims that his scales have high reliability (meaning that a repeated test yields the same results as the initial test) and high validity because the test results correlate well with measures of heart rate*.

Glossary

Aerobic In the presence of oxygen.

Anaerobic In the absence of oxygen.

Basal metabolism Energy that suffices to keep the body alive while no effort is done.

Calorimeter A sealed chamber used to measure the heat eliminated from or stored in a body.

Calorimetry Measurement of the heat eliminated from or stored in a system.

Direct calorimetry Measurement of heat actually produced by the body which is confined in a sealed chamber, calorimeter (See there).

Energy In physics, the capacity of a physical system to do work.

Ergometer A device, usually a stationary braked bicycle, used for measuring the amount of work done by the whole body or by arms, legs, or specific muscles.

Ergometry The study of physical work activity, often done with testing equipment such a treadmills or bicycle ergometer (See there).

Ergonomics The application of scientific principles, methods and data drawn from a variety of disciplines to the design of engineered systems in which people play significant roles.

Indirect calorimetry Estimation of produced body energy by means of the differences of oxygen and carbon dioxide in the inspired and expired air.

Metabolism Chemical processes in the living body; in a narrower sense, the energy-yielding processes.

Oxygen deficit The discrepancy between required oxygen and available oxygen.

Plethysmograph Instrument to record variations in the size of parts of the body, such as of the chest circumference with breathing or of the finger volume with blood pulses.

Resting metabolism Energy that suffices to keep the body functioning while at rest.

Work metabolism Energy that suffices to keep the body functioning while at work.

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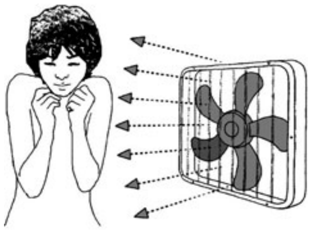
Chapter 9
Thermal Environment



Overview

The body generates energy; some of it is used to do work, the rest must be dissipated as heat, mostly by convection and evaporation. The body may also receive heat from the environment by radiation, convection and conduction. Physiologic and physical means exists for affecting this energy transfer; engineering control of the macro- and micro-climate are at hand for generating suitable ergonomic conditions.

The Model

The human body generates energy and exchanges (gains or looses) energy with the environment. Since a rather constant core temperature must be maintained, suitable heat flow between the body and the environment must be achieved. The internal energy flow is primarily controlled in the body masses between skin and core. Clothing affects the heat exchange with the surrounds. Within built structures, the climate usually can be controlled by technical means.

Introduction

It is convenient to use the simple concepts of "core" and "shell" of the human body although, in reality, the body's temperature regulation system maintains diverse temperatures at various locations under different conditions. The "core" is thought to consist mainly of brain, heart, lungs, and abdominal organs; the "shell" is essentially the skin.

Two overriding principles govern the main aspects of heat flow between the body and the environment, and within the body:

1. Heat flows from the warmer to the colder matter, as per the "Second Law of Thermodynamics".
2. Body core temperature must remain close to 37°C.

K.H.E. Kroemer et al., *Engineering Physiology*, 4th ed.,
DOI 10.1007/978-3-642-12883-7_9,

The Human Body as a Thermo-Regulated System

There is a small temperature fluctuation in the human body throughout the day due to the circadian rhythm and activity, as discussed in Chap. 10. However, the main impact upon the human thermal regulatory system results from the interaction between metabolic heat generated within the body and external energy gained in hot surroundings or lost in cool environments.

The human body has a complex control system to maintain its core temperature near 37°C. Changes in core temperature of ±2°C from 37°C affect body functions and task performance severely; deviations of ±6°C can be lethal.

If the deep body temperature deviates just a few degrees from 37°C, physical and mental work capacities are impaired. Changes in body temperature affect cellular structures, enzyme systems, and many other functions. If the temperature in a human cell exceeds 45°C, heat coagulation of proteins takes place. If the temperature falls to freezing, ice crystals break the cell apart. In the effort to protect itself from conditions that are either too hot or too cold, the body uses an intricate regulation system to keep temperatures well above freezing and, in its outer layers, below the 40s.

The Energy Balance

When discussing the metabolic system in Chap. 7, the energy balance (Eq. 7.1) between body energy inputs and outputs was described as

$$I = M = H + W + S. \tag{9.1}$$

- I is the energy input via nutrition which is converted into the body's
- rate of metabolic energy production M;
- W is the rate of external work done;
- H is the rate of heat that must be released from the body, and
- S is the rate of energy storage in the body.

Traditionally, all energy rates are in Watts or in Joules per second (1 W = 1 J/s), and per square meter of the involved body surface*.

If not all metabolic energy can be dispelled to the environs and/or energy is transferred from the environment to the body, the heat storage S in the body increases. If S becomes smaller, more than H must have been lost from the body to the environment.

If there is no change in the quantity of heat storage S, the system is in balance. Furthermore assuming that the quantities I and W remain unchanged, allows simplifying the equation that describes the energy exchange with the thermal environment: thermal balance is achieved when the energy

$$I - W = H \tag{9.2}$$

is dissipated to the environment while no energy is gained from the environs.

Energy Exchanges with the Environment

The body exchanges heat energy with the environment through radiation, convection, conduction, and evaporation*.

Radiation Heat Exchange

An object at temperature greater than absolute zero emits radiant energy. Heat exchange through radiation (R) depends primarily on the temperature difference between two opposing surfaces, for example of a window pane and a person's skin. (The exchange of heat by radiation does not depend on the temperature of the air between the two exchanging surfaces.) Heat always radiates from the warmer to the colder surface: from the skin to the cold window pane in the winter; in the summer, to the body from a sun-heated pane. Therefore, the body can lose or gain heat through radiation, as sketched in Figs. 9.1 and 9.2.

Fig. 9.1 Heat loss through radiation (adapted from Kroemer and Kroemer, 2005)

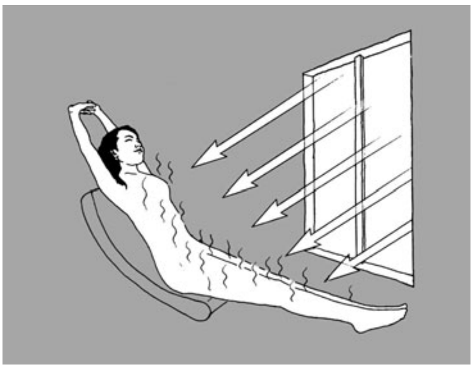


Fig. 9.2 Heat gain through radiation (adapted from Kroemer and Kroemer, 2005)

The “Stefan-Boltzmann Law of Radiative Heat Transfer” allows calculating the amount of radiating energy Q_R (in W = J/s) gained (+) or lost (–) by the human body:

$$Q_R = a \times S\,(d \times T_0^4 - e \times T^4). \tag{9.3}$$

- a = Stefan-Boltzmann Radiation Constant in J/(sm^2 K^4), K in degrees Kelvin – see Fig. 9.3.
- S = body surface participating in the energy exchange, in m^2.
- d = absorption coefficient of the receiving surface – see below.
- T_0 = temperature of the receiving surface, in °K.
- e = emission coefficient of the emitting surface – see below.
- T = body surface temperature of the emitting surface, in °K.

The absorption coefficient d depends on skin color; for solar rays (with wavelengths $0.3 < \lambda < 4$ µm) it ranges from 0.6 for light skinned people to 0.8 for dark skinned persons. The wave lengths of radiation emitted from the human body are in the infrared range, $3 < \lambda < 60$ µm. Hence, it radiates like a black body, with

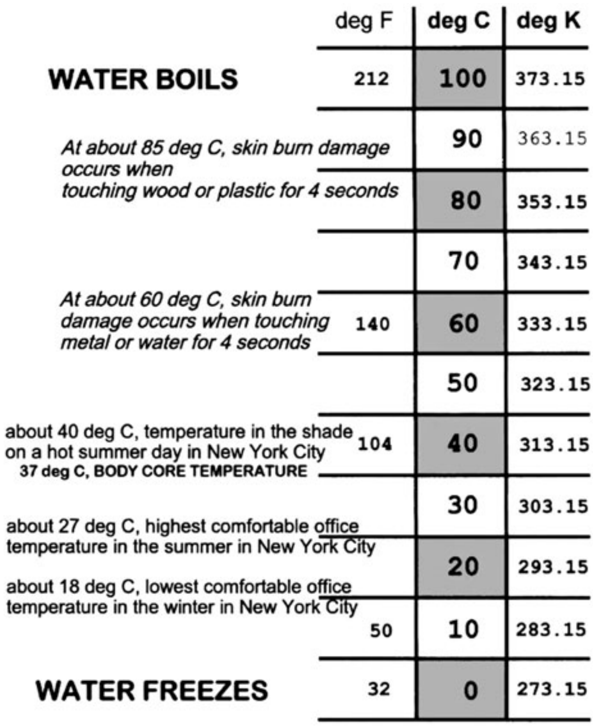


Fig. 9.3 Temperature scales in common use

an emission coefficient e close to 1, independent of the actual color of the radiating human skin. An overall estimate for energy transfer through radiation is about 4.5 W/m^2 of surface and degree of temperature difference*.

Figure 9.3 illustrates the temperature scales in common use: The internationally employed Celsius (also called Centigrade) and the Kelvin scales; the Fahrenheit scale is still in some use in the USA: water freezes at 0°C, 273.15°K and 32°F; water boils at 100°C, 373.15°K and 212°F.

Conduction Heat Exchange

Conduction is heat transfer by molecular contact. Energy exchanges through conduction and by convection (see below) both follow "Newton's Law of Cooling": the amount of heat transferred is proportional to the area of human skin participating in the process, and to the temperature difference between skin and the adjacent layer of the external medium.

Heat exchange through conductance (K) exists when skin contacts a solid body. Energy flows from the warmer body to the colder one; as the temperatures of the contact surfaces become equal, the energy exchange ceases.

The amount of energy exchanged by conduction is

$$Q_K = h \times S\,(t_m - t). \tag{9.4}$$

h = thermal conductivity coefficient – see below.
S = body surface participating in the heat exchange, in m^2.
t_m = temperature of the medium with which S is in contact, in °C.
t = temperature of the body surface S, in °C.

The rate and amount of heat exchanged depend on the ability of the contacting material to transfer heat. At the same low temperature, wood or cork "feel warmer" than metal because their heat conductivity is low whereas the metal accepts body heat easily and conducts it away. The quantity of exchanged energy also depends on the tightness with which the bodies touch. Insulating material between skin and object affects the amount of energy transferred by conduction; more on this below in the discussion of clothing insulation.

Convection Heat Exchange

Convection is the transfer of heat by circulation of particles of a gas or liquid. Exchange of heat through convection (C) takes place when the human skin is in contact with air or with a fluid, usually water. Heat energy migrates from the skin to a layer of colder gas or fluid next to the skin; heat passes to the skin if the surrounding medium is warmer.

As long as the temperatures of the skin and the surround differ, there is some natural movement of the air or fluid: this is called "free convection". As the medium moves along the skin surface, it removes the boundary layer whose temperature has become close to skin temperature; so, relative motion helps to maintain a temperature differential that facilitates convective heat exchange. Forced action (by wind or an air fan, for example, or while swimming in water rather than floating motionless) can produce much more movement: this "induced convection" increases the energy transfer.

The process of exchanging heat via convection Q_C (gain indicated by +, loss by –) is similar to conduction:

$$Q_C = c \times S\,(t_m - t). \tag{9.5}$$

In air, the convection coefficient c_a is between 2 and 25 W/(m^2°C), depending on the relative movement of the medium*. Forced convection in air can be as high as 250 W/(m^2°C); an example is "wind chill", discussed below. For the nude body in still water, the convective transfer coefficient c_w is about 230 W/(m^2°C) for $t_m < t$ when the body is at rest; the value can more than double when the human swims at any speed because of the turbulence of the water layer near the body produced by the swimming motions*.

Evaporation Heat Exchange

Evaporation is the change of a liquid (here, water) to vapor; this phase change requires heat. As evaporation (E) occurs on the skin or in the lungs, the energy is extracted from the body, which cools it. For the human, heat exchange by *evaporation* E is only in one direction: the body loses heat. (There is no condensation of water on the body, which would add heat.) Evaporation of water (sweat) on warm skin requires an energy of about 2,427 J/cm^3 (580 cal/cm^3), which reduces the heat content of the body by that amount.

The heat lost by evaporation Q_E from the human body is a function of participating wet body surface, humidity and vapor pressures*.

$$Q_E \sim [S, h_r\,(p_a - p)] \tag{9.6}$$

S = body surface participating in the heat dispersion.
h_r = relative humidity of the surrounding air.
p_a = vapor pressure in the surrounding air.
p = vapor pressure at the skin.

Of course, Q_E is zero for $p \le p_a$ since heat loss by evaporation can only exist if the surrounding air is less humid than the air directly at the skin. Therefore, movement of the air layer at the skin (see convection) increases the actual heat loss through evaporation if this replaces humid air by dryer air.

Some evaporative heat loss occurs even in a cold environment because there is always evaporation of water in the warm lungs; the evaporation rate increases with enlarged ventilation at heavier work. Also, secretion of sweat onto the skin surface occurs in physical work even in cold environs. The nude body loses, at rest, in the cold 3 to 6 W/m^2 from the respiratory tract and, at work, up to 10 W/m^2 from the skin*.

Heat Balance

Heat balance between the body and its surrounds exists when the heat H developed in the body, change in heat storage S in the body, and heat exchanged with the environment by radiation R, conduction K, convection C, and evaporation E are in equilibrium:

$$H + S + R + K + C + E = 0 \ (\textit{zero}). \quad (9.7)$$

The quantities S, R, K, C, and E are counted as positive if the body gains energy, negative if the body loses energy. The quantity H is always positive, quantity E can only be negative.

Figure 9.4 indicates schematically how the different kinds of heat transfer affect the body. In general, heat loss by radiation diminishes as the environment gets warmer while heat loss by evaporation increases.

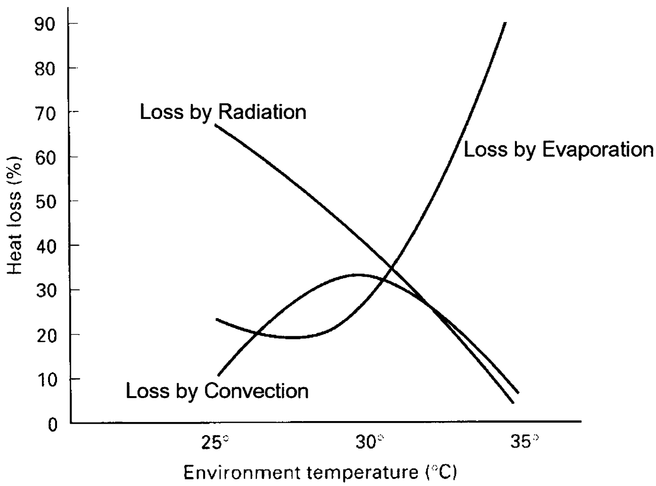


Fig. 9.4 Cooling the body in a warm environment (adapted from Kroemer et al., 2003)

Regulation and Sensation of Temperature

The body produces heat in its "metabolically active" tissues: primarily at skeletal muscles, but also in internal organs, fat, bone, connective and nerve tissues.

Heat energy is circulated throughout the body by the blood. The heart generates the flow of blood and controls its pressure and volume per time. The vasomotor actions of constriction, dilation, and shunting modulate the local flow of blood – see Chap. 6.

Heat exchange with the environment takes place mostly through the skin and at the body's respiratory surfaces.

In a cold environment, the body must conserve heat. This is primarily done by cooling the skin via (unconscious) reduction of blood flow to the skin and by increasing insulation via clothing.

In a hot environment, the body must dissipate heat and also prevent heat gain from the environment. This is mainly done by warming the skin via (unconsciously) increasing blood flow to the skin, by sweat production and evaporation; and by choosing suitable clothing.

The body regulates its temperature to prevent undercooling (hypothermia) or overheating (hyperthermia). The control system strives to keep the temperature of the body core constant, close to 37°C, with only slight variations throughout the day with circadian rhythms. However, there can be large temperature differences between the core and the shell: under normal conditions, the average gradient between skin and deep body is about 4°C at rest, but the difference in temperature can be 20°C or more in cold or hot environments.

Figure 9.5 shows a model of the regulation of the human energy balance with three components: the controlling, the effecting, and the regulated subsystems.

Various temperature sensors are located in the core and the shell of the body. Hot sensors react strongly from about 38 to 43°C while major sensitivity to cold conditions is around 15 to 35°C. Up to roughly 45°C, the perceptions of "cool" and "warm" are highly adaptable. A paradoxical effect is that, near 45°C, sensors signal "cold" while in fact the temperature is rather hot. Below 15 and above 45°C the human temperature sensors are less discriminating but also less adapting.

The human body has given set temperature points, close 37°C in the core and, highly variable, around 33°C at the skin. Temperature sensors detect deviations from existing set values and signal these to the hypothalamus, which initiates counteractions via three different neural pathways: the efferent nervous system changes muscle activities, the sudomotor system regulates sweat production, and the vasomotor system controls blood flow.

Muscular activities can generate only more or less heat but cannot cool the body. So, if internal heat production must be diminished, muscular activities will be reduced, possibly to the extent that no work is being performed anymore.

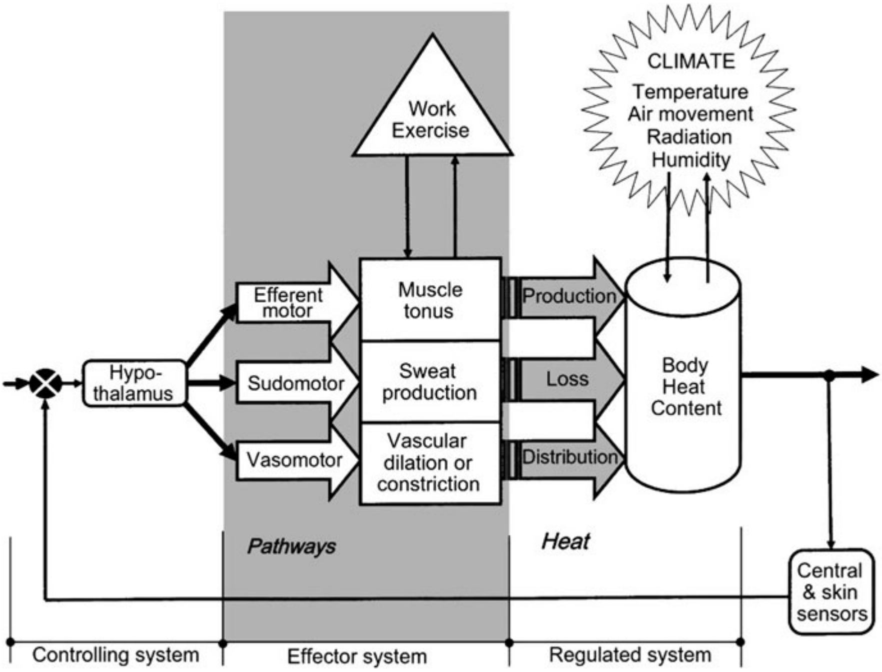


Fig. 9.5 Model of the regulation of body heat content

Conversely, if more heat must be generated, the work or exercise level will be augmented by increased muscular activities. (Given the low efficiency of muscular work, it generates much heat – see Chap. 7.)

In contrast, sweat production only influences the amount of energy lost but cannot bring about a heat gain. Vascular activities can affect the heat distribution through the body and control heat loss or gain, but they do not generate energy.

Muscular, vascular, and sweat production functions regulate the body heat content in direct interaction with the external climate. The climate itself is defined by humidity, radiation, temperature, and air (or fluid) movement, as discussed later.

Achieving Thermal Homeostasis

Overheating or undercooling of the core organs in the brain and the trunk must be avoided, even at the cost of overheating or undercooling the shell. To assure proper temperature at the core, the human regulatory system must generate two suitable temperature gradients:

1. From the core to the skin and
2. From the skin to the surroundings.

The gradient from the core to the skin is of greatest importance. Proper heat flow is *primarily* achieved by regulation of the blood stream from deep tissues and muscles to the skin. The body accomplishes this mostly in the peripheral tissues by vascular dilation, constriction, or shunting (see Chap. 6) in the network of superficial arteries and veins. Regulating the stream of blood is an efficient way to regulate transport and distribution of heat within the body: each gram of blood can absorb and transport about 4 J of energy. Controlling the shell temperature is essential because of the total heat exchanged with the environment, most is transferred through the skin; the remainder is exchanged in the lungs.

Secondary activities to establish thermal homeostasis take place at the muscles. The goal of the regulatory system determines which actions are taken: if more heat is needed, skeletal muscle contractions are initiated; in the cold, this may be involuntary shivering. If too much heat is generated in the body, muscular activities are reduced, even abolished.

Purposeful changes in clothing and shelter are *tertiary* actions to achieve thermal homeostasis. They affect radiation, convection, conduction, and evaporation. "Light" or "heavy" clothes have different permeability and ability to establish stationary insulating layers. Clothes influence conductance, energy transmitted per surface and unit time, and temperature gradient. Also, their color determines how much external radiation energy is absorbed or reflected*. Similar effects are brought about by shelters, which by their material, distance from the body, form and color determine whether heat is gained or lost by the body through radiation, convection, and evaporation.

Measuring Body Temperatures

One way of assessing the exchange of heat energy with the environment is to perform direct calorimetry, where a person is placed into an energy-tight compartment which allows the measurement of all heat energies exchanged – see Chap. 8. However, this is a tedious procedure which severely limits the ability of the person to work "normally". Most methods to assess the heat balance are based on temperature measurements within or at the body.

The so-called safe temperature range of the core is between 35 and 40°C. Below 33 and above 42°C, serious impairment of functions especially in the brain and heart occur. Changes in core temperatures, particularly severe deviations from the "safe" temperatures, indicate work and environmental overloads or dysfunctions of the energy regulatory mechanisms in the body.

A variety of techniques exist to measure the temperature in body parts. A "traditional" site is the rectum, where temperature probes are usually inserted 5–10 cm behind the sphincter. With the hypothalamus providing the reference temperature, the rectal temperature is usually about 0.5°C lower, provided that a steady state has been maintained for about 30 min. The rectal temperature of a resting individual is slightly higher than the temperature of arterial blood and about the same as in the liver. Brain temperature rises more quickly in response to heat influx than rectal temperature.

Temperatures measured at the ear drum follow actual brain temperatures rather closely. Inserting a temperature probe into the esophagus or the stomach allows measurement of deep body temperatures.

Temperature measurement in the mouth, in the armpit or on the skin is less accurate but rather easily done and socially more acceptable.

Skin temperatures may be very different from the core temperature. Skin temperatures can vary substantially over time, such as during exposure to heat or cold. Under cold conditions, with the core temperature maintained at approximately 37°C, the trunk may have skin temperatures of about 36°C; the thighs may be at 34°C, the upper arms and knees at 32°C, the lower arms at 28°C, while the toes and fingers may be at 25°C; this combination may feel quite agreeable. Such large differences in skin temperatures indicate the effectiveness of the human thermoregulatory mechanisms, particularly shunting and vasoconstriction, in the cold. They also indicate how the body must be protected by clothing to avoid chilling of body segments below an acceptable temperature. Obviously, fingers and feet need special protection in cold conditions.

The temperatures of the neck and head do not vary much. Here, the "core" is close to the shell and very little volume below the skin is available for vasomotor and sudomotor functions. To keep the core warm, skin temperature must be maintained at a rather constant and high level.

Measurement of temperatures at skin sites other than on neck and head provides information that is only loosely related to core temperatures. Hence, the concept of an "average skin temperature" is a difficult one; nevertheless, it has been employed by assigning weighting factors to the measurements taken at various body surfaces, depending on the locations and proportions of these surface areas compared to the total body. For example, the well-established "Hardy and Dubois" procedure is to multiply measurements taken at the head by 0.07, the arms by 0.14, the hands by 0.05, the trunk by 0.35, the thighs by 0.19, the lower legs by 0.13, and at the feet by 0.07. The results are added for an "average" skin temperature*.

Other techniques to measure skin temperatures at specific points, or to establish some sort of average skin temperature, use infrared thermography or scanning radiometers. However, such approaches are still subject to the underlying interconnected problems of definition, sampling and statistical treatment.

Various related procedures exist to measure and calculate the mechanisms of heat regulation. For example, if one establishes an "average" skin temperature t_s, measures the rectal temperature t_r, and knows the body mass m in kg, one can calculate the heat content from the "Burton equation":

$$\text{Heat content} = 3.47\, m\, (0.65\, t_r + 0.35\, t_s). \tag{9.8}$$

However, the specific heat of the body, for this equation assumed to be 3.47 kJ/(kg °C), may vary considerably, depending on the individual's body composition. Also, the ratios of t_r and t_s, respectively assumed to be 0.65 and 0.35, are not fixed but range from 0.9 and 0.1 in warm environments and during exercise to 0.6 and 0.4 at rest in a cool environment*.

Assessing the Thermal Environment

Four physical factors describe the thermal environment: ambient air (or water) temperature, ambient humidity, air (or water) movement, and temperatures of surfaces that exchange heat by radiation. The combination of these factors determines the physical conditions of the climate and our perception of it.

Ambient Temperature

Measurement of ambient temperature is traditionally performed with thermometers, usually filled with alcohol or mercury; thermistors, thermocouples and other techniques can be used as well. In any case, it must be ensured that other climate factors (humidity, air movement, and heat radiation) do not affect the measure of the ambient air temperature. The usual way is to keep the sensor dry and shield it in a reflecting bulb from radiated energy. Hence, air temperature is commonly measured with a so-called dry bulb thermometer and often called “dry bulb temperature” or simply “dry temperature”.

Air Humidity

Air humidity, the content of water vapor in air, can be measured with a hygrometer: originally a human or horse hair that changes its length with wetness, now an instrument whose electrical conductivity (resistance/capacitance) changes with the existing humidity. Another instrument is the psychrometer (hygrometer) that consists of one dry and one wetted thermometer; evaporation cools the wet thermometer more than the dry one. The difference is proportional to the humidity of the air, as higher vapor pressure reduces evaporative cooling. A hygrometer is called natural if there is no artificial air movement around it, forced if there is.

Air humidity may be expressed either in absolute or in relative terms. The highest absolute content of vapor in the air, saturation, is reached when any further increase would lead to the development of water droplets, falling out of the gas. This “dew point” depends on air temperature and barometric pressure: higher temperature and pressure allow more water vapor to be retained than lower conditions. However, one mostly speaks of relative humidity, which indicates the actual vapor content (usually in percent) in relation to the possible maximal content at the given air temperature and air pressure.

Air Movement

Air movement is measured with various types of anemometers, usually based on electrical or mechanical principles, such as using windmill. One may also measure air movement with two thermometers, one dry and one wet (similar to what can be done to assess humidity), relying on the fact that the wet thermometer shows more increased evaporative cooling with higher air movement than the dry thermometer. Air movement helps particularly in convective heat exchange because it moves "fresh" (less moist) air to skin surfaces. Here, turbulent air movement is as effective as laminar movement in heat transfer. The effects of wind chill are described below.

Radiant Heat

Radiant heat exchange depends primarily on the difference in temperatures between the individual and the surroundings; it also depends on the emission properties of the radiating surface and on the absorption characteristics of the receiving surface. While there is no problem in measuring surface temperatures, which are the major factors in human-environment energy transmission by radiation, one easy and direct way to assess the amount of energy transferred is to place a thermometer inside a black globe, which absorbs practically all radiated heat energy.

The Combined Effects of Climate Factors

In the past, several techniques were used to express the combined effects of the four environmental factors in one model, chart, or index; prominent examples are the various versions of "Effective Temperature" scales*. However, in most cases of warm and hot environments, the WBGT (Wet Bulb Globe Temperature) index weighs the effects of all climate parameters with sufficient validity, reliability and usability. The index exists in two versions; one applied outdoors, the other indoors.

The WBGT requires measurement of only three variables:

1. WB; natural *Wet Bulb* temperature of a sensor in a wet wick exposed to air;
2. GT; *Globe Temperature* at the center of a black sphere of 15 cm diameter;
3. DB; *Dry Bulb* temperature measured with a sensor shielded from radiation.

These parameters are the factors in the two forms of the WBGT index, which have been internationally accepted for assessing the effects of warm or hot climates on healthy, acclimatized persons wearing appropriate clothing. (There is some concern, however, about the adequacy of the WBGT for extreme conditions, such as in a hot desert, and for combinations of high humidity with little air movement*.)

The outdoors WBGT considers the effect of heat radiation, usually solar radiation outdoors; it also applies to a person in sunlight indoors:

Table 9.1 "Safe" WBGT values for US workers. The WBGTs of the workplace and of the rest area are assumed to be similar (adapted from OSHA Technical Manual TED 01-00-015, 1999)

	Intensity of work (metabolic rate in Watt)		
Hourly work/rest ratio	Light, <230 W	Moderate, 230 to 400 W	Heavy, >400 W
Continuous work	30.0	26.7	25.0
75% work, 25% rest	30.6	28.0	25.9
50% work, 50% rest	31.4	29.4	27.9
25% work, 75% rest	32.2	31.1	30.0

$$\text{WBGT (outdoors)} = 0.7\ \text{WB} + 0.2\ \text{GT} + 0.1\ \text{DB}. \tag{9.9}$$

Without intensive radiated heat, solar or other, the simpler indoors WBGT applies:

$$\text{WBGT (indoors)} = 0.7\ \text{WB} + 0.3\ \text{GT}. \tag{9.10}$$

In different regions on earth, professional, international and military agencies provide WBGT recommendations for "safe" work in hot environments. Table 9.1 lists recommended upper WBGT temperatures for US workers of 70 kg body weight, acclimatized and wearing suitable clothing.

Reactions of the Body to Hot Environments

In hot environments, the body produces heat and must dissipate it by convection, conduction, radiation and evaporation. This body tries to achieve the difficult task of dispelling heat into a warm environment primarily by regulating blood distribution and metabolic rate.

Redistribution of Blood

The easiest way to accomplish outward heat energy flow is to have the skin temperature above the temperature of the immediate environment. To achieve this, the body directs blood flow to the skin: the skin vessels are dilated and the superficial veins fully opened. This can enlarge the blood flow fourfold above the resting level. The increased conductance of surface tissues facilitates energy loss through convection, conduction, and radiation because all are proportional to the temperature differential between skin and environment.

However, in a hot environment it is difficult to increase the skin temperature above the ambient temperature. If not enough heat can be transferred via a temperature differential, the body's sudomotor system activates sweat glands so that evaporation of the produced sweat may cool the skin. Recruitment of sweat glands from different areas of the body varies among individuals. Large differences in the ability to sweat exist among individuals: some persons have few sweat glands, while most have at least 2 million sweat glands in the skin. The activity of each sweat gland is cyclic. The overall amount of sweat developed and evaporated depends very much on clothing, environment, work requirements, and on the individual's acclimatization.

Reduction of Muscle Activities

If heat transfer by blood distribution and sweat evaporation remains insufficient to keep the body cool enough in a hot environment, the body must reduce its muscular activities in order to lower the amount of energy generated through metabolic processes. This is the final and necessary action of the body if otherwise the core temperature would exceed a tolerable limit. If the body has to choose between unacceptable overheating and continuing to perform physical work, the choice will be in favor of core temperature maintenance, which means reduction or cessation of work or exercise.

Indications of Heat Strain

There are several signs of excessive heat strain on the body. The first one is the sweat rate. The normal so-called insensible perspiration is about 50 cm^3/h. Sweat production increases depending on the heat that must be dissipated. In strenuous exercises and hot climates, several liters of sweat may be produced in one hour; sweat losses up to 12 L in 24 hours have been reported under extreme conditions.

Sweat begins to drip off the skin when the sweat generation has reached about 1/3 of the maximal evaporative capacity. Of course, sweat running down the skin, instead of being evaporated, contributes very little to heat transfer.

Other signals of heat strain are increased circulatory activities. To boost blood flow, cardiac output must be enlarged, mostly brought about by higher heart rate. This may be associated with a reduction in systolic blood pressure.

The water balance within the body provides another sign of heat strain. Dehydration indicated by the loss of only 1 or 2% of body weight can critically affect the ability of the body to control its functions. Therefore, the fluid level must be maintained, best by frequently drinking small amounts of water.

Sweating, which extracts water from the plasma, augments the relative salt content of the blood, but diminishes the overall salt content of the body because sweat contains salts, particularly NaCl. Normally, with western diets it is not necessary to add salt to drinking water since the salt in the food is sufficient to resupply salt lost with the sweat.

Among the first reactions to heavy exercise in excessive heat are sensations of discomfort and perhaps skin eruptions ("prickly heat") associated with sweating. As a result of sweating, so-called heat cramps may develop, which are muscle spasms related to local lack of salt. They may also occur after quickly drinking large amounts of fluid.

Heat exhaustion usually results from dehydration and overloading the circulatory system. Associated effects are fatigue, headache, nausea, dizziness, often accompanied by giddy behavior. Heat syncope signals a failure of the circulatory system, demonstrated by fainting. Heat stroke indicates an overloading of both the circulatory and sweating systems and is associated with hot dry skin, increased core temperature, and mental confusion. Table 9.2 lists symptoms, causes, and treatment of heat stress disorders.

Table 9.2 Heat stress disorders (adapted from OSHA Technical Manual TED 01-00-015, 1999)

	Symptoms	Causes	Treatments
Transient heat fatigue	Decreases in productivity, alertness, coordination and vigilance	Not acclimatized to hot environment	Gradual adjustment to hot environment
Heat rash, "prickly heat"	Skin rash in areas of heavy perspiration; discomfort or temporary disability	Perspiration not removed from skin, possibly inflamed sweat glands	Periodic rests in cooler area; shower; dry skin
Heat collapse, "fainting"	Blackout; collapse	Shortage of oxygen in the brain	Lay down, cool down
Heat cramps	Painful spasms of skeletal muscles	Loss or excess of salt; large quantity of water drunk quickly	Adequate salt with meals; salted liquids if recommended by a physician
Heat exhaustion	Extreme weakness or fatigue; thirst; giddiness; nausea; headache; pale or flushed complexion; body temperature normal or slightly higher; moist skin; in extreme cases vomiting and/or loss of consciousness	Loss of water and/or salt; loss of blood plasma; strain on the circulatory system	Rest in cooler area; salted liquids if recommended by a physician
Heat stroke	Skin hot, usually dry and often red or spotted; core temperature 41°C or higher and rising; irrational behavior; mental confusion; deliriousness; convulsions; unconsciousness possible. Death or permanent brain damage may result unless treated immediately	Breakdown of the thermo-regulatory system; stoppage of sweating. The body's ability to remove excess heat is almost eliminated	Remove to cool area; soak clothing with cold water; fan body; *call physician/ambulance immediately*

Acclimatization to Heat

Continuous or repeated exposure to hot conditions brings about a gradual adjustment of body functions resulting in a better tolerance of the climatic stress and in improvement of physical work capabilities. Overall, acclimatization to heat is demonstrated by an increased sweat production, by lowered skin and core temperatures, and by a reduced heart rate, compared with the reactions of the unacclimatized person at first exposure to the hot climate. The process of acclimation is pronounced within about a week and full acclimatization is achieved within about 2 weeks. Interruption of heat exposure of just a few days reduces the lingering effects of acclimatization, which is entirely lost within about 2 weeks after return to a moderate climate.

Specifically, heat acclimatization is brought about by improved control of the vascular flow, by an augmented stroke volume accompanied by a reduced heart rate, and by higher sweat production. The improvement in sudomotor action is most prominent; it manifests itself not only by larger sweat volume but also by an equalization of the sweat production over time and an increase of the activities of the sweat glands of the trunk and the extremities. Perspiration on the face and the feeling of "sweating" becomes less with heat acclimation, although total sweat production may be doubled after several days of exposure to the hot environment. More volume and better regulation of sweat distribution are the primary means of the human body to bring about dissipation of metabolic heat.

This sudomotor advancement intertwines with vasomotor improvements. The reduced skin temperature (lowered through sweating) allows a redistribution of the blood flow away from the skin surfaces, which need more blood during initial exposure to heat. Acclimation re-establishes normal blood distribution within a week or two. Cardiac output must remain rather constant even during initial heat exposure, when an increase in heart rate and a reduction in stroke volume occur. Both rate and volume are reciprocally adjusted during acclimation since arterial blood pressure remains essentially unaltered. There may also be a (relatively small) change in total blood volume during acclimation, particularly an increase of plasma volume during the first phase of adjustment to heat.

A healthy and well-trained person acclimates more easily then somebody in poor condition, but training cannot replace acclimatization. If strenuous physical work must be performed in a hot climate, then such work should be part of the acclimation period.

On average, the female body has smaller mass than the male, meaning a smaller heat "sink"; women usually have relatively more body fat and accordingly less lean body mass than men. However, their surface area is smaller, and their blood volume is smaller as well. Nevertheless, there are no great differences between females and males with respect to their ability to adapt to a hot climate; possibly women have a slightly higher risk for heat exhaustion and collapse. However, these slight statistical tendencies can be easily counteracted by ergonomic means and may not be obvious at all when observing only a few persons of either gender.

Adjustment to heat will take place whether the climate is hot and dry, or hot and humid. Acclimatization seems to be unaffected by the type of work performed, either heavy and short or moderate but continuous. It is important to replace fluid (and possibly salt) losses during acclimation and throughout heat exposure.

Reactions of the Body to Cold Environments

In a cold environment, the body must conserve its produced heat. The most effective actions to this end are behavioral: putting on suitable clothing to cover the skin, seeking shelter, or using external sources of warmth. The human body has only limited natural means to regulate its temperature in response to a cold surround: these are mainly re-distribution of the blood flow and increasing metabolic rates.

Redistribution of Blood

To conserve heat, the body lowers the temperature of its skin: this reduces the temperature difference against the cold outside and, consequently, decreases the outflow of heat. Lowering the skin temperature is done by displacing the circulating blood from the periphery towards the core, away from the skin. This can be rather dramatic; for example, the blood flow in the fingers may be reduced to a very small percentage of what existed in a moderate climate.

Of the total circulating blood volume in the body, around 5 L, normally about 5% flows through the blood vessels in the skin. The body employs several procedures to regulate the distribution of blood, apparently under the control of the sympathetic nervous system (see Chap. 3) in addition to local reflex reactions to direct cold stimuli. One way to control blood flow is cutaneous vasoconstriction, which cuts off many of the blood vessel pathways; so, less blood flows towards the superficial skin surfaces. At the same time, the body re-routs blood from the superficial veins of the extremities near the skin to deep veins. Many deep veins are anatomically close to arteries, which carry warm blood from the heart. Heat exchange between the cooler blood in the veins and the warmer blood in the arteries has two effects: cooling of the body core is reduced because of the warmed venous return of blood, and cooled arterial blood supplying the extremities and skin keeps them cooler, which reduces the conductance of the surface tissues and diminishes the energy flow towards the environment.

An interesting phenomenon associated with cutaneous vasoconstriction is the "hunting reflex", a cold-induced vasodilation: after initial constriction has taken place, suddenly a dilation of blood vessels can occur which allows warm blood to return to the skin, often the hands, which re-warms that body section. Then vasoconstriction returns again, and this sequence may be repeated several times.

The body's automatic reactions to a cold environment demonstrate the overriding need to keep the core temperature high enough. Displacing blood volume from the skin to more central circulation is very efficient in keeping the core warm and the surfaces cold. Peripheral vasoconstriction can bring about a six-fold increase in the insulating capacity of the subcutaneous tissues. The associated danger is that the temperature in the peripheral tissues may approach that of the environment. Cold fingers and toes are mostly just unpleasant but serious damage is possible if tissue temperature gets close to freezing.

The blood vessels of neck and head do not undergo much vasoconstriction so they stay warm even in cold environments, with less danger to the tissues; however, the resulting large difference in temperature to the environment brings about a large heat loss, which can be prevented by wearing a helmet, cap, scarf and the like to create an insulating layer.

Incidentally, the development of "goose bumps" of the skin helps to retain a layer of stationary air close to the skin, which is relatively warm and has the effect of an insulating envelope, reducing convective energy loss at the skin.

Heat loss by convection increases when the air moves more swiftly along exposed skin surfaces. In the 1940s, the US Army performed experiments to determine the effects of cold air movement on the cooling of water and how subjects perceived such "wind chill" on their exposed skin: this lead to tables of so-called wind chill temperatures. Around the turn of the century, Canadian and American scientists performed more realistic investigations on convective energy loss through exposed skin depending on air temperature and velocity.

Table 9.3 lists the metric wind chill temperature equivalents which reflect the effects of wind flow at various temperatures. These wind chill temperatures are based on the cooling of naked skin, not on the cooling of a clothed person. Also, these numbers do not take into account air humidity and solar radiation.

Table 9.3 shows, for example, that at zero-degree air temperature, a wind of 5 km/h cools exposed skin in the same way as calm air of –2°C would do; if the wind increases to 50 km/h, it cools exposed skin as still air at a temperature of –8°C would do. If the actual air temperature is –15°, a 50 km/h wind would cool skin like calm air at a temperature of –29°; if the temperature is actually –35°, the same 50 km/h wind cools skin as a calm air temperature of –56° would do and frost bite can occur in 3 min.

Increased Metabolic Heat Production

The other major reaction of the body to a cold environment is to increase the metabolic heat generation. This may occur involuntarily by shivering (thermogenesis). Shivering usually begins in the neck, apparently to warm the important flow of blood to the brain. Often, an increase in overall muscle tone in response to body cooling precedes the onset of shivering. The increased firing rates of motor units (see Chap. 2) without generating actual movements cause a feeling of stiffness; then suddenly shivering begins, caused by muscle units firing at different frequencies of repetition (rate coding) and out of phase with each other (recruitment coding). Since

Table 9.3 Wind chill temperature equivalents

Wind	Actual air temperature °C												
Calm	10	5	0	–5	–10	–15	–20	–25	–30	–35	–40	–45	–50
km/h	Equivalent wind chill temperature °C												
5	9	4	–2	–7	–13	–19	–24	–30	–36	–41	–47	–53	–58
10	9	3	–3	–10	–15	–21	–27	–33	–39	–45	–51	–57	–63
15	8	2	–4	–11	–17	–23	–29	–35	–41	–48	–51	–60	–66
20	7	1	–5	–12	–18	–24	–31	–37	–43	–49	–56	–62	–68
25	7	1	–6	–12	–19	–25	–32	–38	–45	–51	–57	–64	–70
30	7	0	–7	–13	–20	–26	–33	–39	–46	–52	–59	–65	–72
35	6	0	–7	–14	–20	–27	–33	–40	–47	–53	–60	–66	–73
40	6	–1	–7	–14	–21	–27	–34	–41	–48	–54	–61	–68	–74
45	6	–1	–8	–15	–21	–28	–35	–42	–48	–55	–62	–69	–75
50	6	–1	–8	–15	–22	–29	–35	–42	–49	–56	–63	–70	–76
55	5	–2	–9	–15	–22	–29	–36	–43	–50	–57	–63	–70	–77
60	5	–2	–9	–16	–23	–30	–37	–43	–50	–57	–64	–71	–78
	Tissue may freeze after exposure longer than 30 min					<30 min	Freezing risk in 10 min			Freezing risk in 3 min			

no mechanical work is done to the outside, the entire effort is transformed into heat production, allowing an increase in the metabolic rate to up to four times the resting rate. If the body does not become warm, shivering may become violent when motor unit innervations synchronize so that whole muscles are involved. While such shivering may generate heat that is five or more times the resting metabolic rate, it can be maintained only for a short period at a time.

Of course, muscular activities also can be done voluntarily, either by increasing the dynamic muscular work already in progress or by contracting additional muscles, moving body other segments such flexing the fingers. Since the energy efficiency of the body is very low (see Chap. 7), dynamic muscular work may easily increase the generation of metabolic heat to ten times or more over that at rest.

How Cold Does it Feel?

In a cold environment, an individual's decision to stay in the cold or to seek shelter depends on the subjective assessment of how cold body surfaces or the body core actually are. It creates a dangerous situation if a person either fails to perceive and to react to the body's signals that it is becoming too cold or, worse, if the body temperature becomes so low that further cooling is below the threshold of perception.

The perception of the body getting cold depends upon signals received from surface thermal receptors, from sensors in the body core and from a combination of these signals. As skin temperatures decrease below about 36°C, the intensity of the cold sensation increases; cold sensation is strongest near 20°C, but at lower temperatures perception diminishes. It is often difficult to separate feelings of cold from pain and discomfort.

The conditions of cold exposure may greatly influence the perceived coldness. It can make quite a difference whether one is exposed to cold air (with or without movement) or to cold water, whether or not one wears protective clothing, and what one is actually doing. When the temperature plunges, each downward step can generate an "overshoot" sensation of cold sensor receptors which react very quickly not only to the difference in temperature, but also to the rate of change. Yet, if the temperature stabilizes, the cold sensations become smaller as one adapts to the condition. Exposure to very cold water accentuates the overshoot phenomenon observed in cold air. This may be due to the fact that, at the same low temperature, say zero degrees °C, the thermal conductivity of water and hence the convective heat loss are about 25 times greater than in air. In experiments, subjects (wearing a flotation suit) were immersed into cold water of 10°C; their temperatures at groin, back and rectum were continuously recorded, and the subjects rated how cold they perceived these areas to be. The results of the experiment showed that the subjects were unable to reliably assess how cold they actually were; neither their core nor surface temperatures correlated with their cold sensations*.

Altogether, the results of many experiments and experiences indicate that the subjective sensation of cold is a poor, even dangerously unreliable indicator of core and surface temperature of the body. Measuring ambient temperature, humidity, and air movement and exposure time and reacting to these physical measures is a better strategy than relying on subjective sensations.

Indications of Cold Strain

If vasoconstriction and metabolic rate regulation cannot prevent serious energy loss through the body surfaces, the body will suffer some effects of cold stress. The skin is, as just discussed, first subjected to cold damage while the body core is protected as long as possible.

As skin temperature diminishes to about 15 to 20°C, manual dexterity begins to fail. Tactile sensitivity is severely diminished as the skin temperature falls below 8°C. At local temperatures of 8 to 10°C, peripheral motor nerve velocity is decreased to near zero; this generates a nervous block, which helps to understand why local cooling is accompanied by rapid onset of physical impairment. If tissue temperature approaches freezing, ice crystals develop in the cells and destroy them, a result known as "frost bite".

Strong reductions in skin temperatures are accompanied by a fall in core temperature. Severe reduction of core temperature is dangerous. Vigilance begins to drop at temperatures below 36°C. At core temperatures of 35°C, one may not be able to perform even simple activities. When the core temperature drops even lower, the mind becomes confused, with loss of consciousness occurring around 32°C. At core temperatures of about 26°C, heart failure may occur. At very low core temperatures, such as 20°C, vital signs disappear, but the oxygen supply to the brain may still be sufficient to allow revival of the body from hypothermia.

Severe cooling of the skin and central body goes along with increasing inability to perform activities, even if they could save the person ("cannot light a match") leading to apathy ("let me sleep") and final hypothermia.

In cold water, hypothermia can occur quickly. A person can endure up to two hours in water at 15°C, but becomes helpless in water of 5°C in about half an hour; then death is imminent. Obese persons with much insulating adipose tissue are at advantage over skinny ones. The survival time in cold water can be increased by clothing which provides some insulation. Floating motionless results in less metabolic energy generated and spent than when swimming vigorously; furthermore, the swimming motions destroy the stationary layer of warmed water close to the body which reduces heat loss by conduction.

Table 9.4 lists the primary reactions of the body to cold and warm environments.

Table 9.4 Summary of the body's main thermoregulatory actions

Environment	Purpose	Means
Cold	Prevent heat loss	Reduce skin temperature
Hot	Avoid heat gain, facilitate heat loss	Increase skin temperature and sweat production
Cold	Increase body heat content	Increase muscle activities
Hot	Avoid increase in body heat content	Reduce muscle activities

Acclimatization to Cold

Acclimatization to a cold environment is not very pronounced; in fact, it is debatable that true physiological adjustments to moderate cold take place when appropriate clothing is worn because the actual cold exposure of the body is slight and does not require appreciable increases in metabolism or other major adjustments in vasomotor or sudomotor systems.

When first exposed to cold temperature, some changes in local blood flow appear, particularly increased blood flow through the hands or in the face. In laboratory exposure to extremely cold conditions, with little shelter offered by clothing, some hormonal and other changes have been observed.

On average, the female body has smaller mass (heat "sink") than the male; women usually have relatively more body fat and accordingly less lean body mass; their surface area and their blood volume are smaller as well. Under cold stress, females have slightly colder temperatures at their (thinner) extremities but show no difference in core temperature. While women possibly have a slightly higher risk of cold injuries to the extremities, altogether there are no great differences between females and males with respect to their ability to adapt to cold climates. The slight statistical tendencies can be counteracted easily by ergonomic means.

Working in Heat or Cold

Hot and cold climatic conditions (as well as air pollution and high altitude*) affect the human abilities to perform short or long, light or heavy work in various ways.

Effects of Heat

When exposed to whole-body heating, the human body must maintain its core temperature near 37°C. It does so by raising its skin temperature, increasing blood flow to the skin, accelerating heart rate and enlarging cardiac output. The change in blood routing reduces the blood that can be supplied to muscles and internal organs. Yet, if muscles must work, their raised metabolism poses increased demands on the cardiovascular system.

Cardiovascular Effects

The pumping capacity of the heart is between about 25 ("average" adults) and 40 (elite athletes) L/min. The blood vessels in skin and internal organs can accept up to 10 L, and all muscles together up to 70 L/min. Since the available cardiac output is half or less of these 80 L, the ability of the heart to pump blood is the limiting factor for muscular work in a hot climate.

Effects on Muscles

An increase of muscle temperature above normal does not affect the maximal isometric contraction capability of muscle tissue, but it reduces the dynamic output of muscles. Muscle overheating accelerates the metabolic rate; this can make the muscle ineffective if it must work over some period of time. The loss of power and endurance owing to excessive muscle temperature can be counteracted by cooling muscles before exercise. This reduces the cardiovascular strain and blood lactic acid concentration, and depletes muscle glycogen at a lower rate.

Dehydration

When working in a hot environment, the body loses water. The body can adapt to heat, but not to dehydration. Acute water loss incurred in a few hours or less, called hypohydration, does not reduce isometric muscle strength (or reaction times) if the water loss is less than 5% body weight. However, fast and large water loss (such as introduced by diuretics) generates the risk of heat exhaustion, which is primarily the result of fluid volume depletion. Dehydration reduces the body's capacity to perform aerobic or endurance work.

To counteract water loss, one must drink fluid. Plain water is best. If strenuous activities last longer than 1 or 2 hours, diluted sugar additives may help to postpone the development of fatigue by reducing muscle glycogen utilization and improving fluid-electrolyte absorption in the small intestine. Regular, liberally salted food during meals, as customary in North America, is normally sufficient to counteract salt loss. In fact, salt tablets have been shown to generate stomach upset, nausea, or vomiting in up to 20% of all athletes who took salt tablets.

Effects on Mental Performance

It is difficult to evaluate the effects of heat (or cold) on mental or intellectual performance because of large subjective variations and a lack of practical yet objective testing methods. However, as a rule, mental performance of an unacclimatized person deteriorates with room temperatures rising above 25°C; that threshold increases to 30 or even 35°C if the individual is acclimatized to heat. Brain functions are particularly vulnerable to heat; keeping the head cool improves the tolerance to elevated deep body temperature. A high level of motivation may also counteract some of the detrimental effects of heat. Thus, in laboratory tests, onset of performance decrement in perceptual motor tasks can occur in the low 30°C WBGT range while very simple mental performance is often not significantly affected by heat as high as 40°C WBGT.

Working in the Heat: Summary

Short-term maximal muscle strength exertion is not affected by heat. However, the ability to perform high-intensity endurance-type physical work is severely reduced before acclimation to heat, which takes normally up to 2 weeks. Even after acclimatization, the demands on the cardiovascular system for heat dissipation and for blood supply to the muscles continue to compete. The body prefers heat dissipation, with a proportional reduction of performance capability. Dehydration further reduces the ability of the body to work; hypohydration poses acute health risks. Mental performance is usually not affected by heat as high as 40°C WBGT.

In consideration of these effects on the ability of the human to perform work in a hot environment, a number of technical and administrative measures can be taken. The most important ones are listed in Table 9.5. They concern both the demands of

Table 9.5 Control measures applied to work in hot environments (adapted from Canadian Centre for Occupational Health and Safety CCHS, Hot environments – control measures, dated 2008-07-28)

Engineering controls	
Reduce body heat production	Mechanize tasks
Stop exposure to radiated heat from hot objects	Insulate hot surfaces. Use reflective shields, aprons, remote controls
Reduce convective heat gain	Lower air temperature. Increase air speed if air temperature is below 35°C. Increase ventilation. Provide cool recuperation booths
Increase sweat evaporation	Reduce humidity. Use a fan to increase air movement
Supply suitable clothing	Provide loose clothing that permits sweat evaporation but stops radiant heat. Use cooled protective clothing for extreme conditions
Administrative controls	
Acclimatization	Allow a sufficient acclimatization before full workload
Duration of work	Shorten exposure time and use frequent rest breaks
Rest area	Provide cool (air-conditioned) rest areas
Water	Provide cool drinking water
Pace of work	Allow workers to set their own pace of work
First aid and medical care	Define emergency procedures. Assign one person trained in first aid to each work shift. Train workers in recognition of symptoms of heat exposure

physical effort and the control of environmental factors. Specific design features of the thermal environment are discussed below in this chapter.

Effects of Cold

In a cold environment, as in a hot climate, the body must maintain its core temperature near 37°C. When exposed to cold, the human body first responds by peripheral vasoconstriction, which lowers skin temperature, to decrease heat loss through the skin. Such reduction in blood flow occurs in all exposed areas of the body although least strongly at the head. If control of blood flow away from the periphery is insufficient to prevent heat loss, shivering sets in. Shivering is a regular muscular contraction mechanism but without generating external work since all energy is converted to heat. Muscular activities of shivering and of physical work require increased oxygen uptake which is associated with increased cardiac output.

Cardiovascular Effects

The necessary increase in cardiac output, while heart rate remains at regular level, is brought about mostly by increasing blood pressure to augment the stroke volume.

Yet, keeping the heart rate low as a reaction to cold exposure opposes the natural response associated with physical exercise, which is to increase the heart rate to help enlarge cardiac output.

Effects on Body Temperature

The two opposing cardiac responses to cold and exercise affect body temperature. At light work in the cold, core temperature tends to fall after about one hour of activity. Cold sensations in the skin regularly initiate reactions leading to lowered skin temperature, yet areas over active muscles can remain warmer due to the heat generated by muscle metabolism. Thus, in the cold, relatively much heat is lost through convection (and evaporation). Which of the opposing physiological cold responses predominates depends on the special conditions regarding ambient temperature, type of body activity, and the clothing insulation.

While one can feel the coldness of air in the upper respiratory tract, the warming efficiency of the upper respiratory passages is sufficient to preclude cold injuries to lung tissues under normal conditions. Discomfort and constriction of airways may be felt when inspiring very cold air through the mouth; yet, air temperature is hardly ever too cold for exercise and physical work.

Effects on Work Capacity

For sub-maximal work in the cold, oxygen consumption is increased as compared to working at normal temperatures. (Shivering can cause some increase of oxygen cost at low work levels.) At higher exercise intensities, oxygen cost in the cold is about the same as at normal temperatures. However, often an extra effort is required to “work against” heavy clothing worn to insulate against heat loss.

A cold climate does not seem to affect the ability for maximal exercise as long as the exposure does not exceed about 5 hours. In this case, the physiological stimuli provoked by exercise appear to override those of cold. However, if core temperature gets lower, maximal work capacity is reduced; apparently mostly by suppressing heart rate and thus reducing the transport of oxygen to the working muscles in the blood stream.

Cold exposure can decrease muscle temperature, which reduces muscle contraction capability, hence endurance, causing an early onset of fatigue. If muscles are cold, their isometric strength is impaired.

Dehydration

Dehydration occurs surprisingly easily in the cold, partly because sweating is increased in response to the increased energy demands of working in the cold, and owing to a suppressed thirst sensation. Also, urine production is increased in the cold, which can trigger water loss through more frequent urination. While dryness of cold air may cause respiratory irritation and discomfort, severe dehydration through the lungs does not occur since exhaled air is cooled on its way out to nearly the temperature of the inhaled air, returning water vapor by condensation onto the surface of the airways. (This explains the common experience of a "runny nose" in the cold.)

Effects on Mental Performance and Dexterity

If the core temperature of the body drops below about 36°C, vigilance is reduced. Central nervous system coordination suffers at about 35°C, apathy sets in, and loss of consciousness occurs near 32°C. While muscle spindles are initially more active as muscle temperature drops, at about 27°C their activity is reduced about 50% and is completely abolished at about 15°C. In the hands, joint temperatures below 24°C and nerve temperatures below 20°C severely reduce the ability for fine motor tasks. Manual dexterity is reduced as finger skin temperatures fall below 15°C. Tactile sensitivity is reduced below 10°C. A nervous block occurs if nerve temperature falls below 10°C; movement becomes impossible and motor skills are completely lost. At about 5°C, skin receptors for pressure and touch cease to function, the skin feels numb*. Frost bite is the result of ice crystals destroying tissue cells.

Working in the Cold: Summary

Strong isometric muscle exertions are impaired only if the muscles are cold. The ability for light work is reduced in the cold. Endurance activities are lessened only if core or muscle temperatures are lowered and if dehydration occurs. Clothing worn for insulation may hinder work. Dexterity and mental performance suffer in extreme colds.

For continuous work in temperatures below the freezing point, appropriate clothing is necessary and warming shelters such as heated tents, cabins or rest rooms should be provided. The work should be paced to avoid excessive sweating.

Proper equipment design, safe work practices and appropriate clothing minimize the risk of cold injury and facilitate suitable work outcome.

Designing the Thermal Environment

Various combinations of climate factors (ambient temperature, humidity, air movement and heat radiation) can subjectively appear as similar. The WBGT index, discussed earlier, is currently the most used indicator of climate factors that, combined, have equivalent effects on the human.

For work outdoors, few technical means are available that affect the immediate work environment although temporary shelters, such as tents, can help to reduce the effects of wind and solar radiation. Clothing is the most effective and generally used solution to keep the worker safe and comfortable – yet, in some areas with hot climates minimal or no clothes are worn when climate and customs do not mandate much clothing.

Clothes can affect the individual microclimate strongly. Clothing provides a layer of thermal resistance between the environment and the human body.

The insulating value of clothing is defined (such as in ISO 9920) in clo units: 1 clo = 0.115 m^2°C/W is the insulating value (the reciprocal of thermal conductivity) of "normal" clothing worn by a sitting subject at rest in a room at about 21°C and 50% relative humidity; assuming that the person's clothing covers the whole body surface.

Clothing determines the surface area of exposed skin. More exposed surface allows better dissipation of heat in a hot environment but can lead to excessive cooling in the cold. Fingers and toes need special protection in cold conditions because they are so far away from the warm body core. Colors of the clothes are important in a heat radiating environment, such as in sunshine, because dark colors absorb heat radiation and light ones reflect it.

With appropriate clothing and light work, many people feel that comfortable WBGT ranges are from about 21 to 27°C in a warm climate or during the summer, and from 18 to 24°C ET in a cool climate or during the winter. Skin temperatures in the range of 32–36°C are generally comfortable, associated with core temperatures between 36.7 and 37.1°C. Preferred ranges of relative humidity are between 30 and 70%.

Indoors, available technology allows far-reaching (and often costly) control of all climate factors. The most important factor is air temperature, but humidity also plays an important role; both interact with air movement and air replacement. Table 9.6 lists recommended ranges for air temperature and humidity for offices in North America. Air temperatures at floor level and at head level should not differ by more than about 6°C. Differences in temperatures between body surfaces and side walls should not exceed approximately 10°C. Air velocity should not exceed 0.5 m/s, best remain below 0.1 m/s*.

Table 9.6 Preferred temperature and relative humidity for offices in North America. The temperature ranges meet the needs of at least 80% of individuals (adapted from ASHRAE Standard 55–2004 and CSA Standard CAN/CSA Z412–00)

	Acceptable		Preferred	
Conditions	Relative humidity	Office room temperature °C	Relative humidity	Office room temperature °C
Summer, clothing ~0.5 clo	~30%	24.5 to 28	~50%	21 to 23 or slightly higher
	~60%	23 to 25.5	~50%	21 to 23 or slightly higher
Winter, clothing ~1.0 clo	~30%	20.5 to 25.5	~50%	21 to 23
	~60%	20 to 24	~50%	21 to 23

What is of importance to the individual is not the climate in general, the so-called macroclimate, but the climatic conditions with which one interacts directly. Every person prefers a "personal microclimate" that feels comfortable under given conditions of adaptation, clothing, and work. The suitable microclimate is highly individual and also variable*. The comfortable personal microclimate strongly depends on clothing worn and on the type and intensity of work performed. It depends on gender, as discussed. It depends on the surface-to-volume ratio, which for example in children is much larger than in adults, and on the fat-to-lean body mass ratio. It also depends somewhat on age: with increasing years the muscle tonus is reduced; older persons tend to be less active and to have weaker muscles, to have a reduced caloric intake, and to start sweating at higher skin temperatures.

The individual choice of clothing is influenced by

- efficacy in terms of interaction with the physical environment to generate a preferred "personal microclimate";
- practicality in terms of providing ease of wear and tasks performance, in some jobs combined with mechanical protection;
- appearance, often strongly affected by societal customs, even fashions.

Individual thermocomfort varies by acclimatization, the status of the body (and mind) of having adjusted to changed environmental conditions. A climate that was rather uncomfortable and restricted one's ability to perform work during the first day of exposure may be quite agreeable after two weeks. Relatedly, seasonal changes in climate and work, of clothing and attitude play major roles: in the summer, most people are willing to accept warmer, more humid and draftier conditions in a room than they would in the winter.

With so many variables of climate factors, kinds of work, clothing habits and willingness to adjust to given conditions it is not surprising that, as sketched in Fig. 9.6, some persons deem a certain WBGT temperature too cold, others consider it too warm while most people find it comfortable.

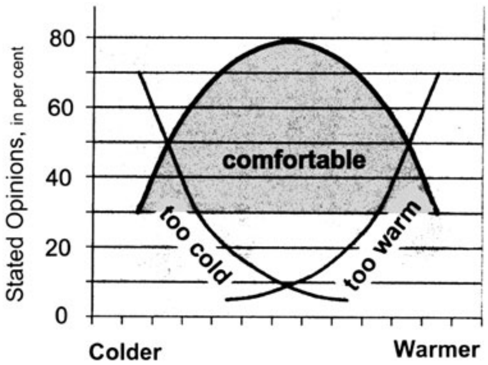


Fig. 9.6 Opinions about climates

Notes

The text contains markers, *, to indicate specific references and comments, which follow.

Body surface: To estimate the area *A* (in m^2) of body surface from the weight of the body (in kg) and its height (stature, in m), the simplified "1916 Dubois and Dubois" equation is often used: $A = 0.202 \times \text{weight}^{0.425} \times \text{height}^{0.725}$ (Parsons, 2003).

The body exchanges heat energy with the environment: Parsons (2003) provides a thorough review and detailed equations.

Energy transfer through radiation: de Dear et al. (1997), Silva et al. (2002). *Convection coefficient*: de Dear et al. (1997), Parsons (2003). *Convective heat loss when swimming*: Nadel (1984).

Vapor pressure: The units for pressure are 1,000 N/m^2 = 1 kPa = 7.52 mmHg = 7.52 Torr.

Heat loss from the respiratory tract and the skin: Nadel and Horvath (1975).

Heat exchange via clothing: Parsons (2003) and Bensel and Santee (2006) provide detailed information on the properties of clothing.

Calculating an "average" skin temperature: Parsons (2003) provides a listing of weighting factors.

Specific heat of the body: Livingstone (1968), Parsons (2003).

Effective Temperature scales: Eissing (1995), Mairiaux et al. (1995), Malchaire et al. (2001), Parsons (2003, 2006). *Adequacy of the WBGT for extreme conditions:* Parsons (2006).

Cold sensations: Hoffman and Pozos (1989).

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Effects of cold body temperatures: Heus et al. (1995).

Climate in a built environment, such as in offices: ANSI-ASHRAE Standard 55, latest edition; Parsons (2008).

Individual microclimate: Fanger (1970).

Summary

The body must maintain its core temperature near 37°C with little variation despite major changes in internally developed energy (heat), in external work performed, in heat energy received from a hot environment or in heat energy lost to a cold environment.

Heat energy may be either gained from or lost to the environment by radiation, convection and conduction, but can only be lost by evaporation.

The major avenues of the body to control heat transfer between its core and skin are the efferent motor pathways (muscle tonus), sudomotor pathways (sweat production), and vasomotor pathways (control of blood flow).

Muscular activities are the major means to control heat generation in the body. Blood flow control affects heat transfer between body core and skin.

In a hot environment, the body tries to keep the skin hot to prevent heat gain and to achieve heat loss. Sweating is the ultimate means to cool the body surface.

In a cold environment, the body tries to keep the skin cold to avoid heat loss.

The thermal environment is determined by combinations of

- *air temperature (affecting convection and evaporation)*
- *air humidity (mostly affecting evaporation)*
- *air movement (affecting convection and evaporation)*
- *temperature of solids in touch with the body (affecting conduction)*
- *temperature of surfaces distant from the body (affecting radiation).*

The combined effects of the physical climate factors can be expressed in form of a "climate index" such as the WBGT. Certain ranges of humidity, temperatures, and air velocity are "comfortable" for given tasks and clothing.

Glossary

Absolute humidity The content of water vapor in air.

Acclimatization Continuous or repeated exposure to hot (or cold) climate which brings about a gradual adjustment of body functions resulting in a better tolerance of the climatic stress and in improvement of physical and psychological work capabilities.

Air humidity See Absolute and Relative humidity.

Air temperature Measured with a sensor kept dry and shielded by a reflecting bulb from radiated energy; hence, often called "dry bulb temperature" or simply "dry temperature".

Body core The concept of central body components in the head and trunk, which are surrounded by the body shell (see there).

Body shell The concept of body components which surround the body core (see there), are close to the skin and are exposed to the environment.

Climate The ambient conditions of air temperature, air humidity, air movement and heat radiation.

Clothing See thermal properties of clothes.

Conduction heat transfer Heat transfer by molecular contact between two solid bodies.

Convection heat transfer Transfer of heat by circulation of particles of a gas or liquid.

Dehydration The process or result of the body losing water.

Dew point The air temperature at which the air has the highest absolute content of vapor (saturation), depending on the barometric pressure.

Dry bulb temperature See air temperature.

Dry temperature See air temperature.

Energy flow Movement of energy (heat) from a warmer body to a colder one; as the temperatures of the contact surfaces become equal, the energy exchange diminishes.

Energy transfer See energy flow.

Ergonomics The application of scientific principles, methods and data drawn from a variety of disciplines to the design of engineered systems in which people play significant roles.

Evaporation The change of a liquid (such as water) to vapor; this phase change requires energy.

Evaporation heat loss As evaporation (see there) occurs on the skin or in the lungs of the human, energy is extracted from the body; so, it becomes cooler.

Heat transfer energy flow.

Humidity The content of water vapor in air.

Hygrometer An instrument to measure humidity (see there).

Hyperthermia Overheating the body.

Hypodehydration Fast dehydration, see there.

Hypothermia Undercooling the body.

Macroclimate The ambient conditions of air temperature, air humidity, air movement and heat radiation in the general environment.

Microclimate The conditions of the climate (see there) with which an individual interacts directly.

Psychrometer An instrument to measure humidity (see there).

Radiation heat transfer Heat exchange through radiation; depends primarily on the temperature difference between two opposing surfaces.

Relative humidity The relation (usually in percent) between the actual vapor content and the possible maximal content at given air temperature and air pressure.

Saturated air Air with the highest possible water vapor content; at the dew point (see there).

Thermal properties of clothes Affect thermal insulation, transfer of moisture and vapor, heat exchange (by conduction, convection, radiation, evaporation) and air penetration.

Thermometer An instrument to measure temperature.

WBGT The Wet Bulb Globe Temperature index.

Wind chill The cooling effects of cold air movement on exposed skin.

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Chapter 10
Body Rhythms and Work Schedules

Overview

The human body follows a regular rhythm of physiological functions throughout the 24-h day. During waking hours, the body is prepared for physical work; at night, sleep is normal. Attitudes and behavior also change regularly during the day. The circadian rhythms can be upset by an imposing new set of time signals and activity–rest regimen, such as those associated with shift work schedules. Shift work should be arranged to least perturb the natural physiological, psychological, and behavioral rhythms. Disturbing the natural circadian rhythms can have negative health and social effects and cause reductions in work performance.

The Model

Daily rhythms are systems of temporal programs within the human organism. They strongly affect well-being and task performance. They should be kept intact for continued normal functioning, both physically and psychologically, by selection of suitable work schedules.

Introduction

Human body functions and behavior follow internal rhythms. Under regular living conditions, these temporal programs are well established and persistent. One is the female menstrual cycle of about 28 days; another is the set of daily fluctuations, called circadian rhythm.

The circadian rhythms (from the Latin *circa*, about, and *dies*, the day) are regular physiological occurrences, which appear, for example, in body temperature, heart rate, blood pressure, and hormone excretion, as sketched in Fig. 10.1. They appear also in common psychological and behavioral patterns.

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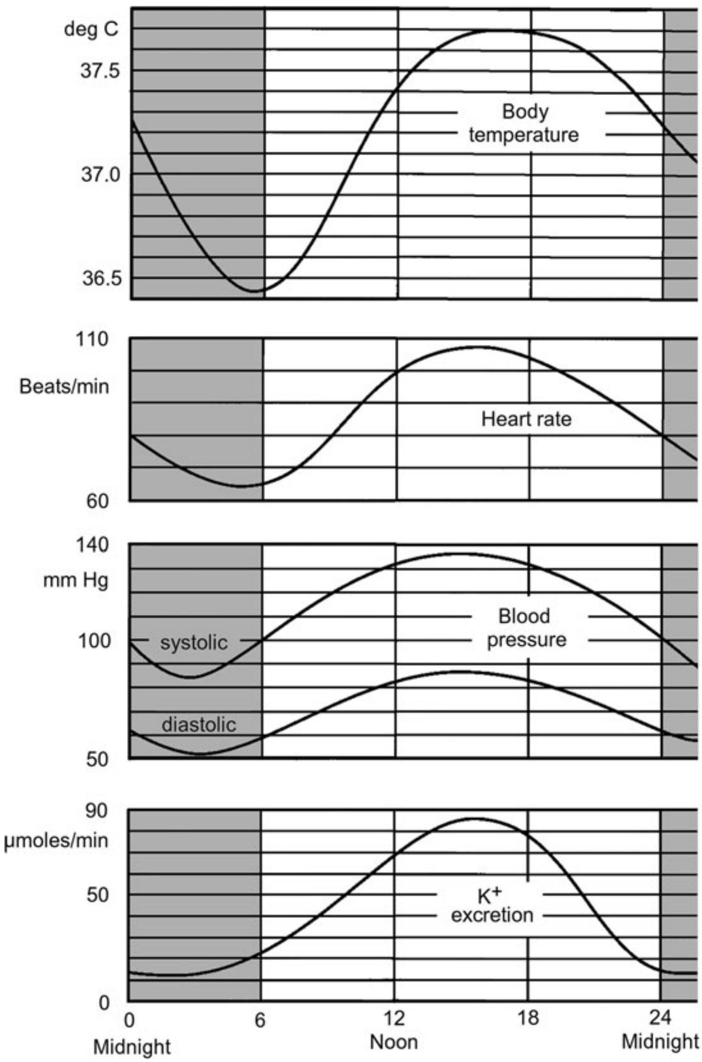

Fig. 10.1 Typical variations in body functions over the day

Daily rhythms are patterns of temporal programs within the human organism. They are evident under rigorous experimental conditions, they persist under varying external settings, they are valid by actual observation and experience and they are important for well-being and performance.

Within the body, self-sustained pacemakers, “internal clocks” running on a cycle of about 24 hours, control the circadian rhythms. Several rhythmic patterns are coupled with each other, such as core temperature, blood pressure, and sleepiness. The inclinations to do certain activities, or to rest and sleep and many other aspects of social behavior follow customs and sequences during the day, which relate to the "chrono-biological" rhythms during the 24-h day; another well documented rhythm is the 28-day menstrual cycle.

Strong external events can put an existing circadian rhythm out of order. Such imposing events contain a "time setter", called zeitgeber (from the German *Zeit*, time; and *Geber*, giver). Among the zeitgebers are daily light/darkness, true clocks, and temporally established activities, such as office hours, meal times and other regular events and habits. The strengths of these markers vary.

Menstrual Cycle

Synchronized activities of the hypothalamus, pituitary, and ovary regulate the female menstrual cycle. The typical 28-day time period is usually divided into five phases: (1) pre-ovulatory or follicular, (2) ovulatory, (3) post-ovulatory or luteal, (4) pre-menstrual, and (5) menstrual. Main hormonal changes occur in the release of estrogen and progesterone around the 21st day of menstruation; estrogen shows a second peak at ovulation. Hormonal release is low during the pre-menstrual phase.

The hormonal changes during the menstrual cycle influence a woman's psychological and physiological states; however, observable events in attitude or performance are usually weak. The bulk of existing research relies on self-reported changes in mood and physical complaints in the course of the menstrual cycle. Fairly little information is available on changes in arousal and on objective measures of performance. There is neurophysiological evidence that estrogen and progesterone affect brain function, yet the two hormones have antagonistic effects on the central nervous system, with estrogen stimulating and progesterone inhibiting. Varying hormone production during the menstrual cycle may weakly affect the capacity to perform certain tasks, but the extent to which hormones actually determine performance depends on how a decrease in capacity may be offset by increased effort*.

The occurrence of negative moods and physical complaints in many women before and during menstruation is fairly well established, but the precise nature of the so-called pre-menstrual syndrome is not yet determined. There is evidence that menstruation can bring about negative social behaviors; however, these can be mediated by social and psychological factors. In summary, the old hypothesis of reduced performance during the pre-menstrual and the menstrual phases is not well supported by objective data.

Circadian Rhythms

Maintenance of physiological functions in spite of external disturbances is one prerequisite for human health. This state of balanced control is called homeostasis. However, a close look at this supposedly "steady state" of the body reveals that many of its functions are in fact not constant but show rhythmic variations; for example, ups and downs in body temperature or hormone secretion follow each other regularly in similar patterns, day after day. The periods of different rhythms are quite diverse, such as the heart beating about once every second, body temperature having its peak value every 24 hours, or a woman's menstrual cycle reoccurring every 28 days. Rhythms with a cycle length of 24 h are called circadian, those that take less than 24 h to repeat are called ultradian; those which repeat in more than 24 h, infradian.

Among the circadian rhythms, well-known physiological variables are body temperature, heart rate and blood pressure. Most variables show a high value during the day and lower values during the night, although hormones in the blood tend to be more concentrated during the night, particularly in the early morning hours. Many variations in amplitude during the circadian circle are fairly small, approximately $\pm 1°C$ for oral temperature; others are in the range of approximately $\pm 15\%$ about the average, such as heart rate and diastolic blood pressure. However, some body functions oscillate considerably: triglycerides vary by nearly $\pm 80\%$ in the blood serum, while the sodium content of the urine vacillates even more. The amount by which the functions change during the course of the day, and the temporal locations of rhythm extremes during the day, can be quite different among individuals and may change even within a person*.

One way to observe the daily rhythms and to assess their effects on performance is simply to watch an individual's freely chosen behavior. During daytime, a person is normally awake, active, and eating but, at night, sleeping and fasting. However, physiological events do not exactly follow that activity pattern. For example, body core temperature decreases for several hours after the person has fallen asleep; the temperature is usually lowest between 3 and 5 o'clock in the morning. Then the temperature rises even before one awakens and gets up; it continues to increase, with some variations, until late in the afternoon. Thus, body temperature is not a passive response to regular daily behavior, such as getting up, eating meals, performing work and doing other social activities, but is self-governed.

Interactions among external activities and internal rhythms and their zeitgebers do exist. Variations due to exogenous influences may occur in observed rhythmic events; for example, skin temperature (particularly at the extremities) increases with the onset of sleep, whenever this happens. Turning the lights on boosts the activity level of birds, regardless of when this occurs. Thus, skin temperature or activity levels do not necessarily indicate the internal rhythm but may just mask the underlying physiological patterns of the body, which are robust, self-regulated, and predisposed to remain in existence even if daily activities change.

Under regular circumstances there is a well established phase coincidence between the external activity signs and the internal events. For example, during the night, the low values of physiological functions in humans, such as core temperature and heart rate, are primarily due to the circadian rhythm of the body; however, they are further helped by nighttime inactivity and fasting. During the day, peak activity usually coincides with high values of internal functions. Thus, normally, the observed circadian rhythm is the result of internal and external events which concur. If that balance of concurrent events is disturbed, negative consequences in well-being, health or performance may result.

When a person is completely isolated from exogenous factors and there are no regular activities or other external zeitgebers, the internal body rhythms are "running free", meaning they are independent of external time cues and are internally controlled. Many experiments have consistently shown that human circadian rhythms persist when freerunning, but their time periods usually are slightly different from the regular 24-h duration: most rhythms run freely at about 25 hours, some take even longer. Since the earth continues to rotate at 24 h relative to the sun, this experience indicates that body rhythms are independent from external stimuli and follow their own built-in clocks. Yet, if a person is subjected again to regular daily time markers and activities, the internal rhythms resynchronize on their 24-h cycles.

Models of Oscillatory Control

The commonly used oscillator model of the human circadian system assumes that various overt rhythms are jointly controlled by a few basic internal oscillators which, however, may have different controlling power. The basic oscillators, probably located in the hypothalamus, are in turn controlled by external stimuli (usually related to the earth's rotation), and also influence each other. If their intrinsic periods are close together, they synchronize. Yet, such internal coordination may fail; for example, when artificial zeitgebers occur within the entrainment range of one oscillator but outside of another. In this case, internal desynchronization takes place: rhythms controlled by one oscillator remain entrained, but those controlled by another oscillator begin to run free; for example, the sleep/wake cycle stays at 24 hours, while the temperature rhythm may freerun at a period of 25 hours*.

Two types of experiments can serve to investigate the constancy of rhythms or their temporal isolation. One set of experiments uses the absence of any natural or artificial time in order to evaluate purely internal control. Other experiments rely on manipulation of strong artificial time markers of various types to evaluate the effects of internal and external factors.

Under constant experimental conditions, such as in a dark isolated cave without external pacemakers, most human circadian rhythms freerun at about 25-h periods, desynchronized from the 24-h zeitgeber.

Manipulation of the zeitgeber allows laboratory simulation of jet lag or shift work. Experiments with strong artificial time setters have shown that these play a major role in entraining or synchronizing the internal rhythms so that they follow the new periodic time cues. Synchronization of the internal rhythms to time events is possible with cycle durations between 23 to 27 h. (At shorter or longer periods of time cues, the circadian rhythms are free-running, though often not completely independent of the time cues.) It appears to be easier to set internal clocks "forward", as it occurs in the spring when daylight-savings time is introduced in North America and in Europe, than to retard the internal clock.

Individual Diurnal Performance Rhythms

As evident from their responses in self-assessment questionnaires, some people are "morning types", early risers, who claim to be especially alert and productive early in the day. These persons seem to have consistently shorter free-running periods than most, entrained to have early peaks in body temperature, heart rate and melatonin excretion. "Evening types", in contrast, are people with long internal rhythms and late peaks. While it is not certain whether females have, on average, a free-running period that is a bit shorter than that of males, young children appear to be more morning-oriented than adults; however, many adults become early risers again as they age*.

Given the robust oscillations in physiological functions during the day, one expects corresponding changes in mood and performance – but the regular organization of the day (getting up, working, eating, relaxing, and going to bed) also affects, and usually strongly so, a person's attitudes and work habits. Experimentally, one can separate the effects of internal circadian rhythms and of external daily organization, but the combined effect of internal and external factors, for example in regard to task performance, is of great practical interest.

Early in the 1900s, it was thought that the morning hours were best for mental activities, and the afternoon more suitable for physical work – but individual traits such as motivation, skill and habits or the specifics of tasks and work environment may overshadow the effects of circadian variations.

Performance in everyday work, especially when it is monotonous, often shows a pronounced reduction just after noon. However, this "post-lunch dip" in performance is not accompanied by a similar change in physiological functions; for example, body temperature does not change appreciably at that period of the day. The interruption of work for lunch might bring about an increased lassitude, a status of deactivation, associated with increased blood glucose resulting from food digestion – so, the post-lunch dip may be caused by the exogenous effects of work break and food intake, "masking" the endogenous circadian effects. In activities with medium to heavy physical work, usually no such dip occurs after lunch (except when food and beverage ingestion was very heavy and if true physiological fatigue had been built up during the pre-lunch activities).

In summary, some of the many different activities performed during the day decidedly follow a circadian rhythm, some less strongly. For some people, exogenous masking effects may be more pronounced than on others. For example, information processing in the brain (including immediate or short-term memory demands), mental arithmetic activities, or visual searches, may be strongly affected by personality or by the length of the activity and by motivation. Thus, it appears that one cannot make "normative" statements about diurnal performance variations or abilities during regular working hours – yet, fatigue resulting from work already performed is likely to reduce performance, as discussed in Chap. 8.

Sleep

Two millennia ago, Aristotle thought that during wakefulness some substance ("warm vapors") in the brain built up which needed to be dissipated during sleep. In the nineteenth century, there were two opposing schools of thought: one that sleep was caused by some "congestion of the brain by blood," the other that blood was "drawn away from the brain." Also, "behavioral" theories were common in the nineteenth century, such as that sleep was the result of an absence of external stimulation or that sleep was not a passive response but an activity to avoid fatigue from occurring. Early in the twentieth century, a common assumption was that various sleep-inducing substances accumulated in the brain, an idea taken up again in the 1960s. In the 1930s and 1940s, various "neural inhibition" theories were discussed, including "sleep-inducing centers" in the reticular formation of the brain. Other theories about the function of sleep assume some kind of recovery from the wear and tear of wakefulness. Alternative theories claim that sleep is simply a form of instinct or non-behavior to occupy the unproductive hours of darkness and a means to conserve energy. Restoration, energy conservation and occupying time appear to explicate certain characteristics of sleep but they do not explain sleep completely or sufficiently. Thus, there is no simple explanation for what sleep does and why we must sleep – but is evident that humans need sleep*.

It is expedient to presume that two central clocks of the body regulate alertness, sleepiness, and many physiological functions: one clock controls sleep and wakefulness, the other clock regulates physiological functions such as body temperature. Normally, the internal clocks synchronize to increase physiological activities during wakefulness and decrease physiological activities during sleep. However, this congruence of the two rhythms may be disturbed, for instance by night shift work, where one must be active during nighttime and sleep during the day. If such patterns continue, the physiological clocks can adjust to the external requirements of the new sleep/wake regimen: the formerly well-established physiological rhythm may flatten out and, after some time, re-establish itself according to the new sleep/wake schedule.

Sleep Phases

The brain and muscles are the human organs that show the largest changes from sleep to wakefulness: their activities can be observed by electrical means.

Electrodes attached to the surface of the scalp serve to observe sleep. They pick up electrical activities of the encephalon (cortex), which wraps around the inner brain (see Chap. 3): so, the measuring technique is named electro-encephalography, EEG. The EEG signals provide information about the activities of the brain. The other common technique records the electrical activities associated with muscles (see Chap. 2) that move the eyes and of muscles located in the chin and neck regions. The recording of activities of muscle (myo) is called electro-myography, EMG; electro-oculography, EOG, records specifically the activities of eye muscles.

EEG signals can be described in terms of amplitude and frequency. The amplitude is measured in microvolts, mV: the amplitude increases as consciousness falls from alert wakefulness through drowsiness to deep sleep. EEG frequency is measured in Hertz; the frequencies observed in human EEG range from 0.5–25 Hz. Frequencies above 15 Hz are called "fast waves," frequencies under 3.5 Hz "slow waves." Frequency falls as sleep deepens; "slow wave sleep" (SWS) is of particular interest to sleep researchers.

Certain EEG frequency bands have been given Greek letters. The main divisions are:

- Beta, above 15 Hz. Such fast waves of low amplitude (under 10 mV) occur when the cerebrum is alert or even anxious.
- Alpha, between 8 and 11 Hz. These frequencies occur during relaxed wakefulness when there is little information input to the eyes, particularly when they are closed.
- Theta, between 3.5 and 7.5 Hz. These frequencies are associated with drowsiness and light sleep.
- Delta, slow waves under 3.5 Hz. These are waves of large amplitude, often over 100 mV, and occur more often as sleep becomes deeper.

Also, certain occurrences in the EEG waves have been labeled, such as vertices, spindles, and complexes, which appear regularly in association with certain sleep characteristics.

The importance placed upon EMG and EEG events by sleep researchers has been changing over decades. Currently, EMG events of the eye muscles serve to primarily divide sleep into periods associated with rapid eye movements, REM, and those without, non-REM (or NREM). Non-REM conditions are further subdivided into four stages, as in Table 10.1, according to their associated EEG characteristics. A related classification maintains non-REM stages 1 and 2 as N1 and N2 but combines stages 3 and 4 as stage N3 "delta sleep", "slow wave" and "deep sleep".

After falling asleep, the brain usually goes quickly to sleep stages 3 and 4 (N3), where brain and skeletal muscles are not active. That sleep phase usually lasts about 1.5 hours. Thereafter, sleep becomes lighter. When it reaches stage 1, the EEG shows low voltage, fast brain activities while rapid eye movements often occur. In this REM sleep, besides the muscles of the eyes, often also those of the hands and feet are active (but most other skeletal muscles stay relaxed) and heartbeat and

Table 10.1 Sleep stages

Condition	Sleep stage	Muscle EMG	Brain EEG	Percentage of sleep (averages)
Awake	None, awake	Muscles active	Brain active, alpha and beta	na
Drowsy, transitional light sleep	1 (N1) non-REM	eyelids open and close, eyes roll	Theta, loss of alpha, sharp vertex waves	5
True sleep	2 (N2) non-REM		Theta, few delta, sleep spindles, k-complexes	45
Transitional true sleep	3 (N3) non-REM		Much delta, slow wave sleep	7
Deep true sleep	4 (N3) non-REM		delta predominant, slow wave sleep	13
Sleeping	REM	Rapid eye movements, most other muscles relaxed	brain alert, much dreaming, alpha and delta	30

breathing speed up irregularly. The REM stage may last just a few minutes, after which the sleeper falls back into the deeper sleep stages. In non-REM sleep, regular and slow breathing and heart rates occur, and the EEG activity is slow but shows high voltage. Each stage appears to have distinct beneficial effects; that concept can explain why, after "disturbed" sleep of altogether usual duration, one still feels tired.

Normally, several sleep cycles repeat during the night. They are probably co-organized between diverse brain regions, thus involving two or more oscillators. The REM/non-REM cycles occur in roughly 1.5-h timings; Fig. 10.2 shows a typical

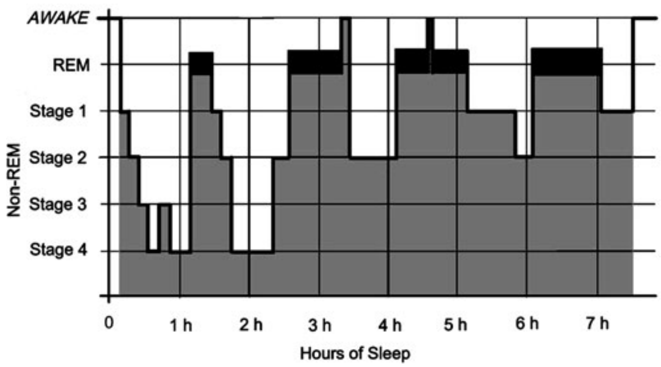

Fig. 10.2 A conceptual example of sleep stages during undisturbed night sleep (adapted from Kroemer, 2009)

pattern of night sleep. While there is much within- and between-subjects variability, commonly the portion of REM increases in the later sleep phases before natural awakening.

Sleep Loss and Tiredness

Surprisingly, it is still not entirely clear why humans (or animals) need sleep. A common opinion is that sleep has recuperative benefits, that it allows some sort of restitution or repair of tissue or brain following the "wear and tear" of wakefulness. However, what is meant by restitution or repair is usually not clearly expressed, nor fully understood. Certainly, sleep is accompanied by rest and, to a large extent, by energy conservation. But a human can attain similar relaxation when awake and resting. Regarding restitution of the body, it is true that certain hormones are released more during sleep than during wakefulness; prominent among these hormones is the human growth hormone. However, few other such "positive" sleep events have been noted. Protein in tissues is continuously broken down into its amino-acid building blocks or reconstituted from recent food intake. If such breakdown were excessive during wakefulness, then the rate of synthesis should be especially high during sleep. This is not the case: in fact, during sleep, protein synthesis is low and breakdown increased, leading to a loss of protein through dissolution, not to an increase through restitution.

Many experiments have failed to show restorative physiological effects of sleep; in fact, even moderate sleep deprivation has little physiological effect (but there are clear signs of impairment of functions in the central nervous system). For example, sleep deprivation does not impair muscle restitution or the physiological ability to perform physical work. Any reduction in performance of physical exercise either under sleep deprivation or during ebb times of circadian rhythms may be entirely due to reduced psychological motivation, because there is no significant decrease in physiological capabilities*.

In contrast, the restorative benefits of sleep to the brain are fairly well researched. Two or more nights of sleep deprivation bring about psychological performance detriments, particularly reduced motivation to perform (but apparently not a reduction of the inherent cognitive capacity), behavioral irritability, suspiciousness, speech slurring, and other performance reductions. These effects indicate some central nervous system (CNS, see Chap. 3) impairment owing to sleep deprivation and, consequently, a need for the brain to sleep. However, even though one feels tired, mental performance is still close to normal after up to 2 days of sleep deprivation on stimulating and motivating tasks; yet, boring tasks show performance reduction. Performance an all tasks is reduced after more than two nights of sleep deprivation. (The regular circadian rhythms still persist: performance levels are lower during nighttime, when the body and brain usually rest, then during daytime.)

One speculative explanation for the ability to perform mental tasks well even after 2 days of sleep deprivation is that, for regular tasks, there is an overcapacity of cerebral neural networks; so, many are not fully used*. However, after sleep deprivation, some circuits become impaired, possibly as a result of missing "restitution"; therefore, the extra circuits are put into service. At first, this suffices to avoid overt effects on performance. With increasing deprivation, more circuits become impaired; finally, the available circuits become overloaded and performance drops.

Within the human body, only the brain assumes a physiological state during sleep which is unique to sleep and cannot be attained during wakefulness. During relaxed wakefulness, muscles can rest but the cerebrum remains in a condition of "quiet readiness," prepared to act on sensory input, without diminution in responsiveness. Only during sleep do cerebral functions show marked increases in thresholds of responsiveness to sensory input. In the deep sleep stages associated with slow wave non-REM sleep, the cerebrum is apparently functionally disconnected from subcortical mechanisms. Regardless of whether the cerebrum needs off-line recovery during sleep from the demands of waking activities or whether it simply disconnects and withdraws, the fact remains that the brain needs sleep to restitute, a process that cannot take place sufficiently during waking relaxation.

Apparently, not all the usual sleep is essential for brain restitution. For example, after sleep deprivation, not all lost sleep may be reclaimed; long-term studies with volunteer subjects have shown that a sleep period that is 1–2 h shorter than usual can be endured for many months without any consequences. It seems that the first 5–6 h of regular sleep (which happen to contain most of the slow-wave non-REM sleep and at least half the REM sleep) are obligatory to retain psychological performance at normal level, but that more sleep, called facultative or optional, mostly serves to occupy unproductive hours of darkness, with dreams (mostly in REM but not totally confined to it) the "cinema of the mind"*.

Normal Sleep Requirements

While there are, as usual, variations among individuals, certain age groups show rather regular sleeping hours. For example, young western adults sleep, on average, 7.5 h with a standard deviation of about 1 h. Some people are well rested after 6.5 h of sleep, whereas others habitually take 8.5 h and more. Individuals naturally sleeping less than 3.5 h are very rare among middle-aged people; no true non-sleepers have ever been found among otherwise healthy persons*. If people can sleep for just a few hours per day, many are able to keep up their performance levels even if the attained total sleep time is shorter than normal. The limit seems to lie around to 5 h of sleep per day, with even shorter periods still being somewhat useful; day-time napping can be helpful.

Figure 10.3 shows the effects of sleep loss on body temperature: the temperature keeps its phase but is elevated during the night and morning. This is indicative of the changes in body functions associated with sleep loss. If a person does not get the necessary amount of sleep, the resulting problem is tiredness; the obvious cure is to get more sleep. However, people who cannot sleep in at will have a problem; night-shift workers, for example, generally find it difficult to make up for lost sleep in the busy daytime.

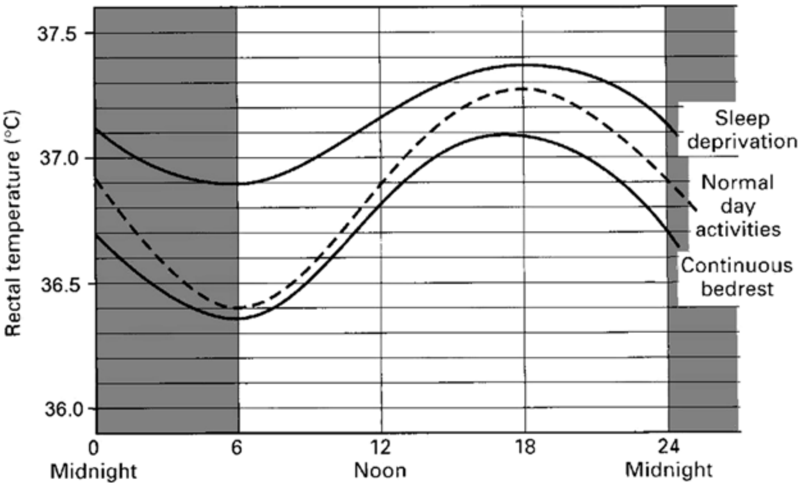

Fig. 10.3 Scheme of changes in body temperature associated with bed rest, normal activities, and sleep deprivation (adapted from Colligan and Tepas, 1986)

Sleep Deprivation and Prolonged Periods of Work

If it is necessary to continue work for long periods of time, such as a full day or longer, this condition also encompasses sleep deprivation. Hence, experienced stress and difficulties in task performance during such long working spells are likely to result both from the extended work itself and from the lack of sleep. That intermingling of causes makes a general discussion of this topic complicated. Furthermore, different types of work tasks may show varying effects; wakefulness or sleepiness appear in cycles during the 24 h of the day and hence have differing effects; and the motivation of the worker often plays an important role regarding performance.

Performing Tasks

On a short work task, one that lasts less than about half an hour, existing sleep loss affects performance less than if the work that must go on uninterruptedly for a longer period. Sleep deprivation strongly affects monotonous work; performance is likely to become worse with each repetition. Implementation of a task new to the operator is only minimally affected by sleep deficiency. Lack of sleep diminishes execution of a complex task more than of a simple one. Tasks which are paced by the work itself deteriorate more with sleepiness than operator-paced tasks.

After losing sleep, it usually takes longer to perform a job, but accuracy may not suffer much. A task that is interesting and appealing, even if it does include complex decision making, can be executed rather well even over lengthy periods of time; but if the task is unappealing, even disliked, decision making takes longer. When people must stay awake for long periods of time, memory use degrades, both in long-stored memory information and short-term memory*.

Incurring Performance Decrement and Recovering From It

In general, performance degrades after one night without sleep; the deterioration becomes more pronounced after additional nights of sleep deprivation. After missing four nights, very few people are able to stay awake and to perform adequately even if their motivation is very high*. The following discussion assumes sleep deprivation of at least one night.

With increasing time at work, so-called microsleeps occur more frequently. The person falls asleep for a few seconds, but these short periods (even if frequent) do not have much recuperative value because the subject still feels sleepy and performance still worsens. Another commonly observed event during long working times coupled with lack of sleep are periods of no performance, also known as lapses or gaps. These are short periods of reduced arousal or even of light sleep.

Naps lasting one to two hours can improve subsequent performance. However, if a person is awakened from napping during a deep-sleep phase, "sleep inertia" with low performance can appear which may last up to 30 min. Temporal placing of a nap may have differing effects: for example, the common early afternoon nap has surprisingly little effect on performance of subsequent work. On the other hand, naps of at least two hours taken in the late evening or during nighttime, when the circadian rhythm is falling, have positive effects lasting several hours, provided that the amount of sleep deficit incurred until this moment is moderate, such as one night without sleep*.

It appears that there is no clear scientific support for the usefulness of "short naps" (especially for people who missed a night's sleep). Many people claim that naps, especially 5 to 15 minutes of rest taken after lunch, perhaps with some caffeine intake, are highly helpful; for some, such naps appear almost necessary to be "ready and fit" for the continued work. Perhaps the recuperative effects are too subtle, too much an interaction between physiological, psychological, and habitual traits, to be easily demonstrated in a scientific experiment.

If long periods of mainly mental activities are necessary, interrupting the work for some physical exercises may prevent performance deterioration. Also, white noise may be beneficial and stirring music may help. Taking drugs, particularly amphetamines, can restore performance to a nearly normal level even after three nights without sleep* – but such drastic action should be reserved for truly critical jobs.

Recovery from sleep deprivation is quite fast. One good night's sleep usually restores performance to a normal level, even after extensive sleep deprivation.

Shift Work

One speaks of shift work if two or more persons, or teams of persons, work in sequence at the same workplace. Often, each worker's shift repeats, in the same pattern, over a number of days. For the individual, shift work may mean either working regularly at the same time (*continual* shift work) or at varying times (*discontinuous* shift work, often as *rotating* shift work).

The Development of Shift Work

Shift work is not new. In ancient Rome, by decree, deliveries were to be done at night to relieve street congestion. Bakers traditionally worked through the late night and early morning hours. Soldiers and firefighters work night shifts. Many alternate work systems have been used; for example, farmers used to start work at dawn and stop at dusk. “Peddlers, politicians, professors” and others have always tried to set their own work schedules, often highly variable, to suit specific circumstances and preferences.

With the advent of industrialization, long working days became common with teams of workers relaying each other to maintain blast furnaces, rolling mills, glass works, and other workplaces where continuous operation was desired. Covering the 24-h period with either two 12-h work shifts, or with three 8-h work shifts, was common practice. Technological or economical concerns have made shift work generally accepted in many industries, trades, and services, in developed and in developing countries.

Since the industrial revolution of the late eighteenth century, when 12-h shifts were common, drastic changes in work systems have occurred. Early in the twentieth century, 6-day workweeks with 10-h shifts were widespread. Today, many work systems rely on an arrangement of 8 hours of work per day but with only 5 workdays per week, a setup introduced in many countries in the 1960s.

The general trend was to reduce the number of days worked per week, usually to allow two weekend days to be free; also, to decrease the number of hours worked per day. Yet, in 1988, the German Secretary of Labor proposed a system of a “compressed workweek” (see below) with 9-h work per day and only 4 days of work a week. In 1996, the average number of hours worked per week was just over 32 in Germany. Many employees in Europe, particularly if working for the government, left their workplaces early on Friday afternoon to return after a long weekend on Monday morning.

As management sees it, many industrial and service systems require two or more work crews to utilize machinery and keep processes going through much or all of the 24-h day and over the 7-day week. Thus, new forms of discontinuous systems are developing, such as 3-shift systems that cover 24 hours, weekly or irregular rotation, work on weekends and 6 or 7 consecutive similar shifts.

Shift Systems

Shift work is different from “normal” day work in such that work is performed regularly during times other than morning and afternoon; and/or at a given workplace, more than that one shift is worked during the 24-h day. A shift may be shorter or longer than an 8-h work period.

Many diverse shift systems exist*. For convenience, they are usually classified into several basic patterns, but any given shift system may comprise aspects of several patterns. Four particular features of shift systems are especially important*:

1. Does a shift extend into hours that would normally be spent asleep?
2. Is a shift worked throughout the entire 7-day week, or does it include days of rest, such as free weekend?
3. Is there one shift or are there two, three, or more shifts per day?
4. Do shift crews rotate or do they work the same shifts permanently?

These aspects, shown in Fig. 10.4, are of particular concern with respect to the welfare of the shift worker, the work performance, and the organizational scheduling.

Other critical identifiers of shifts and shift patterns are the starting and ending time of a shift; the number of workdays in each week; the hours of work in each week; the number of shift teams; the number of holidays per week or per rotation cycle; the number of consecutive days on the same shift, which may be a fixed or

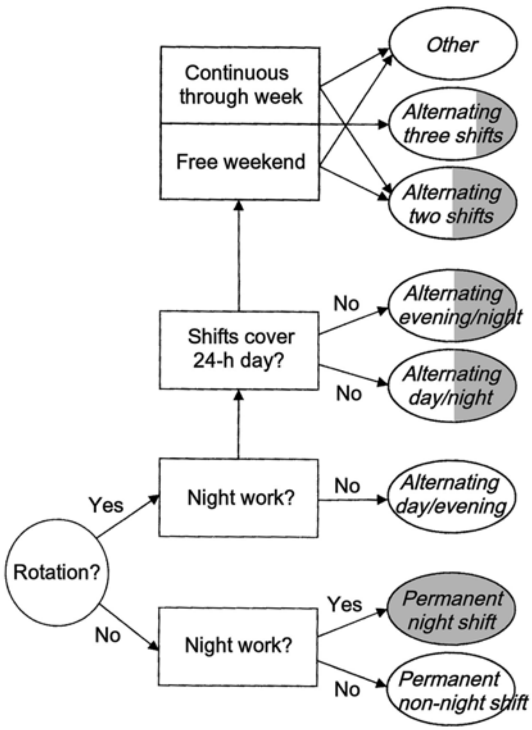

Fig. 10.4 Key features of shift systems. Note that other shift attributes are possible (adapted from Kogi, 1985)

Table 10.2 Examples of shift systems with 5 workdays/week

System	Work days/free days	Shift sequence
Permanent day shift	5/2	D-D-D-D-D-*f*-*f*, D-D-D-D-D-*f*-*f*, . . .
Permanent evening shift	5/2	E-E-E-E-E-*f*-*f*, E-E-E-E-E-*f*-*f*, . . .
Permanent night shift	5/2	N-N-N-N-N-*f*-*f*, N-N-N-N-N-*f*-*f*, . . .
Rotating shifts		
Alternating day/evening	10/4	D-D-D-D-D-*f*-*f*, E-E-E-E-E-*f*-*f*, . . .
Alternating day/night	10/4	D-D-D-D-D-*f*-*f*, N-N-N-N-N-*f*-*f*, . . .
Alternating day/evening/night; forward rotation	15/6	D-D-D-D-D-*f*-*f*, E-E-E-E-E-*f*-*f*, N-N-N-N-N-*f*-*f*, D-D-D-D-D-*f*-*f*, . . .
Alternating day/evening/night; backward rotation	15/6	D-D-D-D-D-*f*-*f*, N-N-N-N-N-*f*-*f*, E-E-E-E-E-*f*-*f*, D-D-D-D-D-*f*-*f*, . . .

D: Day shift, E: Evening shift; N: Night shift; *f*: free day, without scheduled shift

variable number; and the schedule by which an individual worker either works or has a free day or free days.

In terms of organizing the schedule, it is easy to set up permanent or a weekly rotating schedule. Several such solutions are shown in Table 10.2.

In most systems used today in western economies, working the same 8 h shift continues for 5 consecutive days, followed by 2 free days during the weekend. This regimen, however, does not cover evenly all the 21 shift periods of the week; therefore, additional crews are needed to work on weekends or under other "odd" arrangements. If one uses three shifts a day (Day, Evening, Night, *free*) the shift system (for one team) is D-D-E-E-N-N-*f*-*f* with a 6-work/2-free day ratio and a cycle length of 8 days; this is known as the "metropolitan rotation". The "continental rotation", which also uses three shifts per day and four shift crews, has the sequence D-D-E-E-N-N-N, *f*-*f*-D-D-E-E-E, N-N-*f*-*f*-D-D-D, E-E-N-N-*f*-*f*-*f*. Its work/free day ratio is 21/7, its cycle length exactly 4 weeks.

Table 10.3 of shows a schedule for rotating shifts that seems to be particularly suitable for Europeans. Each person works the same shift twice, then rotates forward to the next later shift and works that shift twice, then rotates forward again to the next set of two shifts. Then follow four free days, which, however, do not always include weekend days. The system has a work per free day ratio of 6/4, its cycle length is exactly 10 weeks; on average, each week has 33.6 work hours.

The ratio of work days versus free days in a complete cycle is an important characteristic of any shift system. Table 10.4 presents several other features that describe different shift systems.

Table 10.3 Proposed "6/4" rotation shift schedule (adapted from Knauth, 2007b)

Week	Mo	Tu	We	Th	Fr	Sa	Su	Mo	Tu	We	Th	Fr	Sa	Su
1, 2	D	D	E	E	N	N	*free*				D	D	E	E
3, 4	N	N	*free*				D	D	E	E	N	N	*free*	
5, 6	*free*		D	D	E	E	N	N	*free*				D	D
7, 8	E	E	N	N	*free*				D	D	E	E	N	N
9, 10	*free*					D	E	E	N	N	*free*			

D: Day shift; E: Evening shift; N: Night shift

Table 10.4 Characteristics of shift arrangements (adapted from Kogi, 1985)

Cycle Length in days	$W + f$
Number of free days per year	$365\,f/(W+f)$
Number of days worked before the same set of shifts re-occurs on the same day of the week	$W + f$ if $(W + f)$ is a multiple of 7; or $7(W + f)$ if $(W + f)$ is not a multiple of 7

W: Sum of work days in one shift cycle; *f*: sum of free days in one shift cycle

Flextime

The systems just described all have the traditional 8-h work shifts. A newer trend is toward "flextime," a flexible arrangement of work hours in a shift. Sliding time (akin to the German *Gleit-Zeit*) is a suitable description of this arrangement because it allows the employee to slide the prescribed number of working hours per shift (8, for example) within a longer block of time (such as 10 hours) but so that the work time covers a "core" time (say, of 4 hours) during which all workers must be present. Thus, by floating the day's working time across the core period, a worker can select the starting and closing times of work. Table 10.5 lists potential advantages and disadvantages of flextime.

Compressed Workweeks

Flextime is often, but not necessarily, combined with compressed workweeks which means that the regular numbers of weekly work hours (such as 40) are condensed into fewer than the usual (say, 5) work days per week. This results in more work hours per day, but fewer work days. For example: the common 40 hours of work per week may be performed in only 4 or even 3 days (instead of 5 days) per week. This allows the worker to have 3 or 4 free days each week. Apparently, this is attractive to many employees and employers: There are more work-free days, fewer trips to and from work, and fewer set-ups and close-downs at work. However, there are concerns about increased fatigue due to long workdays and reduced performance and safety – see Table 10.6.

The type of work to be performed determines, to a great extent, whether compressed workweeks can or should be used. Thus, long working days have been

Table 10.5 Advantages and disadvantages of flextime (adapted from Knauth, 2007a; Kroemer et al., 2003)

Positive	
	Appeals generally to employees and employers
	Makes available work-free time at the employee's choosing
	Does not result in reduced employee pay
	Reduces commuting traffic problems
	Less fatiguing for workers
	Increases job satisfaction
	Recognizes and utilizes employees' individual differences
	Reduces tardiness
	Reduces absenteeism
	Reduces employee turnover
	Increases performance
Negative	
	Makes it difficult to cover jobs at all required times
	Makes it difficult to schedule meetings or training sessions
	Reduces communication within the organization
	Increases energy and maintenance cost
	Requires more sophisticated planning, organization, and control
	Requires special recording of work time
	Requires additional supervisory personnel

Table 10.6 Advantages and disadvantages of compressed workweeks/extended workdays. (Adapted from Knauth P 2007. Extended work periods. *Industrial Health 45*, 125–136 and Kroemer KHE, Kroemer HB & Kroemer-Elbert KE 2003. Amended reprint, *Ergonomics: how to design for ease and efficiency*. 2nd ed. Upper Saddle River, Prentice-Hall/Pearson Education.)

Positive	
	Appeals generally to employees and employers
	Makes available more consecutive days away from the job at employee's choosing
	Reduces commuting problems and costs
	Affords more time per day for scheduling meetings or training sessions
	Has fewer startup and warm-up periods
	Increases production rates
	Improves quantity and quality of services to the public
Negative	
	Requires overtime pay
	Decreases job performance due to long work hours
	Tends to fatigue workers
	Furthers tardiness and early departure from work
	Increases absenteeism
	Increases on-the-job accidents
	Increases energy and maintenance costs
	Makes it difficult to schedule child care and family life during the workweek

mostly used in cases where one waits on "standby" during sections of the shift, such as firefighters do. Also, activities that require only few or small physical efforts, which are diverse and interesting, have been done in long shifts. Examples are nursing, clerical and administrative work, technical maintenance, computer supply operations, and supervision of automated processes. Long shifts in manufacturing, assembly, machine operations, and other physically intensive jobs are less suitable.

Existing information on the outcomes of compressed work weeks has been gathered mostly in psychological tests, from statements of employees, and by scrutinizing performance and safety records in industry. The results are contradictory, spotty, and apparently depend much on the given work conditions. In some cases, production and performance are high shortly after introduction of a compressed workweek but fall off after prolonged periods on such a schedule – however, other observations have not shown this trend. The people involved often indicate significantly increased satisfaction, probably more related to ease of arranging personal time than to improvements of the work. Efficacy of the organization may improve with the compressed schedule; however, usually these positive effects are not strong.

Intensive work, especially physical labor, during the whole length of a very long work shift, such as of 12 hours, is likely to produce drowsiness and some reduction in cognitive abilities, motor skills, and in general performance during the course of each work shift. It appears that there is a potential for careless shortcuts to complete a job by a fatigued worker, and that work practices may become less competent in tedious and highly repetitive tasks during very long work shifts, as the workweek progresses*.

Suitable Shift Systems

By nature, the human is used to daylight activity, with the night reserved for rest. This appears to be an inherent feature, governed by the internal clocks of circadian rhythms. Night work, then, seems to be "unnatural"; however, this does not necessarily mean that it is harmful. But it appears that working at night generates "stress" which may be light or severe, depending on the circumstances and the person.

Organizational criteria by which to judge the suitability of shift systems include the number of shifts per day, the length of every shift, or the times of the day during which work is needed or not needed; the coverage of the week by shifts; shift work on holidays; and so forth. Management usually makes the decisions on these "independent variables".

There are "dependent variables" as well which are important to managers: one is the performance of workers on shift schedules. Is the same output to be expected regardless of the time of work during the 24-h day? Are specific activities better done at certain shifts? Do changes in shift work scheduling affect the worker's output? Is work on certain shifts more likely to show accidents?

The well-being of the shift worker is another "dependent variable" of great importance. Do certain shift regimes disturb physiological or psychological health? For example, when a night shift needs to be worked, how does the inability to have normal night sleep affect the worker's health? What are the effects of shift work on social interactions with family, friends, and the society in general?

Health and Well-Being

Evidently, a strong circadian system exists within the body which is remarkably resistant to sudden large changes in routine. This internal system being so stable, theoretical considerations, common sense and personal experiences all suggest that the normal synchrony of behavior in terms of nightly rest and daily activity should be maintained as well as possible. Thus, work schedules should be arranged in accordance with the internal system or, if this is impossible (for example, if night work is necessary), to disturb the internal cycles as little as possible. One of the logical conclusions from this thought is that, if work activities contradict the internal rhythm, these should be kept as short as feasible so that the worker can return to the "normal" cycle as quickly as possible. For example, one should schedule single night shifts, interspersed between blocks of several normal workdays, instead of requiring a worker to do several night shifts in sequence, as in the "metropolitan" and "continental rotation" mentioned earlier. Such a series of night shifts upsets the internal clock, while a single night shift would not disturb the entrained cycle severely.

The other solution, both theoretically sound and supported by experience, is to entrain new circadian rhythms. It takes regular and strong zeitgebers to overpower the regular signals, especially light and darkness. For shift work this means that the same setup (such as working the night shift) should be maintained for long periods of time (weeks, even months) and not be interrupted by different arrangements (in theory, not even by free days, such as on weekends). It appears that certain people are more willing and able to conform to such regular "non-day" shift regimens than others.

Health problems of shift workers* are often mentioned or suspected, but it is difficult to prove negative effects of a dangerous intensity. Night shift workers sleep time is, on average, about half an hour shorter than the sleep of workers who are permanently on day shift. (Persons who steadily work the evening shift have been found to sleep about half an hour longer than persons on the day shift.) Also, persons on night shift often complain about the reduced quality of sleep that they receive during the day, with noise particularly disturbing*.

Some researchers have found statistically significant health complaints as a function of shift work, particularly digestive disorders and gastro-intestinal complaints, yet other researchers have failed to prove significance. No differences seem to exist in mortality of night shift workers compared to workers in other shifts. However, it evident that persons who suffer from health disturbances are more negatively affected by night shifts than by other shift arrangements. It also appears that older workers who experience deteriorating health and difficulties to get enough restful sleep (both phenomena apparently increase with age) may be more negatively affected by shift work than younger workers. In contrast, other older shift workers have relatively fewer health, sleep and social problems than their younger colleagues, probably due to less need for sleep, a shift to "morningness" and looser social bindings.

Performance

Due to reduced quantity and quality of sleep, many night workers suffer from a chronic state of partial sleep deprivation. Negative effects of sleep deprivation on behavioral aspects have been well demonstrated, as discussed earlier. In some tasks, the interaction of circadian discrepancies between body state and work demand, and of sleep deprivation may result in significant detriments to night work performance, including safety. During the first night shift or shifts, performance is likely to be impaired in the very early morning hours, with the worst performance around 4 o'clock, coinciding with a low in body functions. Such impairment, which may be absent or minimal for cognitive tasks, varies in level but is similar to that induced by "legal doses" of alcohol. Accident injuries may be high on night shifts, but related statistics are usually confounded by variables other than the shift factor, such as the work task, worker age and skill, schedules of shift work*.

Tolerance of shift work differs from person to person and varies over time. Three out of ten shift workers have been reported to leave shift work within the first 3 years. Tolerance of those remaining on shift work depends on personal factors (age, personality, health troubles; the ability to be flexible in sleeping habits, to overcome drowsiness), on social-environmental conditions (family composition, housing conditions, social status), and of course on the work itself (workload, shift schedules, compensation). These factors interact, and their importance differs widely from person to person and changes over one's work life. Evening shift workers suffer particularly in their social and domestic relations, while night shift workers are more affected by insufficient sleep and suffer from being required to work while physiologically in a resting stage. However, physiological and health effects are not abundant in shift workers who have been on such assignments for years, possibly because persons who cannot tolerate these conditions abandon shift work soon after trying it.

Social Interactions

A major problem associated with shift work is the difficulty of maintaining customary social interactions when the work schedule enforces working or sleeping during times in which social relations usually occur. This makes family relations complicated as well as interaction with friends and participation in public events such as sports. Common daily activities are also affected, such as shopping or watching television.

Needs for social interactions are individually and culturally different. For example, parents of small children want to be home to be with their offspring and are unlikely to accept unusual work assignments that keep them away. In contrast, older persons who do not interact with their children so intensely may be more inclined to work "non-normal" hours.

Caution is in order, however, when transferring one's own living conditions and social expectations to different countries and cultures: certain events or conditions may be present or not, may be regularly scheduled at different times, and be considered of different value to individuals and the society at large. The siesta time of sunny climate zones is not commonly known in other regions. Some shops that are open continuously in the USA are locked around mid day, close in the late afternoon and may stay locked on weekends in Europe. Family ties are much more important in some cultures than in others and may vary among individuals. Television plays a large role in daily life of some groups of people and not in others. Thus, statements regarding the effects of shift work on social interactions that apply in one case may not be pertinent in another situation.

How to Select a Suitable Work System

The foregoing discussions made it clear that, if at all possible, the working hours should be during daylight, morning and afternoon. However, in many cases this "normal" arrangement is replaced by shift work which covers either the late afternoon and evening hours, or the night.

As Fig. 10.5 illustrates, there is an apparently inevitable fall in performance during night work, related to the circadian rhythm. This is of particular concern when night work period follows poor sleep and, especially, when the work shift is exceedingly long – more on this below. Poor sleep is likely if the assignment to night work is new.

A permanent shift assignment to evening or night shifts should allow the worker's internal rhythms to entrain on this rest/work pattern. However, that reasoning is not as convincing as it might appear: if, as in most shift arrangements, a free weekend interrupts the rhythm entrainment, the shift assignment is not truly constant and permanent. Furthermore, strong zeitgebers during the 24-h day (such as light and dark) remain intact even for a person on a regular late or night shift: these time markers hinder a complete re-entrainment of the internal functions. This leads to the opposite conclusion, also well founded in theory: it is better to work only occasionally during darkness. If there looms only one evening or night shift, most people are able to get through that unusual work session without much detriment, and they remain entrained on the usual 24-h cycle.

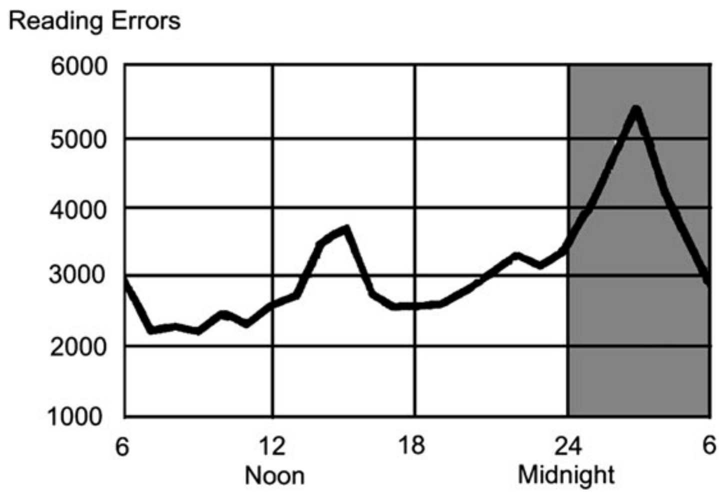

Fig. 10.5 Accumulated errors in gas meter readings, 1912–1931 (adapted from Kroemer, 2009)

For crews of airplanes who must cross time zones in their long distance flights and catch some sleep at their destination before returning, several problems exist. The first is that the quality and length of sleep at the stopover location is often less satisfactory than at home. The resulting tiredness may be masked or counteracted by use of caffeine, even drugs. The second problem is the extended time of duty, which includes preflight preparations, the flight period itself, and the wrap-up after arrival at the stopover. Negative effects are larger after an eastward flight than in westward direction; also, crew members over 50 years are more affected than their younger colleagues.

Recommendations for the shift arrangement for flight crews are fairly well established. In general, flight crews should adhere to well-planned timing which duplicates, as far as possible, the sleep-wake activities at home. Accordingly, at the destination the crew goes to bed at their regular home time and also gets up at the regular home time. Thus, the crew members retain their regular circadian rhythm. Of course, their next flight duty should be during their regular time of wakefulness*.

Entraining a new circadian rhythm needs time; air travelers use as general rule "it takes almost one day each to adjust to every 1 hour of time change". Exposure to sunshine, or bright light of least about 1,000 lux, at times when one feels sleepy but should be awake, counteracts the body's use of its own sleep-inducing hormone serotonin. This is a natural and efficient way to accelerate the resetting of the internal clocks*.

Shift Length

Physically demanding work should not be expected over periods longer than 8 hours unless frequent rest pauses are available; but even an 8-h shift may be too long for strenuous labor. The same axiom applies to work that is mentally very demanding by requiring complex cognitive processes or high attention. For other "everyday" work, durations of 9, 10, even 12 h/day can be quite acceptable. Flextime arrangements often are welcomed by employees, possibly in combination with "compressed" workweeks, particularly if they allow extended free weekends.

In the USA, health care providers habitually worked exceedingly long shifts. Nurses on shifts longer than 12 h can exhibit significantly decreased vigilance on the job, significantly increased risks of making a medical error and of suffering an occupational injury. Physicians-in-training working the traditional on-call shifts of more than 24 h are at greatly increased peril of making a serious or even fatal medical error, of experiencing an occupational injury, and of having a motor vehicle accident on the drive home from work.

It has been argued that large inter-individual differences exist in the responses to acute sleep loss or chronic sleep deprivation, implying that physicians are particularly resistance to such effects. Another reasoning is that resident physicians need training to function specifically when they are sleep-deprived. Similar arguments can be brought forth regarding airplane crews on extremely long flights, for example, or concerning commercial truck drivers on long-lasting drives. There is no evidence that exceptionally many physicians (or pilots, or drivers) are indeed resistant to the effects of sleep loss, and there are no means to monitor their resilience levels. Furthermore, an ethical question remains to be answered by both individuals and by their managers: how to assure the safety of patients (passengers, road users) from unintended misdeeds of tired operators?*

As a part of the decision to select one of the many possible shift plans, establishing a set of criteria helps to arrive at justifiable and orderly judgments:

For example:

- Daily work duration normally should not be more than 8 h.
- The number of consecutive evening or night shifts should be as small as possible; it is best to intersperse only one single late shift between day shifts. (The alternative solution is to stay permanently on the same late shift.)

- A full day of free time should follow ever single late shift.
- Each shift plan should contain consecutive work-free days, preferably including a weekend.

During evening or night shifts, workplaces should have high illumination, 2,000 lux or more, to suppress production of the hormone melatonin, which causes drowsiness. Furthermore, environmental stimuli may help to keep the worker alert and awake, such as occasional "stirring" music and provision of (hot) snacks and of beverages (hot and cold, possibly caffeinated). The work task should be interesting and rewarding, because routine boring tasks are difficult to perform efficiently and safely during the night hours.

The shift worker should use coping strategies for setting the biological clock, obtaining restful sleep, and maintaining satisfying social and domestic interactions. For example, sleep may be taken best directly after a night shift, not in the afternoon. Sleep time should be regular and kept free from interruptions. The shift worker should seek to gain the family's and friends' understanding of the need to rest. Certain times of the day should be set aside specifically and regularly to be spent with family and friends.

Figure 10.6 illustrates and summarizes the foregoing discussions. On the background of the daylight and darkness sequences of the day, it illustrates the circadian rhythm of wakefulness and rest. It shows that working during daylight hours complements the activity period of the internal rhythm while working during the late and night shifts disagrees with the natural inclination to sleep at these times. Sleep after an evening shift is still fairly easy to attain whereas restful sleep following a night shift is difficult to achieve during daylight.

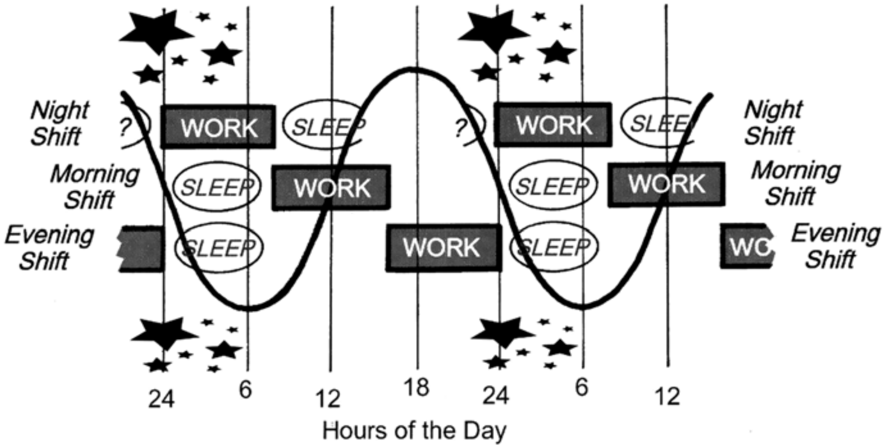

Fig. 10.6 Work-sleep sequences of persons working night, morning or evening shifts

Notes

The text contains markers, *, to indicate specific references and comments, which follow.

The menstrual cycle may affect the capacity to perform certain tasks: Patkai (1985) cites a study in which secretaries showed the highest typing speed before the onset of menstruation and during the first three menstrual days. The idea of a higher effort on these days was rejected by the secretaries since they considered themselves to be working at full capacity all the time.

Circadian rhythm extremes during the day can be quite different among individuals and may change even within a person: Folkard and Monk (1985), Refinetti (2006) provide a history of research on circadian rhythms.

Desynchronization of oscillators; for example, the sleep/wake cycle stays at 24 h, while the temperature rhythm may freerun at a period of 25 h: Wever (1985).

"Evening types" and "morning types": Horne and Oestberg (1976), Di Milia et al. (2004), Refinetti (2006).

No explanation for what sleep does and why we must sleep – but humans need sleep: Horne (1988), Siegel (2003). The Royal Society of Medicine 2005 published a history of sleep research at http://www.neuronic.com/rsm200sleep/presentations/sleepthenandnow.html

Under sleep deprivation or during ebb times of circadian rhythms there is no significant decrease in physiological capabilities: Refinetti (2006).

For regular tasks, there may be an overcapacity of cerebral neural networks; so, many are not fully used: Horne (1988).

Dreams are the "cinema of the mind": Horne (1988, p. 313).

No true non-sleepers have ever been found among otherwise healthy persons: Horne (1988).

When people must stay awake for long periods of time, memory use degrades, both in long-stored memory information and short-term memory: Froeberg (1985).

After missing four nights of sleep, very few people are able to perform adequately even if their motivation is very high: Froeberg (1985).

Naps of at least 2 h taken in the late evening or during nighttime, when the circadian rhythm is falling, have positive effects lasting several hours: Gillberg (1985), Rogers et al. (1989).

Taking drugs, particularly amphetamines, can restore performance to a nearly normal level even after even three nights without sleep: Froeberg (1985).

Many diverse shift systems exist: Described, for example, by Colquhoun (1985), Folkard and Monk (1985), Hurrell and Colligan (1985), Colligan and Tepas (1986), Tepas and Monk (1986), Monk et al. (1996), Smith et al. (1998), Hornberger et al. (2000), Folkard and Tucker (2003), Knauth (2006, 2007a, 2007b), Monk (2006), Popkin et al. (2006).

Four particular features of shift systems are especially important: Kogi (1985).

A fatigued worker may become less competent in tedious and highly repetitive tasks during very long work shifts: Folkard and Tucker (2003), Smith (1998), Knauth (2006, 2007a).

Health problems of shift workers: Costa (2003). *Persons on night shift often complain about the reduced quality of sleep that they receive during the day:* Carvalhais et al. (1988).

Accident injuries may be high on night shifts: Monk (1989, 2006).

Tolerance of shift work differs. Three out of ten shift workers have been reported to leave shift work within the first 3 years: Bohle and Tilley (1989).

Flight crew sleeping arrangements: Graeber (1988).

Exposure to sunshine or bright light is a natural and efficient way to accelerate the resetting of the internal clocks: Czeisler et al. (1990).

Sleep-deprived nurses and physicians: Van Dongen (2006), Czeisler (2006, 2009), Lockley et al. (2007).

Summary

Human body functions and human social behavior follow internal rhythms. Under regular living conditions, these temporal programs are well established and persistent. One is the female menstrual cycle of about 28 days; another is the set of daily fluctuations, called circadian rhythm. The menstrual cycle has little or no effects on work performance; however, circadian rhythm and execution of work are closely related.

The circadian rhythm is evident in body temperature, heart rate, blood pressure, and hormonal excretions and in the associated patterns of sleep (naturally during the night) and of daytime activities. This rhythm can be de-synchronized and put out of order if time markers (zeitgeber) during the 24-h day are changed: activities required from the human at unusual times can have such effect. Sleep deprivation and tiredness influence human performance in various negative ways. Mental performance, attention and alertness usually are reduced, but execution of most physical activities is not. Furthermore, concerns exist that disturbing the internal rhythm, such as by certain types of shift work, might have negative health effects. Being excluded by shift *work from participating in family and social activities is difficult for many persons.*

Shift work is often desired for organizational/economic reasons. Individual acceptance of working in shifts depends on a complicated balance of professional and personal concerns, including physiological, psychological, and social aspects. Of ten persons assigned to shift work, seven or eight are likely to stay on this schedule while the others drop out. Shift work may worsen pre-existing health conditions. Workers on permanent night shifts often complain about insufficient sleep and general fatigue.

Shift workers' task performance mainly depends on four factors: the type of work; the organization of work activities; the internal circadian rhythm of the body; and the individual's motivation and interest in the work. Each factor can govern, influence, or mask the effects of the other factors on task execution. Mental performance capabilities are particularly prone to deterioration during long-continued work and accompanying sleep loss. Long task duration, monotony, complexity, and repetitiveness all have decidedly negative effects. Performance is especially low during "low" periods of the circadian cycle such as in the early morning hours. Sleep-deprived persons do not perform well on either monotonous or complex tasks over long periods of time. Exceptionally high motivation may reduce or prevent performance decrements.

A shift duration of 8 h of daily work is usually adequate, but shorter times for highly (mentally or physically) demanding jobs may be advantageous; longer times (such as 9, 10, even 12 h) may be acceptable for some types of work.

Recommendations for acceptable regimes of working hours and shift work include:

- *Job activities should follow entrained body rhythms.*
- *It is preferable to work during the daylight hours.*
- *Evening shifts are preferred to night shifts.*
- *If shifts are necessary, two opposing rules apply:*

  Either work only one evening or night shift per cycle, then return to day work, and keep weekends free; or stay permanently on the same shift, whatever that is.

Glossary

Circadian rhythm Regular oscillations in body functions which repeat after about 24 hours. This daily rhythm is endogenously (see there) generated and modulated by 24 h environmental repetitions, especially by light and darkness related to the earth's rotation. (From the Latin *circa*, about, and *dies*, the day; see also diurnal rhythms).

Desynchronization Loss off synchronization (see there) within an organism between a rhythm and its zeitgeber (see there), or between two rhythms.

Diurnal rhythm Regular oscillations in body functions during the day time (from the Latin *diurnus*, of the day; see also circadian rhythm).

Endogenous Originating inside an organism or system.

Entrain To synchronize a self-sustaining oscillation or oscillator.

Ergonomics The application of scientific principles, methods and data drawn from a variety of disciplines to the design of engineered systems in which people play significant roles.

Exogenous Originating outside an organism or system.

Freerun The state of a self-sustaining oscillation in the absence of effective zeitgeber (see there) or other environmental events that may affect the period of the oscillation.

Infradian rhythm Regular oscillations in body functions with a frequency lower than circadian; that is, they repeat after more than 24 h.

Masking Disruption in the appearance of an overt rhythm caused by an external event without a direct effect on the period or phase of a pacemaker (see there).

Pacemaker An entity capable of generating an endogenous rhythm and of imposing this rhythm on one or more other entities.

Running free Being in the state of a self-sustaining oscillation in the absence of effective zeitgeber (see there) or other environmental events that may affect the period of the oscillation.

Self-sustaining oscillation An oscillation, caused by a pacemaker (see there), which continues without external support.

Synchronization The action of causing two or more processes to start at the same time and/or to proceed at the same rate.

Ultradian rhythm Regular oscillations in body functions with a frequency higher than circadian; that is, they repeat after less than 24 h.

Zeitgeber A time setter; agent or stimulus capable of resetting a pacemaker (see there) or synchronizing a self-sustaining oscillation (see there). (From the German *Zeit*, time; and *Geber*, giver).

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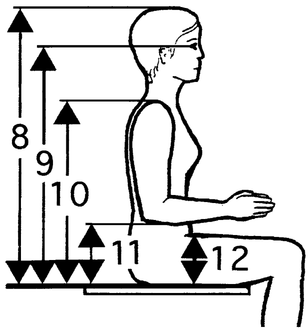
Chapter 11
Engineering Anthropometry



Overview

Anthropometric information describes the size of the human body. Traditional measurements mostly use bone landmarks to determine heights, breadths, depths, distances, circumferences, and curvatures. New assessment techniques rely on 3-dimensional topography of the body surface. Most of the currently available anthropometric information stems from measurements with classical instruments; these describe a limited number of military and civilian populations.

People come in a variety of sizes; their bodies are assembled in various proportions. Thus, designing to suit the human bodies requires careful consideration; using the statistical "average" will not do. Instead, for each body segment to be fitted, we must determine the specific dimensions that are critical for design. For this, we select a minimal or a maximal value, or the range between them.

The Model

Statistical relations among body dimensions help to assess the body's contours, shapes, volumes, and masses, and the motion envelopes of the body. Specific measures explain the mobility and the workspace of hands and arms and of other body segments. Descriptions of the overall size of the body determine the sizes of space and equipment used for work and leisure.

Introduction

The dimensions of the human body and its segment proportions have been of interest to artists and philosophers, physicians and anatomists, to rulers and generals, and certainly to anyone who designs and provides objects for human use. Marco Polo, writing about his travels from Italy eastward into China at the end of the thirteenth

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century, evoked particular interest with his descriptions of the various body sizes and body builds that he saw. Physical anthropology as a recording and comparing science is often traced to his travel reports. Johann F. Blumenbach's 1776 book *On the Natural Differences in Mankind* contains the complete anthropometric information available up to his day. Alexander von Humboldt encompassed all scientific knowledge in his widely read five-volume *Kosmos* published from 1845 to 1862.

In about the middle of the nineteenth century, anthropology split into special branches. Adolphe Quételet applied statistics to anthropological information in the mid-1800s. The science of biomechanics – see Chap. 4 – emerged at the end of the nineteenth century. At that time, Paul Broca made extensive studies on the skull and drew far-reaching conclusions. The rapidly increasing diversity in anthropometric studies led to conventions of physical anthropologists, 1906 in Monaco and 1912 in Geneva, who agreed on standards for anthropometric methods. In 1914, Rudolf Martin published the first edition of his "Lehrbuch der Anthropologie"; it became the authoritative guide and handbook for many decades. From the 1960s on, new engineering needs, developing measuring techniques and advancing statistical techniques caused updates and re-directions in anthropometric techniques and methods*.

While compilations of measured data are available for specific populations*, information on the body sizes of many people on earth is still missing. Global commercial interests und new efficient measurement techniques (see below) may lead to more complete anthropometric information.

Measurement Techniques

The classical measuring technique employed four body postures for measuring how tall a person is, "stature": the subject standing freely but stretched to maximum height; leaning against a wall with the back flattened and stretched to maximum height; standing naturally upright, but not stretched; and lying on the back. The results of the measures when the subject stretches to maximum height either standing freely or leaning are within a couple of centimeters; yet, "slumped" standing can reduce stature by several centimeters. Lying supine (routinely done with babies) results in the tallest measure. This example shows that standardization is necessary to assure uniformity in postures and results.

Terminology and Standardization

Anthropometric measures are traditionally taken in metric units. Body measurements are defined by the two end-points of the distance measured, such as elbow-to-fingertip; stature starts at the floor on which the subject stands, and extends to the highest point on the skull under the hair. The Appendix at the end of the chapter list many terms used in anthropometry.

Professional physical anthropologists are trained to do the measurements; however, with standardization and with an experienced measurer supervising, other non-specialists have successfully taken many measurements. With 3D computerized scanning assessments (see below) evolving, the demands on both measurers and measuring procedures are changing.

For measurements, the subject is nude, or nearly so, and without shoes. To standardize the procedures, the subject's body is placed in defined poses. If measurements involve the head, it is positioned in the so-called Frankfurt Plane, described below. The subject usually assumes an upright posture, as already mentioned, with body segments at either 0, or 90 or 180° to each other. For example, the subject may be required to "stand erect; heels together; arms vertical, wrist and fingers straight and pointing downward. . .": This is close to the so-called anatomical position – but it differs from most natural "working" postures.

To measure a seated subject's major dimensions, the (flat and horizontal) surfaces of seat and foot support are arranged so that the thighs are horizontal, the lower legs vertical and the feet flat on their horizontal support.

Figure 11.1 shows reference planes used in anthropometry. Figure 11.2 illustrates anatomical landmarks of the human body in the sagittal view and Fig. 11.3 shows landmarks in the frontal view.

For measurements involving the head, it may be positioned in the so-called Frankfurt plane: with both pupils at the same height, the right tragion (a point at the ear hole) and the lowest point of the eye socket in the skull (the rim of the right orbit) are placed on the same horizontal plane. This is simple to do with an isolated skull but palpating and finding the orbit on a living subject is a bit awkward. It is easier to position the head using the "Ear-Eye Line", which runs through the right ear hole and the junction of the right eyelids (the external canthus) – see Fig. 11.4. If one places the eye higher than the ear hole so that the EE Line tilts 11° above the horizon, the head is in the Frankfurt plane*.

Classical Measuring Techniques

In conventional anthropometry, the measurement devices are quite simple. One technique relied on a set of grids at the intersection of two orthogonal vertical walls – see Fig. 11.5. The subject sat or stood in front of the grid, and the projections of body landmarks onto the grid served to determine dimensions. Other similar setups include box-like jigs, which provide references for measurements of head and foot dimensions – see Figs. 11.6 and 11.7.

Many body landmarks do not project easily onto grids; hence, special instruments are in use. The most important is the anthropometer, a graduated rod with a fixed branch at one end and a sliding branch, both perpendicular to the rod. The distances between the branches, or from the end of the rod, appear on the scaled rod – see Figs. 11.7 and 11.8. The rod can be sectioned for short measurements and easy transport and storage.

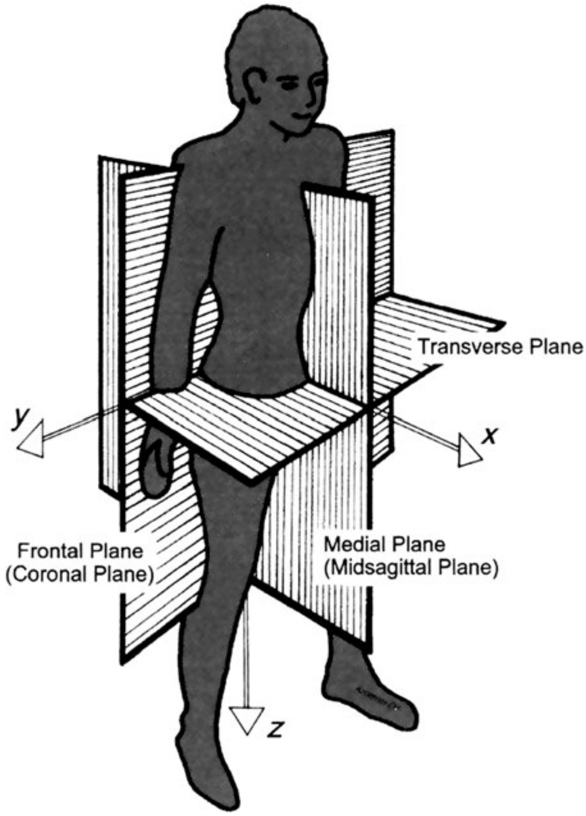


Fig. 11.1 Reference planes used in anthropometry

The spreading caliper consists of two curved branches, joined in a hinge. The distance between the tips of the two opposing ends appears on a scale. A straight sliding caliper serves for short measurements, such as finger thickness or hand breadth – see Fig. 11.9. A special caliper measures the thickness of skinfolds. A cone provides measurements of the diameter around which fingers can close; circular holes of increasing sizes drilled in a thin plate indicate external finger diameters. Tapes, made of flat steel or of non-stretch woven material, serve for measurements of circumferences and curvatures– see Fig. 11.10. Scales, of course, measure weight.

New Measurement Methods

The classical anthropometric techniques use measurement instruments applied with the hands of the measurer to the body of the subject. Most instruments and procedures are simple and the measured person easily understands their use. However, the processes are also somewhat clumsy and certainly time-consuming. Each measurement and tool must be selected in advance; and what was not measured in the

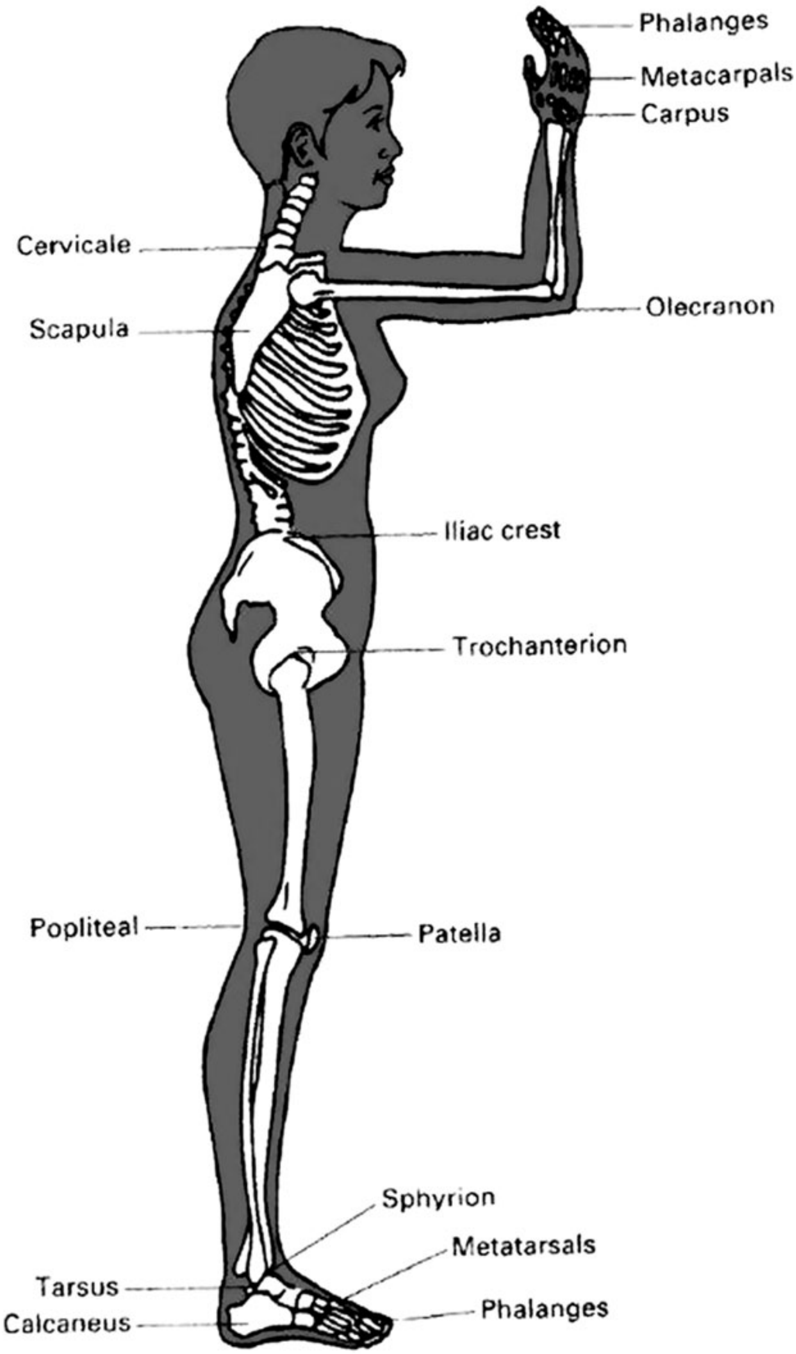


Fig. 11.2 Anatomical landmarks in the sagittal view

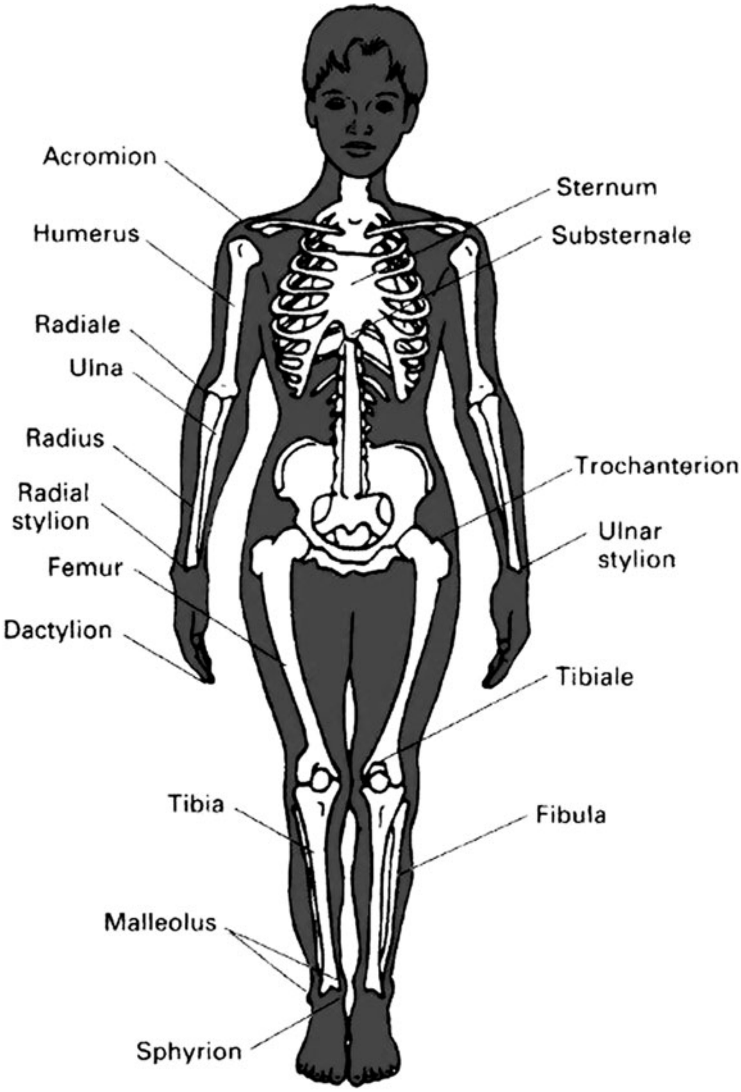
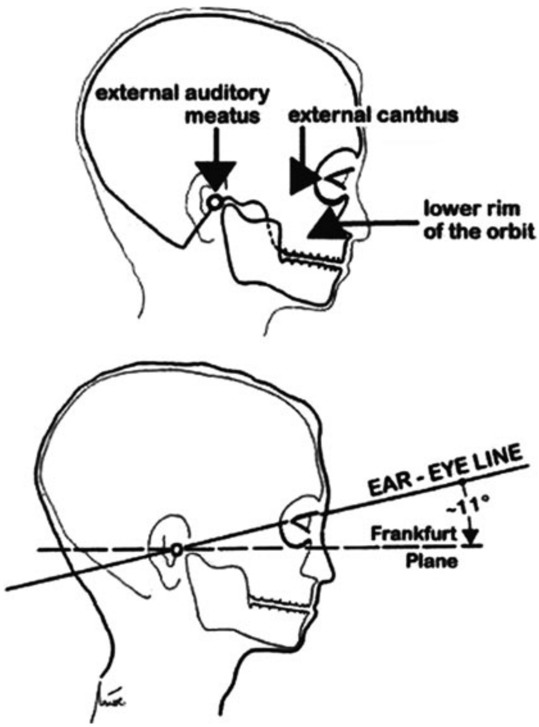


Fig. 11.3 Anatomical landmarks in the frontal view

test session remains unknown unless the subject is called back for more measuring. Another major disadvantage is that many of the classical dimensions do not relate to each other in space. For example, as one looks at a subject from the side, stature, eye height and shoulder height are located in different yet undefined frontal planes. Furthermore, certain parts of the body are sensitive to touch, such as the eyes.

Photographic methods can overcome many of these disadvantages. They instantly record all surface aspects of the human body that are visible. They allow

Fig. 11.4 Positioning the head using Frankfurt Plane and Ear-Eye Line



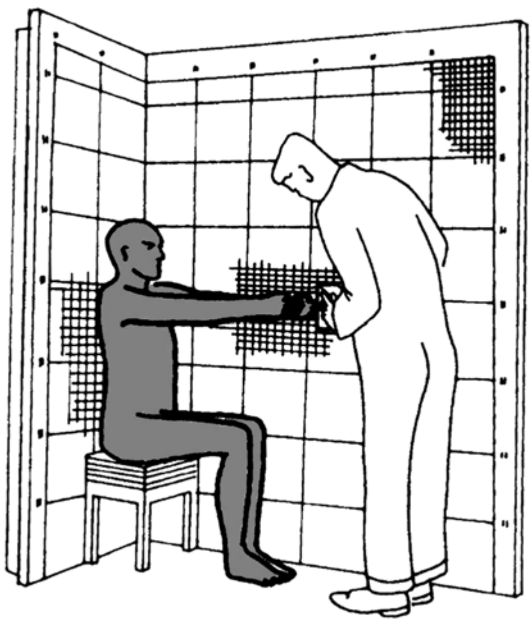


Fig. 11.5 Grid system placed in a corner for anthropometric measurements (adapted from Roebuck et al., 1975)

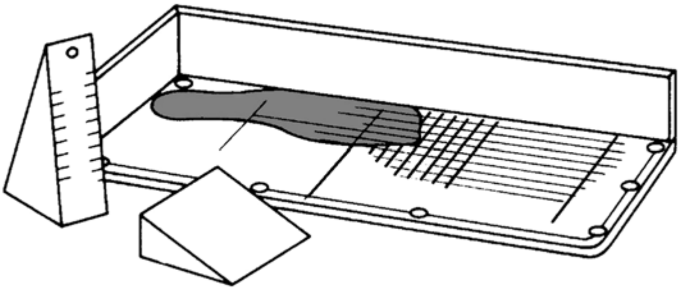
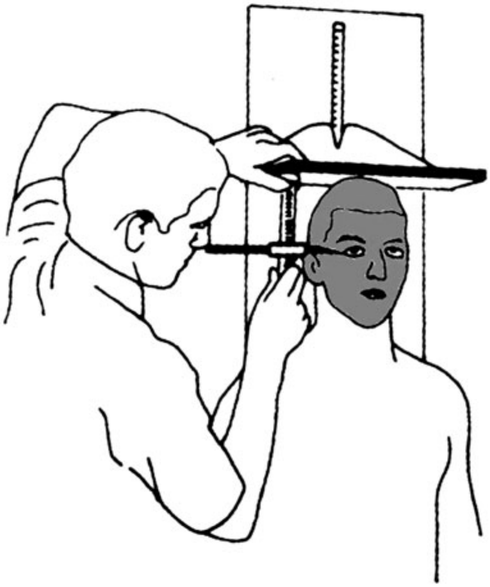


Fig. 11.6 “Measuring box” for foot measurement (adapted from Roebuck et al., 1975)

Fig. 11.7 Typical use of a sliding headboard and a sectioned anthropometer



storage of practically infinite numbers of measurements, which can be retrieved from the record whenever convenient. However, they also have drawbacks: a scale may be difficult to establish on the photographic record, parallax distortions exist and one cannot palpate landmarks under the skin. Even with improvements, such as employing several cameras and mirrors, using videotape and electronic storage instead of still film, utilizing stereophotometry and holography, photographic techniques did not become popular in anthropometry.

A newer technique uses the laser as a distance-measuring device; it may move around the body or the body moves in front of the scanner. Coupled with a computer to store, sort, and reproduce the distance data, topographic techniques can describe the human body surface in minute detail, in three dimensions. Yet, points of interest below the visible surface, joints and bone landmarks (such as the top of the head

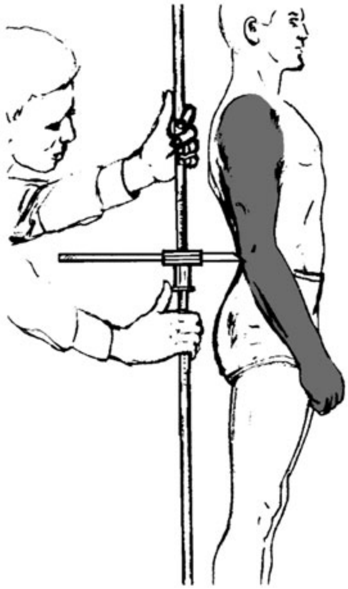


Fig. 11.8 Anthropometer used to measure elbow height (adapted from Roebuck et al., 1975)

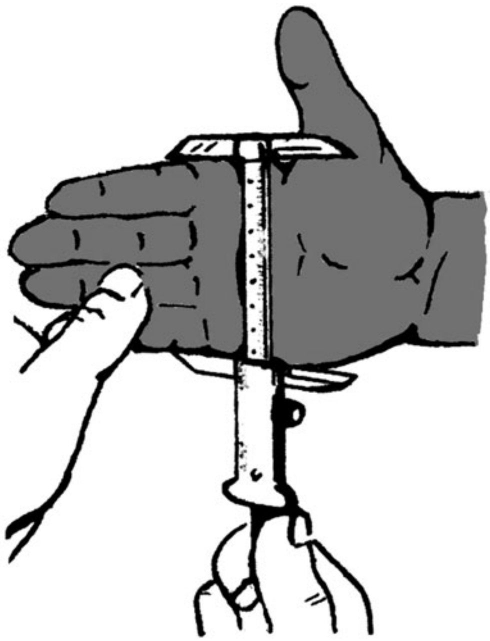


Fig. 11.9 Sliding caliper used to measure hand breadth

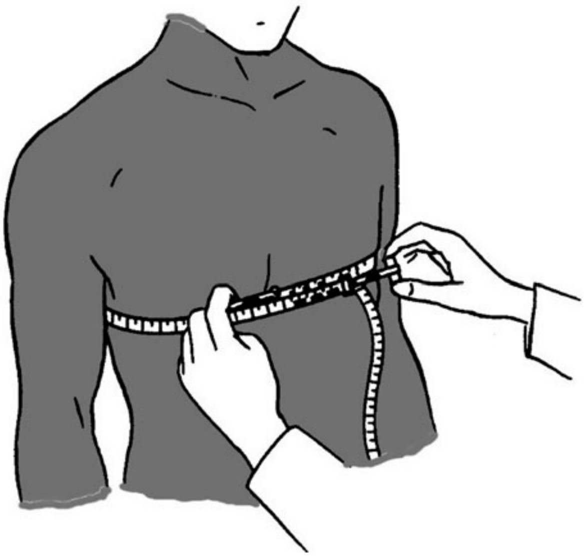


Fig. 11.10 Tape used to determine chest circumference

hidden under hair, or the acromion below skin and other tissues), do not appear in the data set unless "markers" are placed on the skin. One solution is to use information on the contours of the body for calculating the locations of bony landmarks underneath the skin*.

Such scanner systems to gather anthropometric data are expensive but they provide advantages over the classic procedures. They are fast and they collect vast amounts of data in three dimensions. Instruments or hands of the measurer do not touch the subject. Computerized data storage and processing allows 3D-descriptions of shapes of the body and its parts, and of changes by motion, training or aging. Computerized 3-D data promise to meet the increased use of computer models of the human body in engineering design*. Yet, many data acquired with either one of the anthropometric techniques require some conversion to fit the other format.

Obviously, anthropometric technology is in flux. Classical measuring techniques are likely to retain some importance because they can be used simply and easily even under adverse conditions, particularly in static or semi-static situations. However, automated 3D anthropometric measurements are gaining increasing importance.

Body Typology

One can try to assess human body dimensions by describing body components and how these "fit" together. Our images of the beautiful body depend on aesthetic codes, canons and rules based on often ancient (mostly Egyptian, Greek and Roman) concepts of the human body. A well-known example is Leonardo da Vinci's drawing, circa 1500, of a man within a frame of graduated circles and squares to signify the well-proportioned body. Often simplified, this image is widely known; the US *Human Factors and Ergonomics Society* adapted it as its emblem.

Somatotyping (from the Greek *soma* for body) categorizes body builds into different types. Hippocrates developed, about 400 BC, a scheme that included four body types, determined by their fluids. (He thought that black gall created the moist type; yellow gall generated the dry type; slime made the cold type, while blood governed the warm type.) In 1921, the psychiatrist Ernst Kretschmer published a scheme of three body types by which he intended to relate body build to personality traits: his typology consisted of asthenic, pyknic and the athletic body builds. (The athletic type was to indicate character traits, not sports performance capabilities.) In the 1940s, the anthropologist W.H. Sheldon described a system of three body types, meant to describe (male) body proportions. Sheldon rated each person's appearance with respect to three morphic components – see Table 11.1. It is of interest to note that Sheldon originally used intuitive judgment, not actual body measurements: his disciples brought these into the typology system.

These and other attempts (such as the Heath-Carter system) at somatotyping did not provide reliable predictors of body sizes, strength, endurance or other capabilities for work performance. Hence, somatotyping is of little value for human factors engineers.

Table 11.1 Body typologies

Description	Stocky, stout, soft, round	Strong, sturdy, muscular	Lean, slender, fragile
Kretschmer typology	Pyknic	Athletic	Asthenic (leptosomic)
Sheldon typology	Endomorphic	Mesomorphic	Ectomorphic

Anthropometric Data Sets

The military always had a particular interest in the body dimensions of soldiers – for a variety of reasons, among them the necessity to provide fitting uniforms, armor and equipment. Furthermore, armies employ medical personnel willing and capable to perform body measurements on large samples "on command". Hence, anthropometric information about soldiers is extensive and reaches far into the past*. However, soldiers are a select sample of the general population: they are relatively healthy, fit and young adults. Dimensions of the head, hand and foot measured on military populations are apparently similar to those of civilians while other data are likely to differ.

Normality

Anthropometric data usually appear in a reasonably normal (Gaussian) distribution, bell-shaped and symmetrical to the mean, as in Fig. 11.11. Hence, parametric

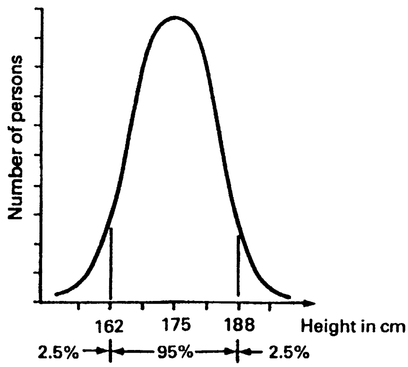


Fig. 11.11 The body height (stature) of Americans shows a normal distribution. About 95% of all males are between 162 and 188 cm tall; about 2.5% are shorter, another 2.5% taller

statistics apply to most anthropometric information – but body weights (and muscle strength data) generally are not distributed normally.

Table 11.2 lists the most common statistical procedures*. The first and easiest check for normality of data uses the *mean, median*, and *mode*: if they concur, normality is likely. Another approach is to calculate the average *m* by first using the complete range of data and then by leaving out the (say, ten) smallest and largest numbers: if both calculations end up with the same mean, normality is often the case. More formal calculations probe symmetry/skewness and peakedness. Regarding skewness: a result of 0 (zero) indicates a symmetrical distribution, a positive (negative) result points to skewness to the left (right). Regarding peakedness (kurtosis): a normal distribution is usually assumed when the numerical result is 3; if the result is larger (smaller) than 3 the distribution is peaked (flat).

Variability

"A pioneer in the field of statistics, Sir Francis Galton [1822–1911] wrote that 'it is difficult to understand why statisticians commonly limit their interests to averages. Their souls seem as dull to the charm of variety as that of a native of one of our flat English counties whose retrospect of Switzerland was that, if its mountains would be thrown into its lakes, two nuisances could be got rid at once.' Basic to virtually all design problems is the fact that mankind is far more like Switzerland than a flat English county, and that, whatever the charms of variety may be, we need statistics to quantify this variety". (Edmund Churchill, the eminent statistician in the field of engineering anthropometry during the second half of the twentieth century; as quoted – shortened – from page IX-5 of NASA/Webb, 1978.)

The standard deviation *S* (called *SD* in some statistics books) describes the variability of anthropometric data: the larger *S*, the flatter (more spread out) is the distri-

Table 11.2 Statistical formulas of particular use in anthropometry

Measures of central tendency		
Mean, Average *m*	$m = \sum x/n$	(11.1)
Median	Middle value of values in numerical order	
Mode	Most often occurring value	
Measures of variability		
Skewness (symmetry)	$\sum (x - m)^3/n$	(11.2)
Peakedness (kurtosis)	$\sum (x - m)^4/n$	(11.3)
Range	$x_{max} - x_{min}$	(11.4)
Standard deviation *S*	$S = (variance)^{1/2} = \left[\sum (x - m)^2/(n-1)\right]^{1/2}$	(11.5)
Coefficient of variation *CV*	$CV = S/m$; {in percent: CV = 100 S/m}	(11.6)
Standard error of the mean *SE*	$SE = S/n^{1/2}$	(11.7)
Measures of relations between variables *x* and *y*		
Correlation coefficient *r*	$r = S_{xy}/(S_x \times S_y)^{1/2}$ $= \sum\left[(x - m_x)(y - m_y)\right] / \left[\sum (x - m_x)^2 \sum (y - m_y)^2\right]^{1/2}$	(11.8)
Coefficient of determination *R*	$R = r^2$	(11.9)
Regression	$y = a + bx$;	(11.10)
	with $b = r \times S_y/S_x$	(11.11)
Percentile value location in a data distribution		
Percentile *p*	$p = m + kS$ (*k* from Table 11.3)	(11.12)
Sampling		
Sample size *N*	$N = [q \times S/v]^2$ (*q* from Table 11.11)	(11.13)
Ratio scaling		
Scaling factor *E*	$E = \mathrm{d}_x/\mathrm{D}_x = \mathrm{d}_y/\mathrm{D}_y$	(11.14)
Combining data sets		
Covariance *COV*	$COV_{(x,y)} = r_{xy} \times S_x \times S_y$	(11.15)
Sum of two mean values	$m_z = m_x + m_y$	(11.16)
Standard deviation of the sum	$S_z = (S_x^2 + S_y^2 + 2r\ S_x \times S_y)^{1/2}$	(11.17)
Difference of two mean values	$m_z = m_x - m_y$	(11.18)
Stand. deviat, of the difference	$S_z = \left(S_x^2 + S_y^2 - 2r\ S_x \times S_y\right)^{1/2}$	(11.19)
Factor *k* in a combined set	$k_z = n_x \times k_x + n_y \times k_y$	(11.20)
Percentile *p* in a combined set	$p_z = n_x \times p_x + n_y \times p_y$	(11.21)

n is the number of data in a data distribution

Table 11.3 Percentile values and associated k factors

Below mean Percentile	Factor k	Above mean Percentile	Factor k	Percentile	Factor k	Percentile	Factor k
0.001	–4.25	25	–0.67	50 (mean)	0	76	0.71
0.01	–3.72	26	–0.64	51	0.03	77	0.74
0.1	–3.09	27	–0.61	52	0.05	78	0.77
0.5	–2.58	28	–0.58	53	0.08	79	0.81
1	–2.33	29	–0.55	54	0.10	80	0.84
2	–2.05	30	–0.52	55	0.13	81	0.88
2.5	–1.96	31	–0.50	56	0.15	82	0.92
3	–1.88	32	–0.47	57	0.18	83	0.95
4	–1.75	33	–0.44	58	0.20	84	0.99
5	–1.64	34	–0.41	59	0.23	85	1.04
6	–1.55	35	–0.39	60	0.25	86	1.08
7	–1.48	36	–0.36	61	0.28	87	1.13
8	–1.41	37	–0.33	62	0.31	88	1.18
9	–1.34	38	–0.31	63	0.33	89	1.23
10	–1.28	39	–0.28	64	0.36	90	1.28
11	–1.23	40	–0.25	65	0.39	91	1.34
12	–1.18	41	–0.23	66	0.41	92	1.41
13	–1.13	42	–0.20	67	0.44	93	1.48
14	–1.08	43	–0.18	68	0.47	94	1.55
15	–1.04	44	–0.15	69	0.50	95	1.64
16	–0.99	45	–0.13	70	0.52	96	1.75
17	–0.95	46	–0.10	71	0.55	97	1.88
18	–0.92	47	–0.08	72	0.58	98	2.05
19	–0.88	48	–0.05	73	0.61	99	2.33
20	–0.84	49	–0.03	74	0.64	99.5	2.58
21	–0.81	50 (mean)	0	75	0.67	99.9	3.09
22	–0.77					99.99	3.72
23	–0.74					99.999	4.26
24	–0.71						

Any percentile value p (in a normal distribution of data) can be calculated from the mean m and the standard deviation S according to $p = m + kS$ (Eq. 11.12)

Examples:
5th percentile is at $m - 1.64S$ because of $k = -1.64$
10th percentile is at $m - 1.28S$ because of $k = -1.28$
50th percentile is at m because of $k = 0$
60th percentile is at $m + 0.25S$ because of $k = 0.25$
95th percentile is at $m + 1.64S$ because of $k = 1.64$

bution. That dispersion of a set of anthropometric data reflects the (true) variability of the underlying data, the accuracy of the measuring techniques and the carefulness used in data handling, especially in their statistical treatment. For example, when comparing the descriptive statistics of two distinct though similar population samples, one may find that one shows a much larger coefficient of variation (*CV* in Table 11.2, see Eq. 11.6) of like dimensions than the other does. From this, one may infer that the more dispersed sample reflects suspicious variability in the measuring technique and/or in data management.

The lowest and the highest values of a measured data set describe its full range; however, seldom is a design adaptable enough to fit the whole spread. Instead, low and high cut-off values are selected, often as successive size sets such as in shoe or clothing tariffs, at pre-determined percentiles. One common procedure considers the fifth percentile as the lowest and the 95th percentile as the highest points; this should accommodate the central 90% of the population, excluding only the smallest 5 and the largest 5%. If the data distribution is normal, known values for the mean *m* (which coincides with the 50th percentile, median and mode; see Eq. 11.1 in Table 11.2) and the standard deviation *S* (Eq. 11.5) allow calculation of the desired percentile point, as Eq. 11.12 and Table 11.3 describe.

Correlations

Some body dimensions relate closely with each other: for example, eye height follows stature closely – but head measures do not show sizable relationships with stature, nor do circumferences or breadths, and neither does weight. The statistical (Pearson) correlation coefficient *r* (Eq. 11.8 in Table 11.2) provides valuable information about the degree of relationship between sets of data.

Figure 11.12 contains scatter diagrams of the distributions of measures of two variables, *x* and *y*. If there is no relation between the variables, the value of the correlation coefficient *r* calculates to *zero* (top of Fig. 11.12). Values of 0.5 or less indicate weak relations whereas a correlation coefficient higher than 0.7 shows a strong dependency. If increasing values of x show exactly equivalent increases in *y*, *r* equals 1; if increases in *x* are followed by linear decreases in *y*, the value of *r* is –1 (bottom of Fig. 11.12).

Table 11.4 lists selected correlation coefficients *r* among body dimensions of US Air Force personnel, male and female, measured in the late 1980s: older tables on soldiers* showed similar relationships among body data. Unfortunately, correlation tables concerning civilian and non-US populations apparently do not exist.

The correlation coefficient provides valuable information about the relationship between sets of data. It is a useful practice in anthropometry – and in human engineering – to require that the predictor variable explain at least 50% of the variation of the predicted value: accordingly, the coefficient of determination ($R = r^2$, see Eq. 11.9 in Table 11.2) must have a value 0.5 as a minimum. This means that the value of *r* must be at least 0.7.

This "0.7 convention" is important for basing decisions on a correlation and, relatedly, for the development and use of regression equations, which express the average of one variable as a function of another variable – see the discussions below under "Body Proportions" and "How to Get Missing Data". If the use of a single predictor variable is not sufficient to establish an overall correlation coefficient between predictor and predicted value of better than 0.7, additional predictor variables may be taken into the equation until the resulting "multiple regression equation" reaches a minimal cut-off point.

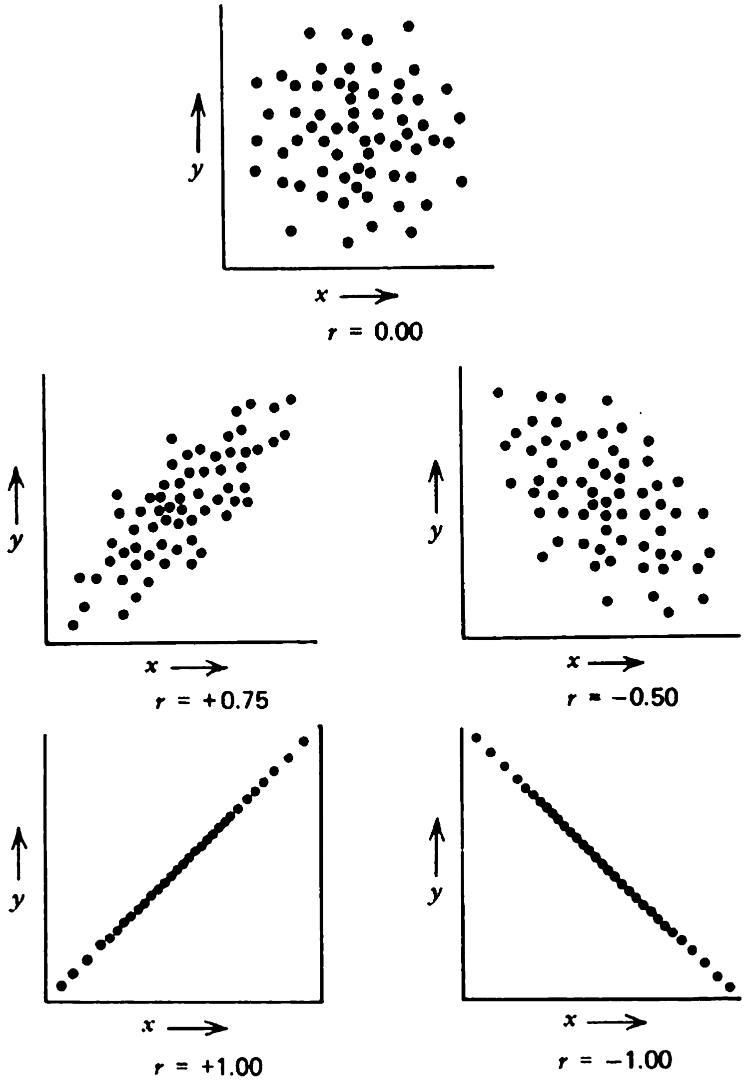


Fig. 11.12 Scatter diagrams of bivariate data distributions and correlation coefficients (adapted from Roebuck et al., 1975)

Body Proportions

It can be convenient to calculate proportional relationships (ratios, indices) between body dimensions. Of course, such procedure is justified and useful only when there is a sufficient correlation between the two variables, as just discussed. Of the body measures listed in Table 11.5, only overhead reach, wrist height, crotch and popliteal

Table 11.4 Correlations between anthropometric data on US soldiers. Values for women are listed above the diagonal, for men below. Values larger than 0.7 carry an asterisk

		1 Age	2 W	3 Stat	4 OFR	5 WH	6 CH	7 SH	8 PH	9 SC	10 CC
1	Age [302]		0.219	0.041	0.017	0.044	−0.055	0.066	−0.074	0.155	0.193
2	Weight [125]	0.195		0.529	0.493	0.491	0.370	0.422	0.242	0.845*	0.806*
3	Stature [100]	−0.021	0.546		0.928*	0.848*	0.840*	0.755*	0.808*	0.377	0.222
4	Overhead fingertip reach[84]	−0.013	0.525	0.937*		0.704*	0.905*	0.554	0.868*	0.384	0.199
5	Wrist height, standing [128]	0.028	0.527	0.856*	0.749*		0.625	0.754*	0.587	0.300	0.255
6	Crotch height [39]	0.090	0.351	0.852*	0.890*	0.673		0.330	0.915*	0.267	0.093
7	Sitting height [94]	0.026	0.447	0.741*	0.578	0.692	0.347		0.343	0.285	0.202
8	Popliteal height, sitting [87]	−0.094	0.341	0.852*	0.883*	0.673	0.924*	0.383		0.188	0.023
9	Shoulder circumference [91]	0.122	0.861*	0.399	0.413	0.334	0.250	0.326	0.256		0.808*
10	Chest circumference [34]	0.279	0.873*	0.312	0.308	0.357	0.135	0.287	0.137	0.859*	
11	Waist circumference [115]	0.364	0.849*	0.276	0.251	0.343	0.060	0.298	0.074	0.703*	0.839*
12	Buttock circumference [24]	0.190	0.935*	0.401	0.380	0.412	0.204	0.373	0.191	0.781*	0.815*
13	Span [99]	−0.016	0.497	0.815*	0.908*	0.535	0.840*	0.398	0.844*	0.445	0.281
14	Biacromial breadth [11]	0.034	0.496	0.487	0.506	0.295	0.370	0.407	0.394	0.633	0.419
15	Hip breadth, standing [66]	0.209	0.831*	0.453	0.416	0.457	0.239	0.464	0.224	0.672	0.727*
16	Head circumference [62]	0.125	0.508	0.342	0.312	0.302	0.224	0.303	0.240	0.433	0.421
17	Head length [63]	−0.002	0.371	0.346	0.315	0.295	0.260	0.302	0.268	0.295	0.271
18	Head breadth [61]	0.198	0.320	0.114	0.098	0.112	0.034	0.128	0.035	0.303	0.311
19	Hand length [60]	0.032	0.453	0.650	0.724*	0.464	0.676	0.300	0.679	0.372	0.242
20	Foot length [52]	0.012	0.512	0.700	0.734*	0.537	0.687	0.383	0.697	0.409	0.299

Table 11.4 (continued)

		11 WC	12 BC	13 Sp	14 BB	15 HiB	16 HC	17 HeL	18 HeB	19 HaL	20 FL
1	Age [302]	0.299	0.258	0.011	0.025	0.283	0.073	0.027	0.044	0.044	0.026
2	Weight [125]	0.767*	0.897*	0.438	0.440	0.778*	0.428	0.329	0.420	0.430	0.493
3	Stature [100]	0.167	0.361	0.787*	0.505	0.372	0.348	0.354	0.124	0.637	0.673
4	Overhead fingertip reach[84]	0.132	0.313	0.907*	0.535	0.294	0.337	0.345	0.095	0.737*	0.732*
5	Wrist height, standing [128]	0.217	0.363	0.453	0.303	0.397	0.250	0.261	0.403	0.403	0.468
6	Crotch height [39]	0.061	0.185	0.870*	0.418	0.146	0.287	0.302	0.043	0.706*	0.703*
7	Sitting height [94]	0.142	0.351	0.336	0.384	0.438	0.246	0.255	0.159	0.256	0.330
8	Popliteal height, sitting [87]	−0.031	0.063	0.840*	0.420	0.051	0.241	0.271	0.020	0.685	0.671
9	Shoulder circumference [91]	0.697	0.726*	0.395	0.574	0.601	0.353	0.264	0.261	0.355	0.379
10	Chest circumference [34]	0.781*	0.707*	0.167	0.304	0.603	0.393	0.191	0.246	0.186	0.288
11	Waist circumference [115]		0.738*	0.109	0.214	0.673	0.223	0.117	0.229	0.127	0.170
12	Buttock circumference [24]	0.859*		0.258	0.327	0.915*	0.313	0.226	0.220	0.258	0.323
13	Span [99]	0.201	0.352		0.565	0.203	0.345	0.338	0.083	0.827*	0.775*
14	Biacromial breadth [11]	0.311	0.411	0.575		0.294	0.287	0.259	0.152	0.441	0.456
15	Hip breadth, standing [66]	0.799*	0.902*	0.355	0.404		0.232	0.160	0.196	0.180	0.250
16	Head circumference [62]	0.376	0.427	0.320	0.301	0.364		0.824*	0.497	0.342	0.360
17	Head length [63]	0.222	0.301	0.304	0.235	0.259	0.820*		0.131	0.337	0.339
18	Head breadth [61]	0.277	0.268	0.131	0.180	0.235	0.541	0.120		0.082	0.113
19	Hand length [60]	0.166	0.320	0.810*	0.433	0.298	0.330	0.306	0.137		0.825*
20	Foot length [52]	0.220	0.390	0.766*	0.445	0.377	0.333	0.304	0.161	0.806*	

Pairs of data that correlate above 0.700 are similar in the male and female groups; also, correlations below 0.300 are similar for both genders.
Source: Cheverud et al. (1990) with their numbering given in brackets.

Table 11.5 Approximate age-related changes in stature observed in Europe and North America

	Change (cm)	
Age (in years)	Females	Males
1–5[1]	+36	+36
5–10	+28	+27
10–15	+22	+30
15–20	+1	+6
20–35[2]	No change	No change
35–40	−1	No change
40–50	−1	−1
50–60	−1	−1
60–70	−1	−1
70–80	−1	−1
80–90	−1	−1

[1]Average stature at age 1 year: females 74 cm, males 75 cm.
[2]Average maximal stature: females 161 cm, males 174 cm.

heights, sitting height and span have correlation coefficients larger than 0.7 with stature. Circumferences, breadths of shoulder and hip, head and hand measures and many other variables, including weight, do not correspond highly with stature. Therefore, the easily measured stature is not a good predictor for most other body dimensions*.

In general, long bone (link) dimensions relate well with each other. Also, many measures of height, of breadth and of depth dimensions, and of trunk circumferences, respectively, correlate well within their groups – but usually do not show a tight association with variables outside their grouping. Hence, if one wishes to predict one dimension from another, one must carefully check whether the relation between the two data sets is sufficiently high.

Variability of Anthropometric Data

Variability in anthropometric data primarily derives from five causes: data management, secular changes, changing populations, intra-individual variations, and inter-individual variations.

Data Management

Sloppiness in subject sampling, in performing measurements, in recording, sorting, analysis, or reporting of anthropometric data is likely to result in data collections that are "unusual" in variability and central tendency (mean, median, and mode) as compared to more valid data. Thus, if one encounters a report of body sizes that is at variance from information on a seemingly related sample, it is advisable to check carefully. The "coefficient of variation" (Eq. 11.6 in Table 11.2) allows a quick first test: caution is in order if its value exceeds 5% for body heights, 10% for breadths, depths, or reaches.

Another set of data-related problems stems from a false assumption of normality (of a Gaussian distribution) in the basic data. Whereas many body size measurements are indeed normally distributed, others are not: body weights are commonly in sets of skewed data, and so are measurements of muscle strength – see Chap. 2. Regrettably, statistics of body weight (and of strength) rely so regularly on the false assumption of normality that it is difficult to find the measured true values in the literature. (Note that even this book follows that deplorable custom by listing body weights and strengths via *mean* (*average*) and *standard deviation* when, instead, the use of nonparametric indices would be correct, such as *median* or *mode.*) Figure 11.13 illustrates the case: Stature data form a normal distribution (similar to Fig. 11.11), but the associated body mass measures are severely skewed, showing a long tail of heavy weights. Obviously, it is numerically possible to calculate mean (here: 69 kg) and standard deviation values and then 5th and 95th percentiles, but this procedure is principally false and practically misleading because the underlying distribution is non-normal*.

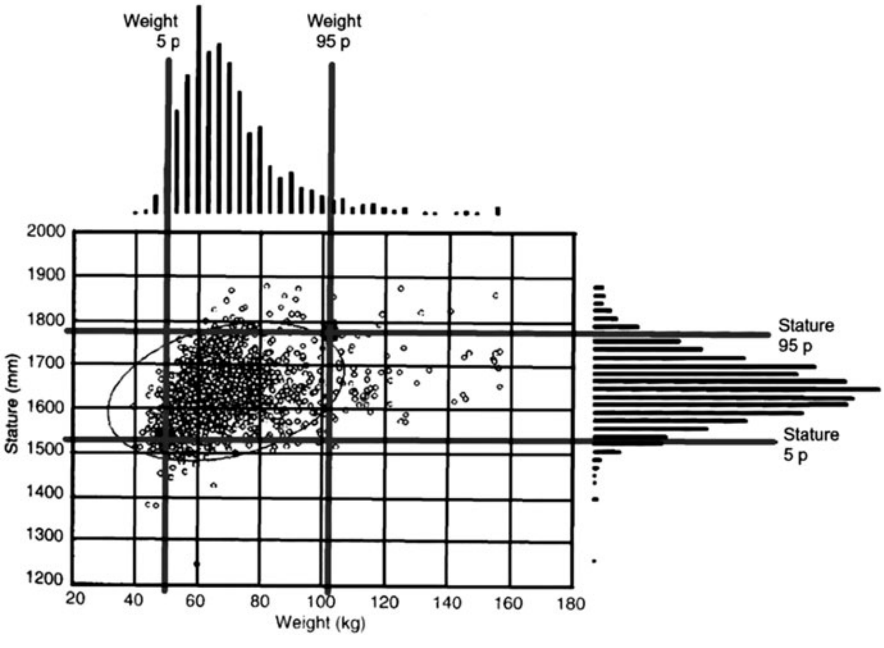


Fig. 11.13 Weight and stature distributions of American women (adapted from Robinette and Hudson, 2006)

Secular Variations

The term "secular" refers to events that appear over long stretches of time. When looking at medieval armor displayed in a museum, we notice the apparently small sizes of soldiers centuries ago; apparently, they grow taller now. Today, we experience that many children grow, on average, to be taller than their parents are. However, "hard" anthropometric data on this development are only available for approximately the last hundred years when anthropometric surveys were done in reasonably consistent manners on sufficiently large samples. Figure 11.14 provides information on stature for a variety of young male civilian samples: the overall trend of increase is apparent. Similarly, Fig. 11.15 presents information on military data measured in the USA during about 120 years.

Surprisingly, the military data show virtually no change from the 1860s until World War I; but there seems to be a pronounced increase thereafter. Why stature was seemingly stable for nearly 60 years and then grew rapidly is open to speculation. Perhaps the recruitment of soldiers from the general population was different during the Civil War from the screening process during World War I; or the general

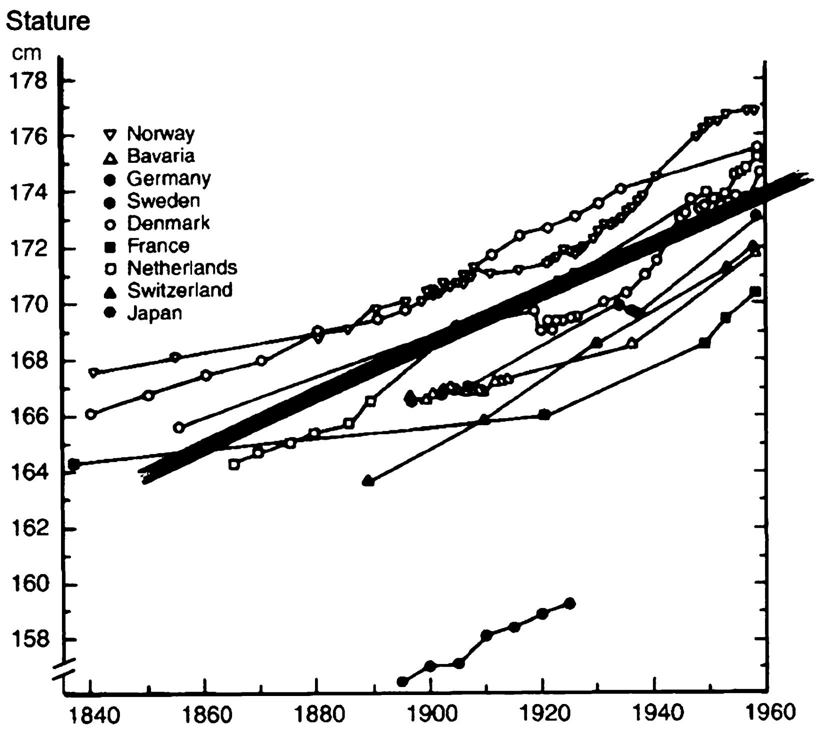


Fig. 11.14 Secular increase in stature of young European and Japanese males. *Heavy line* shows the apparent trend (adapted from NASA/Webb, 1978)

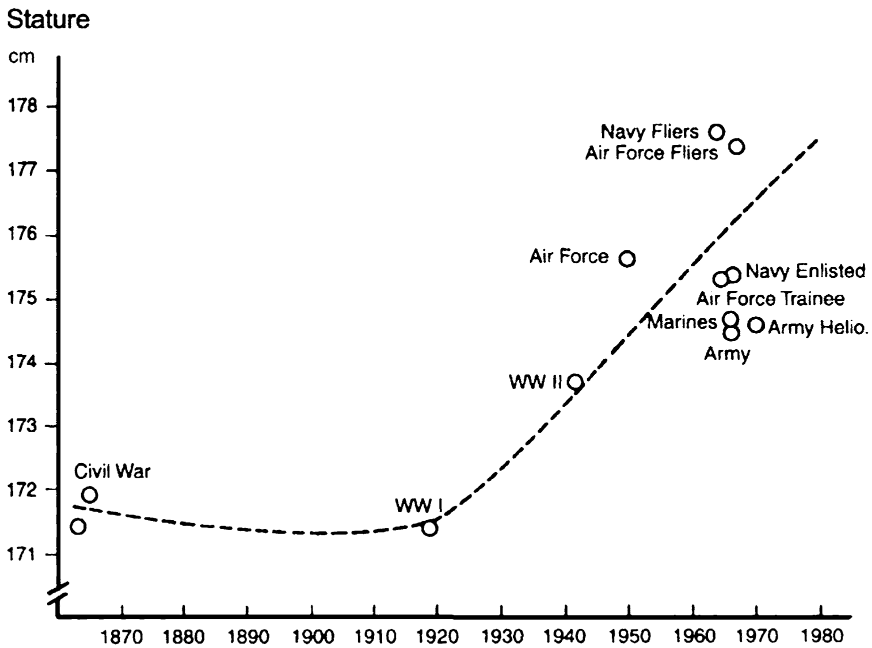


Fig. 11.15 Change in stature of US soldiers (adapted from NASA/Webb, 1978)

population may have had a massive influx of short immigrants; it is even possible that the measurement techniques changed. (This brief discussion points out some of the difficulties in comparing data that are disjointed both in time and in collection technique.)

Nevertheless, the increase observed in stature during the last 50 years is apparently "real". Data from major surveys in the USA, Europe and from Asia indicated an increase in stature of about 1 cm/decade during the twentieth century. Weight increases were even more dramatic, initially in the neighborhood of 2 kg for every 10 years, followed by sudden substantial gains starting in the late 1900s leading to widespread obesity in the first decade of the twenty-first century.

Among the possible explanation of the increases in stature is the generally accepted idea that improvements in living conditions, both hygienic and nutritional, have allowed people to achieve their genetically possible stature more readily than in earlier times. If this is true, one would expect that an "average maximal height" should be approached in the future asymptotically, provided that the whole population benefits from improved living conditions. In fact, the 1988 survey of the US Army shows a slowing of the stature increase: it seems to take about two decades now to gain another centimeter in height.

Altogether, the secular developments of body dimensions are rather slow. Hence, for most engineers the changes in body data should have little practical consequences for the design of tools, equipment, and work places, since virtually none are designed to be used over many decades or even centuries. Most products have a relatively short “design life” for which secular changes in anthropometry of the users have no appreciable importance.

Intra-individual Variations

Some short-term variations in stature appear in just a few hours: in the morning, immediately after rising, one may be several centimeters taller than after a full day “on the feet”. This results mainly from thinning of the intervertebral disks, due to the loss of fluid that they undergo because of compression forces generated by gravity and body activities.

Other examples of intra-individual variations, which become apparent over periods of weeks or months, are variations in weight or circumferences, often associated with changes in nutrition and physical activities. Of course, during pregnancy women experience major changes in body size, proportions, and physical functions, which come and go.

Among the long-term intra-individual variables, the effects of aging on the body are rather obvious. During the growing years, stature, weight and all the other body dimensions increase, and the proportions change – see Fig. 11.16. In early adulthood, body measures and proportions become relatively stable for several decades. Then, with increasing age certain dimensions usually reduce (such as body height) while circumferences and the external diameters of bones commonly increase. Table 11.5 lists, in approximate numbers, changes in stature with age.

Inter-individual Variations

Inter-individual variations are a result of DNA characteristics; about 10^9 possible chromosome combinations exist. An individual’s genetic endorsement determines

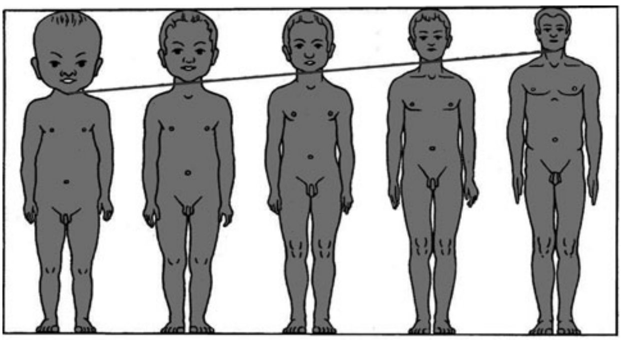


Fig. 11.16 Changes in body proportions from birth to adulthood (adapted from Fluegel et al., 1986)

his/her cellular composition (genotype) and biologically measurable characteristics (phenotype).

Nutrition also has direct effects body size; obviously, over-feeding leads toward obesity and lack of nourishment causes skinniness.

A variety of "recommended" body weight tables exists, usually subdivided for gender, age, and body build. They rely on the assumption that "mortality" probabilities from strokes and specific ailments such as of the heart, of diabetes, cancer and others associate with body weights and weight/stature ratios.

Among the early height/weight tables, long used by physicians in North America, are those originally prepared in 1942 (and then continually updated) by the Metropolitan Life Insurance Company. The underlying idea was that the weights of young adults were "ideal" and should be maintained throughout life. From the beginning, the validity of several assumptions regarding height-weight ratios was questioned*. A particular statistical concern is that body weight does not consistently correlate with stature: r is only about 0.5 among soldiers, as Table 11.4 shows, but even lower within the general population. Nevertheless, many people make judgments by presumably desirable weight-height ratios.

Since the middle 1990s, the so-called Body Mass Index, BMI, has been in wide use. It also relies on a postulated relation between measured body weight and height. To calculate a BMI, one divides a person's weight by the squared stature – see Table 11.6. The result then is compared to a set of listed BMI ranges to assess whether the person is underweight, normal, overweight or obese. There are, however, some bothersome issues, mostly related to the weak statistical linkage between weight and stature. In reality, the relation between the BMI number and body fatness varies by gender, age, race, and fitness. For example: At the same BMI, women tend to have more body fat than men do; likewise, older people tend to have more body fat than younger adults. Highly trained athletes may have a high BMI because of increased muscle mass rather than increased body fatness. The criteria used to interpret the meaning of the BMI number for children and teens are different from those used for adults for two reasons: the amount of body fat changes with age and differs between girls and boys*.

Handedness is a well-known example of inter-individual variability: A general estimate is that among ten persons one person is left-handed. However, handedness needs a careful definition: for example, one may prefer the left hand for writing but the right one for handling a screwdriver. Such information can be of some interest to, say, the manufacturers of special hand tools but otherwise does not imply large differences in arm lengths, or arm circumferences, as reflected in nationwide anthropometric tables.

Changing Populations

Populations do not remain constant but change in age, health, gender and composition. For example, the work force in the industrialized countries today has many women in occupations that men dominated just a few decades ago. Occupations may

Table 11.6 Body Mass Index *BMI* calculation

Metric:

To calculate BMI, divide weight (in kilograms, kg) by squared height (in meters, m).

$BMI = [weight\ (kg)/[height\ (m)]^2$
Example: Height = 1.65 m, Weight = 68 kg

Calculation: $68 / (1.65)^2 = 24.98$

When height is measured in centimeters, divide height in centimeters by 100 to obtain height in meters or use cm but multiply result by 10,000 (10^4):

$BMI = 10^4\ [weight\ (kg)/[height\ (cm)]^2$

Example: Height = 165 cm, Weight = 68 kg
Calculation: $10^4 \times 68 / (165)^2 = 24.98$

Using the old US system:

To calculate BMI, divide weight (in pounds, lbs) by squared height (in inches, in); then multiply with a conversion factor of 703.

$BMI = 703 \times [weight\ (lb)/[height\ (in)]^2$

Example: Weight = 150 lbs, Height = 5'5" (65")
Calculation: $[150 / (65)^2] \times 703 = 24.96$

The standard weight status categories associated with BMI ranges for adults are:

BMI	Status
Below 18.5	Underweight
18.5–24.9	Normal
25.0–29.9	Overweight
30.0 and above	Obese

change drastically as well: in many economies, "blue collar" workers in the traditional sense become fewer as automation, deskwork and computer use replace physical labor.

Life expectancy has increased dramatically in many countries, mostly due to reduced infant mortality. In the USA, life expectancy increased by some 30 years since 1900; it now approaches 80 years. As one consequence, the traditional assumption of a broad-based "population pyramid", where many young people support a few old ones, is no longer true. In 1971, the median age of the US population was about 28 years; in 1980, 30 years; in 1986, 32 years; it reached 36 years in the year 2000. Currently, half as many Americans are over 65 years old as there are teenagers. In 2050, one in five Americans will be at least 65 years old.

In many countries, the overall fertility rate declined: in the USA, from 3.7 births per woman in 1960 to 2.5 in 1970 and to about 1.8 in 1985. Such a low birth rate would lead to a reduction in the total population within just a few decades, but immigration keeps the number of US citizens growing. Estimates are that in 2050

Table 11.7 US population in 2005 and projected to 2050 (adapted from Passel and Cohn, 2008)

	In 2005	In 2050
Population (in millions)	296	438
Foreign born (portions of total)	12%	19%
Racial/ethnic groups (portions of total)		
White	67%	47%
Hispanic	14%	29%
African American	13%	13%
Asian	5%	9%
Age groups (portions of total)		
Children, 17 years or younger	25%	23%
Adults, 18–65 years	63%	58%
Elderly, 65 years or older	12%	19%

the USA will have a population of nearly 440 million, of which about 13% will be of african, 29% of hispanic and 9% of asian ancestry – see Table 11.7.

Recent decades have shown much mobility of population groups. Central Europe, for example, saw a huge influx of "guest workers" and their families coming from african and asian countries. Such massive immigration can lead to distinct changes in the composition of the population: for instance, in Berlin (Germany) and in Paris (France), a large percentage of schoolchildren has immigrant parents. Americans are moving within their country as well: in 1980, for the first time ever, the majority of americans lived in the southern and western states. The "sunbelt", prominently California, Florida, and Texas grew more in population than the other regions in the US; this migration reduced the population in the "snowbelt". Cities used to be magnets for the rural population; in the 1960s and 1970s the flow was reversed, but in the 1980s some metropolitan areas were again growing. Still, many people seem to move away from the very large cities to smaller, not so crowded communities. However, these trends can change quickly, for example with changes in the economy.

As in many other countries, the population of the USA is a composite of several ethnic origins. For example, in 2005 most US citizens said they have caucasian roots, predominantly german, english, or irish. More than 25 million citizens stated to be of african descent; about the same number claimed to be hispanic and millions were of asian origin. Table 11.8 contains details of the 1980/1990/2000 polls.

Recent immigration, especially from central and southern America and Asia, are changing the composition of the US population quickly: estimates are that, within about four decades, the caucasian-derived population section will shrink from two thirds in 2005 (it was 85% in 1960) to less than half in 2050. The percentage of African–Americans will stay at about 13% but the percentage of citizens with asian origin will almost double, to 9% – see Table 11.7.

Anthropometric data show statistically significant differences among several groups of ethnic origins* (Cheverud et al., 1990); there are also some specific differences in body sizes among various professions. For example, on average, US agricultural workers were shorter by about 2.5 cm in stature and had wider wrists

Table 11.8 Ancestry claimed by millions of US citizens in the 1980, 1990 and 2000 US Census Bureau polls (adapted from Brittingham and de la Cruz, 2004; Passel and Cohn 2008)

Ancestry	2000 Poll	1990 Poll	1980 Poll
German	42.8	57.9	49.2
Irish	30.5	38.7	40.2
African American	24.9	23.8	21.0
English	24.5	32.7	49.6
American	20.2	12.4	7.9
Mexican	18.4	11.6	7.7
Italian	15.6	14.7	12.2
Polish	9.0	9.4	8.2
French	8.3	10.3	12.9
American-Indian	7.9	8.7	6.7
Scottish	4.9	5.4	10.1
Dutch	4.5	6.2	6.3
Norwegian	4.5	3.9	3.5
Scotch-Irish	4.3	5.6	nda
Swedish	4.0	4.7	4.4
Russian	2.7	3.0	2.8
Puerto rican	2.7	2.0	1.4
French-Canadian	2.3	2.2	0.8
Chinese	2.3	1.5	0.9
Spanish-Hispanic	2.2	2.0	2.7
Filipino	2.1	1.5	0.8
Welsh	1.8	2.0	1.7
Danish	1.4	1.6	1.5
Czech	1.3	1.3	1.9
Portuguese	1.2	1.2	1.0
Greek	1.2	1.1	1.0
Japanese	1.1	1.0	0.8
Vietnamese	1.0	0.5	nda
Slovak	0.9	1.9	0.8
Swiss	0.9	1.0	1.0
All others	Below 1		

nda: no data available

than other workers. Female american agricultural and manufacturing workers have larger waist circumferences than those in other occupations. Firefighters, police and guards are taller and heavier (males by 7 kg, females by over 10 kg) than americans in all other occupations*. Such differences may be of practical importance for the design and use of certain items in limited localities, though on a nationwide scale these differences among ethnic and professional groups are fairly small and of little practical significance. Variations in body size within groups are usually more striking than differences in averages between groups.

Measured anthropometric data on large civilian populations are rather sparse whereas the body dimensions of military personnel are better known. Since the military is a sample of the overall population, it appears reasonable to infer dimensions of the general civilian population from military data. However, a major concern is that soldiers may be so highly selected (particularly, biased to be young and healthy) that they constitute a special sample, which does not represent the overall population. Yet, if better information is not at hand, there may be no other choice than to use, with proper caution and insight, military anthropometric data to approximate size data of the general population. Fortunately, at least the dimensions of the head, hand, and foot are virtually the same in military and civilian populations*.

To make sure that workspaces and implements fit their users, it is necessary to consider carefully their anthropometric descriptors. Two examples: a computer workstation that fits a college group in Bismarck, North Dakota (or in Amsterdam, NL), may not be of the correct size and adjustment ranges for, say, computer operators in southern Texas (or in Palermo, Sicily); school furniture appropriate for children in Palermo may not suit pupils in Amsterdam*.

Available Body Size Data

Most populations on earth have not been measured thoroughly and completely. Table 11.9 presents an overview of available measured heights and weights, averages and standard deviations, of ethnic, national, and geographic populations. Unfortunately, in many cases only few people were measured; hence, it is unlikely that their summary statistics truly represent the underlying population; therefore, use of data such as listed here requires considerable caution.

Table 11.10 presents most recent information on thirty-six measures of body sizes of chinese, russian, and north-american adults, females and males, and of their weights. Figures 11.17, 11.18 and 11.19 illustrate the body dimensions.

As of 2010, the international literature contained only a few recent collections of measured or estimated anthropometry data on large populations*, such as in Tables 11.9 and 11.10: anthropometric surveys are expensive and time-consuming, whether done in the traditional manner or by automatic scanning.

How To Get Missing Data

Three avenues are open to obtain anthropometric information: first, searching the literature; second, conducting an anthropometric survey; lastly, using statistical procedures to deduce from existing data those that we need to know.

Finding Data in the Literature

The Internet is the most is convenient source for retrieving new anthropometric information. Four categories of publications are most likely to provide reliable

Table 11.9 Measured heights and weights of adults, published since 1989: averages (standard deviations).

	Sample Size	Stature (mm)	Weight (kg)
Algeria			
Females (Mebarki and Davies, 1990)	666	1,576 (56)	61 (13)
Brazil			
Males (Ferreira, 1988; cited by Al-Haboubi, 1991)	3,076	1,699 (67)	nda
Cameroon			
Urban females	1,156	1,620	64
Urban males	558	1,721	75
(35–44 years old) (Kamadjeu et al., 2006)			
China			
Females (Taiwan)	about 600	1,572 (53)	52 (7)
Males (Taiwan) (Wang et al., 2002)	about 600	1,705 (59)	67 (9)
France			
Females	5,510	1,625 (71)	62 (12)
Males (IFTH and Goncalves, personal communication, 2006)	3,986	1,756 (77)	77 (13)
Germany			
Female army applicants	301	1,674	64
Male army applicants (Leyk et al., 2006)	1,036	1,795	75
Great Britain			
Females	3,870	1,611	68
Males (Erens et al., 2001)	3,233	1,746	81
India			
Females	251	1,523 (66)	50 (10)
Males (Chakarbarti, 1997)	710	1,650 (70)	57 (11)
East-Ctr. India male farm workers (Victor et al., 2002)	300	1,638 (56)	57 (7)
South India male workers (Fernandez and Uppugonduri, 1992)	128	1,607 (60)	57 (5)
East India male farm workers (Yadav et al., 1997)	134	1,621 (58)	54 (7)
Iran			
Female students	74	1,597 (58)	56 (10)
Male students (Mououdi, 1997)	105	1,725 (58)	66 (10)
Ireland			
Males (Gallwey and Fitzgibbon, 1991)	164	1,731 (58)	74 (9)
Italy			
Females	753*	1,610 (64)	58 (8)
Females	386**	1,611 (62)	58 (9)
Males	913*	1,733 (71)	75 (10)
Males	410**	1,736 (67)	73 (11)
*(Coniglio et al., 1991)			
**(Robinette et al., 2002)			

Table 11.9 (continued)

	Sample Size	Stature (mm)	Weight (kg)
Japan			
Females	240	1,584 (50)	54 (6)
Males (Kagimoto, 1990)	248	1,688 (55)	66 (8)
Netherlands			
Females, 20–30 years old	68*	1,686 (66)	67 (10)
Females, 18–65 years old	679**	1,672 (79)	74 (16)
Males, 20–30 years old	55*	1,848 (80)	81 (14)
Males, 18–65 years old	593**	1,808 (93)	86 (17)
*(Steenbekkers and Beijsterveldt, 1998)			
**(Robinette and Hudson, 2006)			
Russia			
Female herders (ethnic Asians)	246	1,588 (55)	nda
Female students (ethn. Russians)	207	1,637 (57)	61 (8)
Female students (ethn. Usbeks)	164	1,578 (49)	56 (7)
Fem. factory workers (ethn. R.)	205	1,606 (53)	61 (8)
Fem. factory workers (ethn. U.)	301	1,580 (54)	58 (9)
Male students (ethn. Russians)	166	1,757 (56)	71 (9)
Male students (ethn. Usbeks)	150	1,700 (52)	65 (7)
Male factory workers (ethn. R.)	192	1,736 (61)	72 (10)
Male factory workers (ethn. mix)	150	1,700 (59)	68 (8)
Male farm mechanics (ethnic Asians)	520	1,704 (58)	64 (8)
Male coal miners (ethn. Russians)	150	1,801 (61)	nda
Male construction workers (ethnic Russians) (Strokina and Pakhomova, 1999)	150	1,707 (69)	nda
Saudi Arabia			
Males (Dairi, 1986; cited by Al-Haboubi, 1991)	1,440	1,675 (61)	nda
Singapore			
Males (pilot trainees) (Singh et al., 1995)	832	1,685 (53)	nda
Sri Lanka			
Females	287	1,523 (59)	nda
Males (Abeysecera, 1985; cited by Intaranont, 1991)	435	1,639 (63)	nda
Thailand			
Females	250*	1,512 (48)	nda
Females	711**	1,540 (50)	nda
Males	250*	1,607 (20)	nda
Males	1,478**	1,654 (59)	nda
*(Intaranont, 1991)			
** (Abeysecera, 1985; cited by Intaranont, 1991)			
Turkey			
Male soldiers (Kayis and Oezok, 1991a)	5,108	1,702 (60)	63 (7)

Table 11.9 (continued)

	Sample Size	Stature (mm)	Weight (kg)
United States of America			
Females	about 3,800	1,625	75
Males (Ogden et al., 2004)	about 3,800	1,762	87
US Army soldiers			
Females	2,208*	1,629 (64)	62 (8)
Males	1,774*	1,756 (67)	76 (11)
Males	1,475**	1,760 (nda)	84 (nda)
*(Gordon et al., 1989)			
**(Gordon, 2009)			
North American (Canada and USA)			
Females, 18–26 years old	1,264	1,640 (73)	69 (18)
Males, 18–65 years old (Robinette et al., 2002)	1,127	1,778 (79)	86 (18)

nda: no data available.
Updated 15 June 2009 from Kroemer (2009) who listed all sources except Robinette and Hudson (2006), Gordon (2009).

results. Foremost are those of anthropology research institutions*. The second group includes publications of government agencies* such as in the USA the Centers for Disease Control and Prevention CDC with their grow charts or reports, or the military*; and international institutions such as the UN and its subgroups, for example the International Labour Organization ILO*. A third category includes journals* and books that specialize on ergonomics/human factors topics. Finally, international and regional standards (ISO, ANSI, etc.) can provide information, and trade groups* may supply data which, however, are usually selected to meet special interests.

Conducting an Anthropometric Survey

Doing an anthropometric survey* is a major enterprise and best left to qualified anthropometrists; yet, a few general remarks may be helpful for deciding and planning.

The first task is to select the measuring technique*. The most likely choices are either traditional measures "by hand" or three-dimensional computerized scanning techniques; by their nature, the data obtained by 3D scanners are not exactly the same as those measured by classical anthropometry. Some related issues have already been discussed in this chapter; furthermore, special populations may require particular procedures, for example, to consider specific cultural customs (such as in clothing) or unusual body builds, such as handicapped persons or people with dwarfism.

Preparation and execution of a survey requires involvement of qualified staff for extended periods of time. Unbiased selection of a representative sample is a fundamentally important yet often difficult task. Special interests may determine subject

Table 11.10 Common body measurements and their applications. All measures in mm, except weight in kg (adapted from Kroemer, 2009)

Dimensions, applications	Population	Females Mean (S)	Males Mean (S)
1. Stature [99] A main measure for comparing population samples. Reference for the minimal height of overhead obstructions. Add height for more clearance, hat, shoes, stride	Chinese (Taiwan) Russians (Moscow) US Army soldiers	1,572 (53) 1,637 (57) 1,629 (64)	1,705 (59) 1,757 (56) 1,756 (67)
2. Eye height, standing [D19] Origin of the visual field of a standing person. Reference for the location of visual obstructions and of targets such as displays; consider slump and motion	Chinese (Taiwan) Russians (Moscow) US Army soldiers	nda 1,526 (57) 1,516 (63)	nda 1,637 (55) 1,634 (66)
3. Shoulder height (acromion), standing [2] Starting point for arm length measurements; near the center of rotation of the upper arm. Reference point for hand reaches; consider slump and motion	Chinese (Taiwan) Russians (Moscow) US Army soldiers	1,285 (50) 1,334 (54) 1,334 (58)	1,396 (53) 1,440 (54) 1,443 (62)
4. Elbow height, standing [D16] Reference for height and distance of the work area of the hand and the location of controls and fixtures; consider slump and motion	Chinese (Taiwan) Russians (Moscow) US Army soldiers	978 (38) 1,010 (42) 998 (45)	1,059 (40) 1,083 (48) 1,073 (48)
5. Hip height (trochanter), standing [107] Traditional anthropometric measure, indicator of leg length and the height of the hip joint. Used for comparing population samples	Chinese (Taiwan) Russians (Moscow) US Army soldiers	802 (41) nda 862 (45)	860 (48) nda 928 (48)
6. Knuckle height, standing Reference for low locations of controls, handles, and handrails; consider slump and motion of the standing person	Chinese (Taiwan) Russians (Moscow) US Army soldiers	708 (33) 731 (34) nda	757 (32) 773 (39) nda

Table 11.10 (continued)

Dimensions, applications	Population	Females Mean (S)	Males Mean (S)
7. Fingertip height, standing [D13]	Chinese (Taiwan)	618 (32)	659 (30)
The vertical distance from the floor to the tip of the extended index finger	Russians (Moscow)	635 (32)	668 (37)
of the right hand, when standing	US Army soldiers	610 (36)	653 (40)
8. Sitting height [93]	Chinese (Taiwan)	846 (32)	910 (30)
Reference for the minimal height of overhead obstructions. Add height	Russians (Moscow)	859 (32)	912 (32)
for more clearance, hat, trunk motion of the seated person	US Army soldiers	852 (35)	914 (36)
9. Sitting eye height [49]	Chinese (Taiwan)	732 (31)	791 (29)
Origin of the visual field of a seated person. Reference point for the	Russians (Moscow)	742 (29)	790 (33)
location of visual targets such as displays; consider slump and motion	US Army soldiers	739 (33)	792 (34)
10. Sitting shoulder height (acromion) [3]	Chinese (Taiwan)	561 (27)	602 (26)
Starting point for arm length measurements; near the center of rotation of	Russians (Moscow)	nda	nda
the upper arm. Reference for hand reaches; consider slump and motion	US Army soldiers	556 (29)	598 (30)
11. Sitting elbow height [48]	Chinese (Taiwan)	252 (25)	264 (24)
Reference for the height of an armrest, of the work area of the hand and	Russians (Moscow)	236 (24)	243 (25)
of keyboard and controls; consider slump and motion of the seated person	US Army soldiers	221 (27)	231 (27)
12. Sitting thigh height (clearance) [104]	Chinese (Taiwan)	nda	nda
Reference for the minimal clearance needed between seat pan and the	Russians (Moscow)	148 (14)	151 (18)
underside of a table or desk; add clearance for clothing and motions	US Army soldiers	160 (12)	168 (13)
13. Sitting knee height [73]	Chinese (Taiwan)	471 (24)	521 (29)
Traditional anthropometric measure for lower leg length. Reference for	Russians (Moscow)	527 (24)	562 (25)
the minimal clearance below the underside of a table or desk; add height for shoe	US Army soldiers	515 (26)	559 (28)

Table 11.10 (continued)

Dimensions, applications	Population	Females Mean (S)	Males Mean (S)
14. Sitting popliteal height [86]	Chinese (Taiwan)	379 (18)	411 (19)
Reference for the height of a seat; add height for shoe	Russians (Moscow)	423 (23)	468 (24)
	US Army soldiers	389 (24)	434 (25)
15. Shoulder-elbow length [91]	Chinese (Taiwan)	309 (18)	338 (19)
Traditional anthropometric measure for comparing population samples	Russians (Moscow)	nda	nda
	US Army soldiers	336 (17)	369 (18)
16. Elbow-fingertip length [54]	Chinese (Taiwan)	384 (27)	427 (27)
Traditional anthropometric measure. Reference for fingertip reach when	Russians (Moscow)	nda	nda
moving the forearm in the elbow	US Army soldiers	443 (23)	484 (23)
17. Overhead grip reach, sitting [D45]	Chinese (Taiwan)	1,105 (44)	1,208 (49)
Reference for the height of overhead controls operated by a seated	Russians (Moscow)	1,169 (46)	1,276 (47)
person. Consider ease of motion, reach, and finger/hand/arm strength	US Army soldiers	1,212 (51)	1,310 (55)
18. Overhead grip reach, standing [D42]	Chinese (Taiwan)	1,831 (67)	2,002 (79)
Reference for the height of overhead controls operated by a standing	Russians (Moscow)	nda	nda
person. Add shoe height. Consider ease of motion, reach, and strength	US Army soldiers	1,947 (87)	2,107 (92)
19. Forward grip reach [D21]	Chinese (Taiwan)	651 (33)	710 (36)
Reference for forward reach distance. Consider ease of motion, reach,	Russians (Moscow)	702 (37)	759 (38)
and finger/hand/arm strength	US Army soldiers	686 (34)	751 (37)

Table 11.10 (continued)

Dimensions, applications	Population	Females Mean (S)	Males Mean (S)
20. Arm length, vertical [D3] A traditional measure for comparing population samples. Reference for the location of controls very low on the operator's side. Consider ease of motion, reach, strength	Chinese (Taiwan)	669 (31)	738 (33)
	Russians (Moscow)	nda	nda
	US Army soldiers	724 (38)	790 (39)
21. Downward grip reach [D43] Reference for the location of controls low on the side of the operator. Consider ease of motion, reach, and finger/hand/arm strength	Chinese (Taiwan)	nda	nda
	Russians (Moscow)	nda	nda
	US Army soldiers	609 (33)	666 (33)
22. Chest depth [36] A traditional measure for comparing population samples. Reference for the clearance between seat backrest and the location of obstructions in front of the trunk	Chinese (Taiwan)	213 (19)	217 (19)
	Russians (Moscow)	242 (21)	245 (20)
	US Army soldiers	239 (21)	243 (22)
23. Abdominal depth, sitting [1] A traditional measure for comparing population samples. Reference for the clearance between seat backrest and the location of obstructions in front of the trunk	Chinese (Taiwan)	nda	nda
	Russians (Moscow)	nda	nda
	US Army soldiers	219 (26)	236 (28)
24. Buttock-knee depth, sitting [26] Reference for the clearance between seat backrest and the location of obstructions in front of the knees	Chinese (Taiwan)	530 (26)	558 (31)
	Russians (Moscow)	584 (29)	610 (30)
	US Army soldiers	589 (30)	616 (30)
25. Buttock-popliteal depth, sitting [27] Reference for the depth of a seat	Chinese (Taiwan)	nda	nda
	Russians (Moscow)	496 (29)	517 (26)
	US Army soldiers	482 (27)	500 (27)

Table 11.10 (continued)

Dimensions, applications	Population	Females Mean (S)	Males Mean (S)
26. Shoulder breadth (biacromial) [10]	Chinese (Taiwan)	324 (25)	369 (28)
A traditional measure for comparing population samples. Indicator of the	Russians (Moscow)	360 (16)	397 (25)
distance between the centers of rotation of the two upper arms	US Army soldiers	363 (17)	397 (18)
27. Shoulder breadth (bideltoid) [12]	Chinese (Taiwan)	406 (24)	460 (23)
Reference for the lateral clearance required at shoulder level. Add space	Russians (Moscow)	412 (21)	458 (23)
for ease of motion and tool use	US Army soldiers	433 (23)	492 (26)
28. Hip breadth, sitting [66]	Chinese (Taiwan)	353 (23)	360 (27)
Reference for seat width. Add space for clothing and ease of motion]	Russians (Moscow)	372 (23)	362 (23)
	US Army soldiers	385 (27)	367 (25)
29. Span [98]	Chinese (Taiwan)	1,571 (62)	1,738 (69)
A traditional measure for comparing population samples. Reference for	Russians (Moscow)	1,640 (75)	1,782 (68)
sideway reach	US Army soldiers	1,672 (81)	1,823 (82)
30. Elbow span (arms akimbo)	Chinese (Taiwan)	801 (39)	894 (45)
Reference for the lateral space needed at upper body level for ease of	Russians (Moscow)	870 (38)	935 (37)
motion and tool use	US Army soldiers	nda	nda
31. Head length (depth) [62]	Chinese (Taiwan)	187 (6)	197 (7)
A traditional measure for comparing population samples. Reference for	Russians (Moscow)	nda	nda
headgear size	US Army soldiers	187 (6)	197 (7)
32. Head breadth [60]	Chinese (Taiwan)	161 (9)	167 (8)
A traditional measure for comparing population samples. Reference for	Russians (Moscow)	nda	nda
headgear size	US Army soldiers	144 (5)	152 (5)

Table 11.10 (continued)

Dimensions, applications	Population	Females Mean (S)	Males Mean (S)
33. Hand length [59]	Chinese (Taiwan)	167 (8)	183 (10)
A traditional measure for comparing population samples. Reference for hand tool and gear size. Consider manipulations, gloves, tool use	Russians (Moscow)	168 (8)	188 (9)
	US Army soldiers	181 (10)	194 (10)
34. Hand breadth [57]	Chinese (Taiwan)	75 (4)	86 (5)
A traditional measure for comparing population samples. Reference for hand tool and gear size, and for an opening through which a hand must fit. Consider gloves, tool use	Russians (Moscow)	76 (3)	87 (5)
	US Army soldiers	79 (4)	90 (4)
35. Foot length [51]	Chinese (Taiwan)	nda	nda
A traditional measure for comparing population samples. Reference for shoe and pedal size	Russians (Moscow)	239 (11)	266 (12)
	US Army soldiers	244 (12)	270 (13)
36. Foot breadth [50]	Chinese (Taiwan)	nda	nda
A traditional measure for comparing population samples. Reference for shoe size, spacing of pedals	Russians (Moscow)	88 (4)	97 (6)
	US Army soldiers	90 (5)	101 (5)
37. Weight (in kg)	Chinese (Taiwan)	52 (7)	67 (9)
A traditional measure for comparing population samples. Reference for body size, clothing, strength, health, etc. Add weight for clothing and equipment worn on the body	Russians (Moscow)	60 (7)	71 (9)
	US Army soldiers	62 (8)	79 (11)

Numbers [in brackets] are those used by Gordon et al. (1989) (see below), who provide exact definitions of the measurements. They are also described by Kroemer 2006, 2009.

nda: no data available

Sources of data: Chinese (Taiwan), 25–34 years of age, measured between 1996 and 2000: Wang et al. (2002). Russians, students in Moscow, 18–22 years of age, measured between 1984 and 1986: Strokina and Pakhomova (1999). US Army soldiers, 17–51 years of age, measured 1987 and 1988: Gordon et al. (1989).

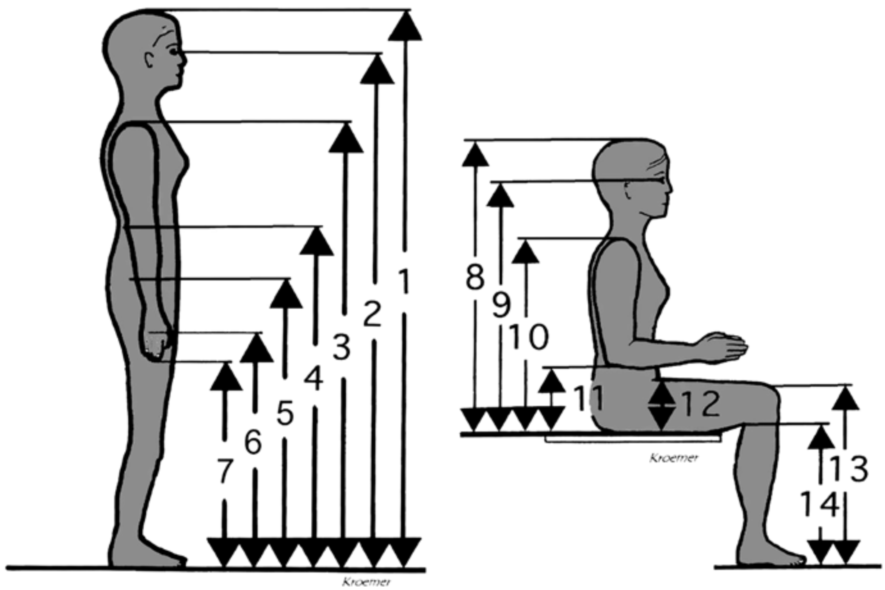


Fig. 11.17 Height measurements taken on subjects in erect postures, standing and sitting. Numbering as by Gordon et al. (1989)

selection and, hence, resulting data; for example, some survey data served military purposes whereas other measures were collected by clothing manufacturers and then considered trade secrets. For various reasons, healthy young-to-middle-aged adults seem of higher interest than very old or young persons or those who are neither healthy nor wealthy.

The next step concerns the determination of the sample size. For expediency, one usually wishes to keep the sample as small as possible. Assuming a normal distribution of the variable to be measured, the required smallest sample size N derives from

$$N = q^2 \times S^2/v^2 \tag{11.13}$$

with q taken from Table 11.11. S is the (known or estimated) standard deviation of the data and v is the desired accuracy of the measurement (v and S expressed in the same units). If the initially calculated sample size N happens to fall below 100, use the following values for v:

$v = 2.00$ if $100 > N > 40$;
$v = 2.05$ if $40 > N > 20$;
$v = 2.16$ if $20 > N > 10$;
$v = 2.78$ if $10 > N$

and repeat the calculation for N.

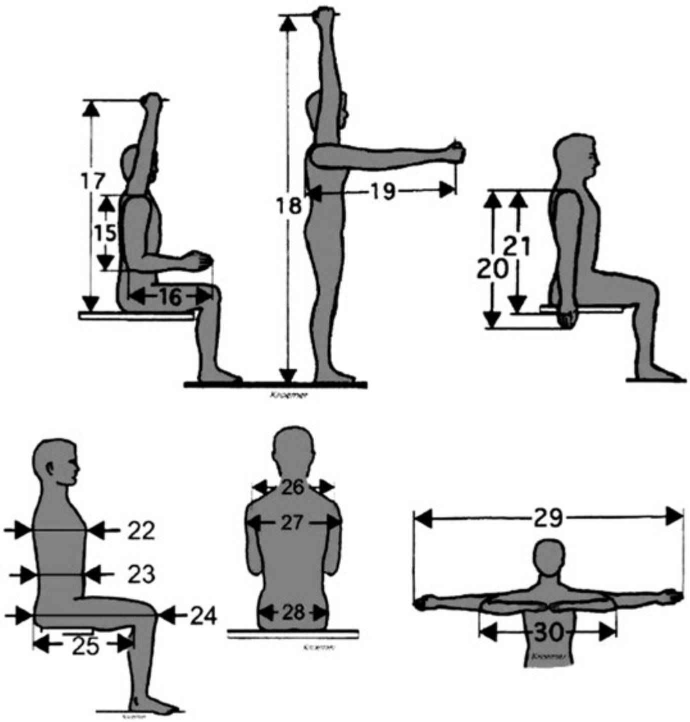


Fig. 11.18 Measurements of reaches, heights, depths, breadths, and spans. Numbering as by Gordon et al. (1989)

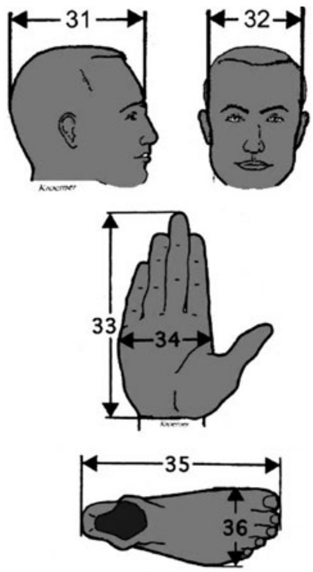


Fig. 11.19 Measurements taken on head, hand, and foot. Numbering as by Gordon et al. (1989)

Table 11.11 Values of *q* for sample size determination

q	Statistic of interest
1.96	Mean
1.39	Standard deviation
2.46	50th percentile
2.46	45th and 55th percentile
2.19	40th and 60th percentile
2.52	35th and 65th percentile
2.58	30th and 70th percentile
2.67	25th and 75th percentile
2.80	20th and 80th percentile
3.00	15th and 85th percentile
3.35	10th and 90th percentile
4.14	5th and 95th percentile
4.46	4th and 96th percentile
4.92	3rd and 97th percentile
5.67	2nd and 98th percentile
7.33	1st and 99th percentile

An example: Table 11.12 shows that data are missing which describe the hand circumference at the knuckles. To get such information, we want to conduct measurements. We assume S to be 10 mm and want to measure with an accuracy of 1 mm, so v = 1 mm. With q = 1.96 from Table 11.11, we calculate $N = [1.96 \times 10/1]^2 \approx 384$. Accordingly, we must take measurements on at least 384 hands.

Table 11.12 Hand and wrist measures, in mm (adapted from Kroemer, 2009)

		Men		Women	
	Population	Mean	SD	Mean	SD
1. Length	British	180	10	175	9
	British, estimated 1986	190	10	175	9
	Chinese, Taiwan	183	10	167	8
	French	190	nda	173	nda
	Germans, civilians	189	9	174	9
	Germans, soldiers 2006	191	nda	176	nda
	Japanese	nda	nda	nda	nda
	Russians, Moscow	188	9	168	8
	US soldiers	194	10	181	10
	US Vietnamese	177	12	165	9
2. Breadth at knuckles	British	85	5	75	4
	Chinese, Taiwan	86	5	75	4
	French	86	nda	76	nda
	Germans, civilians	88	5	78	4
	Japanese	nda	nda	90	5
	Russians, Moscow	87	5	76	3
	US soldiers	90	4	79	4
	US Vietnamese	79	7	71	4

Table 11.12 (continued)

	Population	Men Mean	Men SD	Women Mean	Women SD
3. Maximal breadth	British	105	5	92	5
	Chinese	nda	nda	nda	nda
	French	nda	nda	nda	nda
	Germans, civilians	107	6	94	6
	Japanese	nda	nda	nda	nda
	Russians	nda	nda	nda	nda
	US soldiers	nda	nda	nda	nda
	US Vietnamese	100	6	87	6
4. Circumference at knuckles	British	nda	nda	nda	nda
	Chinese	nda	nda	nda	nda
	French	nda	nda	nda	nda
	Germans	nda	nda	nda	nda
	Japanese	nda	nda	nda	nda
	Russians	nda	nda	nda	nda
	US soldiers	214	10	186	9
	US Vietnamese	nda	nda	nda	nda
5. Wrist circumference	British	nda	nda	nda	nda
	Chinese	nda	nda	nda	nda
	French	nda	nda	nda	nda
	Germans	nda	nda	nda	nda
	Japanese	nda	nda	nda	nda
	Russians	nda	nda	nda	nda
	US soldiers	174	8	151	7
	US Vietnamese	163	15	137	18

nda: no data available

Statistical Body Models

It is often desired to combine body dimensions. For this purpose, two methods have been employed: one is incorrect, but the other is suitable.

The percentile statistic is convenient for determining the location of any *one* given datum on its continuum range, such as 1,504 mm for the 10th percentile value for female stature in Taiwan ($STATp_{10} = 1{,}572 - 1.28 \times 53$; see Table 11.10). However, it is false to assume that all other body component measures of that imaginary 10th-percentile person must also be at their 10th percentile. For example, stacking p_{10} leg length plus p_{10} torso length plus p_{10} head height does not add up to p_{10} stature*: a person of 10th percentile stature may have relatively short legs but a long torso, or long legs and a short torso, or any other combination of torso and leg lengths.

A related model, often used by politicians and journalists, even by some misguided designers, is the so-called "average person", an apparition that consists of only "average" body parts. Obviously, so such ghost exists; statistically, stacking up 50th percentile body parts is just as erroneous as trying to do this with 10th or other solo percentile sections.

However, regression equations are suitable to generate discrete body measures, provided that they employ as predictor variables other dimensions whose values are known for the population sample of interest. In this case, predicted values may be added or subtracted. For example, 10th percentile values for leg, trunk, and head heights predicted from regressions do add up to 10th percentile stature.

Deducing Unknown Values from Existing Data

There are several statistical procedures to estimate data from existing related information.

Estimation by Ratio Scaling

Ratio scaling* is one technique to estimate data from known dimensions, especially to deduce the mean of a dimension or its standard deviation. Ratio scaling relies on the assumption that, though people vary in size, their proportions are likely to be similar. This conjecture mostly holds true for body components that are inter-related to each other. For example, many body lengths correlate highly with each other; also, many body breadths are related as a group, and so are many circumferences within their cluster. However, it is not true, even within their groups, that *all* body lengths (or breadths, or circumferences) correlate highly. Furthermore, many lengths are not related highly to breadths, and breadths are not highly related to many circumferences: see Table 11.4. Thus, one has to be very careful in deriving one set of data from another.

For any ratio scaling, one should use only pairs of data that have a coefficient of correlation of at least 0.7 with each other. This "0.7 convention", already mentioned in this chapter, assures that the variability of the derived information is at least to 50% determined by the variability of the predictor. Certainly, one should not use ratio scaling if it is likely that the base sample has body proportions different from those of the set to be predicted; for example, many asian populations have proportionally shorter legs and longer trunks than people in Europe and North America.

Provided that the data sets in population samples of x and y correlate highly, we can establish an estimated ratio scaling factor E of a desired dimension d_y in the y sample if

- the value d_x of that dimension in the x sample is known and
- values of the primary reference dimension in both samples, D_x and D_y, are known as well.

The following equation defines the scaling factor E:

$$d_x/D_x = d_y/D_y = E. \tag{11.14}$$

With $E = d_x/D_x$ known, we can calculate the desired dimension from

$$d_y = E \times D_y \qquad (11.14a)$$

in stepwise fashion, as shown in the following.

Step 1: In the x sample, establish the scaling factor E between the desired dimension and a known reference dimension. The reference parameter must be common for both population samples.

For example: On average, East German men (x sample) had an eye height (d_x) of 160.1 cm while their average stature (D_x) was 171.5 cm. *If West Germans (y sample) have a mean stature (D_y) of* 179.5 cm, *what is their approximate mean eye height d_y?*

First, determine E:

$$E = d_x/D_x = 160.1/171.5 = 0.933. \qquad (11.14)$$

Step 2: With E now known, the value of a dimension in population the y sample derives from multiplying the reference parameter in the y sample with E:

Eye height in the y sample derives from E multiplied with stature in the y sample:

$$d_y = E\ D_y = 0.933 \times 179.5 \text{ cm} = 167.5 \text{ cm}. \qquad (11.14a)$$

For practical reasons, stature is often the reference value. Note, however, whereas stature generally is related well with other heights, it is not necessarily associated with depths, breadths, circumferences, or weight (as mentioned earlier). Thus, ratio scaling must be done with great caution and careful consideration of the circumstances, especially taking into account statistical correlations.

Estimation by Regression Equation

Another way of estimating the relations among dimensions is through regression equations. If two variables are involved, one often assumes that they relate linearly with each other (that assumption is usually not verified). The general form of such a bivariate regression equation is

$$m_y = \text{a} + \text{b} \times m_x. \qquad (11.10)$$

To calculate m_y, the mean of the y sample, you must know the mean value m_x in the x sample and its constants a (the intercept) and b (the slope). If you are using Eq. (11.10), you expect that the actual values of y are scattered about their mean in a normal (Gaussian) probability distribution*.

Combining Anthropometric Data Sets

Occasionally one must add or subtract anthropometric values; for example, total arm length is the sum of upper and lower arm lengths.

If you add two measures (such as leg length and torso-head length), you generate a new combined distribution (here: stature). In doing so, you must take into account the existing covariation COV between the two measures. (Often, but not always, a taller torso is associated with taller legs.) The correlation coefficient r between the two data sets, x and y, and their standard deviations, S_x and S_y, describe the covariation:

$$COV(_{x,y}) = r_{xy} \times S_x \times S_y \tag{11.15}$$

This allows to calculate the *sum* of the two mean values of the two distributions from

$$m_z = m_x + m_y \tag{11.16}$$

and the estimated standard deviation of m_z from

$$S_z = (S_x^2 + S_y^2 + 2r\, S_x \times S_y)^{1/2}. \tag{11.17}$$

The *difference* between two mean values is

$$m_z = m_x - m_y \tag{11.18}$$

and its standard deviation

$$S_z = (S_x^2 + S_y^2 - 2r\, S_x \times S_y)^{1/2}. \tag{11.19}$$

Example: *What is the average arm (acromion to wrist) length of an American pilot?* For a standing pilot, the 90th percentile of acromial shoulder height was 1,532 mm and 905.6 mm for wrist height; at the 10th percentile, the values were 1,379.5 and 808.6 mm, respectively. You estimate the correlation between shoulder and wrist heights at 0.3.

You first calculate the mean acromion (A) and wrist (W) heights to be able to estimate the standard deviations.

$$\mathrm{m_A} = (1{,}532 + 1{,}379.5)\ \mathrm{mm}/2 = 1{,}455.75\ \mathrm{mm} \tag{11.16}$$

With k = 1.28 taken from Table 11.3,

$$S_A = (1{,}532 - 1{,}455.75)\ \text{mm}/1.28 = 59.6\ \text{mm}$$
$$[\text{or: } S_A = (1{,}455.75 - 1{,}379.5)\ \text{mm}/1.28 = 59.6\ \text{mm}] \qquad \text{(from 11.12)}$$

Likewise,

$$m_W = (905.6 + 808.6)\ \text{mm}/2 = 857.1\ \text{mm} \qquad (11.16)$$

$$S_W = (905.6 - 857.1)\ \text{mm}/1.28 = 37.9\ \text{mm}$$
$$[\text{or: } S_W = (857.1 - 808.6)\ \text{mm}/1.28 = 37.9\ \text{mm}] \qquad (11.12)$$

The average arm length (acromion to wrist, AW) is

$$m_{AW} = m_A - m_W = 1{,}455.75\ \text{mm} - 857.1\ \text{mm} = 598.65\ \text{mm} \qquad (11.18)$$

The standard deviation of the arm length is

$$S_{AW} = v\ (59.6^2 + 37.9^2 - 2 \times 0.3 \times 59.6 \times 37.9)\ \text{mm} = 60.3\ \text{mm} \qquad (11.19)$$

Example: *What is the mass of the torso of a* 75p *female?* The estimated mass of the torso and head combined had a mean of 35.8 kg and a standard deviation of 5.2 kg. The estimated mass of the head, measured separately, had a mean of 5.8 kg with a standard deviation of 1.2 kg. The correlation between head and torso is assumed to be 0.1.

The mean torso mass is the difference

$$\text{mean}_{\text{torso}} = 35.8\ \text{kg} - 5.8\ \text{kg} = 30.0\ \text{kg}. \qquad (11.18)$$

The standard deviation is calculated from

$$S_{\text{torso}} = v\ (5.2^2 + 1.2^2 - 2 \times 0.1 \times 5.2 \times 1.2)\ \text{kg} = 5.2\ \text{kg} \qquad (11.19)$$

The mass of a 75th percentile torso is (with k = 0.67 taken from Table 11.3)

$$\text{mass}_{\text{torso}}75\text{p} = 30.0\ \text{kg} + 0.67 \times 5.2\ \text{kg} = 3.5\ \text{kg} \qquad (11.12)$$

Two-Sample Composite Population

It may be necessary to consider a population that consists of two distinct and known subsamples. For example: The task is to design for a user group that consists of *x*%

females and $y\%$ males; so, $x + y = z = 100\%$. To determine at what percentile of the composite population a specific value of z is, one proceeds stepwise as follows:

Step 1: Determine k factors (as in Table 11.3) in the samples x and y.
For sample x: Using $p_x = m_x + k_x \times S_x$ (Eq. 11.12) yields $k_x = (p_x - m_x)/S_x$. (11.12a)
Similarly, for sample y: $k_y = (p_y - my)/S_y$.
Step 2: Obtain factor k in the combined population:

$$k_z = n_x \times k_x + n_y \times k_y.$$

Step 3: Determine percentile p associated with k from Table 11.3. If percentiles p are known in each group, one may simply add the proportioned percentiles:

$$p_z = n_x \times p_x + n_y \times p_y.$$

Using Anthropometric Data in Design

Anthropometric data describe the body sizes of people in standardized erect postures. Such information is basic for the design of workspaces and equipment, of tools and clothing, which must fit the human body. Table 11.10 describes commonly measured body dimensions; the table also indicates how such information serves human-centered design. However, to utilize this information properly, anthropometric data need proper interpretation and, often, adjustment.

The "Normative" Adult

We have acquired the questionable habit of designing for a "regular adult" who posesses

- "normal" anthropometry, with all body dimensions (such as stature, hand reach or weight) close to their mean values;
- "normal" physiological functions, such as of the metabolic, circulatory and respiratory subsystems; whose nervous control functions, sensory capabilities and intelligence are all near "average".

In reality, however, hardly any person exists who is average in all or many respects; instead, "extraordinary" persons and population subgroups abound: very big or small individuals, temporarily or permanently impaired persons, women during their pregnancy, children and juveniles, or elderly people. So, instead of using the imaginary "normal adult" as design prototype, we must consider the variability that exists naturally among "not-ordinary" people of different body sizes, genders, ages, and abilities*.

Body Positions and Motions at Work

It is difficult to maintain a given posture over long periods of time. Standing and sitting without moving, even lying still, all quickly become uncomfortable and, with time, physically impossible; if enforced by injury or sickness, circulatory and metabolic functions become impaired, bed sores appear. The human body is made for motion; our articulations have various degrees of freedom to move; see Chap. 1 for data on maximal angular displacements in major body joints.

In the past, the same erect body postures, sitting and standing, that subjects assume for anthropometric measurements often served as design models: probably because upright postures are easy to visualize and simply made into design templates. Furthermore, late in the nineteenth century orthopedists had vigorously promoted the idol of upright posture for standing and especially for sitting in a school or office. In spite of the counter-argument that the artificially erect posture, such as commanded by teachers and military officers, required tiring muscular efforts, most of the twentieth century office furniture was constructed for upright sitting. However, people move and stretch and reach to do their jobs, or let their bodies "slump", especially when a supportive chair allows relaxing muscle tension. Accordingly, the human-factors engineer must adjust the standardized anthropometric information to consider such functional motions and postures, as described in Table 11.13. The design of modern equipment reflects this everyday experience; in motor vehicles and airplanes, drivers and pilots and passengers sit comfortably, even if the available space is tight. New office furniture supports upright as well as relaxed postures – see Fig. 11.20 – because it fits the body, especially the curvature of the back, and has adjustable heights and angles of seat pan and back rest.

"Convenient" mobility is somewhere within the range of possible extreme postures. In everyday activities, most movements of the trunk, the head, the elbows and

Table 11.13 Guidelines for the conversion of standard measuring postures to functional stances and dimensions

Slumped standing or sitting	Deduct 5–10% from relevant height measurements
Relaxed trunk	Add 5–10% to trunk circumferences and depths
Wearing shoes	Add approximately 25 mm to relevant standing and sitting heights; more for "high heels"
Wearing light clothing	Add about 5% to relevant dimensions
Wearing heavy clothing	Add 15% or more to relevant dimensions. (Note that heavy clothing may strongly reduce mobility)
Extended reaches	Add 10% or more to relevant reach measures for strong motions of the trunk
Use of hand tools	Center of handle is at about 40% of hand length, measured from the wrist
Forward bending of head, neck and trunk	Ear-Eye Line declines to near horizontal
Comfortable seat height	Subtract up to 10% from popliteal height

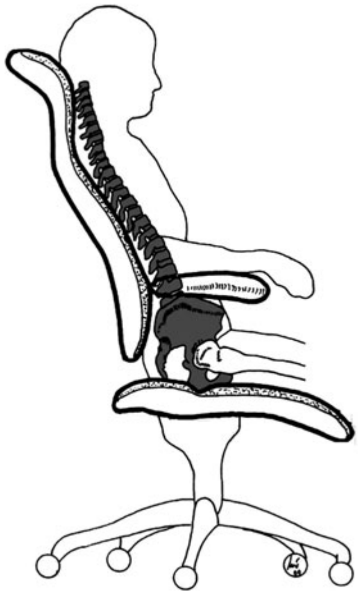


Fig. 11.20 Office chair that fits the body, especially the curvature of the back, and has adjustable heights and angles of seat pan and back rest

Table 11.14 Mobility ranges at work

Body joints/parts	Angles/positions	
Shoulder	Mostly mid-range, upper arm often hanging down	
Elbow	Mostly mid-range, at about 90°	
Wrist	Mostly mid-range, about straight	
Neck/Head	Mostly mid-range, about straight	
Back	Near complete stretch, about erect	
	When walking or standing	When sitting
Hip (side new)	Near complete stretch, at about 180°	Mostly mid-range, at about 90°
Knee	Near extreme stretch, slightly less than or near 180°	Mostly mid-range, at about 90°

of the wrist occur in the midrange of mobility, as do motions of the hips and knees when sitting. However, in contrast, hip and knee movements of a person walking or standing are usually close to full stretch. Table 11.14 contains estimates of everyday motion ranges. Task requirements, work skills and habits may make different ranges preferred – in fact, quite differing work postures are common in various regions on earth: compare Figs. 11.20 and 11.21.

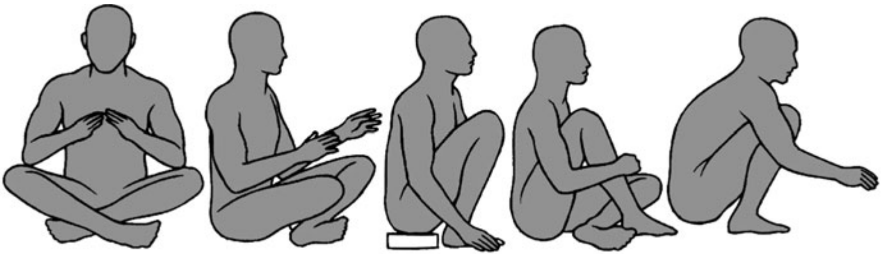


Fig. 11.21 Non-western work postures (adapted from Kroemer et al., 2003)

Designing to Fit the Body

While all humans have heads and trunks, arms and legs, these body parts come in various sizes and in different proportions. As already discussed, compilations of anthropometric data usually show normal (Gaussian) distributions. This fortunate fact allows describing such information by the simple statistical descriptors *mean* (same as *average*) and *standard deviation*.

Yet, misunderstanding and misuse have led to the false idea that one could "design for the average"; by definition, the mean value is larger than half the data, and smaller than the other half. Consequently, an average-sized product is, by design, either too large or too small for its users. Furthermore, it is unlikely ever to encounter a person who displays mean values in several, many or even all dimensions*.

Useful steps in designing for fitting clothing, tools, workstations, and equipment to the body are as follows:

Step 1: *Select those anthropometric measures that directly relate to important design dimensions.* A few examples: hand length relates to handle size; knee height and hip breadth relate to the leg room in a console; shoulder and hip breadth relate to escape-hatch diameter; head length and breadth relate to helmet size; eye height relates to the heights of windows and displays; stature relates to the height of a door frame.

Step 2: *For each of these pairings, determine whether the design must fit only one given percentile – minimal or maximal – of the body dimension, or a range along that body dimension.* Examples: the escape hatch must be big enough to clear the extreme largest values of shoulder breadth and hip breadth, enlarged by clothing and equipment worn. The handle size of pliers should probably best fit a smallish hand; the legroom of a console must accommodate the tallest knee heights. The height of a seat should be adjustable to fit persons with short and with long lower legs. A door opening should be higher than the tallest person to avoid bloody scalps.

Step 3: *Combine all selected design values in a carefully devised sample, computer model, mock-up, or drawing to ascertain that they are compatible.* Example: a tall legroom clearance height, needed for sitting persons with long lower legs, may be very close to, even interfere with the height of the working surface, which depends on elbow height.

Step 4: *Determine whether one design will fit all users – if not, several sizes or adjustment must be provided to accommodate the users.* Examples are: one extra-large bed size fits all sleepers; gloves and shoes must come in different sizes; seat heights should be adjustable.

Selecting appropriate percentile values of the critical dimensions is of great importance for successful design. There are two ways to determine percentile values. A graph of the distribution of data allows to measure, count or estimate critical percentile values. This works well whether the distribution is normal, skewed, binomial, or in any other form. Fortunately, most anthropometric data are normally distributed, which allows the second, even easier and more exact approach: to calculate percentile values from mean m and standard deviation S – see Table 11.2.

To determine a single (distinct) percentile point:

(a) Select the desired percentile value;
(b) Determine the associated k value from Table 11.3;
(c) Calculate the p value from $p = m + k \times S$. (Note that k and hence the product $k \times S$ may be negative.)

To determine a range:

1(a) Select upper percentile p_{max};
1(b) Find related k_{max} value in Table 11.3;
1(c) Calculate upper percentile value $p_{max} = m + k_{max} \times S$;
2(a) Select lower percentile p_{min};

(Note that the two percentile values need not be at the same distance from the 50th percentile – in other words, the range does not have to be "symmetrical to the mean".)

2(b) Find related k_{min} value in Table 11.3;
2(c) Calculate lower percentile value $p_{min} = m + k_{min} \times S$;
3 Determine range $R = p_{max} - p_{min}$.

Determining Tariffs

Often, it is useful to divide a distribution of body dimensions into certain sections, such as in establishing clothing tariffs. An example is the use of neck circumference to establish selected collar sizes for men's shirts. The first step is to establish the ranges (see above) which shall be covered by the tariff sections. The second step is to associate other body dimensions with the primary one, such as chest circumference, or sleeve length, with collar (neck) circumference. Establishing a tariff can become a rather complex procedure*, because the combination of body dimensions (and their derived equipment dimensions), depends on correlations among these dimensions, as already shown in Table 11.4.

Determining the Workspace of the Hands

The human body enjoys particular hand dexterity, with shoulder, elbow and wrist joints together providing extensive freedom of sweep. Classical anthropometric data provide some information on reach capabilities with the body in standardized static postures – see Chap. 1. Preferred work areas of the hands are in front of the trunk, within curved envelopes that reflect the mobility of the forearm in the elbow joint and of the total arm in the shoulder joint. Thus, these envelopes often appear as partial spheres around the presumed locations of the body joints. Figure 11.22 depicts the "convenient" reach area that requires mostly forearm movements and the "extended" reach space that requires motions of the completely stretched arm, possibly even trunk movement.

Human-Centered Engineering

In Ergonomics, the task of the human factors engineer is designing, constructing, and operating the work processes, structures, machines, devices and tools used in industry and in everyday life. The primary goals are to facilitate achieving the task while assuring safety of the human, avoiding overuse and unnecessary effort – see Fig. 11.23.

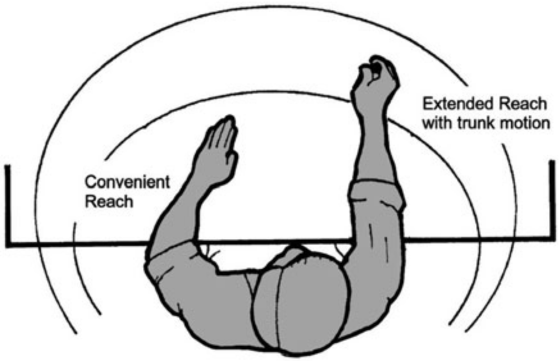


Fig. 11.22 Convenient and extended reaches (adapted from Proctor and Van Zandt, 1994)

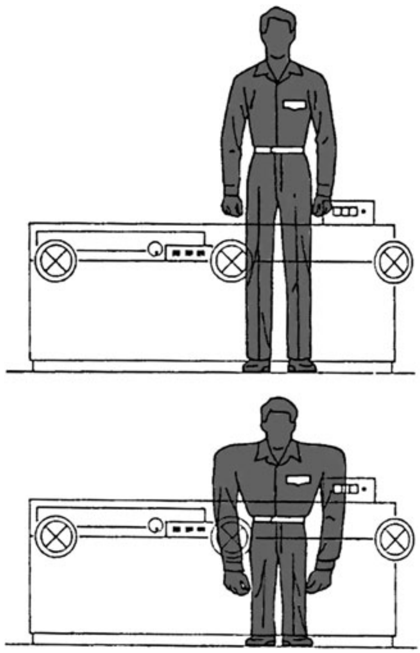


Fig. 11.23 Re-designing the operator or the machine? A lathe with its real and imagined operator (adapted from Eastman Kodak Company, 1983)

Anthropometric data provide basic measurements needed to make equipment and tools accommodate the human body. Together with knowledge about mobility and physical capabilities (such as muscular, circulatory, metabolic – see the related Chaps. 2, 6, and 7, this book), the engineer can achieve usability and usefulness of the design.

Considering anthropometric information as design inputs can be as basic as making door openings so high that nobody strikes the head on the frame – not even in the Netherlands with one of the tallest populations on earth. Other simple design tasks are elevating a short operator to the proper working height, as in Fig. 11.24, or

Fig. 11.24 Providing a platform to stand on is helpful to a short operator of a machine designed for a tall user – but note the danger of stumbling (adapted from ILO International Labour Office, 1986)

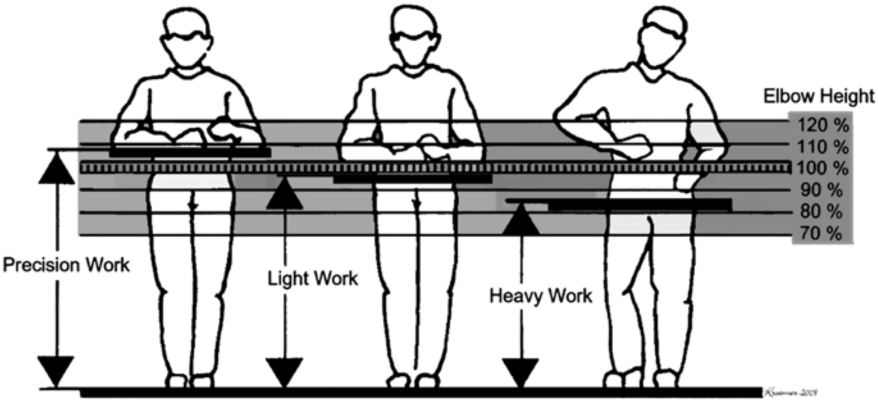


Fig. 11.25 Adjusting the height of the work surface to the size of the operator and the work task (adapted from Kroemer, 2009)

adjusting the height of workbenches to fit different operators and work tasks, shown in Fig. 11.25.

In other cases, considering anthropometry is rather complicated, such as in constructing equipment for use by persons with dwarfism, because the "little people" have distinctly unique bodies, proportioned other than the normal population. Environmental conditions can make the engineering task complex, such as when building space suits or cockpits for high-performance aircraft. Often, the design intentions go beyond fit and usability by aiming at user emotions such as aesthetic appeal, satisfaction and comfort*. Yet, achieving any design goal, from utility to pleasure, requires fitting process and product to the human.

Fig. 11.26 Comfortable sitting (adapted from Kroemer, 2009)

Notes

The text contains markers, *, to indicate comments and references, which follow:

Anthropometric techniques and methods: Hertzberg (1968), Roebuck et al. (1975), Lohman et al. (1988), Gordon et al. (1989), Cheverud et al. (1990), Roebuck (1995), Robinette and Daanen (2003).

Compilations of measured data are available for specific populations: Data in Garrett and Kennedy (1971), NASA/Webb (1978), Peebles and Norris (1998), Landau (2000), Kroemer (2006, 2009).

Frankfurt plane: Publications by Hertzberg (1968), Garrett and Kennedy (1971), Roebuck et al. (1975), NASA/Webb (1978), Lohman et al. (1988), Gordon et al. (1989), Roebuck (1995), Strokina and Pakhomova (1999), Wang et al. (2002), Robinette et al. (2006) contain additional illustrations, descriptions, and definitions of landmarks and measuring techniques.

Calculating the locations of bony landmarks underneath the skin: Burnsides et al. (2001), Leon et al. (2007), Robinette and Daanen (2006), Suikerbuik et al. (2004).

Computer models of the human body in engineering design: Marras and Radwin (2006), Chaffin (2008).

Anthropometric information about soldiers is extensive and reaches far into the past: The NASA/Webb Anthropometric Sourcebook (1978) provides an overview of the data available up to the mid-1970s. More recent information appears in reports on data measured on US Army personnel (Gordon et al., 1989; Gordon, 2009), on Japanese Air Force personnel (Kagimoto, 1990) and German military applicants (Juergens, 2004).

The most common statistical procedures: For more information on the use of statistics in anthropometry see texts on statistics (for example, Hinkelmann and Kempthorne, 1994, 2005; Williges, 2007) and on anthropometry (such as Roebuck et al., 1975; NASA/Webb, 1978; Gordon et al., 1989; Cheverud et al., 1990; Roebuck, 1995; Marras and Karwowski, 2006; Pheasant and Haslegrave, 2006).

Correlation coefficients r among body dimensions of US Air Force personnel . . . older tables: see the 1997 3rd edition of this book and Roebuck et al. (1975).

The easily measured stature is not a good predictor for most other body dimensions: An unpublished 1966 report (the authors may remain unnamed here) contained ratios between stature and many other body segments, even though most of them do not correlate well with stature. Since the ratios were given with three decimals, that misleading model seemed exact and has made ghostly re-appearances in the literature ever since its original misconception.

The weight distribution is non-normal: Statistical procedures are at hand for converting non-normal distributions into normal ones, especially the Box-Cox conversion (Freeman and Modarres, 2006).

The validity of several assumptions regarding height-weight ratios was questioned: As discussed in detail by Andres (1984) and Speakman (1997).

Interpret the meaning of the BMI number: Prentice and Jebb (2001).

Anthropometric differences among several groups of ethnic origins: Cheverud et al. (1990).

Firefighters, police and guards are taller and heavier than americans in all other occupations: Hsiao et al. (2002)

Dimensions of the head, hand, and foot . . . same in military and civilian populations: McConville et al. (1981).

Children: Steenbekkers and Molenbroek (1990), Kroemer (2006), Lueder and Rice (2007).

Recent collections of measured and of estimated anthropometry data: Peebles and Norris (1998), Pheasant and Haslegrave (2006), Kroemer (2006, 2009).

Sources for retrieving new anthropometric information:

Research institutions: such as Roebuck (1995), Lohman et al. (1988), Steenbekkers and Beijsterveldt (1998), Strokina and Pakhomova (1999), Wang et al. (2002), Kroemer (2006, 2009), Lueder and Rice (2007).

Government agencies: Erens et al. (2000), Peebles and Norris (2000).

The military: For example, Gordon et al. (1989), Kagimoto (1990), Robinette et al. (2002), Leyk et al. (2006).

International institutions: ISO TR 7250; Juergens et al. (1990).

Journals: Applied Ergonomics; Ergonomics; Ergonomics in Design; Human Factors, for example.

Trade associations: such as Goncalves (24, 29 May 2006, personal communications), IFTH (2006), Institute of Industrial Engineers.

Doing an anthropometric survey: Kroemer (1989), Roebuck (1995).

Measuring technique: Publications by these authors provide overviews of traditional and emerging anthropometric techniques: Hertzberg (1968), NASA/Webb (1978), Lohman et al. (1988), Paul and Douwes (1993), Roebuck (1995), Annis and McConville (1996), Perkins and Blackwell (1998), Robinette (1998), Bradtmiller (2000), Landau (2000), Paquet et al. (2000), Robinette (2000), Burnside et al. (2001), Feathers et al. (2001), Blackwell et al. (2002), Froufe et al. (2002), Wang et al. (2002), Robinette and Daanen (2003), HFES 300 Committee (2004).

Stacking leg length plus torso length plus head height does not add up to stature: Robinette and McConville (1981).

Ratio scaling: Roebuck et al. (1975), Pheasant (1982), Roebuck (1995).

Estimating the relations among dimensions through regression equations: The estimation of body dimensions of American soldiers by Cheverud et al. (1990) is an example of this procedure. Roebuck (1995) discussed the implications in some detail, including the extension of this concept to develop multivariate regression equations, as well as to principal component analyses and boundary description analyses.

Consider the variability that exists naturally among "extra-ordinary" people of different genders, ages, and abilities: Kroemer et al. (2003), Kroemer (2006), Lueder and Rice (2007) discuss how to design for "extraordinary" populations that deviate in size, strength, or other performance capabilities from the normative adult.

It is unlikely ever to encounter a person who displays mean values in several, many or even all dimensions: see Kroemer et al. (2003), Kroemer (2006), Robinette and Hudson (2006), Kroemer (2009).

Establishing a tariff can become a rather complex procedure: For more information, see Roebuck et al. (1975), Mcconville's Chapter VIII in NASA/Webb (1978), Robinette and McConville (1981), Roebuck (1995).

Aesthetic appeal, satisfaction and comfort: Helander and Zhang (1997), Helander (2003), Helander and Tham (2003), Khalid and Helander (2006).

Summary

Traditional techniques for measuring the human body rely on sets of simple measuring scales, such as rods and tapes. New developments use computer-based three-dimensional electronic scanning techniques.

Many currently available data describe soldiers, traditionally males. Data describing large samples of civilians are still scarce.

Statistical variations in body dimensions result from differences among individuals, secular body size development, aging, changes in health and fitness, and from changing local population composition such as due to immigration. Most changes influence the anthropometry of an entire population only subtly and slowly. However, in fitting equipment to a defined population subgroup, the engineer must consider the body dimensions that are specific to the group.

Body proportions are vastly different among individuals. Hence, neither generalized body types (somatotypes) nor single-percentile phantoms (such as the "average person") are suitable means to describe body dimensions or capabilities for engineering purposes. No 5- or 95-percentile persons exist; design for the average fits nobody. Instead, ranges of body sizes (and of mobility, strengths and other capabilities) establish suitable design criteria. This chapter contains related anthropometric data and explains their measurements and use.

Glossary

Abduct To move away from the body or one of its parts; opposite of adduct.

Acetabulum Cup-shaped cavity at the base of the pelvis (hipbone) into which the ball-shaped head of the femur fits.

Acromion A landmark on top of the shoulder: the highest point on the lateral edge of the scapula above the shoulder joint, at about half the width of the shoulder. Acromial height is usually equated with shoulder height.

Adduct To move towards the body; opposite of abduct.

Anterior In front of the body; toward the front of the body; opposed to posterior.

Articulation Joint between bones.

Asthenic Body build with small bones and muscle, little fat (similar to leptosomic and ectomorphic).

Atlas The top cervical vertebra, supporting the skull.

Axilla The armpit.

Axis Center line of an object; midline about which rotation occurs.

Bending See moment

Biceps brachii (“Two heads”) arm muscle reducing the elbow angle.

Biceps femoris A large posterior muscle of the thigh; flexor of the thigh.

Brachialis Forearm muscle connecting the mid-humerus with the ulna.

Brachioradialis Forearm muscle connecting the humerus with the radius.

Breadth A straight-line, point-to-point horizontal measurement running across the body or a segment.

Buttock protrusion The maximal posterior protrusion of the right buttock.

Canthus A corner or angle formed by the meeting of the eyelids.

Carpus The wristbones, collectively.

Cervical Part of/pertaining to/the cervix (neck), especially the seven vertebrae at the top of the spinal column.

Cervicale The protrusion of the spinal column at the base of the neck caused by the tip of the spine of the 7th cervical vertebra.

Circumference A closed measurement that follows a body contour; hence the measurement usually is not circular.

Clavicle The “collarbone” linking the scapula with the sternum.

Coccyx (Or: sacrum) the tailbone, a triangular bone of fused rudimentary vertebrae at the lower end of the spine.

Compression The pressure (strain) generated in material caused by two opposing forces; opposite of tension.

Condyle Articular prominence of a bone.

Coronal plane Any vertical plane at right angles to the midsagittal plane (same as frontal plane).

Cortical Of/at the outside.

Curvature A point-to-point measurement following a contour; this measurement is neither closed nor usually circular.

Dactylion The tip of the middle finger.

Density Mass of material per unit volume.

Depth A straight-line, point-to-point horizontal measurement running fore-aft the body.

Digit The thumb and four fingers of the hand.

Distal Away from the center, peripheral; opposite of proximal.

Distance A straight-line, point-to-point measurement between landmarks on the body.

Dominant The hand or foot exclusively used for certain actions.

Dorsal Toward the back or spine; also pertaining to the top of hand or foot, opposite of palmar, plantar, and ventral.

Ear-Eye line An easily established reference line for the tilt angle of the head. It runs through the right meatus (ear hole) and the right external canthus (meeting corner of the eye lids). The EE line is angled about 11° above the Frankfurt plane; see there.

Ectomorphic Body build with small bones and muscle, little fat (similar to asthenic and leptosomic).

Endomorphic Body build with much soft, fatty tissue, abdominal protrusion, often with little muscle.

Epicondyle The bony eminence at the distal end of the humerus, radius, and femur.

Ergonomics The application of scientific principles, methods and data drawn from a variety of disciplines to the design of engineered systems in which people play significant roles.

Extend To move adjacent segments so that the angle between them is increased, as when the leg is straightened; opposite of flex.

External Away from the central long axis of the body; the outer portion of a body segment.

Facet Flat articulation surface at the upper (superior) and lower (inferior) parts of the articulation processes of a vertebra.

Femur The thigh bone.

Flex To move a joint in such a direction as to bring together the two parts which it connects, as when the elbow is bent; opposite of extend.

Flexibility Term occasionally used instead of mobility.

Frankfurt Plane The former standard horizontal plane for orientation of the head. The plane is established by a line passing through the right tragion (approximate ear hole) and the lowest point of the right orbit (eye socket), with both eyes on the same level; see Ear-Eye line.

Frontal plane Any vertical plane at right angles to the midsagittal plane (same as coronal plane).

Glabella The most anterior point of the forehead between the brow ridges in the midsagittal plane.

Glenoid cavity Depression in the scapula below the acromion into which fits the head of the humerus, forming the shoulder joint.

Gluteal furrow The furrow at the juncture of the buttock and the thigh.

Height A straight-line, point-to-point vertical measurement.

Humerus The bone of the upper arm.

Iliac crest The superior rim of the pelvic bone.

Inferior Below, lower, in relation to another structure.

Inseam A term used in tailoring to indicate the inside length of a sleeve or trouser leg. It is measured on the medial side of the arm or leg.

Internal Near the central long axis of the body; the inner portion of a body segment.

Ischium The dorsal and posterior of the three principal bones that compose either half of the pelvis.

Knuckle The joint formed by the meeting of a finger bone (phalanx) with a palm bone (metacarpal).

Kyphosis Backward curvature of the spine; opposite of lordosis.

Lateral Lying near or toward the sides of the body; opposite of medial.

Leptosomic Body build with large bones and muscles (similar to asthenic and ectomorphic).

Lordosis Forward curvature of the spine; opposite of kyphosis.

Lumbar Part of/pertaining to/ the five vertebrae atop the sacrum.

Malleolus A rounded bony projection in the ankle region. The tibia has such a protrusion on its medial side, and the fibula one on its lateral side.

Medial Lying near or toward the midline of the body; opposite of lateral.

Medial plane The vertical plane which divides the body (in the anatomical position) into right and left halves; same as mid-sagittal plane.

Mesomorphic Body build with large bones and muscles.

Metacarpal Pertaining to the long bones of the hand between the carpus and the phalanges.

Mid-sagittal plane The vertical plane which divides the body (in the anatomical position) into right and left halves; same as medial plane.

Mobility The ability to move segments of the body.

Moment The product of force and its lever arm when trying to rotate and object about a fulcrum; the stress in material generated by two opposing forces that try to bend the material about and axis perpendicular to its long axis; see also torque.

Olecranon The proximal end of the ulna.

Omphalion The center point of the navel.

Orbit The eye socket.

Palmar Pertaining to the palm (inside) of the hand; opposite of dorsal.

Patella The kneecap.

Pelvis The bones of the "pelvic girdle" consisting of illium, pubic arch and ischium which compose either half of the pelvis.

Phalanges The bones of the fingers and toes (singular, phalanx).

Physis The body as distinguished from the mind.

Plantar Pertaining to the sole of the foot.

Popliteal Pertaining to the ligament behind the knee or to the part of the leg behind the knee.

Posterior Pertaining to the back of the body; opposite of anterior.

Protuberance Protruding part of a bone.

Proximal The (section of a) body segment nearest the head (or the center of the body); opposite of distal.

Radius The bone of the forearm on its thumb side.

Reach A point-to-point measurement following the long axis of the arm or leg.

Sacrum (Or: coccyx) the tailbone, a triangular bone of fused rudimentary vertebrae at the lower end of the spine.

Sagittal Pertaining to the medial (mid-sagittal) plane of the body, or to a parallel plane.

Scapula The shoulder blade.

Scye A tailoring term to designate the armhole of a garment. Refers here to landmarks which approximate the lower level of the axilla.

Secular Referring to events that appear over long stretches of time.

Somatotyping Categorizing body builds into different types. (Greek *soma,* body)

Sphyrion The most distal extension of the tibia on the medial side under the malleolus.

Spine The column of vertebrae.

Spine (or spinal process) of a vertebra The posterior prominence.

Stature Height of the standing human body.

Sternum The breastbone.

Stylion The most distal point on the styloid process of the radius.

Styloid process A long, spinelike projection of a bone.

Sub A prefix designating below or under.

Superior Above, in relation to another structure; higher.

Supra Prefix designating above or on.

Tailbone (Or sacrum, coccyx) triangular bone of fused rudimentary vertebrae at the lower end of the spine.

Tarsus The collection of bones in the ankle joint.

Tension The strain in material generated by two opposing forces that try to stretch the material; opposite of compression.

Thoracic Part of/pertaining to/ the thorax (chest), especially the twelve vertebrae in the middle of the spinal column.

Tibia The medial bone of the lower leg (shin bone).

Tibiale The uppermost point of the medial margin of the tibia.

Torsion The stress in material generated by two opposing forces that try to twist the material about its long axis; see also moment.

Tragus Conical eminence of the auricle (pinna, external ear) in the front wall of the ear hole.

Transverse plane Horizontal plane through the body, orthogonal to the medial and frontal planes.

Trochanterion The tip of the bony lateral protrusion of the proximal end of the femur.

Tuberosity A (large) rounded prominence on a bone.

Ulna The bone of the forearm on its little-finger side.

Umbilicus Depression in the abdominal wall where the umbilical cord was attached to the embryo.

Ventral Pertaining to the anterior (abdominal) side of the trunk.

Vertebra A bone of the spine.

Vertex The top of the head.

Volar Pertaining to the sole of the foot or the palm of the hand.

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