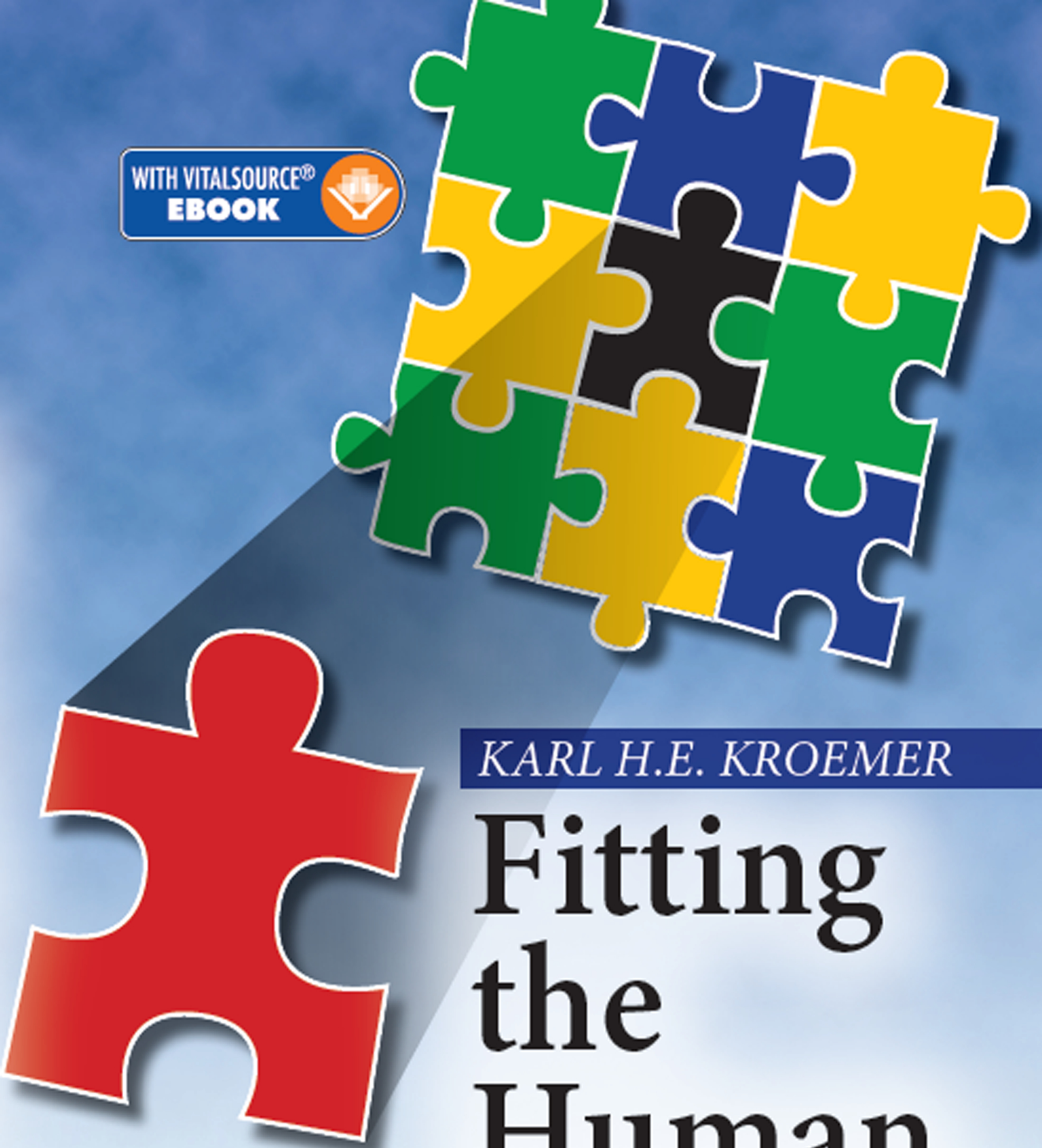

KARL H.E. KROEMER

Fitting the Human

INTRODUCTION TO ERGONOMICS / HUMAN FACTORS ENGINEERING

Seventh Edition

CRC Press
Taylor & Francis Group

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Preface

The 2006 edition of *Fitting the Human* was a CRC bestseller: it provides ergonomic information needed for the user-friendly design of things and tasks. This seventh edition maintains its successful format and offers updated information and practical guidelines and three new chapters: on load handling, on healthcare for patients and providers, and on autonomous automobiles.

Ergonomics

Fitting the Human focuses on the primary ergonomic task: accommodate the human by appropriate selection of

- Equipment and tools
- Work requirements and procedures
- Physical and social conditions at work
- Working hours and shift arrangements

Matching individuals with job requirements by personnel selection and training is mainly in the domain of industrial psychology, which widely overlaps with ergonomics. This book endorses the fundamental and most successful approach: plan and design the overall system and its details to suit the human.

Ease of use

This new edition follows the motto of the previous versions: "solid information, easy to read, easy to understand, easy to apply." Small markers (°) in the text, which do not break the flow of reading, indicate where references or explanations are in order. These appear in a separate Notes section at the end of each chapter, which the reader may skip or consult.

Fitting since 1963

Etienne Grandjean, who died in 1991, authored the first printing in 1963 as *Physiologische Arbeitsgestaltung*. He edited his text in 1969 and 1979. Ott Verlag published all three German editions. In 1980, Taylor & Francis put out the third edition, translated into English, with the title *Fitting the Task to the Man* and, in 1988, printed a revised version. The fifth edition, which I coauthored, appeared in 1997 as *Fitting the Task to the Human*. I completely revised the next edition because the demands on the human continually change, not only in task content, but also in utensils and equipment, and in the physical and social environments as well. Therefore, the title of the sixth and seventh editions is simply *Fitting the Human*.

Human engineering

The aim remains the same: "human engineering" workplaces, tools, machinery, computers, shift work, lighting, sound, climate, work demands, offices, vehicles, the home—and everything else that we can produce—to suit the human body and mind. In this new edition, I strive to continue Etienne Grandjean's direct, lucid, down-to-earth style of providing essential knowledge about design that fits the human body and mind. I hope the book will appeal to students and professionals in engineering, safety, architecture, design, and management and to everybody else interested in making work safe, efficient, satisfying, and even enjoyable.

Do you want more information?

This book is an introduction to ergonomic issues that are—and will be—discussed in the international literature. If you want to stay with me as author/coauthor, you may check out these books: the 2017 O*ffice Ergonomics*, second ed.; the 2010 *Engineering Physiology*, fourth ed.; the 2006 *Extra-ordinary Ergonomics*; and the upcoming third edition of the 2003 *Ergonomics: How to Design for Ease and Efficiency.*

Thank you!

I wish to thank Taylor & Francis/CRC's outstanding professionals for their dedication and many years of support. I particularly enjoyed working with Cindy Carelli, Adel Rosario, and their teams.

Karl H. E. Kroemer
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About the Author

Karl H. E. Kroemer studied mechanical engineering at the Technical University Hannover, Germany: Vor-Diplom (BS) in 1957, Dipl.-Ing. (MS) in 1960, and Dr.-Ing. (PhD) in 1965.

His first full-time employment was as a research engineer in the Max Planck Institute for Work Physiology, Germany, from 1960 to 1966. Then he worked for seven years as a research industrial engineer in the Human Engineering Division of the Aerospace Medical Research Laboratory, Wright–Patterson Air Force Base, Ohio. In 1973, he was appointed as the director of and a professor in the Ergonomics and Occupational Medicine Divisions, in the Federal Institute of Occupational Safety and Accident Research, Dortmund, Germany. In 1976, he became a professor of ergonomics and industrial engineering at Wayne State University, Michigan. In 1981, he began to serve as a professor in Virginia Tech's Department of Industrial and Systems Engineering and Director of the Industrial Ergonomics Laboratory in Blacksburg, Virginia; emeritus in 1998.

He was a member of the committee on Human Factors of the National Research Council, National Academy of Sciences. The Human Factors and Ergonomics Society, and the Ergonomics Society elected him as a fellow. He worked as a United Nations-International Labor Organization expert on Ergonomics in Bucharest, Romania, and in Mumbai, India.

Karl Kroemer has authored and coauthored over 200 publications. His books include the following:

1967: Selection, Arrangement and Use of Controls (in German)

1975: Engineering Anthropometry Methods

1984: Guide to the Ergonomics of Computer Workstations

1997: Ergonomic Design of Material Handling Systems

1997: Fitting the Task to the Human, fifth edition, translated into Serbo-Croatian and Portuguese

2001: Office Ergonomics, translated in 2006 into Korean

2003: Ergonomics, amended second edition; new edition expected in 2018

2006: "Extra-Ordinary" Ergonomics

2009: Fitting the Human, sixth edition

2010: Engineering Physiology, fourth edition

2017: Office Ergonomics, second edition

Contact him at kroemer@vt.edu.

The first page

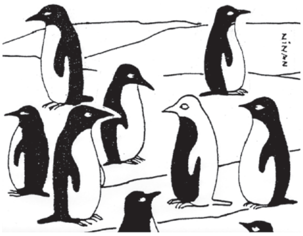
Humans are similar—yet individuals are unique.

Overall, we are alike. Our bodies follow the same design. We all have bones and muscles, the same circulatory and metabolic functions, and a similar brain layout.

Therefore, we can formulate ergonomic principles and guidelines that apply to all people. Recognizing similarities in people is one trademark of ergonomics.

However, individuals differ from each other, for example, in size and appearance, strengths, skills, interests, and expectations.

Therefore, work tasks and work systems must accommodate people of diverse sizes, powers, and wants. Recognizing differences among people is the other hallmark of ergonomics.



All the same?
Courtesy 2015
by Ajit Ninan
The Times of India

Ergonomics is the application of scientific principles, methods, and data drawn from a variety of disciplines to the development of engineered systems in which people play significant roles. That design relies on the knowledge of human characteristics relevant to the system and on the understanding that the system exists to serve humans. User-oriented design acknowledges human variability. (See http://iea.org for more details.)

The ergonomic goal is to make work safe, efficient, satisfying, and even enjoyable.

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SECTION I

The human body

We humans have remarkably similar bodies: the head, two arms, and two legs are attached to the trunk. We use similar sets of muscles and bones to move the body. Respiration, circulation, nervous control, and other basic functions are the same. Yet for people who live in unique climates, consume special diets, and perform distinct activities over long periods, their bodies evolve to adapt to the particular conditions. Thus, within the general similarity of humankind, there are differences in the bodies among groups of people. Furthermore, individuals differ from each other in size and, importantly, in capabilities and ambitions.

We need to recognize and measure existing differences among people so that we can devise clothing and equipment, tasks, and procedures to fit their special needs. The following chapters provide related information:

- Chapter 1 Body sizes
- Chapter 2 Mobility
- Chapter 3 Muscular work
- Chapter 4 Body strength

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CHAPTER ONE

Body sizes

Body sizes differ

We all experience changes in body size: quick growth during childhood followed by a period of fairly constant dimensions during adulthood for about 20–40 or more years until final variations come with senescence. As a rule, men grow to be taller as adults than women do. During any of the age periods, some persons are smaller or bigger than their peers are and body proportions can differ widely among individuals.

1.1 Our Earth's populations

Height and weight

The most common way to describe the bodies of populations, and of individuals as well, is by standing height (stature) and body weight. Table 1.1 contains the 1990 estimates of adult statures for 20 different regions of the Earth.

Such estimates give an overall impression about the differences in adults' body sizes, but designers need more precise anthropometric information. Variances, even though small compared to how similar we are, must be put into exact numbers so that we can set up clothing tariffs, sizes of eyeglass frames, heights of workbenches, cockpit dimensions—all different to fit various user groups.

1.2 Measurements

Anthropometrics around the globe

We can estimate body bulk, or we may ask persons about their body size, and if they know, they can tell us; however, with the current concerns about obesity in many countries, some

Table 1.1 Estimates of average Stature (in mm) in regions of the Earth

Region	Females	Males
Africa		
North	1610	1690
West	1530	1670
Southeast	1570	1680
America, Latin		
Natives	1480	1620
European and African extraction	1620	1750
America, North	1650	1790
Asia		
North	1590	1690
Southeast	1530	1630
Australia		
European extraction	1670	1770
China, South	1520	1660
East, Near	1610	1710
Europe		
North	1690	1810
Central	1660	1770
East	1630	1750
Southeast	1620	1730
France	1630	1770
Iberia	1600	1710
India		
North	1540	1670
South	1500	1620
Japan	1590	1720

Source: Juergens, H. W., Aune, I. A., and Pieper, U., *Occupational Safety and Health*, 65, 21–42, 1990.

respondents are likely to add a bit to their height and slightly reduce their weight. Therefore, actual measurements are in order.

Table 1.2 lists the measured heights and weights of persons all around the globe. When checking the entries in the table we notice that often the measured samples are small and that many regions and populations on Earth are not represented. Yet, altogether, this table alerts us to the magnitudes of differences in average body sizes and weights among groups of people.

Table 1.2 Measured heights and weights of adults: Averages (standard deviations)

	Sample size	Stature (mm)	Weight (kg)
Algeria			
Females (Mebarki and Davies 1990)	666	1576 (56)	61 (1)
Brazil			
Males (Ferreira 1988; cited by Al-Haboubi 1991)	3076	1699 (67)	nda
Cameroon			
Urban females	1156	1620	64
Urban males (35–44 years old) (Kamadjeu, Edwards, and Atanga 2006)	558	1721	75
China			
Females (Taiwan)	about 600	1572 (53)	52 (7)
Males (Taiwan) (Wang, Wang, and Liu 2002)	about 600	1705 (59)	67 (9)
France			
Females	5510	1625 (71)	62 (12)
Males (IFTH and Goncalves, personal communication 2006)	3986	1756 (77)	77 (13)
Germany			
Female army applicants	301	1674	64
Male army applicants (Leyk, Kuechmeister, and Juergens 2006)	1036	1795	75
Great Britain			
Females	3870	1611	68
Males (Erens, Primatesta, and Prior 2001)	3233	1746	81
India			
Females	251	1523 (66)	50 (10)
Males (Chakarbarti 1997)	710	1650 (70)	57 (11)
East-Ctr. India male farm workers (Victor Nath and Verma 2002)	300	1638 (56)	57 (7)

(*Continued*)

Table 1.2 (Continued) Measured heights and weights of adults: Averages (standard deviations)

	Sample size	Stature (mm)	Weight (kg)
East India male farm workers (Yadav Tewari and Prasad 1997)	134	1621 (58)	54 (7)
South India male workers (Fernandez and Uppugonduri 1992)	128	1607 (60)	57 (5)
Iran			
Female students	74	1597 (58)	56 (10)
Male students (Mououdi 1997)	105	1725 (58)	66 (10)
Ireland			
Males (Gallwey and Fitzgibbon 1991)	164	1731 (58)	74 (9)
Italy			
Females	753[a]	1610 (64)	58 (8)
Females	386[b]	1611 (62)	58 (9)
Males	913[a]	1733 (71)	75 (10)
Males ([a]Coniglio et al. 1991) ([b]Robinette et al. 2002)	410[b]	1736 (67)	73 (11)
Japan			
Females	240	1584 (50)	54 (6)
Males (Kagimoto 1990)	248	1688 (55)	66 (8)
Netherlands			
Females (18–65 years old)	691	1679 (75)	73 (16)
Males (18–65 years old) (Robinette et al. 2002)	564	1813 (90)	84 (16)
Russia			
Female herders (ethnic Asians)	246	1588 (55)	nda
Female students (Russians)	207	1637 (57)	61 (8)
Female students (Uzbeks)	164	1578 (49)	56 (7)
Female factory workers (Russians)	205	1606 (53)	61 (8)
Female factory workers (Uzbeks)	301	1580 (54)	58 (9)
Male students (Russians)	166	1757 (56)	71 (9)
Male students (Uzbeks)	150	1700 (52)	65 (7)
Male factory workers (Russians)	192	1736 (61)	72 (10)
Male factory workers (ethnic mix)	150	1700 (59)	68 (8)

(*Continued*)

Table 1.2 (Continued) Measured heights and weights of adults: Averages (standard deviations)

	Sample size	Stature (mm)	Weight (kg)
Male farm mechanics (Asians)	520	1704 (58)	64 (8)
Male coal miners (Russians)	150	1801 (61)	nda
Male construction workers (Russians)	150	1707 (69)	nda
(Strokina and Pakhomova 1999)			
Saudi Arabia			
Males	1440	1675 (61)	nda
(Dairi 1986; cited by Al-Haboubi 1991)			
Singapore			
Males (Pilot trainees)	832	1685 (53)	nda
(Singh Peng Lim and Ong 1995)			
Sri Lanka			
Females	287	1523 (59)	nda
Males	435	1639 (63)	nda
(Abeysecera 1985; cited by Intaranont 1991)			
Thailand			
Females	250[a]	1512 (48)	nda
Females	711[b]	1540 (50)	nda
Males	250[a]	1607 (20)	nda
Males	1478[b]	1654 (59)	nda
([a]Intaranont 1991) ([b]NICE cited by Intaranont 1991)			
Turkey			
Male soldiers	5108	1702 (60)	63 (7)
(Kayis and Oezok 1991a)			
United States			
Females	~3800	1625	75
Males	~3800	1762	87
(Ogden et al. 2004)			
Midwest workers with shoes and light clothes			
Females	125	1637 (62)	65 (12)
Males	384	1778 (73)	84 (16)
(Marras and Kim 1993)			
Male miners	105	1803 (65)	89 (15)
(Kuenzi and Kennedy 1993)			

(*Continued*)

Table 1.2 (Continued) Measured heights and weights of adults: Averages (standard deviations)

	Sample size	Stature (mm)	Weight (kg)
U.S. Army soldiers			
Females (1989)	2208[a]	1629 (64)	62 (8)
Females (2014)	1986[c]	1626 (64)	67 (11)
Males (1989)	1774[a]	1756 (67)	76 (11)
Males (2009)	1475[b]	1760 (nda)	84 (nda)
Males (2014)	4082[c]	1755 (67)	85 (14)
([a]Gordon et al. 1989)			
([b]Gordon 2009)			
([c]Gordon et al. 2014)			
North American (Canada and U.S.)			
Females (18–26 years old)	1264	1640 (73)	69 (18)
Males (18–65 years old)	1127	1778 (79)	86 (18)
(Robinette et al. 2002)			
Vietnamese living in the United States			
Females	30	1559 (61)	49
Males	41	1646 (60)	59
(Imrhan, Nguyen, and Nguyen 1993)			

Source: Kroemer, K. H. E., Kroemer, H. J., and Kroemer-Elbert, K. E. *Engineering Physiology: Bases of Human Factors/Ergonomics*, fourth ed., Springer, Heidelberg, Germany, 2010. All sources except Gordon, Blackwell, Bradtmiller et al. 2014 are listed there.

Note: nda, no data available.

How to measure

The designer needs specific data: describing the size of the head for fitting helmets, for example, or showing reach distances for devising a proper workspace. As a rule, such information cannot be deduced from stature or weight but must be specifically measured. Selecting a representative sample of the group of interest, and performing the measurements on the persons, is usually a formidable task. The traditional technique was to take measurements with handheld devices, such as tapes, anthropometers, and gauges, and then to record the data. A newer technique uses automatic scanning and storing of the three-dimensional dimensions of the surface of the human body°; yet current information still relies predominantly on results of the hands-on approach. Figure 1.1 depicts 36 of the most commonly taken measurements, and Table 1.3 describes these measurements and their use° in anthropometry and design.

Russian and Chinese adults

Table 1.4 is an example of the results of such detailed measures taken on Russian students between 1984 and 1986. Table 1.5 gives anthropometric data measured on young Chinese adults in Taiwan between 1996 and 2000.

Compiling more information

There are compilations of data describing the body sizes of populations in Russia, France, Japan, the United Kingdom, the United States, and a few others; yet, unfortunately, similarly detailed information remains missing on most populaces, probably because it is so laborious and expensive to obtain. Thus, if we need information on other groups of people, we have to estimate the data or, better, do some measuring.

1.3 No "average person"

There is one serious problem with average data, such as those shown in Tables 1.1, 1.2, 1.4, and 1.5. We may not design a glove or a workplace for the average person because that is just a statistical artifact: if we tried to design for that phantom, the resulting glove or workplace would be too small for half the people, while too big for the others. Instead, it is necessary to consider specific users, for example, very big and tall people, so that they can fit into an airplane seat, or we must pay particular attention to small people, such as to make sure that they can reach items stored on a high shelf. If doorways were fixed to suit people of average height, many persons passing through them would strike the lintels with their heads.

The "normal" distribution

To avoid headaches, we need a bit of advice about the statistics° that describe the distributions of anthropometric measurements and, then, to compile them into tables. Figure 1.2 depicts a typical collection of anthropometric measurements, the stature of a group of men. Statisticians call this symmetric bell-shaped curve *normal* (or Gaussian): the data cluster in the middle, and the farther away from the center, the fewer data points exist.

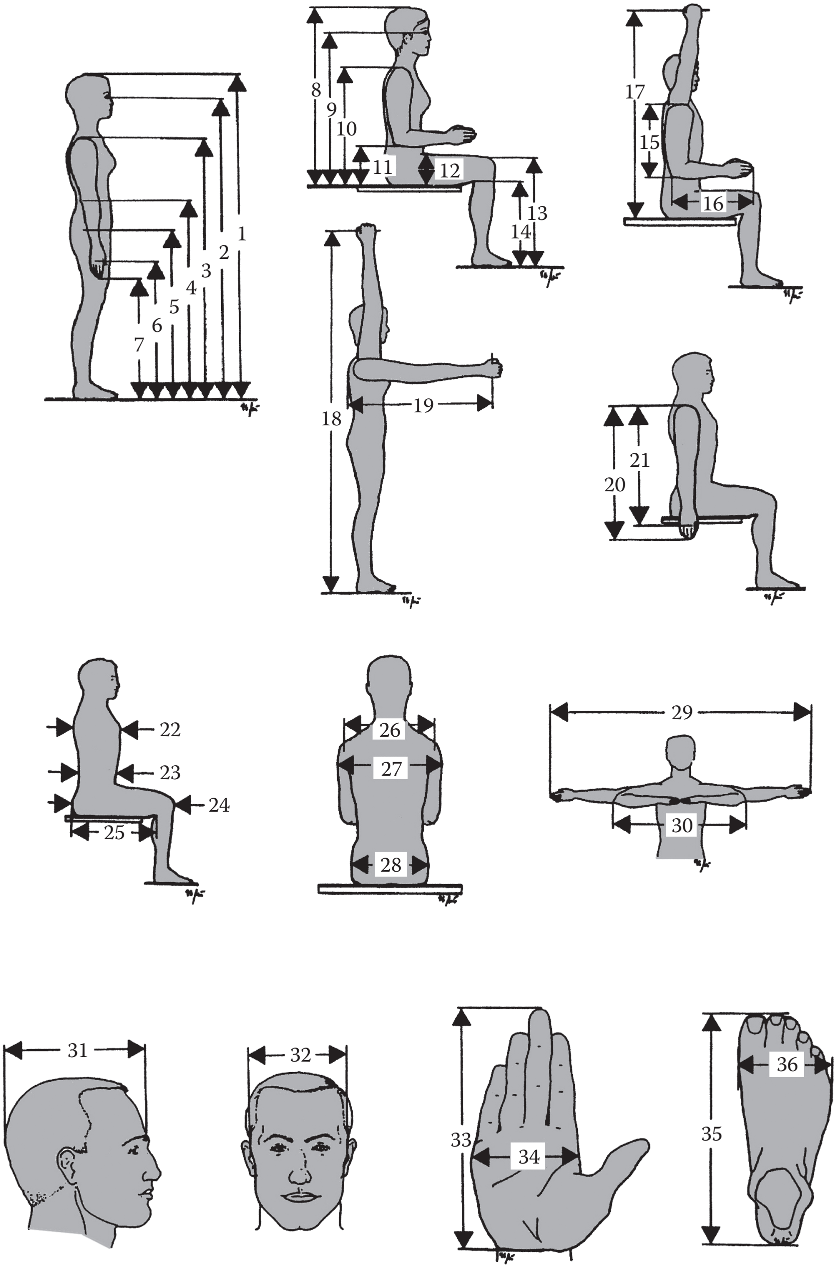

FIGURE 1.1 Illustrations of commonly measured body dimensions. (Adapted from Kroemer, K. H. E., Kroemer, H. J., and Kroemer-Elbert, K. E., *Engineering Physiology: Bases of Human Factors/Ergonomics*, fourth ed., Springer, Heidelberg, 2010.)

Table 1.3 Descriptions of common body measures and their applications

Dimensions	Applications
1. Stature The vertical distance from the floor to the top of the head, when standing	A main measure for comparing population samples. Reference for the minimal height of overhead obstructions. Add height for more clearance, hat, shoes, stride.
2. Eye height, standing The vertical distance from the floor to the outer corner of the right eye, when standing	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.
3. Shoulder height (acromion), standing The vertical distance from the floor to the tip (acromion) of the right shoulder, when standing	Starting point for arm length measurements; near the center of rotation of the upper arm. Reference point for hand reaches; consider slump and motion.
4. Elbow height, standing The vertical distance from the floor to the lowest point of the right elbow, when standing, with the elbow flexed at 90°	Reference for height and distance of the work area of the hand and the location of controls and fixtures; consider slump and motion.
5. Hip height (trochanter), standing The vertical distance from the floor to the trochanter landmark on the upper side of the right thigh, when standing	Traditional anthropometric measure, indicator of the leg length and the height of the hip joint. Used for comparing population samples.
6. Knuckle height, standing The vertical distance from the floor to the knuckle (metacarpal bone) of the middle finger of the right hand, when standing	Reference for low locations of controls, handles, and handrails; consider slump and motion of the standing person.
7. Fingertip height, standing The vertical distance from the floor to the tip of the extended index finger of the right hand, when standing	Reference for the lowest location of controls, handles, and handrails; consider slump and motion of the standing person.
8. Sitting height The vertical distance from the sitting surface to the top of the head, when sitting	Reference for the minimal height of overhead obstructions. Add height for more clearance, hat, and trunk motion of the seated person.
9. Sitting eye height The vertical distance from the sitting surface to the outer corner of the right eye, when sitting	Origin of the visual field of a seated person. Reference point for the location of visual obstructions and of targets such as displays; consider slump and motion.
10. Sitting shoulder height (acromion) The vertical distance from the sitting surface to the tip (acromion) of the shoulder, when sitting	Starting point for arm length measurements; near the center of rotation of the upper arm. Reference for hand reaches; consider slump and motion.

(*Continued*)

Table 1.3 (Continued) Descriptions of common body measures and their applications

Dimensions	Applications
11. Sitting elbow height The vertical distance from the sitting surface to the lowest point of the right elbow, when sitting, with the elbow flexed at 90°	Reference for the height of an armrest, of the work area of the hand and of keyboard and controls; consider slump and motion of the seated person.
12. Sitting thigh height (clearance) The vertical distance from the sitting surface to the highest point on the top of the horizontal right thigh, with the knee flexed at 90°	Reference for the minimal clearance needed between the seat pan and the underside of a structure, such as a table or desk; add clearance for clothing and motions.
13. Sitting knee height The vertical distance from the floor to the top of the right kneecap, when sitting, with the knees flexed at 90°	Traditional anthropometric measure for lower leg length. Reference for the minimal clearance needed below the underside of a structure, such as a table or desk; add height for shoe.
14. Sitting popliteal height The vertical distance from the floor to the underside of the thigh directly behind the right knee, when sitting with the knees flexed at 90°	Reference for the height of a seat; add height for shoe.
15. Shoulder–elbow length The vertical distance from the underside of the right elbow to the right acromion, with the elbow flexed at 90° and the upper arm hanging vertically	Traditional anthropometric measure for comparing population samples.
16. Elbow–fingertip length The distance from the back of the right elbow to the tip of the extended middle finger, with the elbow flexed at 90°	Traditional anthropometric measure. Reference for fingertip reach when moving the forearm in the elbow.
17. Overhead grip reach, sitting The vertical distance from the sitting surface to the center of a cylindrical rod firmly held in the palm of the right hand	Reference for the height of overhead controls operated by a seated person. Consider ease of motion, reach, and finger/hand/arm strength.
18. Overhead grip reach, standing The vertical distance from the standing surface to the center of a cylindrical rod firmly held in the palm of the right hand	Reference for the height of overhead controls operated by a standing person. Add shoe height. Consider ease of motion, reach, and finger/hand/arm strength.
19. Forward grip reach The horizontal distance from the back of the right shoulder blade to the center of a cylindrical rod firmly held in the palm of the right hand	Reference for forward reach distance. Consider ease of motion, reach, and finger/hand/arm strength.

(*Continued*)

Table 1.3 (Continued) Descriptions of common body measures and their applications

Dimensions	Applications
20. Arm length, vertical The vertical distance from the tip of the right middle finger to the right acromion, with the arm hanging vertically	A traditional measure for comparing population samples. Reference for the location of controls very low on the side of the operator. Consider ease of motion, reach, and finger/hand/arm strength.
21. Downward grip reach The vertical distance from the right acromion to the center of a cylindrical rod firmly held in the palm of the right hand, with the arm hanging vertically	Reference for the location of controls low on the side of the operator. Consider ease of motion, reach, and finger/hand/arm strength.
22. Chest depth The horizontal distance from the back to the right nipple	A traditional measure for comparing population samples. Reference for the clearance between the seat backrest and the location of obstructions in front of the trunk.
23. Abdominal depth, sitting The horizontal distance from the back to the most protruding point on the abdomen	A traditional measure for comparing population samples. Reference for the clearance between the seat backrest and the location of obstructions in front of the trunk.
24. Buttock–knee depth, sitting The horizontal distance from the back of the buttocks to the most protruding point on the right knee, when sitting with the knees flexed at 90°	Reference for the clearance between the seat backrest and the location of obstructions in front of the knees.
25. Buttock–popliteal depth, sitting The horizontal distance from the back of the buttocks to the back of the right knee just below the thigh, when sitting with the knees flexed at 90°	Reference for the depth of a seat.
26. Shoulder breadth (biacromial) The distance between the right and left acromions	A traditional measure for comparing population samples. Indicator of the distance between the centers of rotation of the two upper arms.
27. Shoulder breadth (bideltoid) The maximal horizontal breadth across the shoulders between the lateral margins of the right and left deltoid muscles	Reference for the lateral clearance required at shoulder level. Add space for ease of motion and tool use.
28. Hip breadth, sitting The maximal horizontal breadth across the hips or the thighs, whatever is greater, when sitting	Reference for seat width. Add space for clothing and ease of motion.

(*Continued*)

Table 1.3 (Continued) Descriptions of common body measures and their applications

Dimensions	Applications
29. Span The distance between the tips of the middle fingers of the horizontally outstretched arms and hands	A traditional measure for comparing population samples. Reference for sideway reach.
30. Elbow span The distance between the tips of the elbows of the horizontally outstretched upper arms when the elbows are flexed so that the fingertips of the hands meet in front of the trunk	Reference for the lateral space needed at upper body level for ease of motion and tool use.
31. Head length The distance from the glabella (between the browridges) to the most rearward protrusion (the occiput) on the back, in the middle of the skull	A traditional measure for comparing population samples. Reference for headgear size.
32. Head breadth The maximal horizontal breadth of the head above the attachment of the ears	A traditional measure for comparing population samples. Reference for headgear size.
33. Hand length The length of the right hand between the crease of the wrist and the tip of the middle finger, with the hand flat	A traditional measure for comparing population samples. Reference for hand tool and gear size. Consider manipulations, gloves, tool use.
34. Hand breadth The breadth of the right hand across the knuckles of the four fingers	A traditional measure for comparing population samples. Reference for hand tool and gear size and for the opening through which a hand may fit. Consider manipulations, gloves, tool use.
35. Foot length The maximal length of the right foot, when standing	A traditional measure for comparing population samples. Reference for shoe and pedal size.
36. Foot breadth The maximal breadth of the right foot, at right angle to the long axis of the foot, when standing	A traditional measure for comparing population samples. Reference for shoe size and spacing of pedals.
37. Weight (kg) Nude body weight taken to the nearest tenth of a kilogram	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.

Source: Kroemer, K. H. E., *"Extra-Ordinary" Ergonomics: How to Accommodate Small and Big persons, the Disabled and Elderly, Expectant Mothers and Children*. Boca Raton, Florida, CRC, 2006c.

Table 1.4 Body size measures (mm) taken between 1984 and 1986 on Russian and Uzbek students 18–22 years of age

Dimension	Men				Women			
	5th percentile	Mean	95th percentile	SD	5th percentile	Mean	95th percentile	SD
1. Stature								
Ethnic Russians (Moscow)	1664	1757	1849	56	1542	1637	1731	57
Uzbeks (Tashkent)	1615	1700	1786	52	1498	1578	1658	49
2. Eye height, standing								
Ethnic Russians (Moscow)	1547	1637	1728	55	1433	1526	1618	57
Uzbeks (Tashkent)	1496	1581	1665	51	1387	1463	1538	46
3. Shoulder height (acromion), standing								
Ethnic Russians (Moscow)	1351	1440	1529	54	1245	1334	1422	54
Uzbeks (Tashkent)	1313	1391	1469	48	1217	1284	1371	47
4. Elbow height, standing								
Ethnic Russians (Moscow)	1004	1083	1162	48	941	1010	1080	42
Uzbeks (Tashkent)	985	1042	1099	35	909	970	1031	37
5. Hip height (trochanter)	nda	nda	nda	nda	nda	nda	nda	nda
6. Knuckle height, standing								
Ethnic Russians (Moscow)	710	773	836	39	676	731	786	34
Uzbeks (Tashkent)	676	734	792	35	632	687	742	33
7. Fingertip height, standing								
Ethnic Russians (Moscow)	508	668	729	37	582	635	687	32
Uzbeks (Tashkent)	579	635	691	34	546	599	652	32

(*Continued*)

Table 1.4 (Continued) Body size measures (mm) taken between 1984 and 1986 on Russian and Uzbek students 18–22 years of age

Dimension	Men				Women			
	5th percentile	Mean	95th percentile	SD	5th percentile	Mean	95th percentile	SD
8. Sitting height								
Ethnic Russians (Moscow)	860	912	964	32	806	859	911	32
Uzbeks (Tashkent)	858	905	952	29	793	839	885	28
9. Sitting eye height								
Ethnic Russians (Moscow)	737	790	844	33	694	742	790	29
Uzbeks (Tashkent)	737	784	830	28	676	723	771	29
10. Sitting shoulder height (acromion)	nda	nda	nda	nda	nda	nda	nda	nda
11. Sitting elbow height								
Ethnic Russians (Moscow)	202	243	284	25	196	236	275	24
Uzbeks (Tashkent)	186	229	272	26	191	229	267	23
12. Sitting thigh height (clearance)								
Ethnic Russians (Moscow)	122	151	179	18	126	148	172	14
Uzbeks (Tashkent)	120	143	165	14	114	142	170	17
13. Sitting knee height								
Ethnic Russians (Moscow)	520	562	603	25	487	527	567	24
Uzbeks (Tashkent)	494	531	569	23	446	487	528	25
14. Sitting popliteal height								
Ethnic Russians (Moscow)	429	468	508	24	386	423	461	23
Uzbeks (Tashkent)	400	430	460	18	366	398	430	20

(*Continued*)

Table 1.4 (Continued) Body size measures (mm) taken between 1984 and 1986 on Russian and Uzbek students 18–22 years of age

Dimension	Men				Women			
	5th percentile	Mean	95th percentile	SD	5th percentile	Mean	95th percentile	SD
15. Shoulder-elbow length	nda	nda	nda	nda	nda	nda	nda	nda
16. Elbow-fingertip length	nda	nda	nda	nda	nda	nda	nda	nda
17. Overhead grip reach, sitting								
Ethnic Russians (Moscow)	1199	1276	1354	47	1094	1169	1244	46
Uzbeks (Tashkent)	1193	1256	1319	38	1085	1152	1219	41
18. Overhead grip reach, standing	nda	nda	nda	nda	nda	nda	nda	nda
19. Forward grip reach								
Ethnic Russians (Moscow)	697	759	821	38	641	702	763	37
Uzbeks (Tashkent)	686	745	803	36	609	673	737	39
20. Arm length, vertical	nda	nda	nda	nda	nda	nda	nda	nda
21. Downward grip reach	nda	nda	nda	nda	nda	nda	nda	nda
22. Chest depth								
Ethnic Russians (Moscow)	207	245	312	20	209	242	256	21
Uzbeks (Tashkent)	211	244	276	20	200	233	265	20
23. Abdominal depth, sitting	nda	nda	nda	nda	nda	nda	nda	nda
24. Buttock-knee depth, sitting								
Ethnic Russians (Moscow)	561	610	660	30	536	584	631	29
Uzbeks (Tashkent)	541	595	648	33	515	564	612	30
25. Buttock-popliteal depth, sitting								
Ethnic Russians (Moscow)	476	517	557	25	446	496	540	29

(*Continued*)

Table 1.4 (Continued) Body size measures (mm) taken between 1984 and 1986 on Russian and Uzbek students 18–22 years of age

Dimension	Men				Women			
	5th percentile	Mean	95th percentile	SD	5th percentile	Mean	95th percentile	SD
Uzbeks (Tashkent)	459	504	550	28	423	472	520	29
26. Shoulder breadth (biacromial)								
Ethnic Russians (Moscow)	369	397	425	17	334	360	386	16
Uzbeks (Tashkent)	349	377	404	17	320	347	373	16
27. Shoulder breadth (bideltoid)								
Ethnic Russians (Moscow)	416	458	492	23	377	412	446	21
Uzbeks (Tashkent)	409	438	466	17	352	381	410	17
28. Hip breadth, sitting								
Ethnic Russians (Moscow)	323	362	410	23	334	372	411	23
Uzbeks (Tashkent)	316	349	381	20	329	364	399	21
29. Span								
Ethnic Russians (Moscow)	1671	1782	1893	68	1516	1640	1763	75
Uzbeks (Tashkent)	1640	1747	1855	66	1461	1579	1698	72
30. Elbow span								
Ethnic Russians (Moscow)	874	935	995	37	808	870	933	38
Uzbeks (Tashkent)	842	909	976	41	781	837	894	34
31. Head length	nda	nda	nda	nda	nda	nda	nda	nda
32. Head breadth	nda	nda	nda	nda	nda	nda	nda	nda
33. Hand length								
Ethnic Russians (Moscow)	174	188	202	9	155	168	182	8

(*Continued*)

Table 1.4 (Continued) Body size measures (mm) taken between 1984 and 1986 on Russian and Uzbek students 18–22 years of age

	Men				Women			
Dimension	5th percentile	Mean	95th percentile	SD	5th percentile	Mean	95th percentile	SD
Uzbeks (Tashkent)	175	188	201	8	nda	nda	nda	nda
34. Hand breadth								
Ethnic Russians (Moscow)	80	87	95	5	71	76	82	3
Uzbeks (Tashkent)	82	89	96	4	73	79	87	4
35. Foot length								
Ethnic Russians (Moscow)	247	266	286	12	222	239	256	11
Uzbeks (Tashkent)	242	260	279	11	220	237	254	10
36. Foot breadth								
Ethnic Russians (Moscow)	87	97	107	6	82	88	95	4
Uzbeks (Tashkent)	85	96	107	7	81	90	98	5
37. Weight (kg)								
Ethnic Russians (Moscow)	57	71	85	9	49	60	73	7
Uzbeks (Tashkent)	53	65	76	7	45	56	68	7

Source: Strokina, A. N., and Pakhomova, B. A., *Anthropo-ergonomic Atlas*, Moscow State University Publishing House, Moscow, Russia, 1999.

Note: The measured sample consisted of 166 male and 207 female Russians from Moscow and 150 male and 164 female Uzbeks from Tashkent. nda, no data available.

Table 1.5 Body size measures (mm) taken between 1996 and 2000 on nearly 1200 Chinese adults in Taiwan, 25–34 years of age

Dimension	Men				Women			
	5th percentile	Mean	95th percentile	SD	5th percentile	Mean	95th percentile	SD
1. Stature	1608	1705	1801	59	1485	1572	1659	53
2. Eye height, standing	nda	nda	nda	nda	nda	nda	nda	nda
3. Shoulder height (acromion), standing	1309	1396	1484	53	1204	1285	1367	50
4. Elbow height, standing	993	1059	1126	40	915	978	1040	38
5. Hip height (trochanter)	780	860	939	48	735	802	869	41
6. Knuckle height, standing	705	757	809	32	653	708	762	33
7. Fingertip height, standing	610	659	708	30	566	618	670	32
8. Sitting height	861	910	959	30	794	846	898	32
9. Sitting eye height	742	791	839	29	681	732	783	31
10. Sitting shoulder height (acromion)	560	602	645	26	516	561	605	27
11. Sitting elbow height	226	264	303	24	211	252	294	25
12. Sitting thigh height (clearance)	nda	nda	nda	nda	nda	nda	nda	nda
13. Sitting knee height	474	521	569	29	431	471	510	24
14. Sitting popliteal height	380	411	442	19	350	379	408	18
15. Shoulder-elbow length	308	338	369	19	280	309	339	18
16. Elbow-fingertip length	382	427	472	27	339	384	429	27
17. Overhead grip reach, sitting	1128	1208	1289	49	1033	1105	1177	44
18. Overhead grip reach, standing	1872	2002	2133	79	1721	1831	1942	67
19. Forward grip reach	650	710	770	36	597	651	705	33
20. Arm length, vertical	684	738	793	33	618	669	720	31

(Continued)

Table 1.5 (Continued) Body size measures (mm) taken between 1996 and 2000 on nearly 1200 Chinese adults in Taiwan, 25–34 years of age

Dimension	Men				Women			
	5th percentile	Mean	95th percentile	SD	5th percentile	Mean	95th percentile	SD
21. Downward grip reach	nda	nda	nda	nda	nda	nda	nda	nda
22. Chest depth	187	217	248	19	182	213	244	19
23. Abdominal depth, sitting	nda	nda	nda	nda	nda	nda	nda	nda
24. Buttock-knee depth, sitting	507	558	608	31	487	530	572	26
25. Buttock-popliteal depth, sitting	nda	nda	nda	nda	nda	nda	nda	nda
26. Shoulder breadth (biacromial)	323	369	415	28	282	324	366	25
27. Shoulder breadth (bideltoid)	422	460	499	23	367	406	445	24
28. Hip breadth, sitting	315	360	404	27	316	353	390	23
29. Span	1625	1738	1852	69	1469	1571	1672	62
30. Elbow span	820	894	968	45	737	801	866	39
31. Head length	185	197	209	7	176	187	198	6
32. Head breadth	154	167	181	8	146	161	175	9
33. Hand length	168	183	199	10	154	167	181	8
34. Hand breadth	77	86	94	5	68	75	82	4
35. Foot length	nda	nda	nda	nda	nda	nda	nda	nda
36. Foot breadth	nda	nda	nda	nda	nda	nda	nda	nda
37. Weight (kg)	53	67	81	9	40	52	64	7

Source: Wang, M. J. J., Wang, E. M. Y., and Lin, Y. C., *Anthropometric Data Book of the Chinese People in Taiwan*, The Ergomics Society of Taiwan, Hsinchu, Taiwan, 2002.

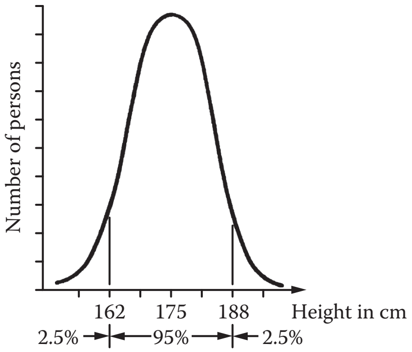

FIGURE 1.2 Typical distribution of anthropometric data.

Mean and average Such a normal distribution is easy to describe by two statistical values: one is the well-known *mean* (*m*), also often called the *average*. The other descriptor is the *standard deviation* (SD), a measure of the peakedness or the flatness of the distribution. (Note that these descriptors do not apply to nonnormal distributions, which require more involved statistical treatments. There is a bit more about this in Chapter 4, which concerns muscle strength data.)

Percentiles If we know the *m* and the SD, we can calculate the numerical value of any point, *percentile* (*p*), in a normal distribution. The fifth percentile is often of design interest: 5% of all data are smaller, 95% are larger. Obviously, the mean (average) is the same as the fiftieth percentile: half the data lie below; the other half, above. The fifth percentile, *p5* for short, is 1.65 SD below the mean; conversely, *p95* is 1.65 SD above *m*. Table 1.6 contains multiplication factors *k* needed to calculate various percentage points in a normal distribution.

Hand sizes For devising gloves, hand tools, or hand-operated controls, we need information about hand sizes. Figure 1.3 shows relevant measurements, and Table 1.7 contains available data. The table shows that for many groups of people, hand data are missing, so we must either measure or estimate the missing numbers.

Further advice Collections of anthropometric data provide a wealth of information to the skilled statistician, but laypersons, including engineers or designers, can use the data as well, for example, to calculate percentiles and cut-off values and to determine

Table 1.6 Values of factor *k* for computing percentiles (*p*) from mean (*m*) and standard deviation (*SD*)

	Percentile (*p*) located below the mean (*m*)	Percentile (*p*) located above the mean (*m*)
k	$p = m - k \times SD$	$p = m + k \times SD$
4.25	0.001	99.999
2.33	1	99
2.06	2	98
1.96	2.5	97.5
1.88	3	97
1.65	5	95
1.28	10	90
1.04	15	85
1.00	16.5	83.5
0.84	20	80
0.67	25	75
0	50	50

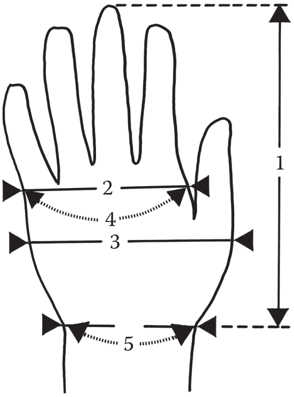

FIGURE 1.3 Common measurements of hand and wrist.

adjustment ranges of uniform or composite population groups. Another task is to estimate the data on groups of people, such as to fill in the vacant cells in Table 1.7. In doing so, it is advantageous to employ the advice given in books written for ergonomists and human factors engineers, listed at the end of the chapter under the section Further Reading.

Table 1.7 Hand and wrist sizes

Hand measures	Population	Men		Women	
		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	189	9	174	9
	Germans, soldiers 2006	191	nda	176	nda
	Japanese	nda	nda	nda	nda
	Russians, Moscow	188	9	168	8
	U.S. soldiers	193	10	180	10
	U.S. 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	88	5	78	4
	Japanese	nda	nda	90	5
	Russians, Moscow	87	5	76	3
	U.S. soldiers	88	4	78	4
	U.S. Vietnamese	79	7	71	4
3. Maximal breadth	British	105	5	92	5
	Chinese	nda	nda	nda	nda
	French	nda	nda	nda	nda
	Germans	107	6	94	6
	Japanese	nda	nda	nda	nda
	Russians	nda	nda	nda	nda
	U.S. soldiers	nda	nda	nda	nda
	U.S. 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
	U.S. soldiers	212	10	187	9
	U.S. Vietnamese	nda	nda	nda	nda

(*Continued*)

Table 1.7 (Continued) Hand and wrist sizes

Hand measures	Population	Men		Women	
		Mean	SD	Mean	SD
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
	U.S. soldiers	176	9	154	8
	U.S. Vietnamese	163	15	137	18

Source: Gordon, C. C., Blackwell, C. L., Bradtmiller, B., Parham, J. L., Barrientos, P., Paquette, S. P., Corner, B. D. et al., 2012 Anthropometric Survey of U.S. Army Personnel: Methods and Summary Statistics. Technical Report NATICK/TR-15/007, U.S. Army Natick Soldier Research, Development and Engineering Center, Natick, MA, 2014; *International Journal of Industrial Ergonomics*, 12, Imrhan, S. N., Nguyen, M. T., and Nguyen, N. N., Hand anthropometry of Americans of Vietnamese origin, 281–287, Copyright (1993), with permission from Elsevier; Kroemer, K. H. E., *Extra-Ordinary Ergonomics: How to Accommodate Small and Big Persons, the Disabled and Elderly, Expectant Mothers and Children*. CRC, Boca Raton, FL, 2006c; Leyk, D., Kuechmeister, G., and Juergen, H. W., *Journal of Physiological Anthropology* 25, 6, 363–369, 2006.

1.4 Designing to fit the body

People differ

Nearly every adult on Earth can fit into an airplane, or use common hand tools, if these products are sized well. Yet individuals within the species vary from each other; we need differently sized shoes to fit the individual feet. Even among seemingly similar groups, body sizes or body segment measurements can differ significantly. For example, in the United States, agricultural workers are, on average, 2.5 cm shorter 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 also heavier (males by 7 kg; females over 10 kg) than persons in all other occupations°.

Design principles

Before we begin to design a glove, a helmet, or other objects that must fit its user exactly, we must decide which range of relevant body sizes we want to accommodate. We have a choice among five approaches:

1. Custom-fit each individual: This is a laborious and expensive solution, justifiable in exceptional cases.
2. Have several fixed sizes: This can be a reasonable solution, but all sizes must be available and "between-sized" users may not be accommodated well.
3. Make it adjustable: This is usually the approach that provides the best fit to all people, but the adjustment features must be easy to use.
4. Design for the extreme body sizes: This is the appropriate solution when we must assure that everybody
    - Can operate a gadget, so locate an emergency stop button within the shortest reach; or
    - Can fit through an opening, so make a door or escape hatch wide enough for even the largest person; or
    - Cannot pass through an opening behind where danger lurks, so make railings or safety guards at machinery tight.
5. Select those persons whose bodies fit the existing design: This is the last and worst resort if we failed to achieve the fundamental principle of good design: all intended users should be able to employ our design effectively and efficiently.

Fit a range

Solutions 2 and 3 are the most common. For this, we need to determine the range of body sizes that we intend to accommodate with our design: we must set the lower and upper end points of the fit range. Often, we aim to fit all persons bigger than the smallest 5% and smaller than the biggest 5%; in other words, we are accommodating the central 90% of a group. In doing so, we knowingly exclude 10%, half of them very small and the others very big.

Select design limits

The design end points, the minimum and the maximum of the range to be fitted, depend on the design purpose and therefore must be selected carefully. We may decide to divide our designs into several sizes (solution 2), each appropriate for a subgroup of all users. This is a routine approach for ready-made clothing: clothes come assembled in size clusters. Within each range, adjustment features (solution 3) can provide further fitting: good examples are shoes with laces and seats of office chairs that can be raised and lowered.

Table 1.8 Guidelines for the conversion of standard measuring postures to functional stances and motions

To consider	Do this
Slumped standing or sitting	Deduct 5–10% from appropriate height measurements
Relaxed trunk	Add 5–10% to trunk circumferences and depths
Wearing shoes	Add approximately 25 mm to standing and sitting heights; more for high heels
Wearing light clothing	Add about 5% to appropriate dimensions
Wearing heavy clothing	Add 15% or more to appropriate dimensions. (Note that mobility may be strongly reduced by heavy clothing.)
Extended reaches	Add 10% or more for strong motions of the trunk
Use of hand tools	Center of handle is at about 40% of hand length, measured from the wrist
Comfortable seat height	Add to subtract up to 10% from the standard seat height

Source: Kroemer, K. H. E., *"Extra-Ordinary" Ergonomics: How to Accommodate Small and Big persons, the Disabled and Elderly, Expectant Mothers and Children*, CRC, Boca Raton, Florida, 2006c.

Statics and dynamics

The measures shown in Figures 1.1 and 1.2 and in Tables 1.1 through 1.4 are dimensions taken on the body while standing or sitting still. In reality, hardly anybody is stiffly static at work; we usually move about. To design for movement, the engineer needs to modify the static data. The recommendations in Table 1.8 can help accomplish this task.

Summary

Fitting equipment and tasks to persons of various body sizes requires (a) anthropometric data and (b) proper procedures. Data on many populations are available; missing information may be estimated or, better, measured following standard procedures. Design procedures often involve the selection of percentile values that serve as lower and upper limits of accommodation ranges.

Fitting steps

Step 1: Determine which body dimensions are important for your design.

Step 2: Decide on the range(s) to be fitted, on cut-off point(s).

Step 3: Design, then test. Modify as necessary.

Further reading

The literature contains the newest anthropometric information, usually published in journal articles or as research reports. Handbooks, encyclopedias, and standards are often a few years behind.

Bradtmiller, B. (2015) Anthropometry in human systems integration. Chapter 8 in Boehm-Davis, D. A., Francis, T. D., and Lee, J. D., eds., *APA Handbook of Human Systems Integration*. American Psychological Association, Washington, DC.

Gordon, C. C., Blackwell, C. L., Bradtmiller, B., Parham et al. (2014) 2012 Anthropometric Survey of U.S. Army Personnel, Methods and Summary Statistics. Technical Report Natick/TR-15/007. U.S. Army Natick Soldier Research. Development and Engineering Center, Natick, MA.

ISO 7250-1:2008 Basic human body measurements for technological design—Part 1: Body measurement definitions and landmarks. International Organization for Standardization, Geneva.

ISO 15535:2012 General requirements for establishing anthropometric databases. International Organization for Standardization, Geneva.

ISO 20685:2010 3-D scanning methodologies for internationally compatible anthropometric databases. International Organization for Standardization, Geneva.

Kroemer, K. H. E. (2008) Anthropometry and biomechanics: Anthromechanics. Chapter 2 in Kumar, S., ed., *Biomechanics in Ergonomics*, second ed. CRC, Boca Raton, FL.

Kroemer, K. H. E., Kroemer, H. J., and Kroemer-Elbert, K. E. (2010) *Engineering Physiology*, fourth ed. Springer, Heidelberg.

Marras, W. S., and Karwowski, K., eds. (2006) *The Occupational Ergonomics Handbook*, second ed. CRC, Boca Raton, FL.

Paquette, S., Gordon, C., and Bradtmiller, B. (2009) Anthropometric Survey (ANSUR) II Pilot Study: Methods and Summary Statistics. Technical Report Natick/TR-09/014. U.S. Army Natick Soldier Research, Development and Engineering Center, Natick, MA.

Notes

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

1.2 Measurements:

Techniques: Bradtmiller 2015; Gordon et al. 1989, 2014; Paquette, Gordon, and Bradtmiller 2009; Roebuck 1995.

Compilations of data: see, for example, Bradtmilller (2015) and Kroemer (2010).

Measurements and their use: ISO Standards 7250, 15535, 20685; Kroemer 2006c, 2010.

Statistics: Gordon et al. 2014; Marras and Karwowski 2006a,b; Paquette, Gordon, and Bradtmiller 2009; Pheasant and Haslegrave 2006 (Appendix); Roebuck 1995.

1.3 Designing to fit the body:

Differences among occupational groups: Hsiao, Long, and Snyder 2002.

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CHAPTER TWO

Mobility

Ancient experiences in agriculture, forestry, fishing, and other traditional work such as masonry and carpentry have taught people how to do the embedded tasks well. However, new tasks, tools, and workplaces in modern industry and commerce, in transportation on land, in water, air, and space must be laid out purposefully to suit the human body and mind. One foundation for human-centered designs is the insight that our body functions best in motion, not in a maintained static stance.

2.1 Work in motion

Made for motion

We are continually changing our body's configuration while we walk or sit, even when we sleep. If injury or disease imposes a fixed body position, circulatory and metabolic functions become impaired; people who must lie in place develop bedsores. Holding still is tiresome, almost impossible for just an hour. Apparently, the human body functions best in motion. Therefore, we should design our equipment and tasks for movement.

No static templates

However, it is convenient to measure the human body while it holds still in a defined upright static posture, standing or sitting, as Figure 1.1 in the first chapter of this book shows. Unfortunately, such artificial measuring stances as shown in Figure 2.1 became misleading templates for workstation layouts; these patterns not only created the false image of a static operator, but also gave the wrong impression that being stiff upright is desirable or healthy. People like to move, not to stay still; if left alone, they will sit any way they want, as sketched in Figure 2.2. Designing for movement° is not difficult, as we will see later in this chapter.

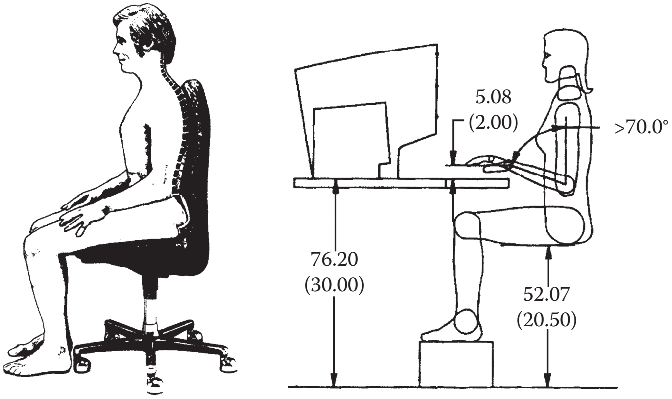


FIGURE 2.1 Unrealistic depictions, ca. 1980, of "orthopedically good" sitting of a computer operator at work.

FIGURE 2.2 People sit as they like. (Adapted from Kroemer, K. H. E., and Kroemer, A. D., *Office Ergonomics*, Korean edition, Kukje Publishing, Seoul, South Korea, 2006.)

Excessive motions

Of course, overdoing motions can lead to trouble. Highly repetitive movement requirements° have been associated with hand/wrist/arm problems since the early 1700s. Excessive demands on the limited motion capabilities of the spinal column can easily result in overloading, especially if torso twisting combines with bending; low back pain° seems to have been with humankind since the earliest times.

2.2 Body joints

Extensive leg and arm mobility

Legs provide us with powerful mobility: these long body members rotate about their articulations with the trunk at the hip joints, which provide a wide-ranging angular freedom°. Simpler angular motions occur in the knee joints. Foot angle changes in the ankles are small but important for balance and subtle actions. Our arms provide us with long reaches and our shoulders and elbow joints with extensive mobility. Thumbs and fingers are able to perform complex finely controlled motions in the articulations of wrist and digits.

Rotations in body joints

Hip and shoulder joints have a pan-like bone structure within which the knob-shaped proximal bones of the thigh and the upper arm can rotate. The technical analogy is a ball joint that can move about three axes of rotation (it has three "degrees of freedom" mobility): the upper leg and the arm can rotate (1) fore–aft as well as (2) left–right, and they can (3) twist. The knee and the elbow are simpler joints, having only one axis of rotation, and so the lower leg and the forearm can only swing forth and back in their hinge-type joints. The ankle articulation is another ball-joint type but with very limited excursions in the three axes.

Hand mobility

2.2.1 The hand The wrist gives the hand wide-ranging mobility, in three axes: bending up and down, left and right, and twisting. (To be exact, the ability to twist is actually within the forearm.) The 27 bones of the hand provide the solid structure; Figure 2.3 shows them and names their articulations. Whereas the main body of the hand is only slightly deformable among its 8 carpal bones, the attached five digits (one thumb and four fingers) provide great dexterity.

Hand digits

As Figure 2.3 shows, the five digits attach to the main body of the hand by their metacarpal bones in the carpal–metacarpal (CM) joints, which have two-axis mobility. The thumb is particularly mobile in its CM joint, but it has only two final segments (phalanges), whereas the four fingers each have three phalanges. The knuckles, metacarpal–phalangeal joints, provide two axes of mobility to the fingers, but their interphalangeal joints (proximal and distal) are simple one-axis hinges.

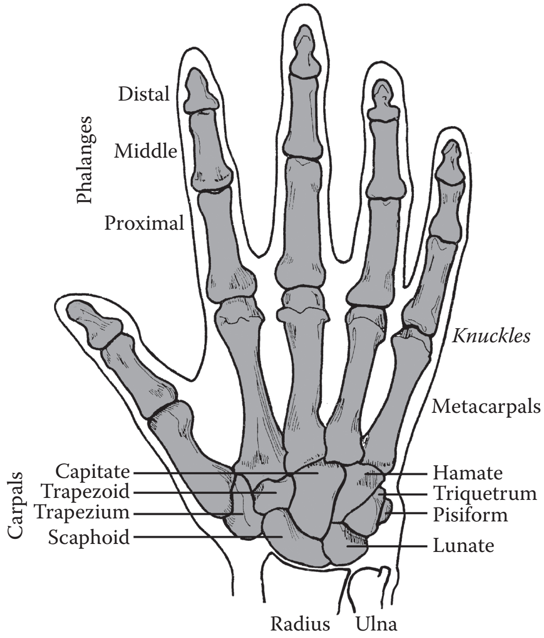


FIGURE 2.3 Bones and joints of the right hand, top view. (Adapted from Kroemer, K. H. E., and A. D. Kroemer, *Office Ergonomics*, London, Taylor & Francis, 2001.)

Movers of the hand

Some of the muscles that bend (flex) and straighten (extend) the hand are located within the hand. These intrinsic muscles control most of the finer details of manipulations. However, other muscles are in the forearm (away from the hand and therefore called *extrinsic*), from where they produce most of the powerful hand flexion and extension activities. Their contractile forces are transmitted to the hand by a pull on the tendons that cross the wrist. Figures 2.4 and 2.5 show the extensor tendons at the back of the hand and the flexor tendons on the palmar side. Sheaths encapsulate the tendons, keeping them in place while providing lubrication for their gliding.

Carpal tunnel

Because only limited space is available for the passage of the tendons at the wrist, bending this joint can create increased pressure between a tendon and its sheath. This usually does not affect the extensor tendons at the back of the hand but can be a problem for the flexors on the palm side—see Figure 2.6. A particularly critical region is the canal-like opening at the base of the hand formed by the carpal bones, covered and made into a tunnel by the strong transverse ligament.

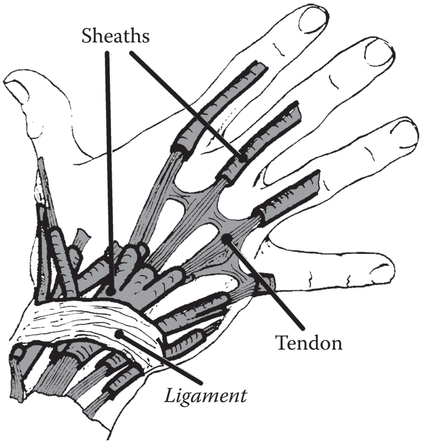


FIGURE 2.4 Digit extensor tendons straighten the digits of the hand. (Modified from Kroemer, K. H. E., and A. D. Kroemer, *Office Ergonomics*, London, Taylor & Francis, 2001; Putz-Anderson, V., *Cumulative Trauma Disorders*, Taylor & Francis, London, 1988.)

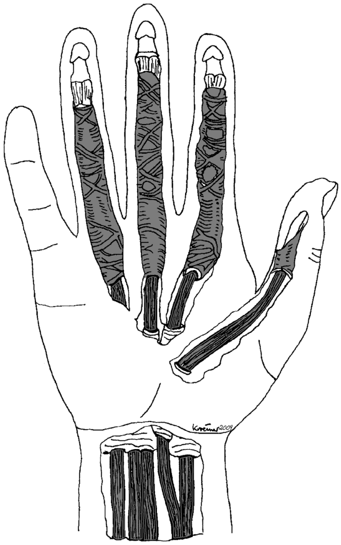


FIGURE 2.5 Digit flexor tendons bend the digits of the hand. (Adapted from Kroemer, K. H. E., Kroemer, H. J., and Kroemer-Elbert, K. E., *Engineering Physiology: Bases of Human Factors/Ergonomics*, fourth ed., Springer, Heidelberg, Germany, 2010.)

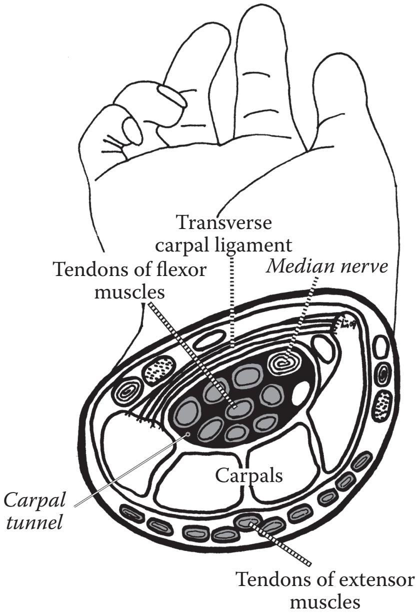


FIGURE 2.6 Cross section of the right hand, distal from the wrist. Carpal bones and the transverse carpal ligament form the carpal tunnel through which pass the digit flexor tendons and the median nerve. (Adapted from Kroemer, K. H. E., Kroemer, H. J., and Kroemer-Elbert, K. E., *Engineering Physiology: Bases of Human Factors/Ergonomics*, fourth ed., Springer, Heidelberg, Germany, 2010.)

Carpal tunnel syndrome

The nine tendons of the extrinsic muscles that flex the hand's digits must pass through this tight tunnel together with the median nerve and blood vessels. The median nerve is a cord about the size of a pencil containing thousands of nerve fibers supplying "feel" to the thumb, index, and middle fingers, and to a part of the ring finger. If swelling occurs in this tightly packed carpal tunnel (such as by inflammation that often results from highly repetitive digit actions, for example, on keyboards), the pressure increases. The resulting compression can make tendon movements difficult and painful and can also affect nervous feedback and control through the median nerve, causing the "carpal tunnel syndrome" often with temporary disability, possibly even permanent injury.

Tendon sheaths

The sheaths of the tendons have complex designs, depending on their locations and purposes. Besides providing lubrication to facilitate the gliding of the tendons, sheaths also supply

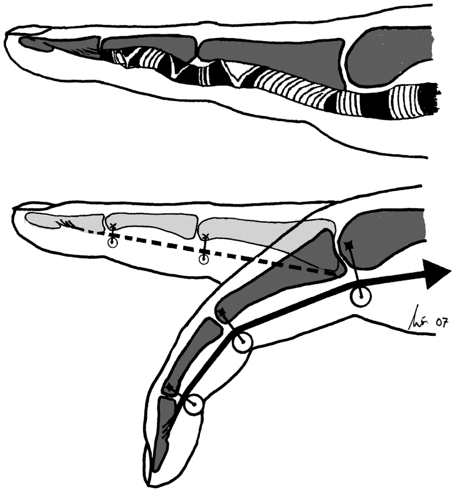


FIGURE 2.7 Ring-like and cruciform ligaments attachments keep the flexor tendon in place at the bones and allow it to bend the finger by pulling. (Adapted from Kroemer, K. H. E., Kroemer, H. J., and Kroemer-Elbert, K. E., *Engineering Physiology: Bases of Human Factors/Ergonomics*, fourth ed., Springer, Heidelberg, Germany, 2010.)

attachments to the bones and provide pulleys at which the tendons pull to articulate the sections of the digits against each other to flex or extend them, as sketched, much simplified, in Figure 2.7. The complex design of the hand with its multiple functions provides wide-ranging, forceful mobility with fine manipulative control.

2.2.2 The spine The spinal column supports the trunk and the head. It is essentially a stack of 24 bones, each called a *vertebra*, on top of the fused tailbone, the sacrum. The spine is the only solid structure in the human rump that keeps the rib cage from falling into the pelvis. It supports the whole mass of the upper body. Weights carried in the hands, on the shoulders, or in the belly of a fat person increase the load on the spinal column: compression, bending, twisting. When seen from the front or the back, the healthy spinal column is essentially straight, but when viewed from the side, it is bent in a series of flat curves, as sketched in Figure 2.8. At the neck is a forward bend, called a *lordosis*; at chest height, the curvature points backward, called a *kyphosis*; below, in the lumbar region, is another lordosis.

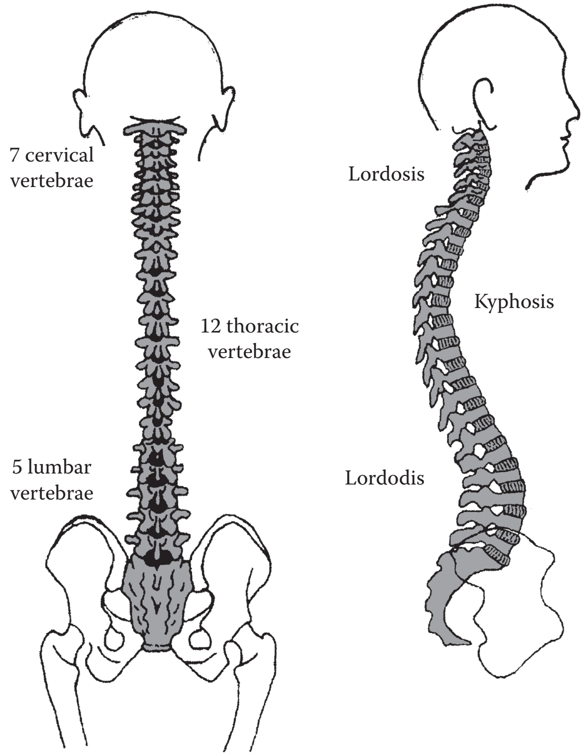


FIGURE 2.8 Curvature of the spinal column.

Spine mobility

The joints and the motion capabilities of the spinal column are quite different from the hands. The main body of each spinal vertebra sits on top of an intervertebral disk, a tough cushion enclosed by a strong fibrous ring. The disk, filled with a viscous fluid, is an elastic pad that absorbs shocks and allows the vertebrae above and below to make small changes in their angles of tilt against each other. However, the small angular displacements add up over the stack of vertebrae and disks, providing the whole spinal column considerable capabilities of twisting and of bending, fore–aft and left–right. Figure 2.9 shows, schematically, a disk between the main bodies of two adjacent vertebrae. It also shows the spinous processes of the vertebrae and the spinal cord with its emanating extensions, often called *nerve roots*.

Spinal vertebra

Figure 2.10 is a perspective sketch of a vertebra: behind the main body is an opening, the vertebral foramen, which protects the spinal cord running up and down. That bony structure has

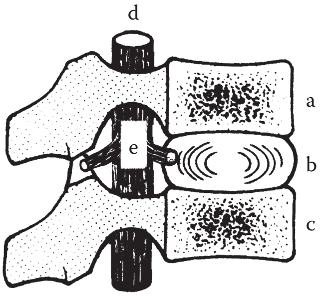


FIGURE 2.9 View, from the right, of the main bodies of (a, c) two vertebrae with a disk (b) between them; at the rear is the (d) spinal cord with (e) its nerve extensions.

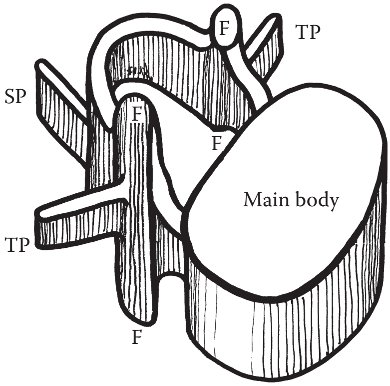


FIGURE 2.10 Basic structure of a vertebra.

three protrusions: the spinous process (SP) points backward and the two transverse processes (TP) point left and right. As Figure 2.11 shows, these protrusions act as lever arms for ligaments and muscles, which, attached to them, stabilize or bend the spinal column by their coordinated pulls.

Figure 2.12 depicts the five lumbar vertebrae (L1 through L5) atop the sacrum, seen from the right. Together with Figures 2.9 and 2.10, this schematic illustrates that each vertebra has six bearing surfaces with the vertebrae above and below: the two interfaces at the bottom and the top of the main body have cushioning disks; but there are no cushions at the facets (F in Figure 2.10), which provide four bony articulations at the two superior and two inferior surfaces. Thus, the design of the spinal joints provides complex yet limited mobility.

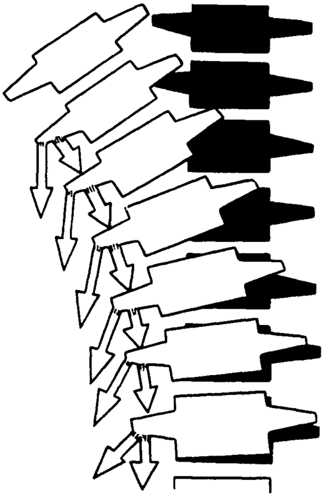


FIGURE 2.11 Pulls on vertebral processes make the vertebrae tilt. (Adapted from Kapandji, I. A. *The Physiology of the Joints*, Elsevier, Amsterdam, the Netherlands, 1988.)

Limited trunk flexibility

Even as only small displacements are possible between adjacent bones of the spine by the deformation of the intermediate disk, the head and the neck can twist and can bend, fore–aft and sideways, within fairly narrow limits, by using the upper section of the spinal column. The larger movements of the trunk, in bending as well as twisting, mostly occur in the lower parts of the spine, especially in the lumbar section. The ability of the spine to transmit large forces, mostly in compression, is remarkable. Yet overloading can cause damage, often to the spinal disks in the lumbar region°, which is frequently the location of discomfort, pain, and injury because it must transmit substantial forces and torques to and from the upper body. Low back pain is common, especially among people who handle loads—see Chapter 21.

Skeletal adjustments for pregnancy

In pregnant women, increasing bulk at the abdomen shifts the center of mass forward; to counteract this, the mother-to-be can lean back slightly, which curves the lumbar spine more. Increasing the lumbar curve can create complications: the vertebrae are more likely to slip against each other, which can cause back pain, even injury. The female spine° developed several features that help to prevent problems: in men, the curve in the lower back mainly includes two vertebrae, but it spans three vertebrae in women, which distributes the strain over a wider area. Furthermore, the facet joints are larger in women than in men, and the joints are

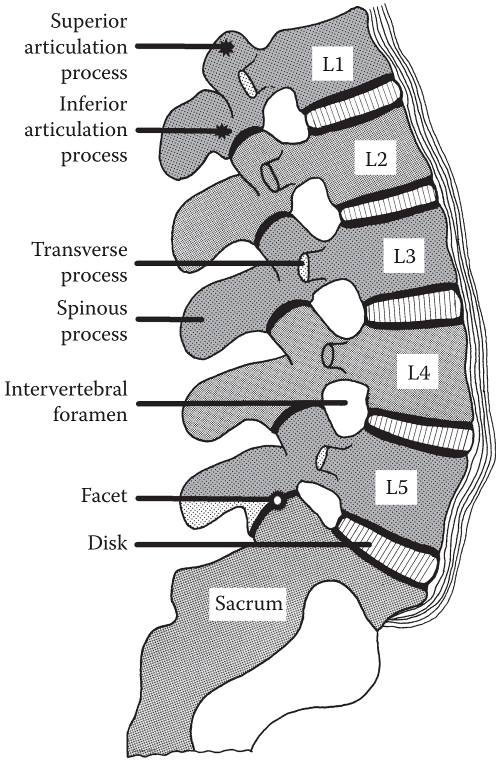


FIGURE 2.12 Lumbar section of the spine, with bearing surfaces drawn in heavy lines; seen from the right.

oriented at a slightly different angle, which makes them able to resist higher force and to better brace the vertebrae against slipping.

2.3 Designing for mobility

Given that we have so many ways to move, it is convenient to describe the rotations in each involved body articulation separately. Figure 2.13 illustrates body joint displacements and their traditional descriptions.

Actual mobility

As we move about, we usually combine movements in several body joints to generate the flexibility needed. Table 2.1 lists mobility measurements taken on physical education students, 100 females and 100 males. Most ordinary people are likely to be less flexible, but, of course, actual ranges of motion very much depend on health, fitness, training, skill, age, and any

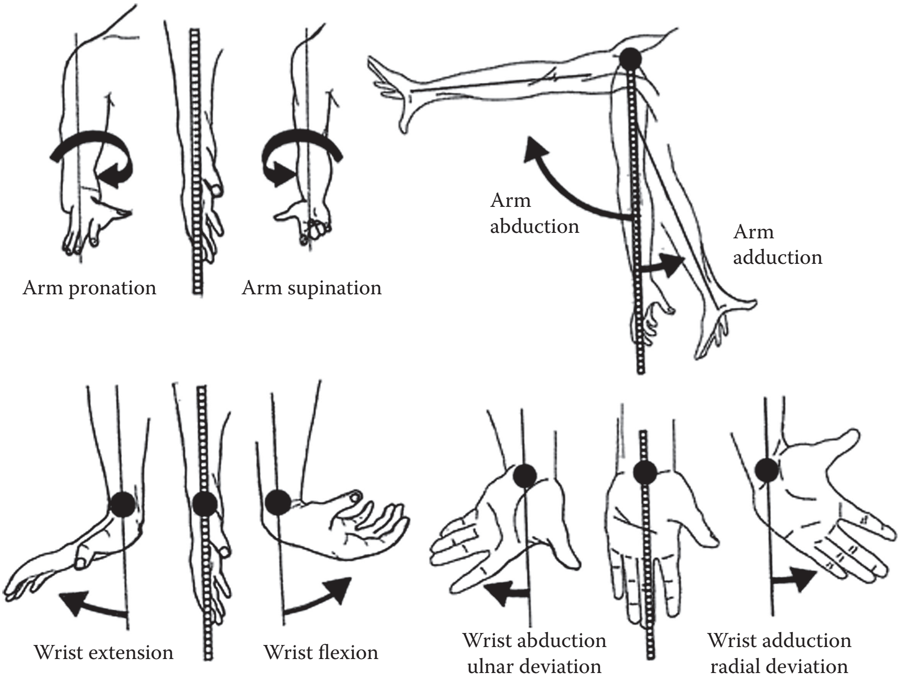


FIGURE 2.13 Arm and wrist displacements.

disability. Furthermore, dissimilar measuring techniques and instructions to the clients can cause great diversity in reported results of the mobility ranges of groups of people°.

2.4 Workspaces

In our everyday activities, at work or leisure, we like to move and walk about; changes in posture are essential for our well-being. Being forced to stand or sit (even lie) still for long periods is difficult to tolerate.

Preferred motions

Preferred motion ranges of the feet or the hands depend on habits and skills, on workplace layout and on dominant task requirements° such as strength, speed, accuracy, or vision. Clearly, there is not just one work envelope; rather, different people prefer to do different tasks in different workspaces.

Everyday motion ranges

Convenient mobility is somewhere within the overall motion range, such as is listed in Table 2.2, but is not always in the

Table 2.1 Comparison of mobility data (in degrees) for females and males

Joint	Movement	5th percentile		50th percentile		95th percentile		Difference[a] at 50th percentile
		Female	Male	Female	Male	Female	Male	
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	122.51	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

(*Continued*)

Table 2.1 (Continued) Comparison of mobility data (in degrees) for females and males

Joint	Movement	5th percentile		50th percentile		95th percentile		Difference[a] at 50th percentile
		Female	Male	Female	Male	Female	Male	
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

Source: Data from Houy, D. A. Range of joint motion in college males, pp. 374–378. In *Proceedings of the Human Factors Society 27th Annual Meeting*. Santa Monica, CA: Human Factors Society, 1983; Staff, K. R. A comparison of range of joint mobility in college females and males. Unpublished Master's Thesis. College Station, TX: Texas A&M University, 1983.

[a] Differences are listed only if significant ($\alpha < 0.5$). NS: Not significant.

Table 2.2 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°

Source: Kroemer, K. H. E., Kroemer, H. J., and Kroemer-Elbert, K. E., *Engineering Physiology: Bases of Human Factors/Ergonomics*, fourth ed., Springer, Heidelberg, Germany, 2010.

middle of the array; often, motions take place close to a joint's flexibility limits. For example, a person walking around on a job site or standing often has the hips and the knees almost fully extended, near 180°. However, when sitting on a chair, both angles cluster around 90°.

Who uses chairs?

However, in many parts of the Earth, working habits differ: for example, chairs are in wide use in the so-called Western countries such as in Europe, the Americas, and Australia/New Zealand. In other regions, persons often hover close to the ground, such as sketched in Figure 2.14. Furthermore, work

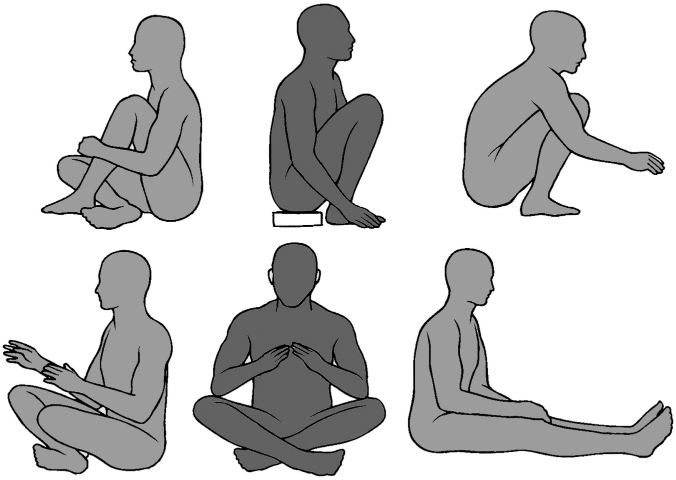


FIGURE 2.14 Non-Western work postures.

tasks may be quite different regionally and require special skills and motions. Unfortunately, few ergonomic recommendations for "non-western" conditions are at hand.

Reach envelopes

In general, preferred work areas of the hands and the feet are before the trunk of the body, within curved envelopes that reflect the mobility of the arms and the legs. Thus, it appears convenient to describe these reach envelopes for hands and feet as partial spheres around the temporary locations of body joints. In reality, however, several parts of the body may move at the same time, and force or vision requirements may establish specific constraints.

Hand workspace

The movement of the forearm in the elbow joint, often close to a 90° bend, combined with rotation in the shoulder, determines the envelope for fine manipulation and other light work; this is the shaded space in Figure 2.15. Elbow supports, as shown in Figure 2.16, may facilitate precision work. Full movements of

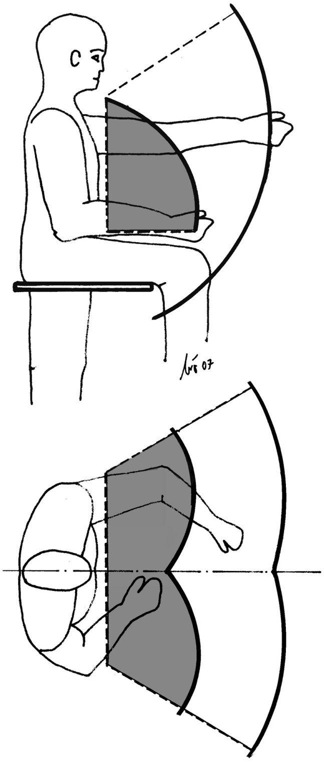


FIGURE 2.15 Workspace of the hands.

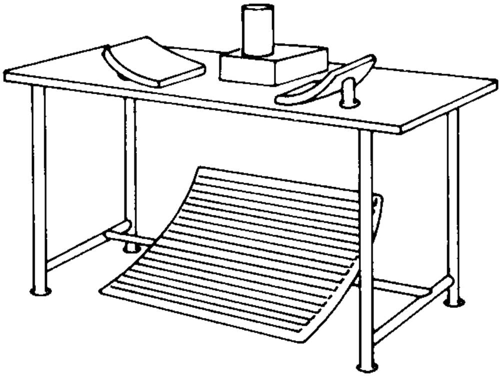


FIGURE 2.16 Workstation with support for the elbows and the feet.

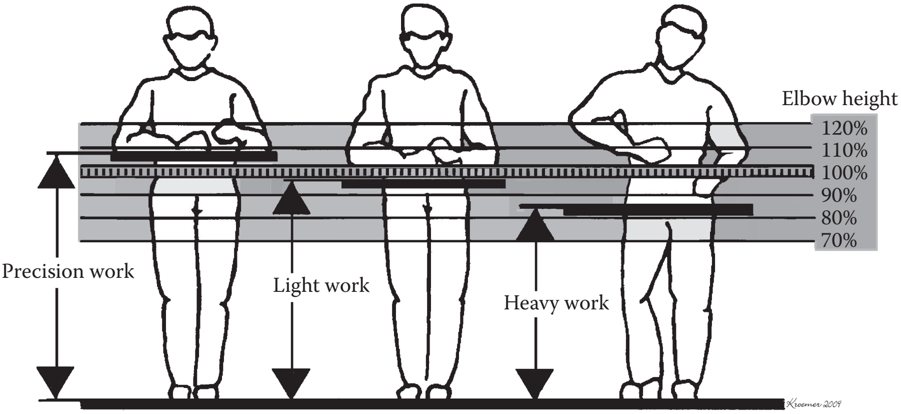


FIGURE 2.17 Height of work surfaces for handwork.

the upper arms and the forearms allow handwork from about the hip to well above the shoulder height in a wide space, mostly in front of the body. The main determinant of the proper height of the workspace is the height of the person's elbow, standing or seated; see Figure 2.17.

Easy foot actions

When a person sits, foot activities usually occur in a shallow area below the knees, shaded in Figure 2.18. The operator can cover this area with small displacements in knee and ankle joints, both usually near 90°. This is the best space for foot activities that require exertion of only small force and energy, usually by pushing down the whole foot, or just the heel or the toes.

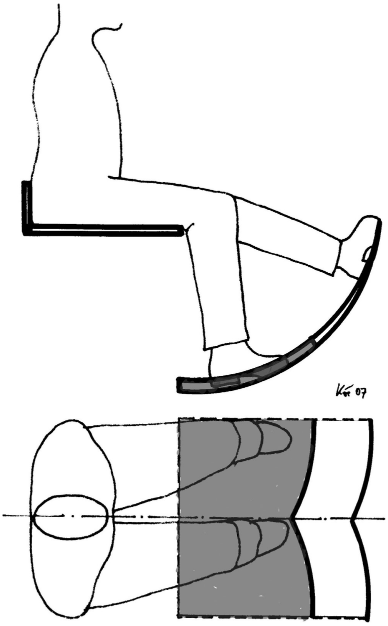


FIGURE 2.18 Workspace of the feet.

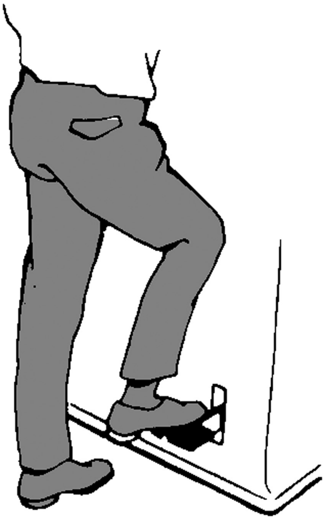


FIGURE 2.19 Forced to stand on one foot.

Strong foot push

In contrast, foot controls that demand substantial forward push force from the seated operator (such as the brake pedal in a vehicle) must be located higher and farther away so that the knee angle is around 150°–160°. However, the designer needs to pay attention to two facts: the almost fully extended leg does not allow for much displacement of the foot; furthermore, a strong backrest is necessary to counteract the pedal push.

No standing on one foot

A seated operator may operate pedals or other foot controls, even with both feet simultaneously, in a suitable workspace: a standing person obviously cannot use both feet at the same time, and even the use of only one foot would require balancing the whole body on the other foot; birds can stand on one foot for a long time, but humans cannot (Figure 2.19).

Summary

Humans cannot maintain any given body position over long periods: we need to move our bodies. Abolishing the idol of fixed postures and instead designing for suitable motion ranges is not difficult. Our bodies' articulations have known movement limits within which we prefer certain regions for tasks that require strength exertion, fast motions, or exact and enduring work.

Fitting steps

Step 1: Determine which specific task must be done.

Step 2: Decide on how to do the work, with hand or foot, and where in the movement space.

Step 3: Design, then test. Modify as necessary.

Notes

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

2.1 Work in motion:

Design for movement: Delleman, Haslegrave, and Chaffin 2004; Freivalds 2011; Kroemer 2006c; Kroemer,

Kroemer, and Kroemer-Elbert 2003, 2010; Marras and Karwowski 2006a,b.

Repetitive movement requirements: Armstrong 2006; Arndt and Putz-Anderson 2006; Kroemer 2001; Violante, Armstrong, and Kilbom 2000; Walji 2007; Wright 1993.

Low back problems: Marras 2008; Snook 2000.

2.2 Body joints:

Articulations of the body: Chaffin, Andersson, and Martin 2006; Kapandji 1988; Oezkaya et al. 2012; Walji 2007.

The hand, carpal tunnel: Freivalds 2006, Hughes and An 2007; Kroemer 2008; Walji 2007.

The spine, low back problems: Deyo and Weinstein 2001; Marras 2008; Violante, Armstrong, and Kilbom 2000; Snook 2000.

Female and male spine features: Already present in *australopithecus* fossils: Whitcome, Shapiro, and Lieberman 2007.

2.3 Designing for mobility:

Diversity in mobility measurements: Wu et al. 2002; data on NASA astronauts at http://msis.jsc.nasa.gov/.

2.4 Work spaces:

Dominant strength, speed, accuracy or vision requirements: Kroemer, Kroemer, and Kroemer-Elbert 2003, 2010.

CHAPTER THREE

Muscular work

Muscles are our body's natural engines. A muscle attaches to a bone and then extends across one or two body joints to another bone. When contracting, the muscle pulls on the body's internal bone framework. That pull can change the angle between bones, setting body segments into motion or stabilizing their position.

Basic physics explain the relations between common strength measurements:

- Force (in Newton, *N*) divided by the transmitting cross-sectional area is *tension* (usually in N/mm^2) or, in the opposite direction, *compression* or *pressure*.
- Force multiplied by a lever arm is *moment* or *torque* (usually in *Nm*).
- The integral of force and distance traveled is *work*.
- Work divided by time is *power*.

Kinds of muscles

The human body has three kinds of muscle. Smooth muscle surrounds vessels, mostly as sphincters that control the opening of blood vessels. Cardiac muscle operates the heart. The smooth and cardiac muscles have characteristics that differ from those of the skeletal muscle°, which is the object of the following text.

3.1 Physiological basics

Muscle components

The human body has several hundred skeletal muscles, known by their Latin names; for example, the biceps (*musculus biceps brachii*) flexes the elbow by pulling the upper and lower arms

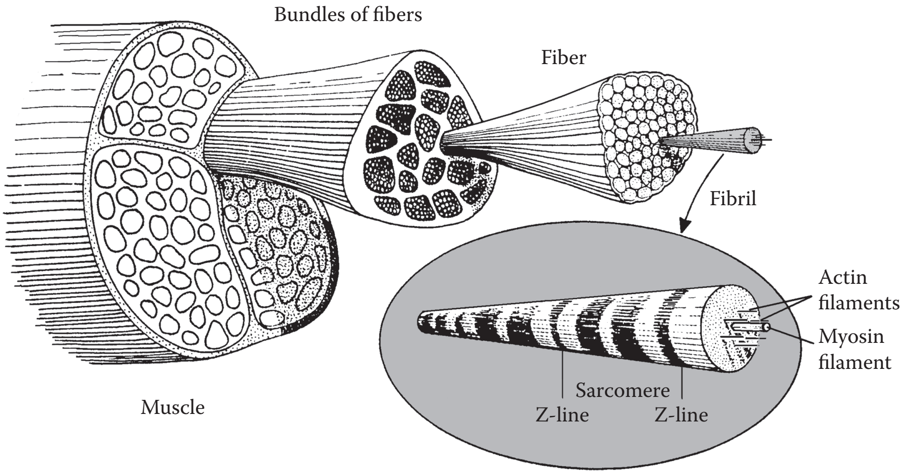


FIGURE 3.1 Basic structures of the skeletal muscle. (Adapted from Astrand, P. O., Rodahl, K., Dahl, H. A., and Stromme, S. B., *Textbook of Work Physiology*, fourth ed., Human Kinetics, Champaign, Illinois, 2003; Wilmore, J. H., Costill, D., and Kenney, W. L., *Physiology of Sport and Exercise*, fourth ed., Human Kinetics, Champaign, Illinois, 2008; Kroemer, K. H. E., Kroemer, H. J., and Kroemer-Elbert, K. E., *Engineering Physiology: Bases of Human Factors/Ergonomics*, fourth ed., Springer, Heidelberg, Germany, 2010.)

together. Every muscle consists of bundles of fibers as sketched in Figure 3.1. The tissue that embeds blood vessels and nerves wraps and permeates the muscle. At the muscle ends, the wrapping tissues combine to form tendons, which are like cables that extend to and attach to bones°.

Power to the muscle

Thousands of individual muscle fibers run in bundles, essentially parallel, along the length of the muscle. Inside the bundles are hundreds of mitochondria. They are the muscle's power factories, cells specialized to liberate chemically stored energy (in ATP, adenosine triphosphate, and CP, creatine phosphate°). That energy enables the muscle to contract. Blood supply is essential for muscle function because it supplies energy and oxygen and removes the by-products of metabolic processes (see Chapter 10) such as heat, water, and carbon dioxide. Nervous signals trigger the actions of the muscle and control their intensity.

Contractile microstructure

Contraction is the only active action that a muscle can take. Elongated protein molecules, side-by-side threadlike filaments, temporarily adhere to each other when triggered by nervous signals. One kind of filament, called *myosin*, has projections that protrude toward the surrounding type of filaments, called

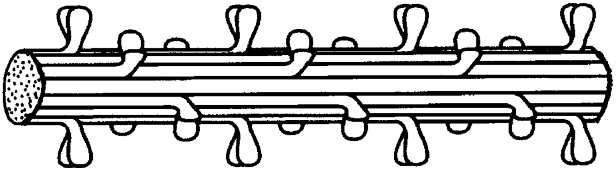


FIGURE 3.2 Diagram of the club-like myosin with its projections that can form cross-bridges with actin filaments. (Adapted from Herzog, W., Determinants of muscle strength, in Kumar, S., ed, *Biomechanics in Ergonomics*, second ed., CRC, Boca Raton, Florida, 2007.)

actin—see Figure 3.2. When the muscle is at rest, the projections remain relaxed and do not transmit forces between the actin and myosin filaments. However, when the muscle receives a signal to contract, the myosin's projections activate and attach to the adjacent actins (forming cross-bridges) and, in ratcheting motions, try to pull the actin rods along the myosin. If that pull is stronger than any opposing force, the ends of actin filaments slide. This shortens the sarcomere (see the following section) and hence shortens the muscle. If the pull is just as strong as an opposing force, the length of the muscle remains unchanged: this is called an *isometric contraction*. If the contraction pull is weak, then the muscle can become lengthened by the external force.

Sarcomere

The distance between adjacent z-lines is the sarcomere. (The letter *z* stands for the German *zwischen*, between.) At rest, the length of a sarcomere is approximately 250 Å. (Since 1 Å = 10^{-10} m, about 40,000 sarcomeres can lie in series within 1 mm of muscle fiber length.) In full contraction, the length of a sarcomere, and hence the length of a muscle, can shorten to about 60% of its resting length.

Striated skeletal muscle

This shortening (or stretching) of the muscle is visible under the microscope when we look at the z-lines. These lines appear as dark stripes that run across the muscle fibers where the fixed ends of the actin filaments connect. When a contraction shortens the muscle, the z-lines are pulled closer to each other. The striping, caused by the z-lines and by other bands crossing the skeletal muscle, provides its second name, striated (striped) muscle.

Strength of skeletal muscle

The larger the number of actin–myosin bundles that exist side by side in a muscle, the more strength it can exert. Hence, the strength of a muscle is proportional to its cross-sectional area.

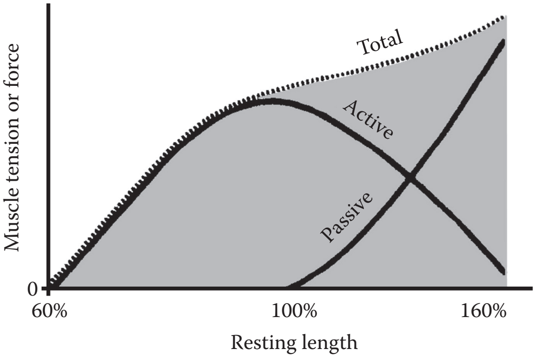


FIGURE 3.3 Active, passive, and combined tensions at different muscle lengths. (Adapted from Kroemer, K. H. E., Kroemer, H. J., and Kroemer-Elbert, K. E., *Engineering Physiology: Bases of Human Factors/Ergonomics*, fourth ed., Springer, Heidelberg, Germany, 2010.)

The muscle's contractile force is largest at about the resting length and decreases as the muscle shortens, as sketched in Figure 3.3.

Muscle tension

A strong force opposing the muscle contraction (such as due to gravity or stemming from the action of another muscle) can lengthen the muscle beyond its relaxed length. The farther the stretch, the more the muscle resists: the overall tension inside the muscle is the result of adding the active and passive tensions, as illustrated in Figure 3.3. That elongation can reach about 160% of the resting length, from which point on structural damage occurs, eventually even breakage. By experience, we use the "prestretch trick" of combining active and passive tensions to increase our muscular power; for example by moving the hand and the arm back behind the shoulder in order to throw an object forward with great force.

Muscle pull around the elbow

Muscles usually appear in pairs: one muscle turns a bone around an articulation in one direction while the other muscle turns the opposite way. The elbow provides a good example: here, the pull of the biceps muscle reduces the elbow angle while the triceps pull increases it, as illustrated in Figure 3.4. As the name *triceps* indicates, this muscle has three heads with three attachments: one reaches across the shoulder joint to the shoulder blade while the other two heads attach to the humerus (the long bone inside the upper arm). The biceps has two heads with two attachments.

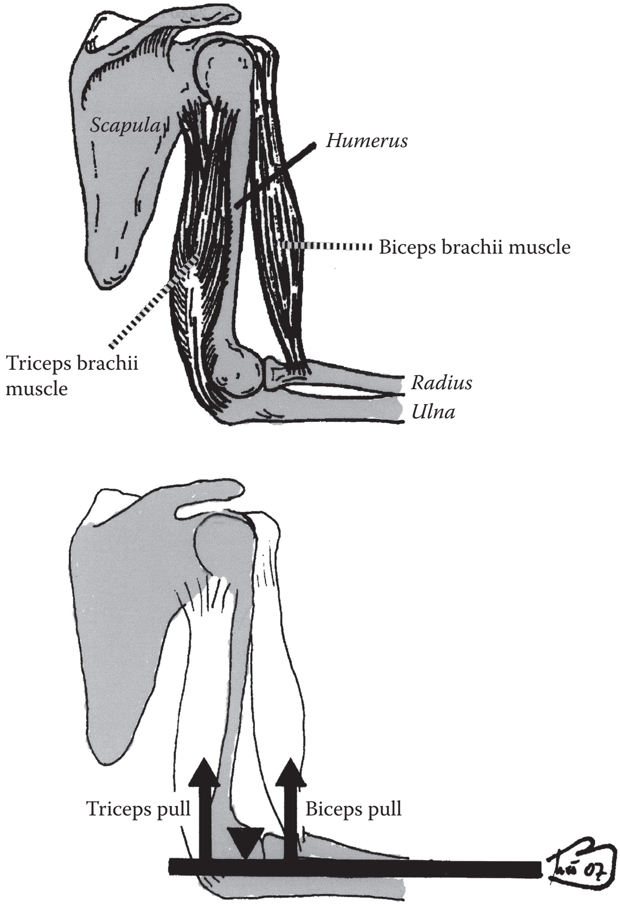


FIGURE 3.4 Triceps and biceps muscles control elbow extension and flexion. (Adapted from Kroemer, K. H. E., Kroemer, H. J., and Kroemer-Elbert, K. E., *Engineering Physiology: Bases of Human Factors/Ergonomics*, fourth ed., Springer, Heidelberg, Germany, 2010.)

Co-contraction

The seemingly simple muscle system around the elbow is actually quite complex, because two more muscles assist the biceps in reducing the elbow angle: the *m. brachialis*, connecting the bones of the upper arm (humerus) and of the forearm (ulna), and the *m. brachioradialis*, linking the humerus to the radius. When muscles simultaneously contract to pull in the same direction, their combined effort obviously increases the overall force on the attached bone(s); however, the co-contraction of two opposing muscles (such as biceps and triceps) generates a coalition of forces that helps to control segment movement.

3.2 Dynamic and static efforts, strength tests

As already discussed in Chapter 2, the human body functions best in motion rather than when immobile. However, it is easier to assess certain traits of the body when it remains motionless in a defined position. Thus, on persons holding still, body sizes are simple to measure (see Chapter 1); likewise, it is relatively easy to assess the muscular strength when muscle lengths remain constant.

Contraction and motion

There is much interplay between the tension (force, energy, power) a muscle can develop and how it moves while contracting. The simplest case is *no motion*: while its myofilaments attempt to contract, the overall length of the muscle does not change (and the involved body segments stay in place). While physiologists call this condition *isometric*, to physicists, it is *static*. If the muscle succeeds in shortening its length, this case of active contraction is called *concentric*. Such shortening can occur only if the muscle is stronger than the resisting force. However, if the opposing force overwhelms the muscle while it attempts to contract, the muscle becomes lengthened. This condition is called *eccentric*. (This shows that the term *contraction* does not necessarily mean that the muscle shortens.)

Dynamics

Dynamic muscular efforts are more complicated to describe than static contractions, and they are more difficult to control in experiments. In dynamic activities, the muscle length changes, and therefore the involved body segments move. This results in displacement. The time derivatives (velocity, acceleration, and jerk) of displacement are of importance° both for the internal muscular effort and for its external effect: for example, change in velocity determines impact and force, as per Newton's second law.

Anthromechanics

The application of physics principles to biological events is called *biomechanics*; when applied to the human body, it is *anthromechanics*. The use of knowledge gained in overlapping traditional disciplines is typical for ergonomics/human factors engineering, as exemplified in this book.

Athletics and sports

We can measure muscle strength in different ways. One kind of assessment relies on measurements of athletic performance, common in sports events with their immense, often-explosive efforts, usually done in competition with other persons selected for their abilities and competitive spirits. The outcome is often scored in terms of records achieved, weights lifted, distances covered, and matches won. However, these experimental conditions are impossible to control and reproduce in the laboratory. Also, these performances have little bearing on everyday work requirements.

Work requirements

At work, extreme efforts are hardly ever required. Instead, moderate muscular labor is usually in demand throughout the working time, such as eight hours a day. These efforts are often intermittent, possibly often repeated during the work shift. Also, the persons doing such work commonly include individuals of different sizes and physical capabilities. So, for various reasons, the required muscular exertions are usually on a fairly low level so that all persons can do them over the duration of the work shift.

Controlled strength tests

To determine work-related muscular capabilities°, strength tests are routinely done in a controlled laboratory environment, where subjects are asked to perform specific exertions; this may be an elbow flexion where the biceps muscle is dominant, or a whole-body lift that involves many muscles. These tests follow carefully planned experimental protocols°. The peak force (or torque or moment) observed during the test performance, which usually lasts three to five seconds, is commonly taken as the strength measurement. While this laboratory approach does not reflect true work conditions, such as in industry or in agriculture, the controlled procedure allows standardization and provides expected test–retest reliability.

Testing muscle strength

The strength of a muscle can be measured objectively and reliably if removed from the body, as has been done with animal models. A less radical approach is to instrument an intact muscle, in situ, with electrodes, which pick up nervous excitation signals. Such EMG° tests have shown that the strength of exertion depends on the muscle length at which the exertion takes place. Figure 3.5 illustrates how active and passive tensions within the muscle change with its length. The actual length at which a muscle performs depends on the body posture at that instant; for example, the strength of elbow extension depends on the angle between the upper arm and the forearm, which determines the length of the triceps muscle. Of course, the actual strength capabilities of muscles basically depend on physiological factors°, such as size (thickness), shape (pennation), fiber composition (fast or slow), state of training, or fatigue.

Maximum voluntary contraction

Clearly, it is not permissible to measure the human muscle strength by forcing muscle fibers to perform a truly maximal effort, which is at a tension where damage might occur.

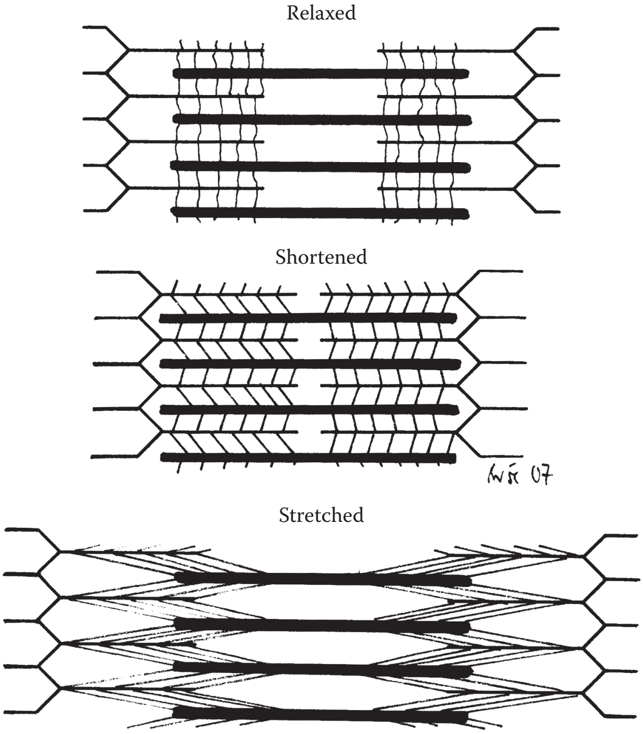


FIGURE 3.5 Patterns of a sarcomere when relaxed, shortened, and stretched. (Adapted from Kroemer, K. H. E., Kroemer, H. J., and Kroemer-Elbert, K. E., *Engineering Physiology: Bases of Human Factors/Ergonomics,* fourth ed., Springer, Heidelberg, Germany, 2010.)

Therefore, all traditional strength measures rely on subjects "giving their best effort"; the literature calls this maximum voluntary contraction (MVC). The subjects regularly receive the cautionary admonition not to hurt themselves in that test. This means that all maximal strength data reported in the literature depend on the subjects' motivation: their will to perform, in turn, depends on various physiological, psychological, and environmental conditions that exist at the moment of measurement.

Influencing test scores

The actual results of strength tests depend on many possible variables. These include age and gender of the subject; health and nutritional and hydration status; fitness, training, skill, and experience; rewards and possible drawbacks such as pain or injury; and, of course, the subjects willingness to participate and perform truly MVCs. Actions of the experimenters, such as instructions, encouragement, even feedback of results,

Table 3.1 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	–

Source: Kroemer, K. H. E., AMRL-TR-72-46: Designing for muscular strength of various populations, Aerospace Medical Research Laboratory, Wright-Patterson AFB, OH, 1974.

can easily influence the subjects' ego involvement and hence the test scores°. Table 3.1 lists conditions that may increase or decrease muscular performance.

Situational conditions

As just mentioned, muscle length, and hence muscle strength, depend on so-called situational variables°: one is obviously posture; another external body support. (More on situational variables in the next chapter.) For example, when you stand upright to exert a horizontal pull with one hand, that pull is weakest when you keep your feet side by side; the pull becomes stronger with one foot is placed forward, and it is strongest if you can grasp with the free hand an external structure that provides support. Another example is pushing with a foot on a pedal when we sit, such as when operating the brake in a vehicle: that push becomes strongest if we can extend the leg almost fully while we brace ourselves against the backrest of the seat.

Test instruments

Surprisingly, there exists no practical non-invasive technique for measuring the strength of a single muscle in the living human body. Instead, external gages are used which, as a rule, record the combined output of several muscles. Their designs and use practices generate a set of situational conditions that affect the strength test score. Most test instruments are of the static type, not of the dynamic sort: the handles of a grip strength tester or of other so-called dynamometers do not give appreciably while the test subject squeezes, pushes, or pulls. With no motion, muscular exertion is isometric. True dynamometers, which measure while muscle length changes, are much less common; most are expensive, complex, and difficult to use, and hence seldom employed. The only simple yet effectual means for dynamic measurements are objects of constant mass: moving an object, called *isoinertial* testing, supplies information on the ability to push and pull and lift and lower loads. Otherwise, there remains a general need for research on measuring dynamic strength exertions° realistically.

Muscle force, calculated

Within a muscle, filament contraction generates tension in longitudinal direction of the muscle fiber. 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. Estimates of muscle tensions range from 16 to 61 N/cm^2; an often used general value called *specific* (*skeletal muscle*) *tension* is 30 N/cm^2. So if the cross-section area is known (such as from magnetic resonance imaging scans or from cadaver measurements), one can calculate the approximate muscle force. Yet, this calculation relies on assumptions about cross-section and specific tension values.

3.3 Fatigue and recovery

Muscle fatigue° is a subjective experience signaling that one is becoming unable to continue or repeat a muscular effort. The onset of fatigue depends on the muscle fiber types involved in different kinds of muscular exertions, such as dynamic or static or sustained or brief. The underlying physiological reasons for fatigue are manifold: they include restriction of blood flow through the muscle tissue due to intramuscular pressure, depletion of energy sources available (especially ATP and CP; see Chapter 10) in the muscle, formation of lactic acid (a by-product of the energy conversion process), and other events caused by a foregoing muscular effort. These events impede especially the processes associated with the formation and the detachment of cross-bridges. Furthermore, so-called central fatigue may occur in the nervous control system, associated with one's sense of effort and motivation; however, often in competitive sports, a new emotional drive to perform can temporarily overcome muscular fatigue.

Fatigue ensues when an individual tries to exert a larger effort than she or he is capable of producing. The required exertion can be too large because of extreme magnitude, unwarranted duration, or an undue combination of amount and time.

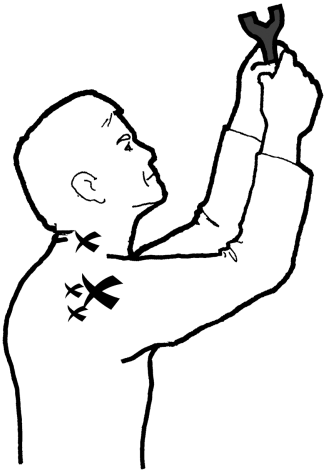


FIGURE 3.6 Fatiguing overhead work. (Adapted from Nordin, M., Andersson, G. B. J., and Pope, M. H., *Musculoskeletal Disorders in the Workplace: Principles and Practice*, Mosby, St. Louis, Missouri, 1997.)

The two variables interact with each other: the longer the effort, the smaller the possible amount of exertion, and vice versa. The limiting organ may not be one that does the actual task, but may be in an auxiliary subdivision of the body: a typical situation is working overhead, requiring the arms to extend upward to reach the work site, and the neck bent backward to see the work, as sketched in Figure 3.6. In this case, the shoulder muscles keeping the arms up, and the muscles bending the neck, are likely to fatigue earlier than the muscles doing the actual work.

Avoid fatigue

Fortunately, simply discontinuing what caused the muscular fatigue and resting regularly lead to complete recovery. The benefit of the feeling of fatigue is the prevention of serious damage to the muscles. Muscle training and skill development are subjective counteractions, effective to some extent. However, the incidence of fatigue indicates the need to improve the task conditions; the proper ergonomic approach is to design out any work requirements that generate fatigue. The human engineering solution is fitting the task to the human.

3.4 Use of muscle strength data in design

Factors affecting strength

As mentioned, the actual strength (usually defined in terms of amount, direction, and duration) that people will generate

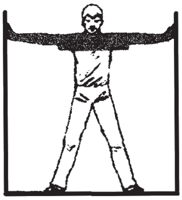
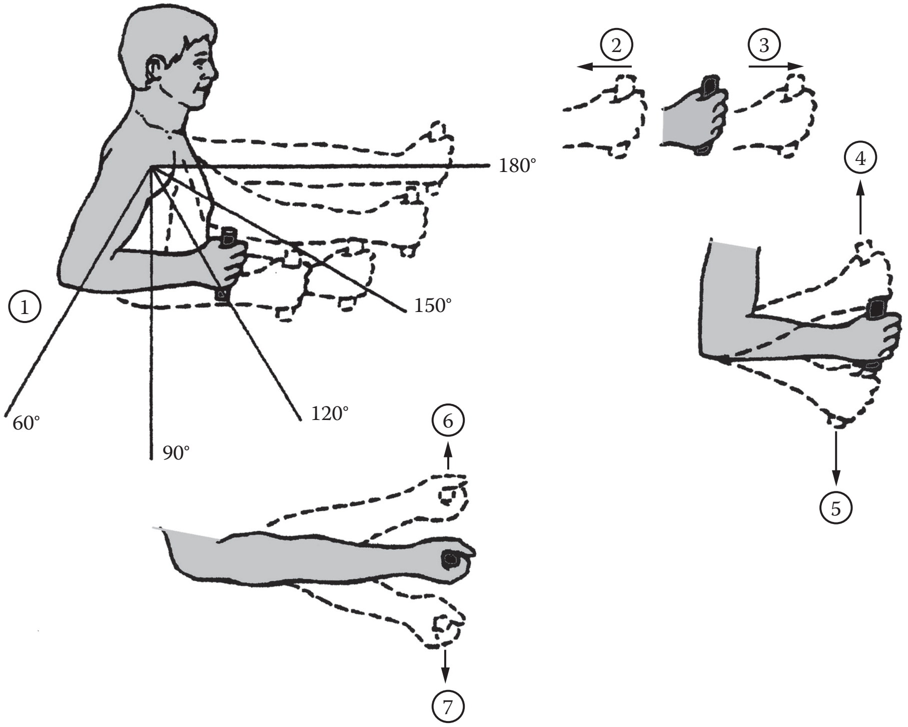
	Height[a] of force plate	Distance[b]	Force, N Mean	SD
	Percent of shoulder height[c]		With both hands	
	50	80	664	177
	50	100	772	216
	50	120	780	165
	70	80	716	162
	70	100	731	233
	70	120	820	138
	90	80	625	147
	90	100	678	195
	90	120	863	141
	Percent of shoulder height[c]			
	60	70	761	172
	60	80	854	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[c]		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[c]	Percent of thumb-tip reach[c]	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[c]	Percent of span[c]		
		50	367	136
		60	346	125
		70	519	164
		80	707	190
		90	325	132

FIGURE 3.7 Average horizontal push forces, in N, exerted by standing military men with hand, shoulder, or back: (a) height of the center of the 20 cm high, 25 cm wide force plate; (b) horizontal distance between the surfaces of the force plate and the opposing bracing structure; (c) anthropometric definitions in Chapter 1. (Adapted from Kroemer, K. H. E., and Robinson, D. E., Horizontal Static Forces Exerted by Men Standing in Common Working Positions on Surfaces of Various Tractions, AMRL-Technical Report 70-114, Aerospace Medical Research Laboratory, Wright-Patterson AFB, Ohio, 1971.)



Fifth 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

FIGURE 3.8 Fifth percentile arm forces, in N, exerted by sitting military men with their arms in various positions. (Adapted from MIL HDBK 759, Naval Publications and Forms Center, Philadelphia, PA, 1981.)

depends decidedly on *individual factors* including gender, age, training, fitness, skill, experience, and motivation. Employing muscles in a suitable body position or motion while bracing the body against a support structure is an example of a *situational factor*, which also definitely affects the strength that persons exert. Figures 3.7 and 3.8 illustrate such effects. The next chapter contains more data and discusses their use in design; Chapter 21 provides information on material handling, lifting and lowering, and pushing and pulling.

Sources of data

The literature provides a wealth of static muscle strength data°. Sources of such information are especially journals because they contain the newest information on human factors engineering/ergonomics issues. International and national agencies, insurance companies, and specialized research groups can provide answers to specific inquiries. Textbooks and handbooks, encyclopedias, and military and industry standards can provide comprehensive overviews of accumulated data.

Naturally, all data published in the literature describe the measurements of strength capabilities of a selected population under selected situational conditions. However, the specific users of tools and equipment whom the designer has in mind may differ from a previously measured group. If differences are expected, in some cases it may be possible to extrapolate information from existing data; however, often it is necessary to run specialized tests on a representative sample of the actual users, under actual use conditions.

Strong or weak persons

For design purposes, the average user strength regularly has no practical importance. (This statement resembles the one made in Chapter 1 regarding the average person phantom.) Instead, usually, the ergonomist must determine the strongest and the weakest strength exertions of relevance. When checking a (normal, Gaussian) distribution of strength data for distinct numbers that delineate the lower and upper limits of the design range, the average (mean, *m*) is useful as a *statistic tool* together with the SD. With these two descriptors of the data distribution, we can calculate the values of strength design points. For example, multiplying the SD of that distribution with, say 4.25 (from Table 1.6 in Chapter 1), and adding that product to the mean (average), leads to the strength value near the 100th percentile, representing the strongest tabulated person. When looking at the other side of the distribution, subtracting 1.65 SD from the mean leads to the fifth percentile operator, a weak person who is stronger than just 5% of his fellow users. (This is the statistical technique to establish minimal and maximal design limits, already discussed in Chapter 1.)

Identifying critical strength values

Figures 3.7 and 3.8 illustrate such statistical exercises. Figure 3.7 contains mean values with their SDs, whereas Figure 3.8 lists 5th percentile strength values. Note that we can calculate an unknown value of SD from a table that lists percentiles: for example, all the fifth percentiles in Figure 3.8 lie 1.65 SDs below the mean. The mean lies, of course, halfway between symmetrical percentiles, such as between the 5th and 95th or the 10th and 90th.

Non-normal data sets

Calculations involving average and SD are easy with normally distributed data; but such procedures lead to false results if the data set is severely skewed or otherwise non-Gaussian. Unfortunately, many collections of strength data show nonnormal distributions. To determine specific points in a nonnormal data distribution, nonparametric procedures are appropriate; they are explained in statistics books°. In some cases, designers might be able to just "eyeball" or otherwise estimate the percentile values of interest.

The MiniMax design rule

Any device requiring strength for operation should be so designed (a) that the device can be operated by applying only very small strength but (b) that even the largest strength applied will not damage the device.

Summary

The literature contains many sources of information on maximal human muscle strength. Most strength statistics concern static exertions. The ergonomist must be cautious when applying the information contained in textbooks, handbooks, design manuals, and data compilations, even national or international standards, because it may rely on test conditions that are different from those during actual work.

Fitting steps

Step 1: Assess which kind and magnitude of body strength is necessary to do a specific task.

Step 2: Determine whether people can do the required exertion. If not, reset the task.

Step 3: Design the test. Modify as necessary.

Notes

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

3.1 Physiological principles:

Tendons attach like cables to bones: Chaffin, Andersson, and Martin 2006; Kroemer 1998; Kumar 2004, 2007; Nordin and Frankel 1989; Oezkaya et al. 2012.

Chemically stored energy: Astrand et al. 2003; Hall 2015; Kroemer, Kroemer, and Kroemer-Elbert 2010; Rodahl 1989; Kenny, Wilmore, and Costill 2015.

Smooth, cardiac, and skeletal muscle: Astrand et al. 2004.

3.2 Dynamic and static efforts, strength tests:

Time derivatives of displacement are important: Marras et al. 1993.

Work-related strength tests: Kroemer 1999.

Strength test protocols: Chaffin, Andersson, and Martin 2006; Kroemer 1999; Kroemer, Kroemer, and Kroemer-Elbert 2003; Marras et al. 1993.

EMG, electromyogram: Merletti, Farina, and Rainoldi 2004; Sommerich and Marras 2004.

Experimenters can influence test scores: Kroemer 1999.

Situational variables: Daams 1993, 1994, 2001; Kroemer and Robinson 1971.

Dynamic strength tests: Dempsey 2006; Kumar 2004, 2007; Marras et al. 1993; Winter 2009.

"*specific (skeletal muscle) tension*": Enoka 1988.

3.3 Fatigue and recovery:

Muscle fatigue: Astrand et al. 2004; Chaffin, Andersson, and Martin 2006; Kroemer, Kroemer, and Kroemer-Elbert 2010; Kumar 2004, 2007; Toomingas, Mathijssen, and Tornquist 2011; Winter 2009.

3.4 Use of muscle strength data in design:

Strength data in textbooks, …, and standards: Chengular, Rodgers, and Bernard 2003; Karwowski 2006a; Konz and Johnson 2007; Kroemer, Kroemer, and Kroemer-Elbert 2003; Marras and Karwowski 2006b; Peebles and Norris 1998, 2000, 2003; Salvendy 2012; University of Nottingham 2002.

Standards: U.S. military standards such as 759, 1472; NASA 3001; ISO standards.

Statistics books: Hinkelmann and Kempthorne 1994, 2005; Sprent 2000; Tamhane 2009; Williges 2007.

CHAPTER FOUR

Body strength

Individual strength factors

The actual strength that people generate depends primarily on two clusters of factors (already mentioned in the foregoing chapter) whose effects overlap and influence each other°.

The first group consists of individual factors, generally related to body build, gender, age, training, and fitness; specific muscle properties are as follows:

- Muscle cross-sectional area
- Length (stretch) of the muscle
- Speed of motion (dynamic or static exertion)
- Fatigue
- Neurophysiological excitation

Situational strength factors

The second group of factors is situational: these are conditions that affect—often strongly so—the amount of body strength that a person will or can apply. Situational factors include the following:

- Motivation, ego involvement, will to succeed or fear of injury
- Skill and experience
- Body motion or lack thereof
- Ability to brace the body against a support structure
- Body posture, for example, allowing the use of strong muscles at advantageous leverage
- Body site used for exertion, such as one foot or both feet, shoulder, hand, or hands
- Coupling between body and object

Obviously, both groups of factors are of great importance for the human factors engineer who wants to make muscle use easy: the last five situational factors are of particular concern to the designer of work equipment and tools.

4.1 Static and dynamic strength exertions

Body motion, or lack thereof, is a major factor that determines the force, the torque, the work, the power, or the impulse transmitted from the body to an external object°. When the body does not move, the muscles involved in this static strength exertion do not change in length. In physiological terms, this called an *isometric* muscle contraction. In physics terms, all forces acting within the system are in equilibrium, as Newton's first law requires.

"Iso"

For characterizing strength exertions, the prefix *iso* has been in use for decades: from the Greek *equal*, it indicates "same", "not varying," or "constant":

- Isometric: At the same length; no change in (muscle) length
- Isoinertial: With the same mass (weight); no change in mass (weight) (This term does not describe the kinematics or the kinetics of the muscle.)
- Isotonic: At the same tension (force); no change in (muscle) tension (force), isoforce
- Isokinematic: At the same speed of the handle or the pedal; no change in speed, so the same as isovelocity (This term does not describe the kinematics or the kinetics of the muscle.)
- Isokinetic: At the same force; no change in (muscle) tension

Static exertion

The static condition is theoretically simple and experimentally easily controllable. It allows rather simple measurements of muscular effort. Therefore, much of the information available on body strength describes the outcomes of static (isometric) testing. Figure 4.1 shows, schematically, measurements of static torque about the elbow, taken every few degrees.

Note of caution

Connecting the measured values with a continuous line, habitually done as in Figures 4.1 and 4.6, can be misleading. The connecting curve seems to imply motion when in fact strength was exerted and measured in separate static positions, independently, one after the other with a break after each exertion.

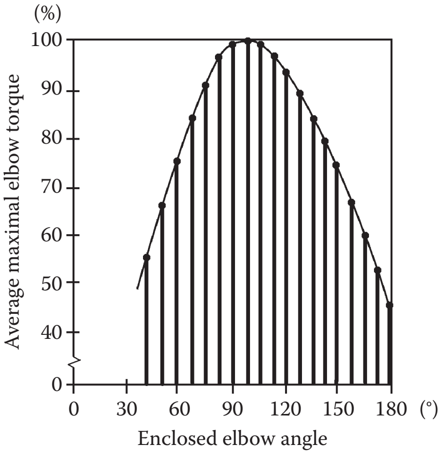


FIGURE 4.1 Schematic of static elbow torque measurements. The curve connects the results of single isometric efforts.

Isometric, isokine(ma)tic, and isoinertial strength tests

The ease of measurement explains why, for a long time, assessments of human muscle strength routinely used isometric muscle contractions. Accordingly, most tables on body segment strength in the human engineering and physiologic literature contain static strength data. Occasionally, strength is measured when exerted to a handle or a pedal that moves at constant speed, often called *isokinetic* or, correctly, *isokinematic*. The other exception involves isoinertial tests, where a person moves a constant external mass. This procedure often serves to determine lifting and lowering abilities, briefly mentioned in Chapter 3 and in Section 4.5 and, applied to material handling, extensively discussed in Chapter 21.

Static or dynamic?

Does the real world require a static or a dynamic strength exertion? This question is of great concern to the human factors engineer who intends to design for the easy use of muscles:

- If it is static, the information about isometric strength capabilities is obviously appropriate.
- As a rule, the strength exerted in movement is of lower magnitude than the static strength values measured in positions located on the path of motion.
- If the motion is very slow, especially when eccentric, the data on isometric strength measured at points on the path usually yield a reasonable estimate (although usually a

bit high) of the maximally possible exertion. (*Eccentric* means that the muscle actually lengthens during the exertion.)

- Isometric data do not estimate fast exertions well, especially if they are concentric and of the ballistic/impulse type, such as throwing or hammering. (*Concentric* means that the muscle shortens during the exertion.)
- If the dynamic action is fast or variable, special experiments° may be necessary to measure the strength capability that is specific to the demanded kind of exertion.

4.2 Maximal or minimal strength exertion

Strong and weak operators

A designer who wants to consider the operator strength has to make a series of decisions when developing a new process or device. The first decision follows from the answer to the question, “Is a strong or a weak strength exertion the critical design factor?” The structural integrity of the object must be above the maximal strength that any user might apply, because even the strongest operator should not break a handle or a pedal. Therefore, the design value should be, with a safety margin, above the highest perceivable strength application. The other extreme is the minimal strength expected from the weakest operator, which still yields the desired result; an example is successfully operating a brake pedal in a vehicle under the worst foreseeable circumstance, such as failure of the power booster.

No average user

Consequently, the designer must carefully determine both the minimum and the maximum of expected operator strength exertions. These values usually bracket the design range because the average user strength usually has no value for design (as already mentioned in Chapter 3). Determining the upper and lower design limits requires that we know the actual distribution of the strength data. With this knowledge, we set the lower cutoff of so that everybody, or nearly everybody, can operate the equipment; a common cutoff is the 5th percentile strength, meaning that only 5% of the users are weaker than expected. The upper cutoff is commonly selected at the 95th percentile strength; however, this may not be high (safe) enough, because the strongest 5% of users can still break the equipment.

MAX and MIN values

It is easy to calculate percentile points in a normal (Gaussian) data collection, which appears in the well-known symmetrical bell-shaped distribution, often encountered with anthropometric data; see, for example, Figure 1.2 in Chapter 1. Many strength data, however, are not so evenly distributed but show irregular (nonparametric) accumulations. In this case, the usual parametric statistical procedures should not be used; yet we can still determine, simply by eyeballing or by other estimates or by formal nonparametric procedures°, where we want to set our minimal and maximal design limits.

4.3 Hand strength

Most tasks, at work and in our private lives, involve grasping, holding, turning, pressing, pushing, pulling, and other manipulations done with our hands' digits, on objects held between the thumb and the fingers and the palm of the hand. Given that importance of our ability to handle objects, a large number of publications discuss hand capabilities°, especially hand forces.

Intrinsic and extrinsic hand muscles

Hand force depends on the combined effect of intrinsic and extrinsic muscles. Intrinsic muscles and their tendons are within the hand; extrinsic muscles are in the forearm, connected to the hand digits with tendons that cross the wrist joint (more on this in Chapter 2). Most intrinsic muscles contribute to finely controlled actions of the digits, while the extrinsic muscles primarily generate large forces for moving the whole hand about the wrist joint and for exercising the individual digits. Like all other skeletal muscles of the human body, they can be strengthened by use and weakened by disuse, and they can suffer fatigue and recover from it.

Types of hand tasks

There are three major types of requirements in hand tasks: for accuracy, for strength exertion, and for displacement. One may divide hand tasks further in this manner:

- Fine manipulation of objects, with little displacement and force: Examples are writing by hand, assembly of small parts, adjustment of controls.
- Fast movements to an object, requiring 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: an example is in an assembly task where small parts must be taken from bins and assembled; another example is typing on a keyboard.
- Forceful activities with moderate displacement, such as with many fabrication or repair activities: for example, when turning hand tools, such as wrenches, against resistance.
- Forceful activities with large displacements: an example is hammering.

Grips and grasps

Tools serve as extensions of the hands, fortifying and protecting them. Depending on the nature of the job, the tools are held in different ways between the digits and the palm of the hand. Some hand tools require a fairly small force but precise handling, such as surgical instruments, screwdrivers used by optometrists, or writing utensils. Commonly, the manner of holding these tools is called *precision grip*. Other gadgets must be held strongly between large surfaces of the fingers, the thumb, and the palm in what is often called a *power grasp*. Yet there are many transitions from merely touching an object with a finger (such as pushing a button) to pulling on a hooklike handle, from holding small objects between the fingertips to transmitting large energy from the hand to the handle. Figure 4.2 classifies couplings between hand and object.

Hand tool design

Shaping the tool handle° to provide high friction (often helped by wearing a glove), even to achieve mechanical interlocking between the hand and the handle (with suitable grooves, bulges, and serrations), facilitates secure holding and transfer of energy. Proper tool design and use should keep the wrist straight, not bent, to avoid the overexertion of connective tissues (muscles, tendons, tendon sheaths) and especially to prevent the compression of the median nerve in the carpal tunnel at the base of the hand. The carpal tunnel syndrome (Chapter 2) is a painful and disabling affliction that often results from repetitive motions of the hand, such as in assembly work or keyboard use.

Avoid wrist bending

The natural grasp centerline of a straight handle is not perpendicular to the forearm axis but at an angle of about 60 to 70 degrees; see Figure 4.3. For example, the use of a common straight-nose pliers often requires a strong bend in the wrist, and neither the direction of thrust nor the axis of rotation correspond with those of the hand and the arm. This often results

1. Finger touch: one finger touches an object without holding it.
2. Palm touch: some part of the inner surface of the hand touches the object without holding it.
3. Finger palmar grip (hook grip): one finger or several fingers hook(s) onto a ridge or a handle. This type of finger action is used when thumb counterforce is not needed.
4. Thumb–fingertip grip (tip grip): the thumb tip opposes one fingertip.
5. Thumb–finger palmar grip (pinch of plier grip): thumb pad opposes the palmar pad of one finger (or the pads of several fingers) near the tips. This grip evolves easily from coupling #4.
6. Thumb–forefinger side grip (lateral grip or side pinch): thumb opposes the (radial) side of the forefinger.
7. Thumb–two-finger grip (writing grip): the thumb and two fingers (often forefinger and index finger) oppose each other at or near the tips.
8. Thumb–fingertips enclosure (disk grip): the thumb pad and the pads of three or four fingers oppose each other near the tips (object grasped does not touch the palm). This grip evolves easily from coupling #7.
9. Finger–palm enclosure (collet enclosure): most, or all, of the inner surface of the hand is in contact with the object while enclosing it.
10. Power grasp: the total inner hand surface is grasping the (often cylindrical) handle which runs parallel to the knuckles and generally protrudes on one or both sides from the hand.

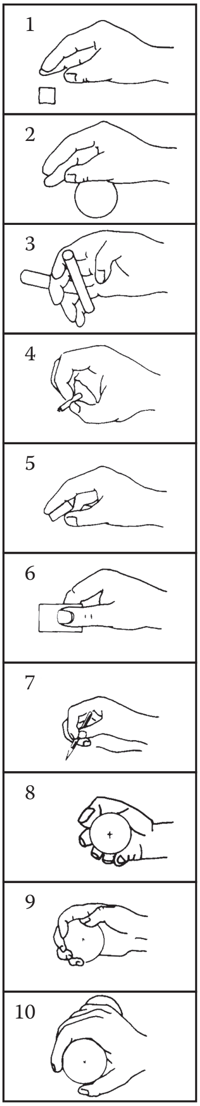


FIGURE 4.2 Couplings between hand and handle. (Adapted from Kroemer, K. H. E., *Human Factors*, 28, 337–339, 1986.)

in wrist bending, which reduces the force that can be applied. Bending the tool, not the wrist, improves that situation, as shown in Figure 4.4.

Lefties

Most women and men are right-handed, but about 1 of 10 persons prefers to use the left hand and has better skills and more strength available there. While many tools can be used with

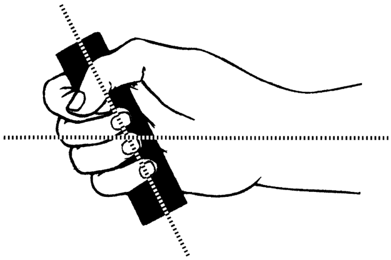


FIGURE 4.3 Natural angle between the forearm and the hand's grasp centerline.

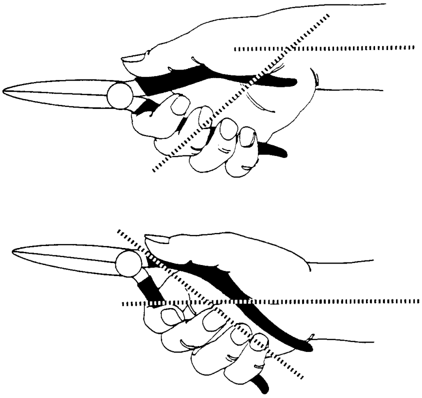


FIGURE 4.4 Bend the tool, not the wrist.

either the left or the right hand, some tools are shaped to fit only the right hand. So it may be advisable to provide left-handers with tools specifically designed to accommodate the left hand.

4.4 Foot strength

If a person must stand at work, fairly little force and only infrequent operations of foot controls should be required because, during these exertions, the operator must support the body solely on the other leg.

Bicycle pedals

For a seated operator, however, the operation of foot controls is much easier because the seat carries the body. Thus, the feet can move more freely and, given suitable conditions, can exert large forces and energies, such as when pedaling a bicycle. Bicycle pedals are best underneath the body, so that the body weight above them provides the reactive force to the foot force transmitted to the pedal. Placing the pedals higher and forward makes body weight less effective for the generation of reaction force, but if a suitable backrest is present against the buttocks and the low back, the feet can push forward on the pedals. That is the design principle in the so-called recumbent bicycles and, similarly, in automobiles.

Foot controls

Obviously, we can walk and run well on our feet, but compared to hand motions, foot movements are relatively slow and clumsy, especially when they involve the rather large leg masses. Yet, with proper seat support, our feet can exert large forces in the down and forward directions, a fact utilized in the early years of automotive design (and, surprisingly, still used today) when the driver had to stomp hard on the pedals—actions that are now, with power-assist in modern vehicles, much less demanding.

Foot thrust

A nearly fully extended leg can generate a very large foot thrust force, but only along the direction of the lower leg. If there is no seat providing support to the butt and the back, or the angle enclosed at the knee becomes smaller or larger than about 160°, the pedal force diminishes dramatically, as Figure 4.5 demonstrates. Thus, there is very small space available within which the designer can place the pedal. This case is a striking example

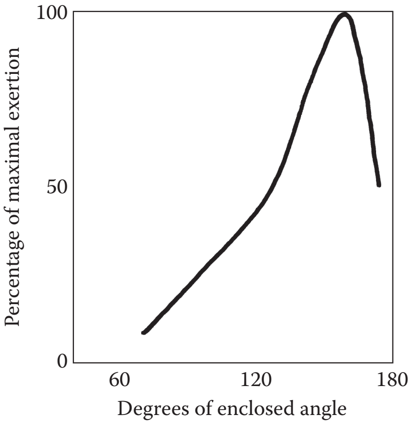


FIGURE 4.5 Effects of knee angle on static pedal push force. (Based on diagrams in Kroemer, K. H. E., Kroemer, H. B., and Kroemer-Elbert, K. E., *Ergonomics: How to Design for Ease and Efficiency*, second ed., amended reprint of the 2001 edition, Prentice-Hall/Pearson Education, Upper Saddle River, New Jersey, 2003.)

of how the strength of a body exertion depends not only on the existent muscle strength, but also on how the seat provides the needed reactive support and, as well, on how muscle strength gets transmitted across the hip/knee/ankle joints. An improper seat, a frail hip, a weak knee, or a hurting ankle, even a bad coupling at the shoe, may all make for a weak kick.

4.5 Whole body strength

Just a few jobs require the use of only one finger; most hand tasks involve the hand, the arm, and the shoulder as well. Likewise, foot use typically also entails leg activity. These other body parts involved, such as the shoulder and the legs and the back, also have characteristic strength capabilities, both individual and situational.

Chains of strength vectors

Pushing and pulling and lifting and lowering loads (discussed in detail in Chapter 21) are examples of isoinertial strength exertions that involve more than one body segment engaged to perform the task; often nearly the whole body participates. A chain of strength-transmitting segments starts at the hand on the steering wheel, at the foot on the brake pedal, and at the shoulder pushing against a stuck car; these chains then run through all body parts involved to the surface that provides the reaction force: usually the seat when sitting, the ground when standing. Figure 4.6 depicts the chaining of strength-transmitting body segments. Every involved body segment must be able to perform its duty; if one fails, the task cannot be done. The weakest segment determines the strength of the whole chain. Furthermore, (according to Newton's third law) reaction forces must be strong enough to counteract the forces exerted by the hand, the foot, or the shoulder.

Pulling and pushing

In Chapter 3, Figures 3.7 and 3.8 showed examples of one-time static push and pull forces measured under experimental conditions set up so that the subjects kept their bodies still while they exerted one-time maximal efforts on nonmoving measuring devices. In reality, however, people usually actually move objects by dynamically pushing and pulling on them; these activities include body motions and are often repetitive. Psychophysical experiments have been conducted to assess tasks done by firefighters and soldiers and, for industrial work, while handling loads; material handling is discussed in some detail in Chapter 21.

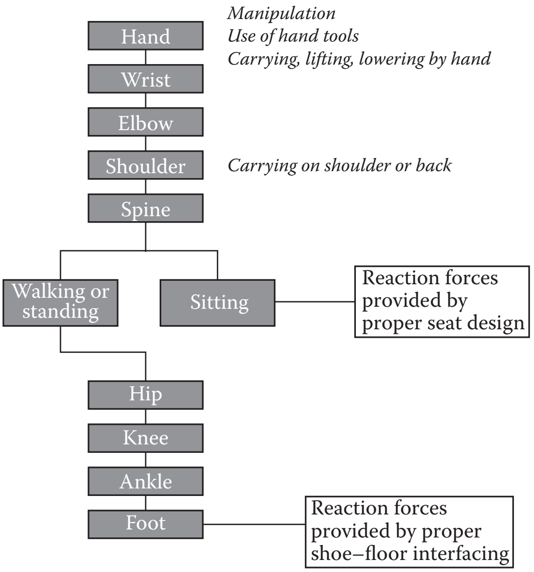


FIGURE 4.6 Chain of strength-transmitting body segments. (Adapted from Kroemer, K. H. E., Kroemer, H. J., and Kroemer-Elbert, K. E., *Engineering Physiology*: *Bases of Human Factors/ Ergonomics*, fourth ed., Springer, Heidelberg, Germany, 2010.)

4.6 Design for use preferences

If muscle strength is critical for operating a hand or a foot control or for task performance in general, the chosen design must primarily consider that strength requirement. When the need for forceful operation is met, other safety and use criteria become important for design decisions. These include ease of performance, following customs, striving for similarity with other operations, utilizing skills and habits, suiting individual preferences, and generating a pleasing appearance.

Carrying loads on the body

Load carrying can be done in many ways, not only in the hands, but also on shoulders, on the back, on the chest, held, strapped on, and contained in some sort of pocket. Table 4.1 compiles the results of several studies on the ways of carrying weighty objects on the body. In contrast to the preceding discussions of designing for strength, the recommendations for carrying load on the body do not primarily rely on muscle strength but reflect several other criteria, including energy consumption, feeling of discomfort, and stability and ease of movement. Chapter 21 deals with such assessments related to material handling.

Table 4.1 Techniques for carrying loads of approximately 30 kg

	Estimated energy expenditure for carrying 30 kg on straight flat path (kcal/min)	Estimated muscular fatigue	Local pressure and ischemia	Stability of loaded body	Special aspects	
In one hand	?	Very high	Very high	Very poor	Load easily manipulated and released	Suitable for quick pickup and release; for short-term carriage even of heavy loads.
In both hands, equal weights	Very high, about 7	High	High	Poor		
Clasped between arms and trunk	?	?	?	?	Compromise between hand and trunk use	
On head, often supported with one hand	Fairly low, about 5	(High if hand guidance needed)	?	Very poor	May free one hand: strongly limits body mobility; determines posture; pad is needed	If accustomed to this technique, suitable for heavy and bulky loads.
On neck often with sherpa-type, strap around forehead	Medium, about 5.5	?	?	Poor	May free hand(s); affects posture	

(*Continued*)

Table 4.1 (Continued) Techniques for carrying loads of approximately 30 kg

	Estimated energy expenditure for carrying 30 kg on straight flat path (kcal/min)	Estimated muscular fatigue	Local pressure and ischemia	Stability of loaded body	Special aspects	
On one shoulder	?	High	Very high	Very poor	May free hands; strongly affects posture	Suitable for short-term transport of heavy and bulky loads.
Across both shoulders by yoke, held with one hand	High, about 6.2	?	High	Poor	May free hand(s); affects posture	Suitable for bulky and heavy loads; pads and means of attachment must be carefully provided.
On back	Medium, 5.3, with backpack; 5.9 with bag held in place by hands	Low	?	Poor	Usually frees hands; forces forward trunk bend; skin-cooling problem	Suitable for large loads and long-time carriage. Packaging must be done carefully, attachment means shall not generate areas of high pressure on body.
On chest	?	Low	?	Poor	Free hands; easy hand access; reduces trunk mobility; skin-cooling problem	Highly advantageous for several small loads that must be accessible.

(*Continued*)

Table 4.1 (Continued) Techniques for carrying loads of approximately 30 kg

	Estimated energy expenditure for carrying 30 kg on straight flat path (kcal/min)	Estimated muscular fatigue	Local pressure and ischemia	Stability of loaded body	Special aspects	
Distributed on chest and back	4.8, lowest	Lowest	?	Good	Frees hands; may reduce trunk mobility; skin-cooling problem	Highly advantageous for loads that can be divided or distributed; suitable for long durations.
At waist, on buttocks	?	Low	?	Very good	Frees hands; may reduce trunk mobility	Around waist for smaller items, distributed in pockets or by special attachments; superior surface of buttocks often used to partially support backpacks.
On hip	?	Low	?	Very good	Frees hands; may affect mobility	Often used to prop up large loads temporarily.
On legs	?	High	?	Good	Easily reached with hands; may affect walking	Requires pockets in garments or special attachments.
On foot	Highest	Highest	?	Poor	Usually not useful	

Summary

The engineer or the designer wanting to consider operator strength must ask questions and, based on the answers, make a series of decisions. These include the following:

1. Is the action static or dynamic? If static, the information about isometric capabilities can be used. If dynamic, additional considerations apply, concerning, for example, physical (circulatory, respiratory, metabolic) endurance capabilities of the operator or prevailing environmental conditions. Sections I, II, and V of this book provide related information.

   Most body segment strength data are available for static (isometric) exertions. They also provide reasonable guidance for slow motions. As a general rule, strength exerted in motion is less than that measured in the static positions located on the path of motion.
2. Is the exertion by hand or by foot, or with other body segments? For each, specific design information is available as described earlier in this chapter.
3. Is a maximal or a minimal exertion the critical design factor?

   Maximal user strength determines the necessary structural strength of an object so that even the strongest operator cannot break it; therefore, the design value is to be set, with a safety margin, above the highest perceivable strength application. However, normal use depends on the ability of the weakest operator to perform the necessary task.
4. Is muscle strength only one design criterion among other use criteria, such as ease of movement, body stability, avoidance of discomfort or fatigue? If the strength requirement is met, the actual design may be chosen to satisfy use preferences.

Fitting steps

Step 1: Determine which specific task must be done. Can a machine do it? If not, proceed to step 2.

Step 2: Decide on how an operator can do the work best, where in the movement space, with the hand or the foot.

Step 3: Design; then test. Modify as necessary.

Further reading

Chaffin, D. B., Andersson, G. B. J., and Martin, B. J. (2006) *Occupational Biomechanics*, fourth ed. Wiley, New York.

Freivalds, A. (2011) *Biomechanics of the Upper Limbs: Mechanics, Modeling and Musculoskeletal Injuries*, second ed. CRC, Boca Raton, FL.

Kumar, S., ed. (2007) *Biomechanics in Ergonomics*, second ed. CRC, Boca Raton, FL.

Oezkaya, N., Nordin, M., Goldsheyder, D., and Leger, D. (2012) *Fundamentals of Biomechanics*. Springer, Heidelberg.

Stanton, N., Hedge, A., Brookhuis, K., Salas, E., and Hendrick, H., eds. (2005) *Handbook of Human Factors and Ergonomics Methods*. CRC, Boca Raton, FL.

Notes

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

Individual and situational strength factors: Daams 1993, 2001; Kumar 2004, 2007.

4.1 Static and dynamic strength: Astrand et al. 2004; Kroemer 1974, 1999; Marras et al. 1993; Winter 2009.

Special experiments: Hinkelmann and Kempthorne 1994, 2005; Williges 2007.

4.2 Maximal or minimal strength, nonparametric statistics: Gibbons 1997; Sprent 2000.

4.3 Hand strength: Fagarasanu and Kumar 2004; Feathers, D'Souza and Paquet 2015; Kumar 2007.

Shaping the handle: Freivalds 1999; Konz and Johnson 2007; Kroemer, Kroemer, and Kroemer-Elbert 2003.

4.5 Whole body strength, pulling and pushing:

Static tests: Dempsey 1998; Stanton et al. 2005.

Psychophysical testing: Psychophysics (psychophysiology) is the branch of psychology that deals with the relationships between physical (physiological) stimuli and sensory responses. Dempsey 1998; Snook and Cirielo 1991; Vol 45/Nr. 14, 2002 issue of J. Ergonomics.

4.6 Design for use preferences:

Physiological criteria: Physiological criteria relate to metabolic and circulatory body functions; see Chapter 10 in this book.

SECTION II

The human mind

The second section of this book on fitting the human discusses how we receive and perceive information about our environment. What deals with such information is generally called the *mind*, physically consisting primarily of our body's network of nerves and the brain. This command and control center has many complex functions, of which Chapter 5 treats how and what we see; Chapter 6 deals with our hearing; Chapter 7 concerns our sensing of objects and energy; and Chapter 8 describes how we interact with the climate around us. Chapter 9 discusses how the brain process inputs and makes decisions about actions to be taken. Current knowledge about the brain functions provides guidance to the ergonomist for the design of human-controlled systems.

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CHAPTER FIVE

How we see

Our eyes sense energy from the outside in the form of light rays and convert these into nerve impulses, which the brain integrates into a visual picture of the outside world. However, this perceived picture is a subjective modification of what the eye reports. For example,

- A straight line appears distorted against a background of curved or radiating lines.
- A color seems darker when seen against a bright background than when appearing on a dark background.
- The perceived hue and intensity of greenish blue is different from person to person and may change when the beholder's eyes grow old.

People differ greatly in their interpretation of visual data, depending on their age, experience, attitude, and preconceived ideas. People also differ in their abilities to recognize colors and focus clearly on visual targets, and usually significant changes in these abilities occur as one ages. Nevertheless, there is general similarity in how the human visual sense functions, which allows us to develop ergonomic recommendations.

Seeing requires light

We cannot see objects without light. Some objects generate light, such as the sun, a lamp, or an electronic display. Other objects reflect light, for example, the moon, the walls of a room, or a page of print. Unless we look directly into a light source, the light energy reflected from a surface (its luminance), activates the eye and is hence the most important factor for human vision.

5.1 Our eyes

The eyes continually adjust the amount of light they let in, change their focus on objects far and near, and produce continuous images, which they instantly transmit to the brain.

The eyeball is a roughly spherical organ, about 2.5 cm in diameter, surrounded by a layer of fibrous tissue called *sclera*. Light enters through the cornea, a transparent dome on the front surface of the eye. The cornea serves as a protective covering and as a weak lens that helps to focus light on the retina at the back of the eye—see Figure 5.1.

Pupil in the iris

After passing through the cornea, light enters the pupil, the opening that appears as a small round black area in the middle of the iris. (The pupil looks black because no light emerges from the inside of the eye. However, the pupil can appear red in a photo when a flash lights up the inside, which has many blood vessels.) The iris is the circular, colored area of the eye. The pupillary dilator and sphincter muscles open and close the pupil (like the aperture of a camera lens does) to control the amount of light that enters the eye: letting more light in when the environment is dim but admitting less light when the surroundings are bright.

The lens focuses

The lens is behind the iris. It focuses light onto the retina by changing its shape. When thin, it is a weak lens (in optical° terminology) that focuses on distant objects. The contracting ciliary muscle pulls on the lens and thus makes it thicker and optically "stronger" so that it may focus on nearby objects. The

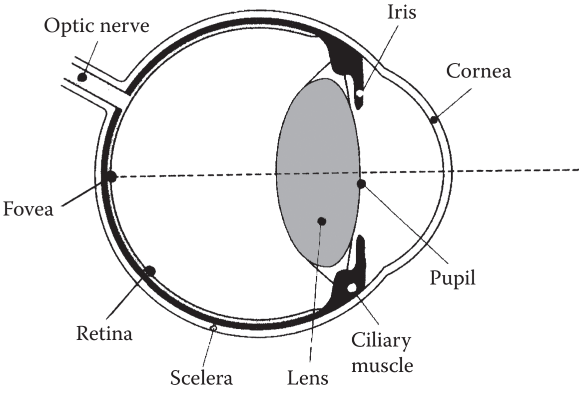

FIGURE 5.1 The right eye as seen from above.

eyes of a healthy young adult can usually focus on an object as close as 10 cm, but with aging, the lens becomes less flexible and is hence less able to thicken, which diminishes its ability to deal with nearby objects. As a consequence, the accommodation distance commonly increases. This condition is called *farsightedness* or *presbyopia*.

Light focused by the cornea and the lens travels through the vitreous humor, a gel-like fluid (with refractory properties similar to those of water) that fills the interior of the eyeball. Finally, the light reaches the retina, a thin tissue lining about three quarters of the rear inner surface of the eyeball. Many arteries and veins amply supply the retina with blood.

Rods for white/gray/black perception

The retina carries about 130 million light sensors. Their arrangement is densest in the center, the fovea, straight behind the lens. The light sensors are of two kinds, named for their shape. Rods are prevalent with about 120 million. They contain only one pigment, which responds to even low-intensity light. Rods set off electrical impulses that travel along the optic nerve to the brain for the perception of white, black, and shades of gray. Rods provide us with the most important visual information.

Cones signal color

The retina also carries about 10 million cones, located mostly in the fovea. They respond to colored light if it is sufficiently bright. Each cone contains one pigment that is most sensitive to either blue, green, or red wavelengths. An arriving light beam, if intense enough, triggers chemical reactions in one of the three types of pigmented cones, creating electrical signals that pass along the optic nerve to the brain, which can compose and distinguish among about 150 color hues.

Optic nerve

The optic nerve exits the eye at its rear, but not directly in line with the centers of the cornea and the lens but rather offset from the fovea by about 15° toward the inside (medially). Since there are no light sensors in this area, we cannot see an image refracted on this so-called blind spot. However, since both blind spots of eyes are medially located, they do not overlap in our field of vision and, therefore, we are usually not aware of their existence.

Visual control system

Proper vision requires continuous actions of a complex control system, sketched in Figure 5.2. It shows, first, the adjustment of the lens (1) behind the cornea to provide a sharply focused image on the retina. The information (2) about that image transmits along the optic nerve (3) to the brain. Various nervous

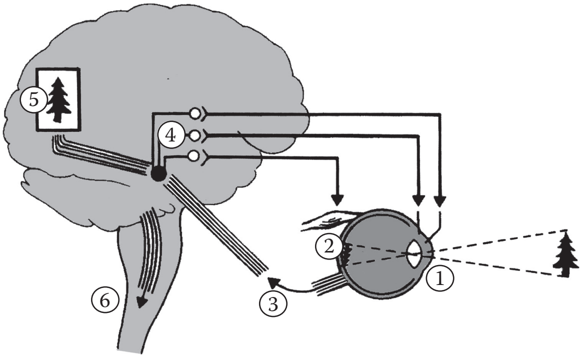

FIGURE 5.2 Diagram of the visual system.

control mechanisms (4) readjust the position of the eyeball, the size of the pupil, and the form (refractive property) of the lens continually. The visual perception of the external world takes place in the conscious sphere of the brain (5) and leads to command signals that travel through the spinal cord (6) to instigate appropriate actions of the body.

5.2 Seeing the environment

The visual field

We can see objects in the so-called visual field°, which is a roughly conical space in front of the eyes. Yet, within this space, we can discern visual targets with high acuity only if they appear within a very narrow cone and at a suitable distance. For example, when we focus on written text, only a few adjacent letters appear clear, while the surrounding letters blur, more so the farther away they are.

Fixated eyes

The areas that the two eyes can see do not overlap perfectly, partly because the nose is in the way. When the eye maintains fixation on a single spot straight ahead, researchers measure the size of the visual field by presenting test objects away from this position. On the outside, we can notice the presence of objects within about 90° to the side, but colors appear only within the inner about 65°; upward, we can achieve about 45° yet observe color only to about 30° upward; downward, we attain about 70°, but the area in which we see color only extends downward to about 40°.

Rotating the eyes

Rotating the eyeball increases the visual area to the outside beyond the *field of fixation*, but adds nothing in the upward, downward, or inside directions, because the eyebrows, the cheeks, and the nose stay in place. Several muscles attach to the outside of the eyeball, working together to move the eye. Rotational movements are most eminent but some forward and back motions of the eyeball also occur. We can rotate our eyes up to about 50° both in pitch (up and down) and yaw (left and right). However, the eyes seldom rotate to these extreme angles.

Fixation on a visual target

When we try to look at an object at the periphery of our field of vision, the initial fixation is mostly by eye rotation, usually accompanied by a quick turn of the head in that direction. With the strong preference for body movement rather than extreme eye motion, we commonly use adjustments of body posture to fixate on a peripheral target so that our eyes can operate comfortably and precisely close to their normal resting positions.

Eye tracking

The eye can continuously track a visual target that moves to the left or to the right at less than 30° per second or which cycles at less than 2 Hz. Above these rates, the eye is no longer able to continuously follow but must move in saccades; it lags behind and then jumps to catch up.

Avoid eye fatigue

The so-called eye fatigue is often the result of excessive demands on the muscles of the eye those that move the eyeball, and those that adjust the lens and iris. Eye fatigue is particularly a problem for older people whose lenses have become stiff and who often find it difficult to move the neck and the trunk as easily as they did in their youth. Apparently, many instances of fatigue of which computer users often complain are related to the poor placement of monitor, source documents, or other visual targets (see Section V of this book) or to unsuitable lighting conditions at their workplace, as discussed later in this chapter.

Locating visual targets

It is important to arrange visual targets properly: in front, not to the side, at a distance to which the eyes can easily accommodate, and so low that we can rotate the eyeballs slightly down while keeping the trunk, the neck, and the head in comfortable positions. Makers of eyeglasses and optometrists always knew that looking down on small visual targets, such as printed text, is easier than looking up; therefore, they put the reading section of (bifocal or trifocal) corrective spectacles into the lower parts of the lenses. If several similar visual targets are present, they should be placed close to each other so that eye and head movements are small, as Figure 5.3 illustrates.

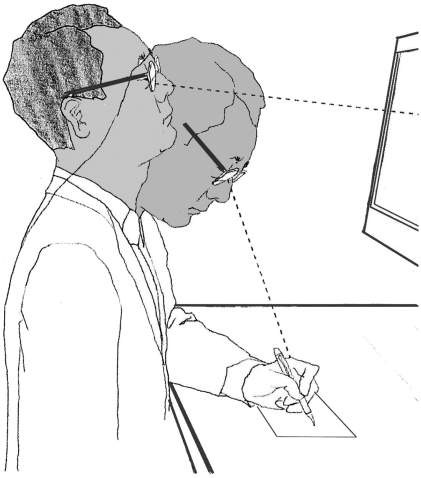

FIGURE 5.3 Excessive eye/head/neck movements can be avoided by placing visual targets close to each other. (Adapted from Kroemer, K. H. E., and Kroemer, A. D., *Office Ergonomics*, Korean edition, Kukje Publishing, Seoul, South Korea, 2006.)

Line of sight

When we look at an object in front of us, we unconsciously adjust two pitch angles: that of the eyes within the head and that of the head against the trunk. As we fixate on a target, the line of sight (LOS) runs from the center of the retina through the midpoints of the lens and the pupil and from there to the target. Thus, inside the eyeball, the LOS is clearly established. However, a suitable reference is needed to describe the LOS direction from the eye to the visual target; the ear–eye line can serve as reference.

Looking down on the job

In the past, the so-called Frankfurt plane served as reference, but its anatomical definition by landmarks on the bony skull made it difficult to use. The ear–eye (EE) line is simpler to establish; it runs through the easily discerned ear hole and the junction of the eyelids, as shown in Figure 5.4 in a side view of the head. The angle between the LOS and EE is the pitch angle of the eye, LOSEE, as it looks at the target. The LOSEE° is best around 45° when reading a text, on paper or a computer screen. The LOSEE becomes smaller as the observed object gets farther way; it is about 15° (close to horizontal) when we look straight ahead. The position angle P describes how we hold the head compared to the horizon. When the head is upright, P is about 15°.

Size of the visual target

If a visual target is not a point but has a measurable length or breadth perpendicular to the LOS, then the target size is usually expressed as the subtended visual angle—the angle formed at

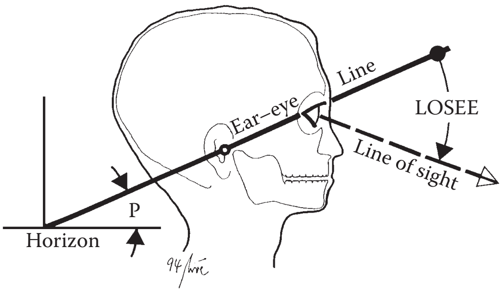

FIGURE 5.4 LOS angled against the EE line.

the pupil. The magnitude of this angle α depends on the size *L* of the object and on the distance *D* from the eye, as described in Figure 5.5. The subtended visual angle is usually described in degrees of arc (with 1° = 60 minutes = 60 × 60 s of arc). The equation is

$$\alpha \text{ (degrees)} = 2 \times \arctan (0.5 \times L \times D^{-1}).$$

For visual angles not larger than 10°, this can be approximated by

$$\alpha \text{ (degrees)} = 57.3 \times L \times D^{-1}$$

or by

$$\alpha \text{ (minutes of arc)} = 60 \times 57.3 \times L \times D^{-1} = 3438 \times L \times D^{-1}.$$

The human eye can perceive, at a minimum, a visual angle of approximately 1 minute of arc. Table 5.1 lists the visual angles of some familiar objects. For ease of use, technical products should be designed so that the angle subtends at least 15 minutes of arc, increasing to at least 21 minutes of arc at low light levels.

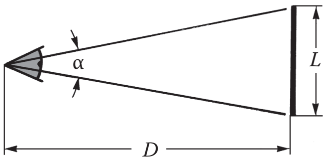

FIGURE 5.5 The subtended visual angle.

Table 5.1 Visual angles of familiar objects

Object	Distance D	Visual angle (arc)
Instrument, 5 cm diameter	0.5 m	5.7°
The sun; the moon		About 30′
Character on computer monitor	0.5 m	About 17′
Book letter at reading distance	About 0.4 m	About 13′
U.S. quarter coin	At arm's length, 0.7 m	2°
	At 82 m (90 yards)	1′

Source: Kroemer, K. H. E., Kroemer, H. B., and Kroemer-Elbert, K. E., *Ergonomics: How to Design for Ease and Efficiency*, second ed., Prentice Hall/Pearson, Upper Saddle River, New Jersey, 2003.

Diopter

The target distance D is measured in meters; its reciprocal, $1/D$, is called the *diopter*. The diopter indicates the optical refraction needed for best focus. Thus, a target at infinity has the diopter value of zero, whereas a target at 1 m distance has the diopter value unity (one). Table 5.2 shows values for some typical target distances.

Focusing

Accommodation describes the ability of the eye, mostly through shaping its lens, to bring into sharp focus objects at varying distances, from infinity down to the nearest point of distinct version. If we hold up a finger in front of the eye, we can sharply focus on it, but the background remains blurred; alternately, we can concentrate on the features of the background, leaving the finger indistinct. We can clearly see only those objects whose images appear focused on the retina.

Table 5.2 Focal points (diopter) and target distances (m)

Target distance D (m)	Focal point (diopter)
Infinity	0
4	0.25
2	0.5
1	1
0.67	1.5
0.5	2
0.33	3
0.25	4
0.2	5
0.1	10

Incessant changes

If our gaze sweeps to various objects in the near field of vision, the lens must continuously change its curvature to keep adapting its focal length so that sharp images appear on the retina; even when maintaining its focus on a near target, muscles continuously adjust their contracting forces. For example, when we read a text, the lens does not hold still but oscillates at a rate of about four times per second. At the same time, the iris continuously changes the size of its central opening, the pupil. This keeps its dilator (opening) and sphincter (closing) muscles constantly active to adjust the diaphragm of the eye according to the light conditions in the visual field. During daylight, the pupil size is usually 3–5 mm in diameter, which increases at night to more than 8 mm. The aperture of the pupil contracts when we focus on near objects and opens when the lens relaxes. Furthermore, the pupil reacts to emotional states, dilating under such strong emotions such as alarm, joy, pain, or intensive mental concentration; it narrows with fatigue and sleepiness. Therefore, changes in the pupil size have been used to assess persons' attention and attitudes.

Overcoming ocular problems

A healthy young eye can accommodate from infinity to very close distances, such as 10 cm, meaning that a diopter range from 0 to about 10 can be achieved. The minimal distance increases to about 5 diopter (20 cm) at about the age of 40 years and to about 1 diopter (1 m) at age 60, on average. With increasing age, the accommodation capability of the eye decreases, because the lens becomes stiffer by losing water content. The result is difficulty in making light rays from targets at differing distances converge exactly on the retina. If the convergence point is in front of the retina, the condition is called *myopia*; if it is behind, *hyperopia*—see Figure 5.5. A nearsighted (myopic) person has no trouble seeing close objects but finds it difficult to focus on far targets. This condition often improves with age, when commonly the lens remains flattened. In contrast, farsightedness (hyperopia) usually becomes more pronounced with age, meaning that it gets even more difficult to focus on near objects. Both problems, myopia and hyperopia, can be corrected fairly easily by either contact lenses or eye glasses—as shown in Figure 5.6. (Note that the refractive properties are measured when the eye lens is relaxed.)

More light, please!

In many people, the pupil shrinks with age. This means that less light strikes the retina, and therefore, to achieve sufficient visual acuity, many older people need to increase the illumination on visual objects. Another problem often encountered

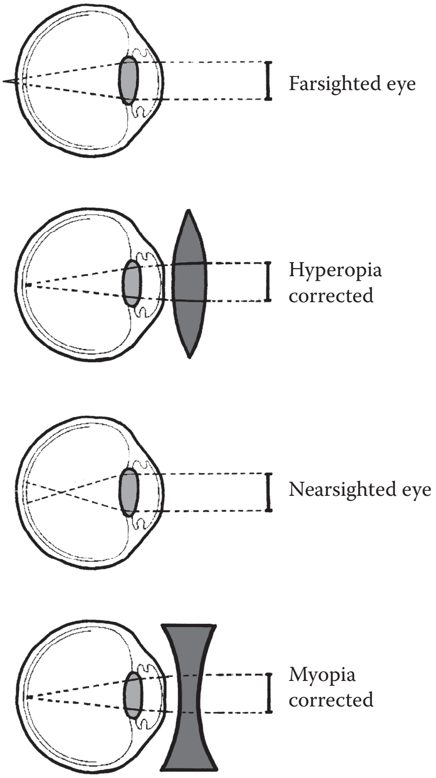

FIGURE 5.6 Convex and concave lenses can correct refractive (focusing) eye deficiencies.

with increasing age is the yellowing of the vitreous humor. The more yellow it becomes, the more energy it absorbs from the light passing through; consequently, again, increasing the illumination of the visual target helps to improve acuity. However, light rays may be refracted within the yellowed vitreous humor, bringing about the perception of a light mist or veil in the visual field. If bright lights are in the visual field, the resulting veiling glare can strongly reduce one's vision. Obviously, artificial lenses cannot correct the yellowing problem.

Floaters

So-called floaters appear like small flecks in front of the eye. In reality, they consist of small clumps of gel or cells suspended in the vitreous humor. Frequently they are not noticed because the eye adjusts to these imperfections. Floaters are visible to the individual only when they are on the LOS, casting a shadow on the retina. They are more easily perceived when one is looking at a plain background. Fortunately, occasional floaters are usually harmless.

Checking for glaucoma

Glaucoma is the leading cause of blindness in the United States especially among older people. It is a disease of the optic nerve, related to high pressure inside the eye. Regular eye examinations help to detect the beginning of glaucoma and prevent further damage.

Helping the ailing eye

Another frequent problem in the aging eye is having cataracts, patterns of cloudiness inside the normally clear lens. When vision is severely impaired, an eye surgeon may remove the cloudy lens and replace it with an artificial implant. Two other vision deficiencies, usually not related to aging, can usually be improved by surgery or lenses:

- Astigmatism occurs if the cornea is not uniformly curved, so that, depending on its position within the visual field, an object is not sharply focused on the retina. Often, the astigmatism is a spherical aberration, meaning that light rays from an object located at the side are more strongly refracted than those from an object at the center of the field of view, or vice versa.
- Chromatic aberration is fairly common: An eye may be hyperopic for long waves (red) and myopic for short waves (violet or blue).

Color perception

Even for fully functioning eyes, the perception of color requires sufficient light energy arriving at the cones to activate them. In North America, color vision deficiencies occur in approximately 8% of the male population, whereas only about 0.5% of the female population have that problem. “Color weakness” is most prevalent; persons cannot distinguish as many gradations of colors as people with normal color vision do. A few individuals miss one of the cone systems and are therefore not able to distinguish some basic colors from one another. Only very few people can see only one color or none at all.

Blind at night

Night blindness is the condition of a person having less than normal vision in dim light—that is, when the visual target has low illumination or luminance.

5.3 Dim and bright viewing conditions

We need light to see

Without light, we cannot see. The sun, a lamp, or an electronic display generates light. The moon, the walls of a room, or a page of print reflect light. The most important factor for human vision is luminance, the light energy reflected from a surface (unless we stare into a light source). The energy that falls onto the retina stimulates rods and cones. Because the human eye adapts to lighting conditions, our eyes do not convey reliable information on the absolute lighting level, but they respond to variations in illumination, luminance, and color as these occur over time and space.

Illuminance and luminance

Illuminance/illumination is light falling upon an object; *luminance* is light reflected or emitted from an object.

Colors that we may see

The fully functioning human eye senses and can adapt to increases and decreases in illumination° of the retina over a wavelength range of about 380–720 nm, that is, from violet to red. We can see objects if they are bright enough (either by generating light or by reflecting it) to carry sufficient visible energy onto the retina. On the retina, the minimal intensity required to trigger the sense of light perception is 10 photons, causing an illuminance of about 0.01 lux. At such low intensity, the main perception is of dim light, not of color, because only rods are activated. When the illuminance of the retina exceeds about 0.1 lux, both rods and cones respond, and the cones report colors. We experience this at twilight and dawn, when we can see color in the brighter sky, but all dimmer objects appear only in shades of gray as reported by the rods.

Seeing in the dark

Some interesting events can occur in darkness:

- If one stares at a single light source on a dark background, the light seems to move. This is the so-called autokinetic phenomenon.
- Night vision capabilities deteriorate with decreasing oxygen. Thus, at an altitude of about 1300 m, vision is reduced by about 5%; at 2000 m, the reduction is about 20%; yet, up to 40% in smokers whose blood has lost some capability to carry oxygen.
- If the horizon shows no visual cues, the lens relaxes and focuses at a distance of about 1–2 m, making it difficult for a person to notice faraway objects. This is known as *night myopia*.

Adaptation to light and dark

Between dark to bright conditions, the eye can change its sensitivity through large ranges of illumination and luminance°. Figure 5.7 scales the luminance values that we perceive.

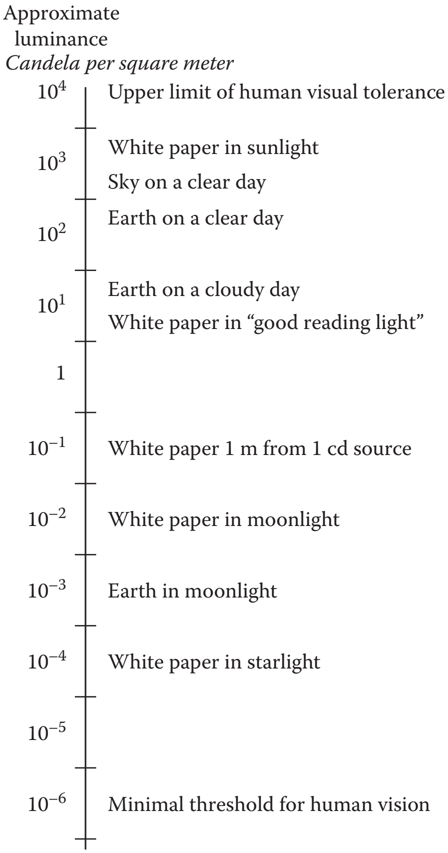

FIGURE 5.7 Luminances of objects that humans can see.

The adjustments of the pupil, the stimulation of rods and cones, and the spatial summation of stimuli all contribute to sensitivity. The actual change in response of the eye during adaptation to dark or light also depends on the luminance and the duration of the previous condition to which the eye had adapted, on the wavelength of the illumination, and on the location of the light stimulus on the retina.

Adaptation to darkness

Full adaptation from light to darkness takes up to 30 minutes; during this period, initially the cones are most sensitive, and the rods follow more slowly. Adaptation to darkness mostly depends on the change in threshold in the cones. Even after full adaptation, the sensitivity at the fovea (with its many cones) is much less than at the periphery of the retina (where there is a preponderance of rods). Therefore, weak lights can be noticed in the periphery of the field of view, but not if one looks directly at them to make them appear on the fovea. People who suffer from dark blindness have nonfunctional rods and can adapt only via cones. Our eyes adjust faster to red and yellow lights than to blue light during adaptation to darkness, after having been in a lighted environment.

Adaptation to lightness

In contrast, adaptation to light is quick, fully achieved within a few minutes. During that period, the fovea perceives wavelengths in the yellow region of the visible spectrum most easily. Therefore, it is best to illuminate instruments in vehicles driven at night with yellowish or reddish light, with the yellow color probably more suitable for the older eye. These colors maintain the dark adaptation of the rods so the driver can still observe the mostly black–gray–white events on the road. Furthermore, the driver's eyes adjust relatively fast to red and yellow lights after having been in a lighted environment.

Visual acuity

Visual acuity can be defined in several ways, usually done as the ability to detect small details and discriminate small objects by eyesight. Visual acuity depends on the shape of the object and on the wavelength, the illumination, the luminance, the contrast, and the duration of the light stimulus.

Acuity testing

Visual acuity is usually measured at viewing distances of 6 m (20 ft) and 0.4 m (1.3 ft), because factors that determine the resolution of an object differ in far and near viewing. For determining acuity, high-contrast patterns are presented to the observer. The most common patterns are either Snellen letters or Landolt rings; see Figure 5.8. The smallest detail detected or identified is taken as the threshold. These measures of acuity primarily depend on the ability to see edge differences between black and white stimuli at rather high illuminance levels. Such measurement of static edge acuity is simple, but it is neither the

FIGURE 5.8 Examples of visual targets used in acuity testing.

only nor the best measure of visual resolution capabilities. For example, people with perfect Snellen acuity may not do well detecting targets on a busy background or observing highway signs at given distances.

Color perception Sunlight contains all visible wavelengths of the spectrum, but objects onto which the sun shines absorb some of the radiation. Thus, the light that we see on objects is what they transmit or reflect; its energy distribution differs from the light (illumination) that the objects received. However, a human looking at the object does not analyze the spectral composition of the light reaching the eyes; in fact, what appears to be of identical color may have different spectral contents°.

Trichromatic vision Color-matching experiments show that humans can perceive the same color stemming from various combinations of the three primary colors: red, green, and blue. Therefore, the human color vision is called *trichromatic*°.

Color is an experience The brain does not measure wavelengths; it simply classifies incoming signals from different groups of wavelengths. We judge colors by comparison and we name them by habit. Some societies do not bother to distinguish between certain colors of the spectrum and lump blue and green together, while others have many words for shades of red. Human color perception is a psychological experience, not a single, specific property of the electromagnetic energy we see as light.

Describing colors The physics of color stimuli arriving at the eye can be described well (although often with considerable effort); however, perception, interpretation, and reaction to colors are highly individual and variable. Thus, people find it very difficult to describe colors verbally, given the many possible combinations of individually perceived hue, lightness, and saturation values.

Reactions to colors People may experience emotional reactions to color stimuli. For example, reds, oranges, and yellows are usually considered warm and stimulating. Violets, blues, and greens are often felt to be cool and generate sensations of cleanliness and restfulness. However, the attraction to certain colors and to their combination varies by age, culturally and regionally, for example, between Asia and Europe.

Designing illumination

The characteristics of human vision provide the bases for engineering procedures to design environments for proper vision. Here are the most important concepts:

- Proper vision requires appropriate luminance of an object, that is, the energy reflected or emitted from it, which meets the eye.
- Incident illuminance on an object, and how much thereof it reflects, determine its luminance.
- Quantity and direction of illumination need to be carefully selected by the designer.
- Special requirements on visibility, such as the diminished seeing abilities of the elderly, require particular care in the arrangement of proper illumination.
- Use of colors, if selected properly, can be helpful; but color vision requires sufficient light.

Summary

The eyes provide a huge portion of the information that we need in daily life and at work. In order to see objects and events in detail, they must appear in bright light. When the light dims, objects lose their colors; in the dark, they are invisible. Even a well-lit visual target must be at such a distance from our eyes that we can distinguish particulars. If our eyesight is defective, which is a usual occurrence as we age, it is especially important to have suitable lighting and we may have to use artificial lenses.

Fitting steps

Step 1: Make sure that the eyes function properly; if in doubt, see an eye physician.

Step 2: Provide a suitable combination of visual targets/tasks and illumination.

Step 3: Adjust conditions as desired.

Further reading

Boyce, P. R. (2014) *Human Factors in Lighting*. Taylor & Francis, London.

Sheedy, J. (2006) Vision and work. In Marras, W. S., and Karwowski, W. (eds), *The Occupational Ergonomics Handbook: Fundamentals and Assessment Tools for Occupational Ergonomics*, second edition, Chapter 18. CRC, Boca Raton, FL.

Notes

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

5.1 Our eyes:

Optics: Optics is the branch of physics that deals with vision and visible light.

5.2 Seeing the environment:

The visual field: Sheedy 2006.

LOSEE is best: Hill and Kroemer 1986; Sheedy 2006.

5.3 Dim and bright viewing conditions:

Illuminance, illumination: Illuminance or illumination is the light falling upon an object.

Luminance: *Luminance* is the light reflected/emitted from an object.

The definition and measurement of light has been complicated in the past by the use of different procedures and units, as explained by Boyce (2014) and Howarth (2005).

Spectral contents of color: For measuring and specifying colors see, for example, Howarth (2005). For ergonomic applications see, for example, Kroemer, Kroemer, and Kroemer-Elbert (2003).

Trichromatic vision: The data of a color-matching experiment can be displayed as vectors in a three-dimensional (red, green, and blue) space, called a *chromaticity diagram*, standardized in 1931 and still in common use.

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CHAPTER SIX

How we hear

The ear senses energy from the outside world in the form of pressure waves in the air and converts these into nerve impulses, which the brain integrates into a psychoacoustical perception of the sound environment. This interpretation is a subjective modification of what the ear reports. For example, the perceived sound and appeal of music is different from person to person, and is likely to change as the person grows older.

People greatly differ in their interpretation of acoustical events, depending on their experience, attitude, and preconceived ideas. People also differ in their ability to recognize sounds and react to them, and aging regularly brings significant changes. Nevertheless, existing similarities in how hearing functions allow us to develop ergonomic recommendations.

6.1 Our ears

Pathways of sound

Sound can reach the inner ear via two different paths. Sound may be transmitted through bony structures, but this requires very high intensities to be effective. Normally, the sound that we perceive is airborne and travels through the ear canal, where it excites the eardrum and then the structures behind it, as described in the following.

The outer ear (*auricle* or *pinna*) collects and funnels airborne sound waves into the auditory canal (*meatus*). At its end, the eardrum (*tympanic membrane*) closes the canal, separating the air-filled middle ear from the environment. More to the inside, two other membranes separate the inner ear from the middle ear by closing two “windows”, one called *oval*, and the other *round*. A watery fluid (called *endolymph* or *perilymph*)

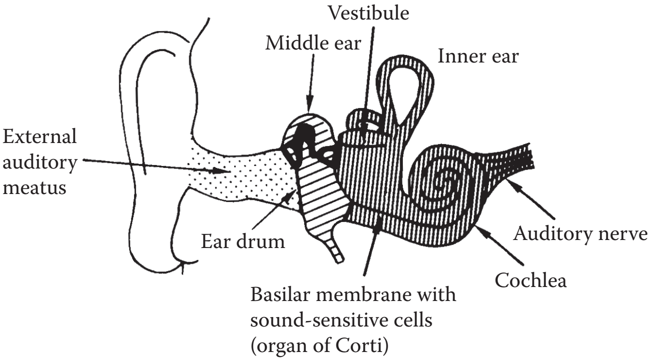

FIGURE 6.1 Main features of the anatomy of the ear: the air-filled outer and middle ear sections, separated by the eardrum, and the fluid-filled inner ear with the cochlea and the vestibule.

fills the inner ear, which carries the organs that sense sound (and body position, discussed in Chapter 7). Figure 6.1 shows the main features of the anatomy of the ear.

Outer ear

After traveling through the ear canal, a sound wave arriving at the eardrum makes it vibrate according to the frequency of the sound. Resonance effects within the outer ear and the canal amplify the intensity of the sound by 10–15 decibels (dB; Section 6.2, below, explains the units) by the time it reaches the eardrum.

Middle ear

Three bones (*ossicles*) in the middle ear—the hammer (*malleus*), the anvil (*incus*), and the stirrup (*stapes*)—mechanically transmit the sound from the eardrum to the oval window. With the area of the eardrum (about 60 mm^2) larger than the surface of the oval window (about 4 mm^2), the sound pressure that enters the inner ear at the oval window's membrane is about 15 times larger than it was at the eardrum.

Inner ear

The inner ear contains the receptors for hearing (and for body position, the vestibulum; see Chapter 7). Fluid shifts in the inner ear propagate sound waves from the oval window to the round window through the *cochlea*, a tube (about 2 mm in diameter and 30 mm in length) wound into two and one-half turns like a snail shell (cochlea). The motions of the fluid deform the *basilar membrane*, the organ of Corti, running the length of the cochlea. The movements stimulate sensors, cilia, feathery hair cells in the organ of Corti. Depending on their structure and location, the sensors respond to specific frequencies and generate impulses, which are transmitted through the auditory nerve to the brain for interpretation.

The Eustachian tube connects the middle ear to the pharynx (part of our breathing apparatus). When the tube is open, it allows the air pressure in the middle ear to remain equal to the external air pressure. But when the tube is obstructed, such as in the case of a cold or an ear infection, pressure equalization may not function, and one feels pressure in the ear, even pain, and cannot hear well. In an airplane, especially during rapid descent, a clogged Eustachian tube can delay the equalization of pressure between the inner ear and the environs. You may try to open the tube by chewing gum or by willful excessive yawning, but "pumping" your outer ear with the hand will not help your middle ear.

6.2 Hearing sounds

Sound

Sound is a vibration that stimulates an auditory sensation. A sound contains a mixture of frequencies, whereas a *tone* is a single-frequency oscillation. The measurement unit of frequencies is hertz (Hz; oscillations per second). We often describe our personal perception of tone frequencies as pitch.

Frequencies that we hear

We cannot hear sounds below 16 Hz, but we may feel such infrasonic vibrations°; nor can we hear ultrasonics, above 20 kHz, but dogs and other animals do. Infants can hear tones from about 16 to 20.000 Hz (20 kHz), a span of nearly nine octaves. With aging, the human ability to hear high frequencies strongly diminishes. Old people can rarely hear high tones above 10 kHz. Our normal hearing is most sensitive between about 1 and 5 kHz. In human speech, vowel sounds are below 1 kHz, while sibilant consonants can exceed 5 kHz; yet most speech occurs within the 300–700 Hz range.

How loud?

Loudness describes our sensation of the intensity (sound pressure level, power, amplitude) of an audible vibration. The low-pressure threshold of human hearing is about 20 μPa (20×10^{-6} Nm^{-2}; 1 Pa = 1 N/m^2) in the frequency range of 1000 to 5000 Hz. When the sound pressure exceeds 140 Pa, the ear experiences pain. Figure 6.2 shows the ranges of human hearing.

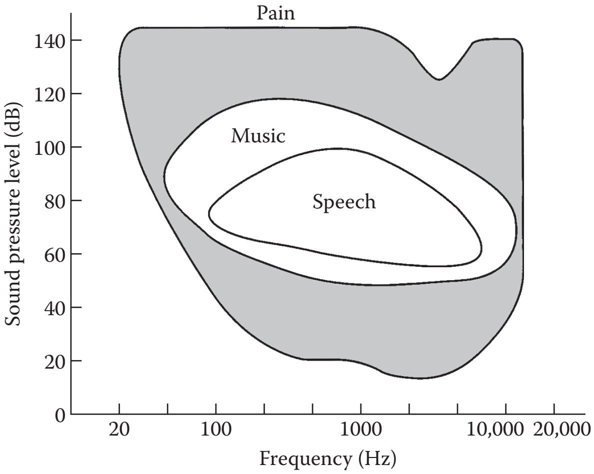

FIGURE 6.2 Typical hearing ranges of adult humans. (Adapted from Kroemer, K. H. E., Kroemer, H. B., and Kroemer-Elbert, K. E., *Ergonomics: How to Design for Ease and Efficiency*, second ed., Prentice-Hall/Pearson Education, Upper Saddle River, New Jersey, 2003 amended reprint.)

10 dB = 1 bel

We humans perceive sound pressure in a roughly logarithmic manner. Therefore, loudness is measured in a logarithmic unit° called *decibel* (dB). The threshold of hearing serves as the reference. This leads to stating the sound pressure level (SPL) as the ratio between two sound pressures: P is the present sound pressure (rms) and P_o is the threshold of hearing. So the definition of sound pressure level is SPL = 10 log $\left(P^2/P_o^2\right)$ or

$$\text{SPL (dB)} = 20 \log_{10}(P/P_o).$$

Thus, in decibels, the dynamic range of human hearing from 20 10^{-6} Pa to 200 Pa is

$$20 \log_{10} [200/(20\ 10^{-6})] = 140 \text{ dB}.$$

The sound intensity level (SIL) is, accordingly,

$$\text{SIL(dB)} = 10 \log_{10}\left(I^2/I_o^2\right),$$

where I is the (rms) sound intensity and I_o is 10^{-12} W/m^2. Figure 6.3 illustrates the ranges of SILs.

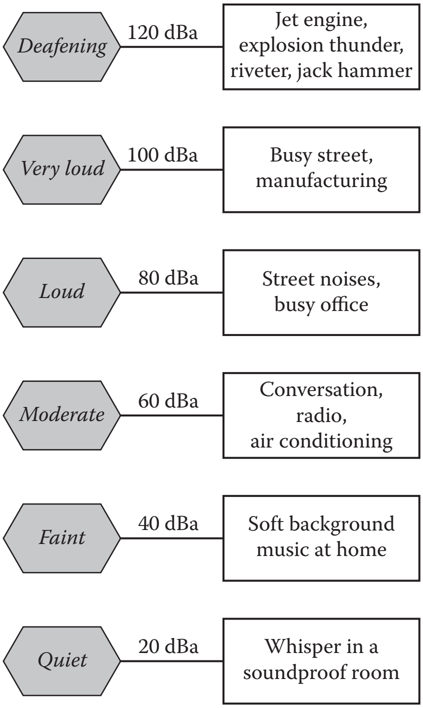

FIGURE 6.3 Typical sound intensity levels. (Adapted from Kroemer, K. H. E., Kroemer, H. B., and Kroemer-Elbert, K. E., *Ergonomics: How to Design for Ease and Efficiency*, second ed., Prentice-Hall/Pearson Education, Upper Saddle River, New Jersey, 2003 amended reprint.)

The emitted sound power (such as from a loudspeaker or a running engine) is measured in watts; it relates to sound pressure via $W/m^2 = P^2/[(\text{air density}) \times (\text{speed of sound})]$. Thus, sound power is proportional to the square of sound pressure.

Sounds occurring together

Because of the use of logarithms, doubling the SPL causes an increase of 6 dB; a 1.41-fold increase in sound pressure causes an increase of 3 dB. If two sounds occur at the same time, one can approximate their combined SPL from the difference between their intensities as follows:

- If the difference is 0 dB, add 3 dB to the louder sound.
- If the difference is 1 dB, add 2.5 dB to the louder sound.
- If the difference is 2 dB, add 2 dB to the louder sound.
- If the difference is 4 dB, add 1.5 dB to the louder sound.

- If the difference is 6 dB, add 1 dB to the louder sound.
- If the difference is 8 dB, add 0.5 dB to the louder sound.
- If the difference is 10 dB or more, take the louder sound by itself.

The last point explains that one can measure the sound level emitted by a specific source, for example, by a loudspeaker or a rumbling machine, even when background sound is present if the source is at least 10 dB louder than the background.

Psychophysics of hearing

Physical measurements describe acoustical events, but people interpret them and react to them in very subjective ways, for example, finding certain sounds attractive or annoying. The sensation of a tone or of a complex sound depends not only on its intensity and frequency, but also on how we feel about it.

Loudness

Because of the special sensitivities of human hearing, both the frequency and the intensity of a sound affect our perception of its loudness in a rather complex manner. Sounds of more than 100 dB are earsplitting at all frequencies, but quieter sounds show different patterns, especially so at frequencies below 1000 Hz. Figure 6.4 displays the so-called phon° curves: they

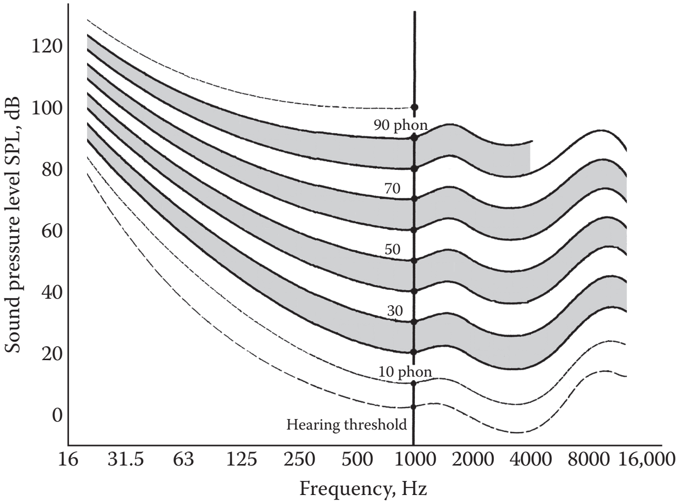

FIGURE 6.4 Phon curves represent combinations of sound pressure and frequency that we sense as equally loud. (Adapted from International Organization for Standardization, ISO 226-2003: Acoustics–Normal Equal-Loudness-Level Contours, International Organization for Standardization, Geneva, 2003.)

indicate which combinations of tone frequency and sound pressure appear of equal loudness as they do at 1 kHz. The highest contour is the threshold of pain; the lowest contour is the minimal threshold of hearing.

Equally loud

Following a phon contour, such as that of 50 phon, one learns that at frequencies below about 500 Hz, the SPL of low-frequency tones must be increased so that they appear equally loud: for example, a 50 Hz tone must have about 85 dB to sound as loud as a 1000 Hz tone with 50 dB. A 50 Hz tone at 45 dB is barely audible, similar to a 200 Hz tone at 15 dB; both are near the zero phon contour. However, at higher frequencies, especially in the range of approximately 2000–5000 Hz (where healthy hearing is rather sensitive), the tone intensity can be lowered and it still sounds as loud as at 1000 Hz. Yet around 8000 Hz, the SPL must be increased again, above the level of 1000 Hz, to sound equally loud.

These curves of equal loudness are valid only for pure tones because they do not reliably reflect the subjective impression of loudness if we hear different frequencies at the same time, which is the case in most of our daily environments. In spite of some doubts about their accuracy°, the phon curves do illustrate the sensitivity of human hearing at different frequency ranges; for example, Figure 6.4 shows that low-frequency (bass) tones at small intensities are difficult to hear.

Measuring like human hears

Filters on sound-measuring equipment can imitate human sensitivity to tones of different frequencies. These filters, usually in the form of software, correct the physical readings to what the human perceives. The A filter° mimics the human hearing response at 40 dB. The notation dBA or dB(A) denotes A-corrected SPL values.

Responses to music

Music is among the oldest human expressions and art forms. Making music has long accompanied activities, for example, singing during fieldwork, rhythmical tunes for marching. Yet even today, little is known systematically about the psychophysical consequences of different kinds of music and rhythm and their effects on well-being and productivity.

"Music while you work" is meant to break up monotony, to generate mild excitement and an emotional impetus toward activity. It is usually not continuous (as most background music° is, discussed below) but programmed to appear at certain times; it commonly has varying rhythms with vocals, and it may contain popular hits. Such music played while people work has been linked to improved morale and productivity, but a definite proof of connections between specific components of music and arousal theory is difficult. Thus, selecting the musical content, the rhythm, the loudness, and the presentation at certain times during work is a matter of guesses rather than of science.

Muzak

Background music, also called *muzak*, appears like acoustical wallpaper in places like shops, hotels, and waiting rooms. It is meant to create a welcoming atmosphere, to relax customers, to reduce boredom, and to mask disturbing sounds. Usually, its character is subdued, its tempo intermediate, and it does not contain vocals. It may produce a monotonous environment for those continuously exposed to it, although it may feel pleasant to the transient customer.

Music is art

Certain kinds of music do appeal to different individuals under varying circumstances, yet predicting the relations between listeners and tunes and choosing particular kinds of music for certain activities, environments, and listener populations is an art. Providing music is popular partly because it appears to have plausible effects, partly because it is a useful market ploy: many people seem to be happier and more productive when there is something humming into their ears. And even if it is not effective, music appears harmless when it is quiet and if the listener can turn it on or off.

Acoustic experiences

Some interesting acoustic events occur°:

- Directional hearing: Humans are able to tell from where a sound is coming by using the difference in arrival times (phase difference) or in intensities (as a result of the inverse square law of energy flux) to determine the direction of the sound. Yet the ability to use stereophonic cues varies among individuals and is much reduced when earmuffs are worn.
- Distance hearing: The ability to determine the distance of a sound source is related to the fact that sound energy diminishes with the square of the distance traveled, but the human perception of energy also depends on the frequency of the sounds, as just discussed. Thus, a source of sound appears more distant when it is low in intensity and frequency and appears closer when it is high in intensity and frequency.
- Frequency shifts: As the distance between the source of sound and the ear decreases, one hears an increasingly

higher pitch; as the distance increases, the sound appears to become of lower frequency. The larger the relative velocity, the more pronounced is the shift in frequency. This so-called Doppler effect can be used to measure the velocity at which the source and the receiver move against each other.

- Common-difference tone: When a common frequency interval of 100 Hz or more separates several tones, one hears an additional frequency based on the common difference. This effect explains how one may hear a deep bass tone from a sound system that is physically incapable of emitting such a low tone.
- Concurrent tones: When two tones of the same frequency are played in phase, they are heard as a single tone, its loudness being the sum of the two tones. Two identical tones exactly opposite (180°) in phase cancel each other completely and cannot be heard. This physical phenomenon (called destructive interference or *phase cancellation*) can be used to suppress the propagation of acoustical or mechanical vibrations and, with current technology, is particularly effective at frequencies below 1000 Hz.

6.3 Noise and its effects

Noise

Noise is any unwanted and objectionable sound, loud or quiet: many aspects of noise are psychological and subjective. For instance, the dripping of water produces single and short sounds of low intensity, which can appear as noise—just as a neighbor's loud, lasting, complex music may do. Noise surrounds us, day and night: at home, at work, anywhere. There are many sources of noise, such as traffic, barking dogs, construction, industry, spectator events, car races, shooting and hunting, even our own music that we like to hear through loudspeakers or headsets.

What noise can do

Any sound may be annoying and thus felt as noise. The threshold for noise annoyance varies depending on the conditions, including the sensitivity and the mental state of the individual. Noise can

- Create negative emotions, feelings of surprise, frustration, anger, and fear.
- Delay the onset of sleep, awaken a person from sleep, or disturb someone's rest.

- Make it difficult to hear desirable sounds.
- Produce temporary or permanent alterations in body chemistry.
- Interfere with human sensory and perceptual capabilities and thereby degrade the performance of a task.
- Temporarily or permanently change one's hearing capability.

Permanent threshold shift and temporary threshold shift

The noise-caused change in hearing capability of sound is physical, not merely psychological. The exposure to intense sounds, such as an explosion, can cause a permanent threshold shift (PTS), which is an irrecoverable loss of hearing; if the exposure is less acute, the result may be a temporary threshold shift, from which the hearing eventually returns to normal. A PTS may stem from damage to the bones of the middle ear; in the inner ear from damage to the cochlear cilia, the organ of Corti, the basilar membrane, or the nerves leading to the neutral nervous system. Which of these are injured depends on the frequency and, of course, on the intensity of the incident noise. The timing and the severity of the loss are dependent upon the duration of exposure, the physical characteristics of the sound (its intensity and frequency), and the nature of the exposure (whether it is continuous or intermittent). Damage may be immediate, such as by an explosion, or may occur over some time, such as with continuous exposure to noise.

One of the sinister aspects of noise-induced hearing damage is that the victim may not become aware of a developing injury and therefore does not take action to avoid more damage. Noise-induced threshold shift occurs, of course, first at the frequency range of the noise, typically around 4000 Hz, but then it spreads to higher and lower frequencies.

Effects of noise on task performance

Simple and repetitive tasks show little impairment by the presence of noise, but noise often degrades the execution of difficult tasks especially when they require attention, perception, and information processing. Unexpected and irregular noise causes greater degradation than continuous noise does; the sudden onset can create a startle response.

Signal-to-noise "ratio"

One of the most noticeable effects of noise is its interference with spoken communications and hearing of signals. Workers in loud environments often complain that they must shout to be heard and that they cannot hear and understand others who try to communicate with them. The difference between the intensities of speech (signal) and noise is critical to determine whether speech and signals can be detected in noise. For example, with speech at 80 dBA in noise of 70 dBA, the signal-to-noise relation, S/N°, is simply the difference, +10 dB (*not* the ratio, 80/70). The detection of a signal is a prerequisite for its discrimination from other signals, for the identification and the location of its source, for the recognition of its intended meaning or urgency, and for the judgment of its importance.

Shouting in noise

People have a tendency to raise their voices to speak over noise, and to return to normal when the noise subsides. (This is called the *Lombard reflex*.) In a quiet environment, males normally produce about 58 dBA; in a loud voice, 76 dBA; and when shouting, 89 dBA. Women normally have a voice intensity that is 2 or 3 dBA less at lower efforts and 5 to 7 dBA less at higher efforts. People can easily increase the S/N by raising their voices at low noise levels, but the ability to compensate lessens as the noise increases. Above about 70 dBA, raising one's voice becomes inefficient, and it is insufficient at 85 dBA or higher. Furthermore, this forced effort of a shouting voice often decreases intelligibility because the articulation becomes distorted at the extremes of voice output.

Noise-induced hearing loss

High-intensity noise can cause damage to hearing. In industrialized countries, noise-induced hearing loss (NIHL) usually occurs around 4000 Hz. It may spread into lower ranges, but it mostly extends into higher frequencies, culminating at about 8000 Hz. Yet reduced hearing at 8000 Hz (and above) is also brought about by aging. This may make it difficult to distinguish between cases related to noise or age.

Age-related hearing loss

Losing some hearing capabilities as one ages is normal. In general, we can expect the following reductions:

- 10 dB at 50 years
- 25 dB at 60 years
- 35 dB at 70 years

Figure 6.5 shows the hearing capabilities measured on the same person at 20, 70, and 80 years of age. The audiogram of the young person indicates fairly normal hearing with all measurement points close to the zero-loss line. However, at age 70, the hearing has been reduced by about 20 dB in all frequencies below 2000 Hz. Above 2 kHz, the audiogram shows the typical age and the noise-induced reduction, which is worst near

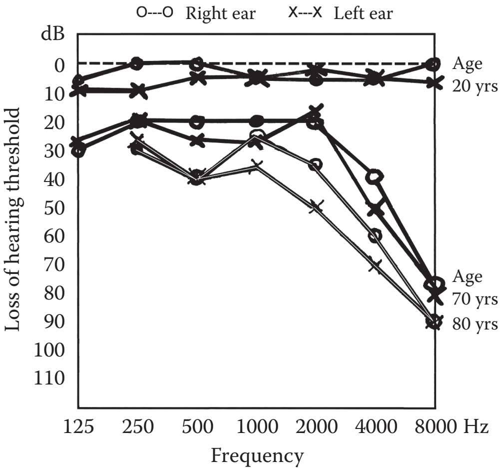

FIGURE 6.5 Audiogram taken on the same person at the ages of 20, 70, and 80 years.

8 kHz. The losses are even more pronounced at age 80: why the decline in the left ear is larger than on the right side remains unexplained.

Sounds that damage

Sounds that are sufficiently strong, lasting, or repetitive can damage one's hearing in the involved frequencies. Not all persons respond to sound in the same manner, but, in general, sound levels of about 85 dBA or more are potentially hazardous because of the energy that they contain. So the magnitude of the actual hearing loss directly relates to the sound level. In the United States, current regulations allow 16 hours of exposure to 85 dBA, 8 hours to 90 dBA, and 4 hours to 95 dBA, for example.

Signs of hazardous sounds

Simple subjective experiences can indicate whether one is exposed to a hazardous sound. The presence of a dangerous sound environment is indicated, for example, by hearing a sound that is appreciably louder than conversational level, by a sound that makes it difficult to communicate, by ringing in the ear (tinnitus) after having been exposed to a noisy environment, and by experiencing that sounds seem muffled to the naked ears after leaving a noisy area.

Three strategies to prevent NIHL

Exposures to excessive sound, in either level or duration or both, generate risks of NIHL. Common sources of noise are guns, many occupational environments, power tools, leaf blowers, chain saws, airplanes, vehicles, and, unfortunately, music (whether heard live or through loudspeakers or headphones). NIHL can occur whether one likes the sound or not.

Countering noise

There are three major approaches to fight the damaging effects of noise.

- Avoid generation: The first, fundamental, and most successful strategy is to avoid the generation of excessive sound by properly designing machine parts such as gears or bearings, reducing rotational velocities, changing the flow of air, or replacing a noisy apparatus with a quieter one.
- Leave the area: Another successful strategy is to remove humans from noisy places altogether, or do so at least for parts of the working time.
- Impede transmission: The last strategy is to impede the transmission of sound from the source to the listener. In occupational environments, one might try to put mufflers on the exhaust side of a machine, encapsulate the noise source, physically increase the distance between the source and the ear, and place sound-absorbing surfaces in the path of the sound.

Planning for "no noise"

Not generating sound is the one fundamentally successful way to avoid noise. Therefore, planning to avoid noise is most important for engineers and architects. This is primarily done by selecting such technologies and machines that do not produce unacceptable sounds. That principle applies to offices, where machines, keyboards, and conversations should be kept quiet. It applies to assembly facilities were no hand tools should be used that produce a racket, such as pneumatic cutters and mechanical riveters. This approach also applies to manufacturing for which machinery and processes should be selected that are quiet, by design and nature. Noisy engines can be muffled, clinking dies eliminated, and hammering and riveting replaced by welding and gluing. Of course, avoiding the generation of traffic noise in transportation is essential as well: mufflers on trucks and buses, cars, and motorcycles are required and so are noise-abating takeoff and landing procedures for airplanes on airport runways.

Prevent noise propagation

To engineer out unnecessary sound is an important tasks—but certain pieces of machinery, and certain jobs, are inherently noisy. In this case, the next step is to prevent noise propagation.

The laws of physics tell us that sound energy decreases with the square of the distance from the source. So the architect chooses to locate offices and other workplaces apart from the source of noise, such as traffic or machinery. If a factory itself is noisy, the sections were people work should be as far away from the sound sources as possible; intervening spaces, for example, used for storage, can act as buffers.

Noise barriers

Of course, the best way to reduce the propagation of sound is to completely enclose a noise source. However, we often put only a partial barrier between us and the noisemaker. Outdoors, having trees and bushes is helpful, although their usefulness as barriers depends on their density: with all the air spaces among foliage and branches, several rows of trees and bushes may be necessary to achieve sufficient sound abatement; bare trees in a leafless season do not work.

Another efficient way of reducing noise propagation to the human is to enclose people by buildings. Suitable materials for walls, doors, and windows can easily reduce the inside sound load by 20 to 30 dB. The weak spots are the openings for doors, windows, cables, and plumbing. Table 6.1 lists noise abatements that can be expected from building materials.

Table 6.1 Noise attenuation provided by building materials

Building component	Attenuation (dB)	Comment
Regular single door	20–30	Regular speech is clearly understandable[a]
Regular double doors	30–40	Loud speech is clearly understandable[a]
Heavy special door	40–45	Loud speech is audible[a]
Window, single glazing	20–25	
Window, double glazing	25–30	
Window, soundproofed	30–35	
Brick wall, 6–12 cm thick	35–40	
Brick wall, 25–38 cm thick	50–55	
Double brick walls, spaced apart, each 12 cm thick	60–65	

[a] On the other side of the door.

Hearing-protection devices

The last resource for protecting human hearing is to wear a hearing-protection device° (HPD) that reduces the harmful or annoying effects of sounds. HPDs are either worn externally (usually as sound-isolating helmets or earmuffs) or as earplugs inserted into the ear canal. These hearing protectors are variously effective, depending partly on the intensity and the frequency spectrum of the sound arriving at the ear and partly on the fit of the protector to the wearer's ear.

Passive HPDs

Conventional HPDs are passive: they achieve attenuation by making sounds pass through material that absorbs, dissipates, or otherwise impedes energy flow. In spite of these simple features, conventional HPDs can be highly protective—if they are selected properly and worn correctly—by impeding ambient noise above about 80 dBA that would overly strain human hearing. One unfortunate trait of most passive devices is that they reduce high-frequency sound more than low-frequency sound, which reduces the power of consonants and distorts speech. Persons who have already suffered a hearing loss at higher frequencies therefore experience further difficulties in understanding speech when they use a conventional HPD.

Plugs and muffs

Below 500 and above 2000 Hz, as a rule, earplugs provide greater noise attenuation than earmuffs do, whereas earmuffs are typically more effective in attenuation between 0.5 and 2 kHz. For any type of HPD, the effectiveness strongly depends on the proper fitting and use of the devices. A poor initial fit, loosening of the device during activity, and, of course, not even wearing the equipment cut its effectiveness. The user generally finds muffs easier to fit, although, in hot and humid environments, they may be uncomfortable—yet they can be used to insulate the ears from a cold environment.

Speaking and hearing while wearing an HPD

Generally, conventional HPDs cannot differentiate between the energies of speech and noise and hence cannot selectively pass the desired signals. Therefore, most devices do not directly improve the S/N. However, they can occasionally improve clearness in intense noise by lowering the total energy of both speech and noise that reaches the ear, thereby reducing distortion due to overload in the cochlea. An HPD has little or no degrading effect on intelligibility in noise above about 80 dBA, although it can reduce hearing acuity during quiet periods (when worn even though protection is not needed). Some of the negative effects of the device may be due to the tendency to lower one's own voice because the protector amplifies the bone-conductive voice feedback inside the head, mostly at low frequencies. Consequently, we may perceive our own voice as louder in relation to the noise than it actually is, often resulting in a compensatory lowering of the voice by 2–4 dB. Therefore, one should make a conscientious effort to speak louder when wearing an HPD.

Active HPDs

Since conventional hearing protection devices alter *all* received signals, and may affect the judgment of sound content, direction, and distance, newer hi-tech HPDs have attenuation qualities that can adjust to prevailing noise levels, job demands, and individual users' hearing abilities. Active noise-reduction HPDs use destructive interference by generating sound waves that are of the same nature as the noise but 180° out of phase. Such noise cancellation works particularly well below 1000 Hz. With high-speed signal processing, active HPDs combine noise abatement and improved communication; typically they cancel external noise and then transmit desired signals such as speech or music.

Voice communications

Understanding verbal communications is a psychological process that requires suitable acoustical conditions. A sufficient portion of the voice message must penetrate the noise to achieve understanding. Face-to-face communication provides visual cues that enhance the intelligibility of speech, even in the presence of background noise. Indirect voice communications lack the visual cues. The distance from the speaker to the listener, the background noise level, and the voice level are important considerations. The ambient air pressure and the gaseous composition of the air affect the efficiency and the frequency of the human voice and, consequently, of speech communication.

Intelligibility

The ability to understand the meanings of words, phrases, sentences, and entire speeches is called *intelligibility*. For satisfactory communication of voice messages over noise, usually at least 75% intelligibility is required. The intensity of a speech signal relative to the level of ambient noise is a fundamental determinant of the intelligibility of speech. The commonly used speech-to-noise ratio is, in fact, not a fraction but a difference, as mentioned earlier. With an S/N of 10 dB or higher, people with normal hearing should understand at least 80% of spoken words in typical broadband noise. As the S/N falls, the intelligibility drops to about 70% at 5 dB, to 50% at 0 dB, and to 25% at –5 dB. People with reduced hearing capability often experience larger reductions in intelligibility.

Understanding speech

In voice communication, frequencies are from about 200 to 8000 Hz, with the range of about 1–3 kHz most important for intelligibility. Men use more low-frequency voice energy than women do. Filtering or masking frequencies below 600 or above 3000 Hz has little effect on intelligibility, but interfering with voice frequencies between 1000 and 3000 Hz drastically reduces understanding. In speech (as is also true with written text), consonants are more critical for understanding words than are vowels. Unfortunately, consonants have higher frequencies and, concurrently, generally lesser speech energy than vowels and are therefore more readily masked by ambient noise; hence, they are more difficult to understand, especially for older persons.

Components of speech communication

Speech communication has five major components:

1. The message
2. The speaker
3. The transmission of the message
4. The environment
5. The listener

The message itself becomes clearest if its context is expected, its wording is clear and to the point, and the ensuing actions are familiar to the listener. The speaker should speak slowly and distinctly and use common and simple vocabulary with only a limited number of terms. Redundancy and use of phonetically discriminable words can be helpful. The International Spelling Alphabet is shown in Table 6.2. The transmission of

Table 6.2 International spelling alphabet

A: Alpha	N: November
B: Bravo	O: Oscar
C: Charlie	P: Papa
D: Delta	Q: Québec
E: Echo	R: Romeo
F: Foxtrot	S: Sierra
G: Golf	T: Tango
H: Hotel	U: Uniform
I: India	V: Victor
J: Juliet	W: Whiskey
K: Kilo	X: X-ray
L: Lima	Y: Yankee
M: Mike	Z: Zulu

speech should be by a high-fidelity system that produces little distortion in frequency, amplitude, or time. The listener's natural ability to understand the message is, of course, affected by environmental noise.

Design of warning signals

Warning signals should be carefully designed to penetrate surround sound; one solution is to use frequencies below 500 Hz. A positive side effect of low frequencies is that they easily diffract around barriers; however, they need very high sound pressure levels to be heard—see Figure 6.4. Therefore, most warning signals are in the range of 1000–4000 Hz, unless noise is prevalent in these frequencies. If such masking noise exists, its harmonic frequencies (double, triple, etc.) should not be used for signals. Signals should be in contrast to the masking noise, in tonal qualities such as intensities and frequencies, and in their modulation over time, such as by increases and decreases. A rule of thumb is that the intensity of a signal should be about 15 dB above any masking noise levels. In can be very effective to combine auditory signals with other indicators that are seen or felt, such as lights and vibrators.

Improving defective hearing

Many deficiencies in hearing, natural or caused by noise, can be remedied with modern digital hearing aids. In contrast to older analog devices, they are smaller, are less likely to malfunction (whistle), can actively filter out background noise, can amplify desired sounds, and even make the sounds clearer.

Hearing aids

Hearing aids that are fitted to the ear canal are popular because they are easily hidden but they may give a stuffed-up feeling if they block the ear canal. That blockage may prevent the wearer from benefiting from actually existing hearing ability. Many current open-ear hearing aids sit behind the top of the pinna of the ear, but, in contrast to traditional behind-the-ear fittings, these new devices are small and have a barely visible thin tube that extends into the ear canal: they are fairly comfortable to wear and easy to switch on and off.

Adjustments

New hearing aids often have a surround microphone, manual or automatic, which picks up sound no matter where it comes from. Some new devices provide different adjustments for varying environments: one setting for a quiet room, one for a concert, and yet another for use in a restaurant, for example. These options are preprogrammed, so all one has to do is select the proper setting, possibly with a remote control; some devices switch to the suitable setting automatically. Another feature is the automatic adjustment between the aids for the left and right ears, when the person can hear better in one ear than in the other. The technology can also automatically fine-tune the sections in both ears as the listening environment changes.

Surgical implants Several kinds of surgical implants can help persons with severe hearing loss.

- Bone-anchored hearing aids work for those with single-sided deafness. A transmitter, attached to the skull on the deaf side, picks up sound and then conducts it to the good side.
- Middle ear implants can help people with mild to moderate hearing loss. They attach directly to the middle ear bones and amplify sound signals. A component behind the ear houses the microphone, the sound processor, and the battery.
- Cochlear implants help in the case of severe hearing loss. They convert sound into nerve impulses and send them to the brain. A transmitter is placed under the skin behind the ear, and electrodes are implanted inside the cochlea.

Some techniques can be used in combination, such as cochlear implants with bone-anchored hearing aids.

Summary

Our ears provide information that we need in daily life and at work. The acoustic information is coded in combinations of sound frequencies and of intensities that change over time. We interpret that information according to our individual experiences and hearing capabilities.

Noise surrounds us. It can be a mere annoyance, it may interfere with sleep and rest, it can reduce our well-being and affect our performance, and it may damage our ability to hear. To avoid noise-induced damage, various hearing protection devices are available, some of which can actively improve the perception of sound signals.

Fitting steps

Step 1: Make sure that the ears function properly: if in doubt, see an ear physician.

Step 2: Provide a suitable acoustic environment; avoid noise and its effects.

Step 3: Wear appropriate hearing protection as needed.

Notes

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

6.2 Hearing Sounds:

Infrasound: More on felt mechanical vibrations in Kroemer, Kroemer, and Kroemer-Elbert 2003; Stanton et al. 2005.

Loudness is stated in a logarithmic unit: The measuring unit decibel, dB, is more convenient to use in acoustics than the basic unit Bell, B. 1 dB = 1/10 bel.

Music at work: Fox 1983; Owen 2006.

Acoustic events: Adapted from Kroemer, Kroemer, and Kroemer-Elbert 2003.

The signal-to-noise relation, S/N: Oddly, the algebraic difference between the intensities of signal and noise has been mislabeled as a ratio.

Phon curves are equal-loudness contours, developed by Fletcher and Munson in 1933, now defined in international standard ISO 226:2003; Permanen 2012.

A filter: McMin 2013.

6.3 Noise and its Effects:

Hearing-protection devices: Berger et al. 2003; Casali and Gerges 2006; Casali and Robinson 2006.

CHAPTER SEVEN

How we sense objects and energy

We have several kinds of body sensors that are usually active at the same time to provide redundant information to us. For example, a bicyclist feels body movement, speed, and terrain bumps through tactile and haptic sensors; sees the path ahead and the objects in the immediate proximity as he or she rushes by; and hears warning signals coming from other riders or vehicles. A blind person moves the fingertips over Braille to "read" text that the eyes cannot see. We bring our hand cautiously close to an object to find out whether it is hot. We can touch an object to determine whether its surface is smooth or rough. Yet architects and engineers have made surprisingly little use of the existing information about human sensory capabilities. For example, round doorknobs give no indication, by feel or view, in which direction they must be turned to open the door; emergency bars that one must push to open a hinged door usually provide no cues, neither for touch nor for vision, as to which side the door will open.

7.1 Sensing body movement

Combined signals The central nervous system (CNS; see Chapter 9) receives signals from various human senses simultaneously, providing us with specific information that generates a general picture of the events taking place within and outside the body. For example, as we lift a load, muscle and skin sensors tell us what force we exert on the object. We know how it moves even if we cannot see it because the Ruffini joint organs report the location of our limbs and the angles of their joints; and cutaneous sensors provide more details because the bending of a joint stretches some skin around the joint and relaxes other sections.

Vestibulum

The vestibulum provides the primary information about posture and movement of the body. It is a pea-sized nonauditory organ, located in each inner ear, next to the cochlea. The vestibulum has three semicircular canals, shown in Figure 7.1, filled with fluid (endolymph). The arches of the three vestibular canals are at about right angles to each other, which makes them sensitive to different rotations of the head. Although the canals share a common cavity in the utricle, each canal functions like an independent fluid circuit. Close to its junction with the utricle, each canal has a widening (called *ampulla*), which contains a protruding ridge, which carries cilia, sensory hair cells: they respond to displacements of the endolymph. Cilia are also located in both the utricle and the saccule. The hair cells generate signals that travel along the vestibular nerves to the CNS.

Sense of body balance

The vestibulum informs us about body balance because it senses the magnitude and the direction of accelerations of the head, including the gravitational pull. The system adapts to constant acceleration, and it may not perceive small changes. Placing the head into a new posture requires that the brain compare signals not only with a new spatial reference system, but also with new inputs from the sensors, because the endolymph now loads the cilia in different ways. With the many other signals

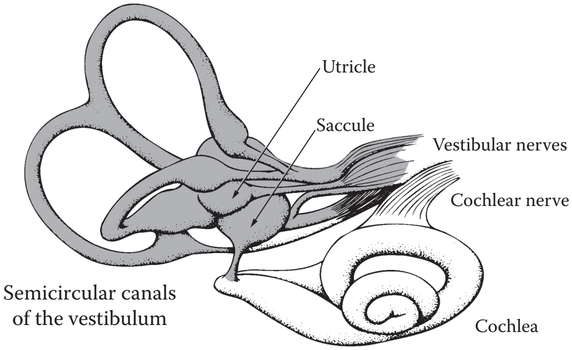

FIGURE 7.1 The three semicircular canals of the vestibulum. (Adapted from Kroemer, K. H. E., Kroemer, H. J., and Kroemer-Elbert, K. E., *Engineering Physiology: Bases of Human Factors/Ergonomics*, fourth ed., Springer, Heidelberg, Germany, 2010.)

simultaneously coming from various other sensors, which also relate to the body's position and motion, the brain has a complex task of integration and interpretation. Thus, it is not surprising that several vestibular illusions can occur. The best known of these is motion or space sickness, which is probably due to conflicting inputs from the vestibular and other sensors. Others are as follows:

- When the body is aligned with the gravitation vector, for example, of a person in an airplane that turns left or right, one does not perceive the plane's roll.
- Illusionary tilt is the interpretation of linear acceleration as body tilt.
- Elevator illusion is a change in gravitational force that produces an apparent rise or lowering of seen objects.
- A person in zero gravity, or lying in a prone position, may have the illusion of inversion, of being upside down.

7.2 The feel of objects, energy, and pain

Four different groups of sensory capabilities rely on sensors located in the skin°:

- Mechanoreceptors, which sense taction as contact or touch, tickling, pressure.
- Thermoreceptors, which sense warmth or cold, relative to each other and to the body's neutral temperature.
- Electroreceptors°, which respond to electrical stimulation of the skin.
- Noci(re)ceptors° (from the Latin *nocere*, "to damage"), which sense pain. Some sensors are deep inside the body.

Taction

The taction sense relates to contact and touch at the skin. One speaks of a tactile sensation when the stimulus solely acts at the skin, while a haptic sensation exists when information flows at the same time from sensors in muscles, tendons, and joints (kinesthetic proprioceptors). Most of our everyday perception is haptic.

Tactile sensors

The most common type of tactile sensors is a free nerve ending, a proliferation of a nerve that dwindles in size and then disappears. Thousands of such tiny fibers extend through the layers of the skin. They respond particularly to mechanical displacements and are most sensitive near hair follicles. In smooth and hairless skin, encapsulated receptors are also common and are shown in Figure 7.2. Among these are the Meissner and the similar Merkel corpuscles; both respond to pressure. They are especially numerous in the ridges of the fingertips. The Pacinian corpuscle is an encapsulated nerve ending of a single, dedicated nerve fiber. These highly responsive tactile receptors are densely located in the palmar sides of the hand and the fingers and in distal joints. They are also prevalent near blood vessels, at lymph nodes, and in joint capsules. Krause end bulbs are particularly sensitive to cold but probably respond to other stimuli as well.

In 1826, E. H. Weber° demonstrated that skin sensors react to the location of a stimulus, and to certain kinds of stimuli, especially force or pressure, warmth, and cold. Yet, in spite of nearly 200 years of research, the sense of taction is still not fully understood. Taction stimuli are often not well defined: What is the relation between pressure, force, and touch? Which sensors respond to each stimulus in what way? Do the sensors respond singly or in groups? If in groups, in what patterns do they respond? Does one sensor respond to only one stimulus or to several stimuli? A single Meissner corpuscle may connect to up to nine separate nerves, which may also branch to other

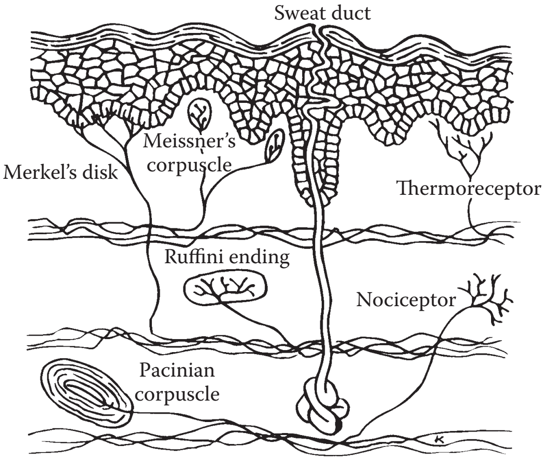

FIGURE 7.2 The common skin sensors. (Adapted from Kroemer, K. H. E., Kroemer, H. B., and Kroemer-Elbert, K. E., *Ergonomics: How to Design for Ease and Efficiency*, second ed., Prentice-Hall/Pearson Education, Upper Saddle River, New Jersey, 2003 amended reprint.)

corpuscles. It is not clear how such simultaneous convergence and diversion of neural pathways can reliably generate and code neural signals.

Temperature

Our temperature sensations are relative and adaptive. Objects at skin temperature appear as neutral or indifferent, at "physiological zero." We call a temperature below this level *cool* and a temperature *warm* if it is above. Slowly warming or cooling the skin near physiological zero may not elicit a change in sensation. That range of temperature neutrality differs in parts of the body; for the forearm, the neutrality zone is from approximately 31 to 36 degrees Celsius.

Feeling cold or warm

Some nerve sensors respond specifically to falling and cold temperatures, whereas others react to increasing and hot temperatures. The two scales may overlap, which can lead to paradoxical or contradictory information. For example, spots on the skin, which consistently register cold when stimulated, may also report "cold" to a warm object of about 45°C. An opposite paradoxical sensation of warmth also exists. We sense more easily changes from physiological neutral toward warm temperatures than changes toward cold temperatures. Warm sensations adapt within a short period, except at rather high temperature levels. Adaptation to cold is slower and does not seem to occur completely. Rapid cooling often causes an overshoot phenomenon; that is, for a short time, one feels colder than one physically is. Chapter 8 discusses more interactions of the body with the environment.

Sensing electricity

While one feels electrical currents on the skin, we still do not know of a receptor specialized to sense electrical energy; electricity can apparently arouse almost any sensory channel of the peripheral nervous system. The threshold for electrical stimulation depends heavily on the configuration and the location of the electrode used, the waveform of the electric stimulus, the rate of stimulus repetition, and the individual subject. Generally, the threshold is about 0.5 to 2 mA if the pulse lasts 1 ms.

Pain

Tissue injury, hard touch or pressure, electricity, and warmth and cold can arouse unpleasant, burning, itching, or painful sensations. Some related research results are difficult to interpret because of the various levels and categories labeled "pain." Current understanding is that nocireceptors and other nerve cells possess specialized molecules for detecting pain-causing stimuli. The cells transmit signals to the nerve cells in the spinal cord and on to the brain, which identifies the messages as painful. We may feel sharp or piercing pain, usually associated with events on the surface or in the teeth or the head, and dull or numbing pain, often coming from deep in the body.

Pain can range from barely felt to unbearable. The threshold for pain is highly variable, probably because pain is so difficult to separate from other sensory and emotional components. Under certain circumstances and to certain stimuli, one can even adapt to pain. Some people have experienced so-called second pain, which is a new and different pain wave following a primary pain after about two seconds. *Referred pain* indicates the displacement of the location of the pain, usually from its visceral origin to a more cutaneous location; an example is the appearance of cardiac anginal pain in the left arm.

Not all pain is worrisome. For example, the acute kind that accompanies a minor tissue injury is protective because it encourages us to avoid further damage. This kind tends to be temporary and to lessen over time.

7.3 Designing for tactile perception

In modern daily life, we mostly rely on our vision and audition for information input, while other senses remain underused, for instance, touch and smell. Some of that disparity of use has to do with what is technically practical, but there is also a lack of specific and quantitative knowledge about how other human senses work. Apparently, many current engineering applications mostly rely on past experience because very limited experimental data are at hand. Yet new technology easily leads to novel uses such as making a portable phone produce a sound and, at the same time, also vibrate to alert us that somebody is trying to call.

Research needs

Indeed fairly little is still known about using our sense of smell (olfaction) for engineering purposes; but we know that our reactions to odors are slow, similar to our (gustation) reactions to tastes in food and drink. Surprisingly, after about two centuries of studying the human senses, even our knowledge about the cutaneous sensitivities is still spotty. First, stimuli were often not well defined in older research. Second, sensors are located in different densities all over the body. Third, the functioning of sensors is not exactly understood: many sensors react to two or more distinct stimulations simultaneously and produce similar outputs, and it is often not clear whether or which specific sensors respond to a given stimulus. Fourth, the pathways of signal conduction to the CNS are complex; they may be a composite of several afferent paths from different regions of the body. Finally, the CNS interprets arriving signals in unknown manners. Given all these uncertainties, much more research needs to be performed to provide complete, reliable, and relevant information on the cutaneous senses for use in human-engineered design°.

Taction sensitivity

Given the lack of reliable experimental information, the following guidelines for design applications of the taction sense mostly rely on extrapolations of experience and on educated guesses.

Mechanoreceptors can differentiate touch information by the following:

- The strength of the stimulus
- The temporal rate of change
- The size of the area of the skin (i.e., the number of receptors) stimulated
- The location of the stimulated skin

Sensitivity to taction stimuli is highest in the facial area and at the fingertips, fair at the forearm and the lower leg. Some other body areas, such as the eyes, are most sensitive, but are obviously out of bounds.

Tactile sensitivity also depends on temperature: for example, if a stimulus of low intensity appears slowly on cold skin, it may not be noticed.

Using temperature signals

For several reasons, our sense of temperature is difficult to use for communication purposes. It has a relatively slow response time, and it is poor in identifying location. Furthermore, it adapts to a stimulus over time and it may integrate into one signal several stimuli that are distributed over an area of skin. Finally, interactions exist between mechanical and temperature sensations; for example, a cold weight feels heavier on the skin than a warm weight.

The strength of thermal sensation depends on the location and the size of the sensing body surface. The temperature sensation is made stronger by increasing the following:

- The absolute temperature of the stimulus, and its difference from physiological zero
- The rate of change in temperature

- The exposed surface; an example is the immersion of the whole body in a bath as compared to the immersion of a hand or a foot.

Assuming a neutral skin temperature of about 33°C, the following rules of thumb apply for naked human skin:

- A skin temperature of 10°C appears painfully cold; 18°C feels cold; and 30°C still feels cool.
- The highest sensitivity to changes in coolness exists between 18 and 30°C.
- Heat sensors respond well throughout the range of about 20 to 47°C.
- Thermal adaptation—that is, physiological zero—can be attained in the range of approximately 18 to 42°C, meaning that changes are not felt when the temperature difference is less than 2°C.
- Distinctly cold temperatures (near or below freezing) and hot temperatures above 50°C provoke sensations of pain.
- Compared to warmth, cold is sensed more quickly, particularly in the face, the chest, and the abdominal areas. The body's ability to feel warmth is less distinct, but it is best in hairy parts of the skin, around the kneecaps, and at the fingers and elbows.

Using the smell sense

Olfactory information is seldom used by engineers, because few research results are available, because people react quite differently to olfactory stimuli, because smells can be easily masked, and because olfactory stimuli are difficult to arrange. Among the few industrial applications is allowing people smell leaking gas by adding odorous methyl mercaptan to natural gas and pyridine to argon. Some restaurants seem to attract customers by emitting enticing food smells.

Using electric signals

Electricity is seldom used as an information carrier, although it has great potential for transmitting signals to the human. Attaching electrodes is convenient. The energies that are transmitted are low, requiring only about 30 μW at the electrode–skin junction, up to a tolerable limit of about 300 mW. Coding can be via placement, intensity, duration, and pulsation. Electrical stimulation can provide a clear, attention-demanding signal that is resistant to masking; however, responses to weak electrocutaneous signals usually have a long response latency, many misses, and false alarms. In complex environments that require a heightened level of vigilance, electrical signals are suitable to provide redundancy.

Do not use pain as signal stimulus

Pain does not lend itself to engineering applications, primarily because one is ethically bound not to cause pain, but also because the sensation of pain follows any damage already done too slowly to prevent more damage.

Reaction and response

Reaction time° is the period from the appearance of a stimulus (such as electrical signal, touch, or sound) to the beginning of a responding effector action (for example, movement of a hand):

Reaction time + motion time = response time

Simple reactions

Table 1.7 lists approximate shortest possible simple reaction times. This is a selective compilation of data from many experiments on reaction time, which were conducted before the 1960s and have appeared in engineering handbooks. Today, the origin of most underlying data and the experimental conditions under which they were measured and the accuracy of the measurements are no longer known.

This list shows little time differences in reactions to electrical, tactile, and sound stimuli. The slightly longer reaction times for sight and temperature stimuli may lie well within the range of measuring accuracy or of variations among persons. However, the time following a smell stimulus is distinctly longer and that for taste yet longer; it takes by far the longest to react to the infliction of pain.

Complex reactions

Table 7.1 contains so-called *simple reaction* times; they apply if a person knows that a particular stimulus will occur, is prepared for it, and knows how to react to it. If conditions become more complex, such as when there is uncertainty about the appearance of the signal, the reaction takes longer. If a person has to choose among several actions that can be taken, so-called *choice reaction* is involved, which takes longer than a

Table 7.1 Shortest reported simple reaction times

Sensory stimulus	Approx. shortest reaction time (ms)
Electric shock	130
Touch and sound	140
Sight and temperature	180
Smell	300
Taste	500
Pain	700

simple reaction. Time expands even further if it is difficult to distinguish among several stimuli of which only one should trigger the response. This indicates that one should expect, in real-life situations, reaction times that are considerably longer than those listed in Table 7.1.

Motion time

Motion time follows reaction time. Movements may be simple, such as lifting a finger in response to a stimulus, or complex, such as swerving a car to avoid a collision. Swerving the car involves not only more intricate movement elements than lifting a finger but also larger body and vehicle masses that must be moved, which takes time.

Response time

Minimizing response time—the sum of the reaction and the motion lags—is often a goal of human factors engineering. This involves three intertwined choices: selecting

- the stimulus most appropriate to the situation, which initiates the shortest possible reaction time
- the body part that is best suited to do the task of reacting
- the equipment that allows the fastest execution of the task

Chapter 9 expands the foregoing discussion of actions and reactions in feedforward and feedback loops.

Summary

Much of our daily life relies on receiving information from our environment and appropriately interpreting it to guide our actions. Obviously, this is one of the most ancient and natural features that we use instinctively. Research done during the last century or so has explained the overall sensory processes and many of their intricacies, but many details are still unknown or uncertain. The lack of technically useful information offers many opportunities and challenges for future investigations; examples are the perception of smell, temperature, and electrical signals.

Fitting steps

Step 1: Select the primary stimulus to provide critical information.

Step 2: Add a secondary stimulus of a different type as supplement or backup.

Step 3: Establish and fine-tune the parameters of the stimuli.

Notes

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

7.2 The feel of objects, energy, and pain:

Skin: Sensors located in the skin are called *cutaneous* (from *cutis*, Latin for *skin*) or *somesthetic* (from *soma*, Greek for *body*); Jarrett 1973.

Electroreceptors: It is has been disputed whether such specific sensors exist, or whether the related sensations stem from the stimulation of other taction sensors. A similar discussion concerns nocireceptors: some researchers hold that there are no specific pain sensors, but that other sense organs transmit pain. More information by Basbaum and Julius (2006) and Boff and Lincoln (1988).

Ernst Heinrich Weber, 1795–1878, is called the founder of experimental psychology.

7.3 Designing for tactile perception:

Research needs on human sensory capabilities for engineering applications: Gavande 2008; Kroemer 2006c, Chapter 2.

Reaction and motion times: More details by Boff, Kaufman, and Thomas (1986), Boff and Lincoln (1988), and Kroemer, Kroemer, and Kroemer-Elbert (2003).

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CHAPTER EIGHT

How we experience indoor and outside climates

The human body generates heat: the amount of heat production fluctuates with the intensity of the physical work done. The body must dissipate excess heat to its surroundings: this is easy in a cold climate but difficult in a hot environment.

Two overriding facts govern the heat flow within the body, and the exchange of heat with the environment:

1. Physiology: The body core temperature must remain close to 37°C.
2. Physics: Heat flows from the warmer to the colder matter.

The physiological requirement of keeping the body core temperature the same establishes the need for proper human engineering of the environmental climate. The physics principle of heat energy flow from warm to cold provides the engineering tools to create suitable environmental climates.

8.1 Human thermoregulation

We are not "cold-blooded"—which is a somewhat misleading term—because our body temperature does not slavishly follow the outside temperature. The human body has a complex control system to maintain its internal body temperature near 37°C (99°F). A deviation in deep body temperature of just a few degrees from that value affects cellular structures, enzyme systems, and other body functions, and it impairs physical and mental work capacities. However, minor fluctuations in temperature occur throughout the day and from day to day, mostly due to circadian rhythms (see Chapter 15). Major impacts upon the human thermal regulatory system result from the interaction between the (metabolic) heat generated within the body (especially when it does strenuous work) and the external energy gained in hot surroundings or lost in cool environments.

Body heat production and distribution

The body produces heat in its metabolically active tissues: primarily at skeletal muscles, but also in internal organs, fat, bone, and connective and nerve tissue. Blood carries that heat energy throughout the body. The circulatory system is able to modulate the flow of blood by constriction, dilation, and shunting of its vessels, mostly of its superficial arteries and veins. This generates and controls heat dissipation from warmer to colder parts of the body. Heat exchange with the environment takes place at the body's respiratory surfaces of the lungs and, of course, through the skin.

Body heat control

The body regulates its heat content to prevent undercooling or overheating. The temperature of core tissues (such as the brain, heart, lungs, and abdominal organs) must be kept constant at about 37°C. So all the management of varying temperatures takes place in the body's external tissues. Accordingly, there is often a large temperature difference between the core and the shell. A gradient of about 4°C between the skin and deep inside the body is normal at rest in a comfortable climate, but in the cold, the temperature difference may be 20° or more.

Hot skin in a hot environment

Usually the body must dissipate heat energy through its skin and lungs in order to avoid overheating its core. That heat dissipation is not a problem if the environment is colder than the lung and skin surfaces because of the natural flow of heat from warm to cold. However, because of this physics principle, heat dissipation becomes a problem in an environment that is hotter than the body surfaces are. Nature's solution is trying to increase the skin temperature above the environment's temperature in order to evaporate water, sweat, on the skin. Evaporation of 1 cm^3 of water requires the energy of about 2440 J (580 cal); extraction of energy from the body cools the body. When it cannot disperse enough energy, the body must reduce its internal heat production, meaning that it abandons physical activities as much as possible.

Cold skin in a cold environment

If an environment is very cold, the body may have to struggle to conserve its heat; it primarily does this by reducing the blood flow to the skin, which lowers its temperature and hence reduces the outflow of heat. Obviously, increasing insulation by wearing proper clothing is a prudent action. When the body loses too much heat, it can increase its heat production by contracting muscles, done voluntarily or by reflex shivering; both generate heat energy.

Heat exchanges with the environment

The body's heat control systems (muscular, vascular, and sudomotor, as discussed earlier) must interact with the physical components of the environment. The interactions are by convection, conduction, radiation, and evaporation.

Heat exchange by convection or conduction

Traditionally, one calls energy exchange with air or water *convection*, but it is called *conduction*° when it is with a solid matter. However, both rely on the same principle: 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 heat exchanged by convection or conduction is a function of

- The body surface area participating in the heat exchange
- The temperature of the body surface
- The temperature of the medium that is in contact with the body
- The heat conduction coefficient between the body and the medium

Cork or wood that we touch "feel warm" because their heat conduction coefficients are below that of the human tissue, but cool metal accepts body heat easily and conducts it away. Heat exchange is facilitated if the medium moves quickly along the skin surface, which helps in maintaining a temperature differential. As long as there is a temperature gradient between the skin and the medium, there persists some natural movement of air or fluid: this is called *free convection*. A forced action (by an air fan or while swimming in water rather than floating motionless) can produce more movement: this is called *induced convection* and is shown in Figure 8.1.

Heat exchange by radiation

Heat exchange through radiation° primarily depends on the temperature difference between two opposing surfaces, for example, between a windowpane and a person's skin. Heat always radiates from the warmer to the colder surface, for example, from the body to the cold window in winter or from a sun-heated pane to the body in summer—see Figures 8.2 and 8.3.

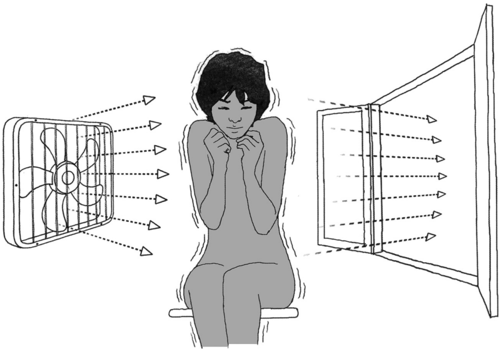

FIGURE 8.1 Air flow helps heat exchange by convection. (Adapted from Kroemer, K. H. E., and Kroemer, A. D., *Office Ergonomics*, Korean edition, Kukje Publishing, Seoul, South Korea, 2006.)

FIGURE 8.2 Heat radiated from the body to a cold windowpane. (Adapted from Kroemer, K. H. E., and Kroemer, A. D., *Office Ergonomics*, Korean edition, Kukje Publishing, Seoul, South Korea, 2006.)

This radiative heat exchange is not affected by the temperature of the air between the two opposing surfaces but it depends on

- The body surface area participating in the energy exchange
- The temperature of the emitting surface
- The emission coefficient of the emitting surface

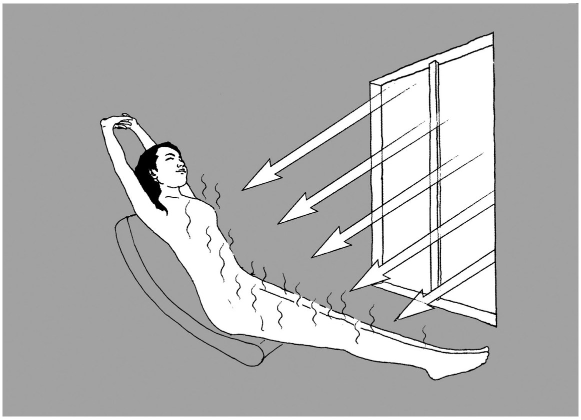

FIGURE 8.3 Heat radiated by the sun to the body. (Adapted from Kroemer, K. H. E., and Kroemer, A. D., *Office Ergonomics*, Korean edition, Kukje Publishing, Seoul, South Korea, 2006.)

- The absorption coefficient of the receiving surface
- The temperature of the receiving surface

The wavelengths of radiation from the human body are in the infrared range. Hence, it radiates like a black body, that is, with an emission coefficient close to 1 (unit), independent of the color of the radiating human skin. However, its absorption coefficient depends on skin color.

Heat exchange by evaporation

Heat exchange by evaporation is only in one direction: the human loses heat by evaporation. There is no condensation of water on the skin, which would add heat. The evaporation of water (sweat) on the skin requires an energy of about 2440 J (580 cal) for every cubic centimeter of water. The heat lost by evaporation depends on

- The volume of sweat evaporated (which is partly a function of the area of wet body surface participating in evaporation)
- The vapor pressure on the skin
- The relative humidity of the surrounding air
- The vapor pressure in the surrounding air

Of course, heat loss by evaporation requires that the surrounding air is less humid than the air directly on the skin. Therefore, the movement of the air layer on the skin not only enhances convection but also increases the heat loss through evaporation because dryer air replaces humidified air, as sketched in Figure 8.4. Evaporative heat loss occurs even in a cold environment because there is always evaporation of water in the warm lungs, and some secretion of sweat onto the skin surface continues during physical work.

Evaporation is by far more effective for body cooling than convection and radiation are, as Figure 8.5 illustrates, when the temperature of the environment is warmer than about 30°C.

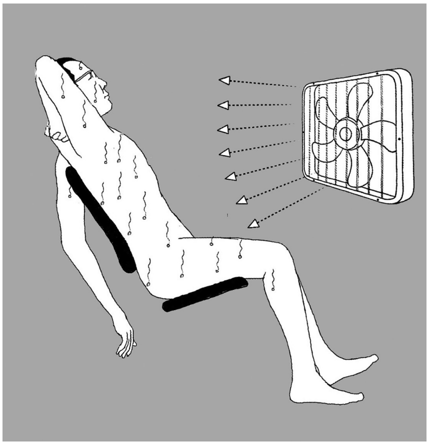

FIGURE 8.4 Air flow helps evaporation. (Adapted from Kroemer, K. H. E., and Kroemer, A. D., *Office Ergonomics*, Korean edition, Kukje Publishing, Seoul, South Korea, 2006.)

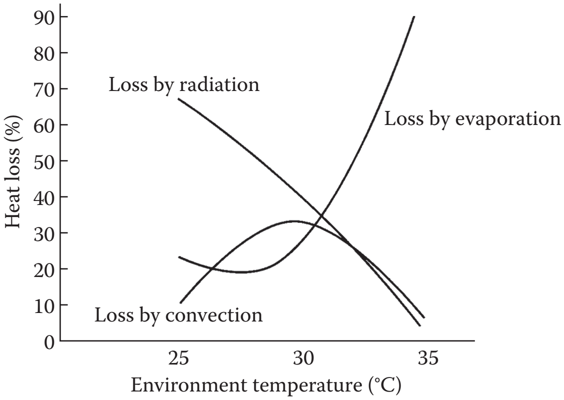

FIGURE 8.5 Cooling the body in a warm environment. (Adapted from Kroemer, K. H. E., Kroemer, H. B., and Kroemer-Elbert, K. E., *Ergonomics: How to Design for Ease and Efficiency*, second ed., Prentice-Hall/Pearson Education, Upper Saddle River, New Jersey, 2003 amended reprint.)

8.2 Climate factors: Temperatures, humidity, drafts

Four physical factors define the thermal environment:

1. Air (or water) temperature
2. Air humidity
3. Air (or water) movement
4. Temperature of surfaces

The combination of these four factors determines the physical conditions of the climate, its effects on us, and how we perceive it.

Measuring temperature

The measurement of temperature is commonly performed with thermometers, now usually filled with alcohol instead of mercury; or with thermistors or thermocouples. Whichever technique is used, it must be ensured that the ambient air temperature is not affected by humidity and air movement. To measure the so-called dry temperature of air, one keeps the sensor dry and shields it to reflect radiated energy; these are the main properties of the dry bulb (DB) thermometer.

Measuring humidity

Air humidity may be measured with a hygrometer: originally a human or a horse hair that changes its length with wetness, now an instrument whose electrical conductivity (resistance/capacitance) alters with the existing humidity. Another instrument is the psychrometer, which uses one dry bulb (DB) and one wet bulb (WB) thermometer; the wet bulb is more cooled by evaporation, in proportion to the humidity of the air. A psychrometer is called *natural* if there is no artificial air movement and *forced* if there is.

Vapor in the air

Air humidity may be stated either in absolute or in relative terms. The highest absolute content of vapor in the air exists 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 lower pressure allow more water content than cooler air under higher compression. One usually speaks of relative humidity, which indicates the actual vapor content in relation to the possible maximal content at the given air temperature and air pressure.

Measuring air flow

Air movement is measured with various types of anemometers, which were basically wind mills turned by the flow of air; now various other electric/electronic techniques have largely replaced the measuring mechanisms.

Measuring radiant temperature

Radiant temperature is determined by measuring the temperature via a thermometer placed inside a black globe, which absorbs radiated energy. That globe temperature (GT) reading needs a correction for the existing air temperature.

Interactions among climate factors

Air temperature is the climate factor that most obviously affects body temperature; in fact, we habitually use the labels *hot* or *cold* to describe our overall perception of a climate. Air humidity determines our ability to sweat, which is the body's last resort to avoid overheating. Movement of air around our skin affects our ability to exchange energy by convection and to lose heat by evaporation. The energy exchange by radiation primarily depends on the temperatures of the emitting and receiving surfaces.

These examples demonstrate that most climate factors can affect the measurement values of other components; furthermore, the manifold combinations of the factors can lead to very different effects on humans by that composite, which we call *climate*, and on how we perceive it. Various techniques exist to express the combined effects of the environmental factors in one model, or index—such as the "Effective Temperature" chart, used widely in the late twentieth century, which relied on measurements of air temperature, air velocity, and relative humidity.

Wet bulb globe temperature

A convenient way to assess the existent climate is to combine a set of special measurement instruments in one device, which weighs the separate measurement results according to their effects on the human body and from there derives a single index. The currently used version is the so-called Wet Bulb Globe Temperature, abbreviated WBGT. It primarily applies to warm environments and weighs the effects of several climate parameters:

- WB is the wet bulb temperature of a sensor with a wet wick exposed to natural air current.
- GT is the globe temperature at the center of a black sphere of 150 mm diameter.
- DB is the dry bulb air temperature.

For outdoors, with solar load:

$$\text{WBGT (outdoors)} = 0.7\ \text{WB} + 0.2\ \text{GT} + 0.1\ \text{DB}$$

The WBGT is simpler for indoors (or outdoors without sun):

$$\text{WBGT (indoors)} = 0.7\ \text{WB} + 0.3\ \text{GT}$$

8.3 Our personal climate

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 microclimate that feels comfortable under given conditions of work, adaptation, and clothing. The suitable microclimate is highly individual and variable. It depends somewhat on age, where with increasing years, muscle tonus is likely to decrease; older persons tend to be less active and have weaker muscles, have a reduced caloric intake, and start sweating at higher skin temperatures. The suitable microclimate also depends on the surface-to-volume ratio, which, for example, is much larger in children than in adults, and on the fat-to-lean body mass ratio.

The work performed, its type and intensity, is a major determiner of a person's thermal comfort. Physical work in the cold may lead to increased heat production and hence to less sensitivity to the cold environment, while in the heat, hard physical work could make it very difficult to achieve an energy balance. The effects of the microclimate on mental work are rather unclear, with the only sure common sense statement that extreme climates hinder mental work.

Clothing

Clothing can have decisive effects on the thermal balance of the body and on the person's well-being. Clothing has three major traits: insulation, permeability, and ventilation.

Insulation is a measure of the resistance to heat exchange by convection, conductance, and radiation. In hot or cold environments, it impedes energy exchange by convection and radiation in either direction. Light-colored clothing minimizes heat gain by radiation from the sun on a sunny day, while dark-colored clothes worn outside absorb the sun's radiated heat. In the cold, clothing helps to reduce body heat loss by convection and radiation. Clothing also reduces the risk of injury by conduction when touching either a hot or a very cold object.

The insulating value of clothing is defined in clo units, the reciprocal of thermal conductivity: $1 \text{ clo} = 0.115 \text{ m}^2 \text{ °C W}^{-1}$ is the insulating value of normal clothing worn by a sitting subject at rest in a room at about 21°C and 50% relative humidity—see Table 8.1. Air bubbles contained in the clothing material or between the clothing layers provide increased insulation, both against hot and cold environments.

Permeability is a measure of how clothing permits the movement of water vapor through the fabric. This is important in

Table 8.1 Typical clothing insulation values

Type of clothing	Insulation in Clo[a]
None	0 (zero)
Light informal summer clothing	about 0.3
Light work outfit	about 0.6
Light business suit	about 1
Heavy business suit	about 1.5
Snow suit	about 2
Arctic quilted thermo parka outfit	about 2.5

Source: Havenith, G., *Handbook of Human Factors and Ergonomics Methods*, CRC, Boca Raton, Florida, 2005.

[a] 1 Clo = 0.155 m^2 °C W^{-1}.

hot environments, where good permeability allows evaporation from the skin, and hence cooling of the body. However, permitting water vapor to escape is also important in a cold climate to avoid the clammy feeling of water trapped in and under clothes. Permeability may also play a role in protecting the body against chemical exposure.

Ventilation is a measure of the ability of ambient air to move through the clothing. Such airflow is advantageous in a hot environment to enhance evaporative and convective cooling; in contrast, it is usually undesirable in a cold environment.

Exposed skin

Clothing also determines the surface area of exposed skin. More exposed surface areas allow 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 far away from the warm body core. The head and the neck are close to the core and have warm surfaces, which is advantageous in the heat but not in the cold.

Windchill

Clothing can strongly affect the individual microclimate by avoiding the so-called windchill, which is a special kind of convective heat loss. If the air moves more swiftly along exposed skin surfaces, their cooling becomes more pronounced. Figure 8.6 shows the energy loss, expressed as equivalent windchill temperatures, depending on wind speed and actual DB air temperature (but not considering humidity) on the naked human face as determined in 2001 by the Canadian and U.S. National Weather Services°. Naturally, with stronger wind and colder air, the cooling of exposed skin

Wind velocity (km/h)	*Actual dry air temperature (°C)*										
0	5	0	−5	−10	−15	−20	−25	−30	−35	−40	−45
5	4	−2	−7	−13	−19	−24	−30	−36	−41	−47	−53
10	3	−3	−9	−15	−21	−27	−33	−39	−45	−51	−57
15	2	−4	−11	−17	−23	−29	−35	−41	−48	−54	−60
20	1	−5	−12	−18	−24	−30	−37	−43	−49	−56	−62
25	1	−6	−12	−19	−25	−32	−38	−44	−51	−57	−64
30	0	−6	−13	−20	−26	−33	−39	−46	−52	−59	−65
35	0	−7	−14	−20	−27	−33	−40	−47	−53	−60	−66
40	−1	−7	−14	−21	−27	−34	−41	−48	−54	−61	−68
45	−1	−8	−15	−21	−28	−35	−42	−48	−55	−62	−69
50	−1	−8	−15	−22	−29	−35	−42	−49	−56	−63	−69
55	−2	−8	−15	−22	−29	−36	−43	−50	−57	−63	−70
60	−2	−9	−16	−23	−30	−36	−43	−50	−57	−64	−71
65	−2	−9	−16	−23	−30	−37	−44	−51	−58	−65	−72
70	−2	−9	−16	−23	−30	−37	−44	−51	−58	−65	−72
75	−3	−10	−17	−24	−31	−38	−45	−52	−59	−66	−73
100	−3	−11	−18	−25	−32	−40	−47	−54	−61	−69	−76

Equivalent windchill temperatures (°C)

FIGURE 8.6 Windchill temperature equivalents (metric).

Table 8.2 Windchill index conditions

Windchill index (WCI)	Effects on the body
200	Pleasant
400	Cool
1000	Cold
1200	Bitterly cold
1400	Exposed flesh freezes
2500	Intolerable

Source: Parsons, K. C., Ergonomic assessments of thermal environments, in Wilson, J. R., and Corlett, N. (eds.), *Evaluation of Human Work*, third ed., Taylor & Francis, London, 2005.

Note: WCI = 1.16 $(10v^{1/2} + 10.45 - v)(33 - DB)$ in Wm^{-2} with v the air velocity in ms^{-1} and DB the dry bulb air temperature.

and hence the danger of frostbite increase, as both Table 8.2 and Figure 8.6 show. Obviously, simply covering the skin, for example with a face mask, increases insulation against heat loss by windchill.

Acclimatization

Acclimatization is the status of adjustment of an individual's body (and mind) to changed environmental conditions. The process of getting there is called *acclimation*. Acclimation of the body to a hot environment mostly improves the control of blood flow to the skin, facilitates sweating, and increases the stroke volume of the heart without increase in heart rate. Healthy and fit persons achieve heat acclimatization in one or two weeks but can lose it just as quickly. In contrast, in a moderately cold environment usually very little physiological acclimation of the whole body takes place since most of the adjustment made concerns proper clothing, beneath which the body performs in its usual microclimate. However, the blood flow to exposed surfaces of the face and the neck and to the hands and the feet can adapt to cold conditions.

After days or a couple of weeks of acclimation, a climate may be quite agreeable that, during the first exposure, was rather uncomfortable and restricted one's ability to perform physical work. Relatedly, seasonal changes in climate, in type of work, of clothes worn, and in personal attitude play major roles in determining what feels acceptable or not. In areas with distinct summer and winter seasons, during the summer most people are willing to accept as comfortable conditions that are warmer, more humid, and draftier than they would tolerate during the winter.

8.4 Working in hot environments

Blood distribution

The human body produces heat, much of which must be released to the surroundings to prevent overheating. As already discussed, the physical means to disperse heat are convection, conduction, radiation, and evaporation. These heat dissipations work best when the skin temperature is well above the temperature of the immediate environment. To achieve this, the body's circulatory system redistributes its blood flow in order to facilitate heat transport to the skin: skin vessels dilate and superficial veins are fully open (actions contrary to the ones taken in the cold). The blood flow may become fourfold larger than at rest, bringing about "hot red skin in the heat" and increasing the conductance of the tissue.

Sweating

If heat transfer to the outside is still not sufficient, the body activates its sweat glands because the evaporation of the produced sweat cools the skin. Sweating reduces the water content of the body, which must be replenished by water° through drinking and eating. The recruitment of sweat glands from different areas of the body varies, and large differences in the ability to sweat exist among individuals: most adults have two to four million sweat glands in their skin, but some persons have fewer. During acclimation, the body learns to control its sweating. The amount of sweat developed and evaporated depends on the number of glands, the clothing, the environment, the work requirements, and the individual's acclimatization.

Reducing physical effort

If heat transfer by blood distribution and sweat evaporation remain insufficient, the body reduces its muscular activities to lower the amount of energy generated through metabolic processes. In fact, 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 activities.

Signs of heat strain

There are several signs of severe heat strain on the body. One is an increase of circulatory activities: cardiac output enlarges, mostly brought about by higher heart rate. This may be associated with a reduction in systolic blood pressure. A superfluous sweat rate is another sign of excessive heat strain. Even at rest, the body maintains so-called insensible perspiration (in the neighborhood of about 50 cm^3/hr); sweat production increases depending on the heat that must be dissipated. During normal work, about one liter of sweat is produced in one hour; maximal sweat rates are 2 to 4 liters an hour and 10 to 14 liters per day in extremely strenuous efforts in hot climates. Sweat begins to drip off the skin when the sweat generation has reached about one third of the maximal evaporative capacity. Of course, sweat running down the skin contributes very little to heat transfer.

Drink water

Normally, we replenish our bodies' need for water from our food (which by volume is mostly water) and by taking sips of fluids°. However, sweating due to strenuous efforts, especially in a hot environment, can dehydrate the body. Dehydration of only one or two percent of body weight can critically affect the ability of the body to control its functions. (One percent of a 100 kg body mass converts to 1 L of water.) Maintaining a sufficient fluid level is easily done by frequently drinking small amounts of water. Sweating not only extracts water from the plasma but also carries some salt from the blood onto the skin. Generally, it is not necessary to add salt to drinking water since, in western diets, the salt in the food is more than sufficient to resupply the salt lost by sweating.

Heat distress

Among the first reactions to heavy exercise in excessive heat are sensations of discomfort and perhaps skin eruptions ("prickly heat") associated with clogged sweat ducts. As a result of sweating, so-called *heat cramps* may develop, which are muscle spasms related to the local lack of salt, which may occur after quickly drinking large amounts of fluid. *Heat exhaustion* is a combined function of dehydration and overloading of the circulatory system. Associated effects are fatigue, headache, nausea, and dizziness, and it is often accompanied by giddy behavior. *Heat syncope* indicates 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.

Working hard in the heat

The ability for short exertion of maximal muscle strength is not affected by heat or the body's water loss. However, the ability to perform high-intensity and endurance-type physical work is severely reduced during acclimatization to heat. Even after one is acclimatized, the demands on the cardiovascular system for heat dissipation and for blood supply to the muscles compete with each other. The body prefers heat dissipation, with a proportional reduction in a person's capability to perform.

8.5 Working in cold environments

The human body has few natural defenses against a cold environment. Most of the actions that we can take are behavioral in nature, such as putting on suitably heavy clothing covering the skin, seeking shelter, or using external sources of warmth. The body has only two major ways to regulate its temperature: redistribution of blood flow and increase in metabolic rates.

Redistribute blood

To conserve heat, the body lowers the temperature of the skin to reduce the temperature difference against the outside. This is done by constricting blood vessels near the body surface, thus displacing the circulating blood toward the core, away from the skin. The effects can be rather dramatic; for example, the blood flow in the fingers may be only 1% of what exists in a moderate climate. Vasoconstriction generates the appearance of pale skin in the cold.

The hunting reflex is a cold-induced automatic body action: after the initial vasoconstriction has taken place, a sudden dilation of blood vessels occurs, which allows warm blood to return to the skin, such as of the hands, which rewarms that body section. Then vasoconstriction returns; this sequence may repeat several times.

Wear gloves and caps

The displacement of the blood volume from the skin to the central circulation is an efficient way to keep the body core warm and its surfaces cold. The associated danger is that the temperature in the peripheral tissues may approach that of the environment. Thus, very cold fingers and toes may result, with possible damage to the tissue if the temperatures get close to freezing. The blood vessels of the head do not undergo as much vasoconstriction so the head stays 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, preventable by wearing a cap and a collar or scarf to create an insulating layer.

Increase metabolism

The other major reaction of the body to a cold environment is to increase its metabolic heat generation. This may occur involuntarily: shivering usually begins in the neck, apparently to warm the most important flow of blood, to the brain. Shivering is caused by muscle units firing at different frequencies of repetition and out of phase with each other. Since they do no mechanical work to the outside, the total activity is transformed into heat production, allowing an increase in the metabolic rate, which may reach four times the resting rate. If the body does not become warm, shivering may become rather violent when the motor unit innervations become synchronized so that large muscle units are contracted.

Of course, voluntary muscular activities can also augment heat production, such as by either increasing the dynamic muscular work performed or by additionally moving body segments, contracting muscles, flexing the fingers, and the like. Since the energy efficiency of the body is very low, dynamic muscular work can easily increase the generation of metabolic heat tenfold over that at rest.

Goose bumps

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 energy loss at the skin.

How cold does it feel?

An individual's decision to stay in the cold or to seek shelter depends on the subjective assessment of how cold the body surfaces or the body core actually are. Dangerous situations can develop either when a person fails to perceive and to react to the body's signals that it is becoming dangerously cold, or 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 thermal receptors at the surface and on signals from sensors in the body core. As skin temperatures decrease below 35.5°C, the intensity of the cold sensation increases; cold sensation is strongest near 20°C; yet, at even lower temperatures, sensitivity decreases. It is often difficult to separate feelings of cold from pain and discomfort.

The conditions of cold exposure may greatly influence the perceived coldness. Obviously, it makes quite a difference whether or not one wears suitable protective clothing and what one is actually doing when exposed to cold air or water. Experiments have shown that subjects find it very difficult to assess how cold they actually are: neither core nor surface temperatures reliably correlate with cold sensations. When the temperature plunges, each downward step can generate an overshoot sensation of cold sensors, which react not only to the difference in temperature, but also to the rate of change. Exposure to very cold water accentuates the overshoot phenomenon observed in cold air. This may be due to the fact that the thermal conductivity of water is about a thousand times greater than that of cold air at the same temperature.

Signs of cold strains

The subjective sensation of cold is an unreliable, possibly a dangerous indicator of core and surface temperatures of the body. Measuring ambient temperature, humidity, air movement, and exposure time and rationally acting on these physical measures is a better strategy than relying on subjective assessments.

If vasoconstriction and metabolic rate regulation cannot prevent serious energy loss through the body surfaces, the body will suffer some effects of cold stress. As just discussed, the skin is first to suffer from cold damage, while the body core is protected as long as possible. If the skin temperature approaches freezing, ice crystals develop in the cells and destroy them, a result known as frost bite.

In the hands, joint temperatures below 24°C and nerve temperatures below 20°C reduce the ability for fine motor tasks. Manual dexterity drops as finger skin temperatures fall below 15°C. Tactile sensitivity diminishes below 10°C and becomes severely reduced as the skin temperature falls below 8°C. At about 5°C, skin receptors for pressure and touch cease to function, and the skin feels numb.

When the nerve temperature falls to 8°C, the peripheral motor nerve velocity may decrease to near zero; this generates a nervous block, which explains the rapid onset of physical impairment by local cooling. Deep cooling makes people incapable of performing activities, even if they could save the person: “cannot light a match.”

Reduction of the core temperature can have serious consequences. Vigilance begins to drop at temperatures below 36°C. At core temperatures of 35°C and below, central nervous system coordination suffers so that one is not be able to perform even simple activities. When the core temperature drops even lower, apathy sets in ("let me sleep") and the mind becomes confused. Loss of consciousness occurs around 32°C. Heart failure may occur at core temperatures of about 26°C. At around 20°C, vital signs disappear, but the oxygen supply to the brain may still be sufficient to allow revival of the body from hypothermia.

Working hard in the cold

With appropriate clothing, a cold environment does not restrict one's ability to perform medium and even heavy work. However, bulky clothing may hinder the exertion of certain tasks.

8.6 Climate effects on mental tasks

It is difficult to evaluate the effects of moderate heat or cold on mental and intellectual performance because of large subjective variations and because of a lack of practical yet objective testing methods. However, in general, the mental performance deteriorates with rising room temperatures, starting at about 25°C for the unacclimatized person; that threshold increases to 30 or even 35°C if the individual is used 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 of perceptual motor tasks, the onset of performance decrement 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.

8.7 Designing comfortable climates

Comfortable climates

In confined spaces, such as buildings or cabins of vehicles, many technical ways are available to generate a warm environment° that suits persons who perform very light physical work and wear appropriate clothing. For most western populations, comfortable climate conditions are in the ranges of about 21 to 27°C in a warm climate or during the summer, and from 18 to 24°C in a cool climate or during the winter. Preferred ranges of relative humidity are between 30 and 70%. In rooms, air temperatures at floor level and at head level should differ by

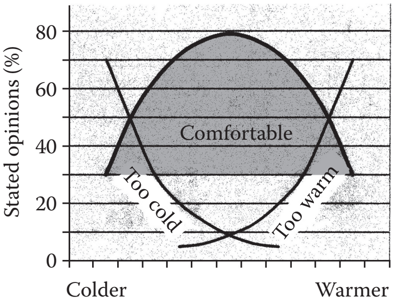

FIGURE 8.7 Different opinions about climates.

less than 6°C, best about 3°, keeping the head cool and the feet warm. Differences in temperatures between body surfaces and windows, walls, or other surfaces should not exceed approximately 10°C. The velocity of cool air, especially if irregular, should not exceed 1.5 m/s.

The technical means to influence the climate must be seen, obviously, in interaction with the work to be performed, with the acclimatization conditions of the individuals, with their clothing, and with their psychological inclination either to accept given conditions or to consider them uncomfortable. The preferred personal climate varies from person to person, and within a person. For example, selecting clothing and changing the intensity of physical effort can make major differences on the perceived suitability of the physical conditions of the climate, the temperatures, the humidity, and the air movement. Various combinations of these climate factors can subjectively appear as similar. However, with that many variables, it is not surprising that a combination of climate factors, which many people consider agreeable, is felt by some persons as too warm, while still others find that same condition too cold, as sketched° in Figure 8.7. Selecting appropriate clothing is often a simple and effective way to create a comfortable personal climate by adding layers of clothing when one feels cold, and changing into lighter clothes when one feels hot.

Summary

The body must maintain a core temperature near 37°C with little variation even in the presence of major changes in internally developed energy (heat and physical work), in heat energy received from a hot environment or in heat energy lost to a cold environment.

Heat energy may be gained from or lost to the environment by several kinds of physical exchanges:

- Convection
- Conduction
- Radiation
- Evaporation (which can only transfer energy from the body to the environment)

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. Proper clothing strongly affects the energy exchanges in both hot and cold environments.

The thermal environment is determined by combinations of

- Air humidity (mostly affecting evaporation)
- Air temperature (affecting convection and evaporation)
- Air movement (affecting convection and evaporation)
- Temperature of solids in touch with the body (affecting conduction)
- Temperature of surfaces adjacent to the body (affecting radiation)

The combined effects of all or some of these physical climate factors can be integrated into a climate index. Several indices are in use, with the WBGT currently favored. It identifies certain ranges of air and surface temperatures and of air velocity and humidity, which are physically suitable and perceived as comfortable for given tasks and clothing.

Fitting steps

Step 1: Determine what and how work is to be done.

Step 2: If indoors, establish a comfortable climate. For outdoors, set up a suitable work regimen and provide appropriate clothing and shelter.

Step 3: Encourage individual adjustments, especially in clothing.

Notes

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

8.1 Human thermoregulation:

Temperature scales: The physicist Daniel Gabriel Fahrenheit (1686–1736) set the temperature of a mix of ice and water to 32° and the temperature of boiling water to 212°. This is the Fahrenheit temperature scale, with 180°F between freezing and boiling. In 1742, the astronomer Anders Celsius (1701–1744) suggested a metric scale: 0°C is the temperature when water freezes and 100°C when it boils. This centigrade scale is called the *Celsius scale* and in common use everywhere except in the United States. The physicist and engineer William Thomson Baron Kelvin (1824–1907) determined the lowest limit to temperature (absolute zero) as –273.15°C. Absolute temperatures are stated in units of kelvin (K); 1 K has the same magnitude as 1°C.

The conversion of temperature degree values from one scale to the other considers the different settings for freezing and boiling temperatures of water as well as the number of degrees between freezing and boiling:

Fahrenheit to Celsius: $(°F - 32)(5/9) \rightarrow °C$

Celsius to Fahrenheit: $(9/5°C) + 32 \rightarrow °F$

(The 5/9 ratio comes from 100/180 and, of course, 9/5 = 180/100.)

Heat exchanges by convection or conductance: Both follow Newton's law of cooling, Bernard (2002) and Bernard and Dukes-Dobos (2002).

Radiative heat exchange follows the Stefan-Boltzmann law of radiative heat transfer; Bernard (2002) and Bernard and Dukes-Dobos (2002).

Wind chill temperatures: Go to the website of the U.S. Weather Service at http://www.weather.gov.

8.2 Climate factors:

Temperatures, humidity, drafts: For equations for heat exchange by convection or conductance, radiation, and evaporation, see Bernard (2002), Bernard and Dukes-Dobos (2002), Havenith (2005), and Youle (2005).

8.3 Our personal climate:

Windchill: The latest version of the Wind Chill Index is available at http://www.nws.noaa.gov/om/windchill/. This table was developed in the United States jointly with the Canadian weather service and is used in both countries with no regionalization. Other countries have their own versions, which one can obtain through their meteorological agencies, or through the World Meteorological Organization.

8.4 Working in hot environments:

Sweating reduces the water content of the body, which must be replenished by water° in drink and food: Carroll 2015.

Designing comfortable climates: Further information for the built environment, such as in offices in Europe and North America, is contained in the ANSI-ASHRAE Standard 55, latest edition, and, more generally, in ISO standards such as listed by Parsons (2003, 2014).

Mound (inverted U) curve: This up-down curve (and its mirror image, the down-up valley or *U*) are often employed to describe human physical and physiological behavior—for other examples, see Figures 11.4 and 11.5.

CHAPTER NINE

Mental activities

Two internal systems control the human's functioning: one is the endocrine system, which essentially consists of the glands of internal secretion, a group of organs that produces hormones and secretes them into the blood stream. Hormones are substances that affect activities in body cells at another site. While the biochemistry of hormones and of their effects is known, the endocrine system does not lend itself to ergonomic exploitation and therefore is not a topic in this book.

The other controller of the human body is the nervous system, governed by the brain. Its anatomy and functions are well studied, but its actual functioning is still only generally understood. Our current knowledge provides ample opportunities to appreciate the interactions between body and brain actions and hence indicates to the human factors engineer how to design work and work equipment to take advantage of the intricate capabilities of the nervous control system.

9.1 The brain–nerve network

The brain

The brain is the control center of the body. It creates the human "mind" which generates within its about 100 billion neurons and their various connections emotions, moods, beliefs, memories, behaviors, and thoughts. The brain receives sensory signals in regard to body position and movement, touch, smelling, hearing, and seeing; coordinates and interprets these; and develops reactions and consequent actions, often in milliseconds. For this, the brain requires the continuous presence of oxygen, so the supplying flow of blood takes about 20% of the total output of the heart.

Observing brain functions

In the 1920s, Berger attached metal electrodes to the skin of the head and recorded brain waves, electrical neural activity of the brain, the encephalon, via electroencephalograms (EEGs). At about that time, Hess demonstrated that electrical impulses in cat brains affect their emotions and behaviors. Several decades later, Delgado showed related events in humans. Since the 1990s, a new noninvasive technique, functional magnetic resonance imaging (fMRI), detects changes in blood flow through the brain; stimulated regions appear on a screen as blotches of color. Unfortunately, the area lights up only when huge numbers of neurons become active; so the interpretation of fMRI is difficult because different neuronal events usually blur together. Today's fMRIs are not precise enough to reveal what individual brain cells are actually doing. There is hope for more distinct information° in the future, for example, by optogenetics, a technology used on animals so far: it makes individual brain cells photosensitive and then activates them with flashes of light delivered through fiber-optic wires. This allows the observation of distinct circuitry and provides means to affect behavior by the stimulation of identified cells.

Understanding how the brain works

While the anatomy of the human brain is well mapped, neuroscientists still do not clearly understand how this organ with its billion of neurons and their various connections actually functions as the mind that can generate, in milliseconds, emotions, thoughts, behaviors, and actions. Lacking sophisticated detail knowledge and useful technology, we still rely on rather broad images to describe functions of the brain rather superficially. Sleep features, for example, are recorded and classified by EEGs and especially by electrooculograms, which describe eye movements, particularly their rapidity—more on this in Chapter 15.

Neuroplasticity

Recently, our understanding of the blueprint of the brain and how it works underwent a major conceptual change. Well into the twentieth century, it had been commonly accepted that, after growing and developing during youth for about 20 years, the anatomy and the functions of the brain became fixed like in a wondrous computer with hardwired circuits set to perform certain unchangeable functions. If not injured, afterward, the brain would change only during its decline with age.

Around the middle of the twentieth century it became evident that, in fact, even the adult brain is not immutable. It does improve its functions with every activity performed; at times, the brain can reorganize itself, it may alter its structure and

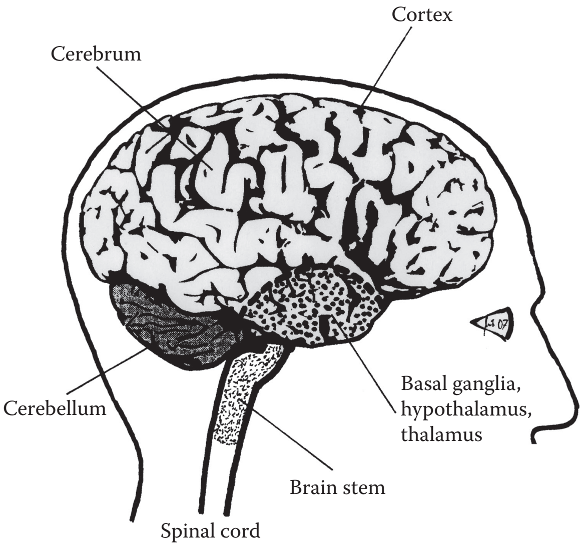

FIGURE 9.1 Major components of the brain.

develop new ways to function, for example, when young brain cells fail to develop properly or when injury damages cells. That ability of the brain to modify° is called *neuroplasticity*.

Parts of the brain

The three major anatomic components of the brain, shown in Figure 9.1, are the cerebrum, the cerebellum, and the brain stem.

Cerebrum

The cerebrum consists of dense, convoluted masses of tissue divided into two halves, the left and right cerebral hemispheres, connected by nerve fibers. The cerebrum contains the frontal, parietal, occipital, and temporal lobes. The frontal lobes control skilled motor behavior, including speech, mood, thought, and planning. The parietal lobes interpret sensory information from the rest of the body and control body movement. The occipital lobes deal with vision. The temporal lobes generate memory and motions, process and retrieve long-term memories, and initiate communication or action. The outer layer of each cerebral hemisphere consists of the cortex, the gray matter opposed to the whitish appearance of other brain matter. The cortex is associated with voluntary movement, thought, perception, memory, language, and individuality.

Cerebellum

The cerebellum, which lies beneath the cerebrum just above the brain stem, coordinates the body's movements. A special collection of nerve cells is at the base of the cerebrum: the basal ganglia, the hypothalamus, and the thalamus. The basal ganglia help to smooth out movements. The hypothalamus coordinates automatic functions of the body, such as sleep and wakefulness; it maintains body temperature and regulates the body's water balance. The thalamus organizes sensory messages to and from the highest level of the brain, the cerebral cortex.

Brain stem

The brain stem connects the brain to the spinal cord. The brain stem automatically regulates body functions such as the rate at which the body uses food, and it controls body posture, breathing, swallowing, and heartbeat. It increases alertness when needed. Severe damage to the brain stem destroys these functions and death follows.

Spinal cord

The spinal cord is an extension of the brain. It makes reflex decisions and it carries pathways for nervous signals. The spinal cord begins below the brain stem and continues down the rear side of the vertebral column, which provides protection within its bony rings that encircle the foramen, already shown in Figure 2.10 in Chapter 2. This is the opening through which the spinal cord passes, a long fragile structure that can be damaged by displacements of the vertebral bones, often in an automobile accident or by a fall. Figures 9.2 and 9.3 show details of a vertebral segment with the spinal cord and its nerve extensions. Nerves at the front (anterior) of the spinal cord carry information from the brain to the muscles. These are the motor nerves. Nerves at the rear (posterior) of the spinal cord carry information from sensors of the body toward the brain. These are the sensory nerves.

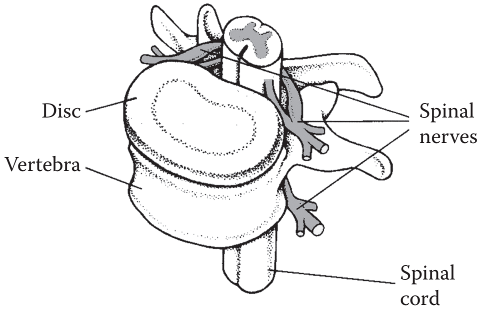

FIGURE 9.2 Typical segment of the vertebral column with the spinal cord and emanating nerve extensions. (Modified from Kapandji, I. A., *The Physiology of the Joints*, Churchill Livingstone, Edinburgh, London, 1988; *Merck Manual of Medical Information*, Merck & Co., Inc., Whitehouse Station, New Jersey, 1997 home edition.)

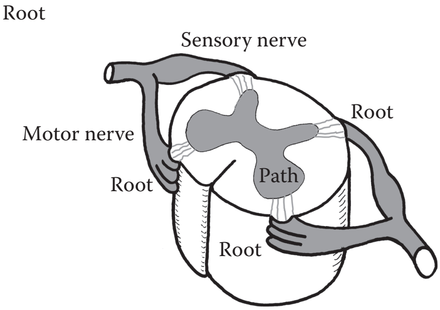

FIGURE 9.3 Segment of the spinal cord. (Modified from Kapandji, I. A., *The Physiology of the Joints*, Churchill Livingstone, Edinburgh, London, 1988; *Merck Manual of Medical Information*, Merck & Co., Inc., Whitehouse Station, New Jersey, 1997 home edition.)

Nerves

The spinal cord provides the main pathways for nervous signals, which relay both incoming (afferent) sensory messages and outgoing (efferent) motor commands.

Nerve impingements

Between pairs of vertebrae, two nerve bundles emerge (looking like roots) from the spinal nerve, as Figure 9.3 shows. Displaced vertebrae and material from a ruptured disk can impinge on the spinal nerve extensions with dire consequences for efferent and afferent signals. Wounding a motor nerve may cause weakness, even paralysis of the muscle it serves. Damage to a sensory nerve can lead to feedback of pain and numbness that, in certain cases, may mislead the brain. For example, pain may seem to come from body sections such as the buttocks and the thighs, which are innervated by the sciatic nerve; but the problem might not be there but at the point of impingement of the sciatic nerve at the spinal column.

Neurons

The basic functional unit of the human nervous transmission system is a nerve cell, the neuron. The nervous system contains about one billion such cells that extend like strings throughout the body. A neuron has a cell body, soma, which is a few thousands of a millimeter thick, and short extensions, dendrites, where connections from other neurons arrive across synapses. Figure 9.4 sketches a motor nerve cell with its single long extension, called *axon*, which can be more than a meter long. Nerves transmit their messages electrically in one direction: from the axon of one neuron to the dendrites of the next neurons. At the synapses, the contact points between neurons, the axons secrete chemical neurotransmitters, which trigger the receptors on the next neurons to generate a new electrical current.

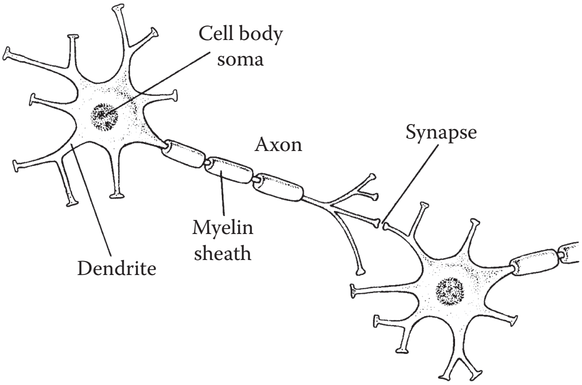

FIGURE 9.4 Scheme of a motor neuron. (Adapted from Kroemer, K. H. E., Kroemer, H. J., and Kroemer-Elbert, K. E., *Engineering Physiology: Bases of Human Factors/Ergonomics*, fourth ed., Springer, Heidelberg, Germany, 2010.)

Signal transmission

Synapses are not just simple transmitters; they also serve as filters or switches, because they can inhibit the transmission of incoming signals that are infrequent and weak. Neurons come in several types and sizes, some of which are able to transmit as many as a thousand impulses per second, whereas others may not convey more than 25 signals per second. The velocity of impulse travel is a constant for each nerve fiber, ranging from about 0.5 to about 150 m/s. The speed is slow in thin fibers such as the ones transmitting pain. Thick axon fibers with myelin sheaths serve skeletal muscles; this setup allows the highest speed of conduction.

Action potential

Incoming signals, arriving via synapses, may be too weak to stimulate the nerve cell, but, if strong enough, the cell generates an electrical spike, shown in Figure 9.5. The peak is some 100 mV above the resting potential; this impulse, called the *action potential*, travels to the next neuron. In a motor neuron, the impulse passes from the axon to the so-called motor end plates in the muscle where it triggers a contraction.

Motor unit

At the muscle, a motor nerve divides into several fibers, each controlling several muscle fibers. A motor unit consists of all the muscle fibers that one motor neuron innervates. In muscles that carry out precise movements, there are only three to six muscle fibers in a motor unit, whereas muscles set to perform heavy work may have 90 or more muscle fibers controlled by just one neuron.

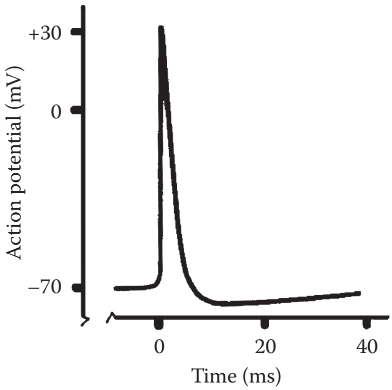

FIGURE 9.5 Action spike of about 100 mV above the resting potential of –70 mV.

Electromyograms

Electromyograms (EMGs) allow us to observe the strength and the frequency of activation commands sent from the CNS. These electrical signals, picked up by surface or indwelling electrodes, provide information not only about the frequency of activations of muscle units, but also about their status of fatigue. Figure 9.6 shows sample EMGs of the extensor muscle of the upper arm. The muscle executed a series of contractions of equal strength. After four minutes of repetitions, muscle fatigue is apparent because the amplitude of the EMG has been enlarged to cause the same contraction as initially; after 16 minutes, the even larger signal amplitude indicates extensive fatigue.

Feedforward/ feedback loop

Figure 9.7 sketches the innervation of a muscle by its motor nerve and the sensory feedback loop to the spinal cord and brain. The incoming action impulses transmit contraction

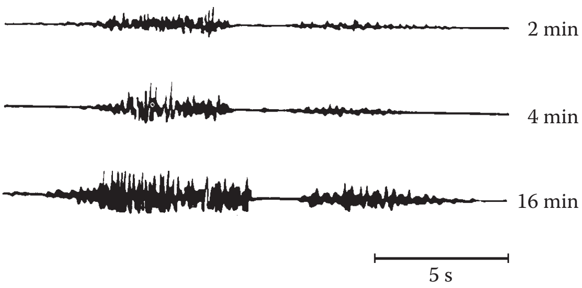

FIGURE 9.6 Sample EMGs taken after 2, 4, and 16 minutes of contractions of equal strength.

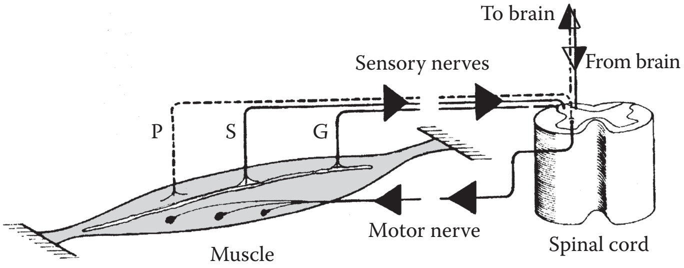

FIGURE 9.7 Muscle innervation and feedback control. G: signal from Golgi organ; S: signal from muscle spindle; P: pain signal.

commands to the muscle at the motor end plates. Feedback information about the ensuing events travels in sensory nerves toward the spinal cord. Important signals originate at the Golgi organs (G), which react to tension in the tendons; they also start at muscle spindles (S), which sense muscle stretch; and they can include messages of pain (P). Such feedback partly goes to the spinal cord for reflex-type automatic adjustments of the muscular effort; other signals arrive at the brain for continuous evaluation and control of task performance.

Design for simple movement control

Motor nerves carry action orders from the brain to the muscles where they cause contractions; sensory nervous feedback reports on the conditions of the muscle. The integration of the sequence of forward and feedback information provides the means to control muscular activities.

The body can perform some motions without the involvement of the brain proper; yet most muscular activities need fine regulation. This requires various degrees of involvement of higher brain centers, such as the cortex, the basal ganglia, and the cerebellum. Channeling information along lengthy transmission paths through numerous neurons and decision processes is laborious and time consuming. Thus, learning to execute complex movements is difficult and slow, as we know from the experience of acquiring a new complicated skill, especially as we get older. This indicates that job activities should be performed in the simplest possible way, using the least decision-making and the fastest path of information transmission, and employing the smallest possible body mass. Clearly, controlling the speed of an automobile by complicated movements of the feet to and from invisible pedals is not a good example of modern human factors engineering.

The brain–nerve network

The brain and nerves are structures of a complex communication system. Normally, it can send and receive copious amounts of information simultaneously. The brain is the control center that communicates with the body through the nerves that run up and down the spinal cord. The sensory nerves carry information to the brain about pressure, pain, heat, cold, vibration, and the feel and the shape of objects. They also carry messages from internal body sensors, for example, about positions and motions of body parts and about the related tension in muscles and tendons. This information about events outside and inside the body enables the brain to make decisions about what to do; the information loop closes when the brain then receives feedback about the results of the taken actions.

Reflexes

Even though to a much lesser extent than the brain, the spinal cord is also a source for coordination of certain actions, such as in reflexes. A reflex usually begins with the stimulation of a sensory receptor, for example, one located just below the front of the kneecap. This sends a signal to the spinal cord, which evokes an immediate response command that travels rapidly to the appropriate muscle to do a knee jerk. In this way, a muscle reaction is possible within a few milliseconds after the stimulus occurred since no time-consuming higher brain functions are involved.

Central and Peripheral Nervous Systems

It is customary to partition the human nervous system into divisions. One approach is to divide by anatomy, as done above: accordingly, the *central nervous system (CNS)* consists of the brain and the spinal cord. The CNS controls the body by gathering information, making decisions, and initiating actions. The *peripheral nervous system (PNS)* runs from the sensors, located in all parts of the body, to the CNS, and from there to the organs, especially to the muscles and the glands. Peripheral nerves are bundles of single nerve fibers, some of which are very thin, less than half a millimeter in diameter, while others are thicker than 5 mm. The PNS does not control but delivers signals°.

Somatic system

Another way to distinguish is by function. The *somatic nervous system* comprises the sensory and motor nerves of the PNS, together with their associated parts in the CNS, all needed to control conscious actions and mental activities. The somatic system links the body to the outside world through perception, awareness, and actions, especially by muscle activation.

Autonomic system Other functional components form the *autonomic nervous system*. It unconsciously governs the internal organs that are essential to the life of the body such as blood circulation, breathing, and digestion. This system (also called *visceral*) is responsible for the automatic functioning of the body, for emergency responses and emotions.

Sensory receptors The nervous system monitors all the sensations that come from inside the body and its surfaces as well as through the eyes and the ears. If the signals are strong enough, they are transmitted to the CNS where the information is perceived and a judgment is made regarding whether an action is needed. If needed, the CNS activates the muscles and monitors the results of the actions taken.

External receptors Section II of this book discusses in some detail how we perceive the world around us by seeing, hearing, and touching. The senses of gustation and olfaction allow us to taste and smell, and we can feel temperature, electricity, pressure, and pain. Different kinds of surface sensors are embedded in the layers of the skin in varying concentrations. Figure 9.8 shows the divisions of skin surface areas (dermatomes), which convey information to specific sensory nerve extensions of the spinal cord. Certain parts of our bodies, for example, our lips and fingertips, have dense concentrations of sensors, while other sections are fairly numb, such as our backs.

9.2 Taking up and processing information

Cognitive concepts of information processing Cognition is the act or the process of knowing in the broadest sense; of special interest in the human factors domain is the intellectual process by which knowledge is gained from perception. Regarding mental processing, in cognitive psychology the common concept is that information must pass through three stages of mental processing: sensory input, short-term memory, and long-term memory. “Stage” and “parallel-distributed” processing models are prominent among current theories of how humans process information.

Mental work Much of our mental work consists of sensing information, then processing it, and finally acting on it. Of course, most of these activities intermingle with other mental tasks that occur simultaneously; nevertheless, it is convenient to consider these mental activities as occurring in stages that follow each other in series. Figure 9.9 illustrates the concept of the human as such a linear processor of signals°: First, a sensor detects information

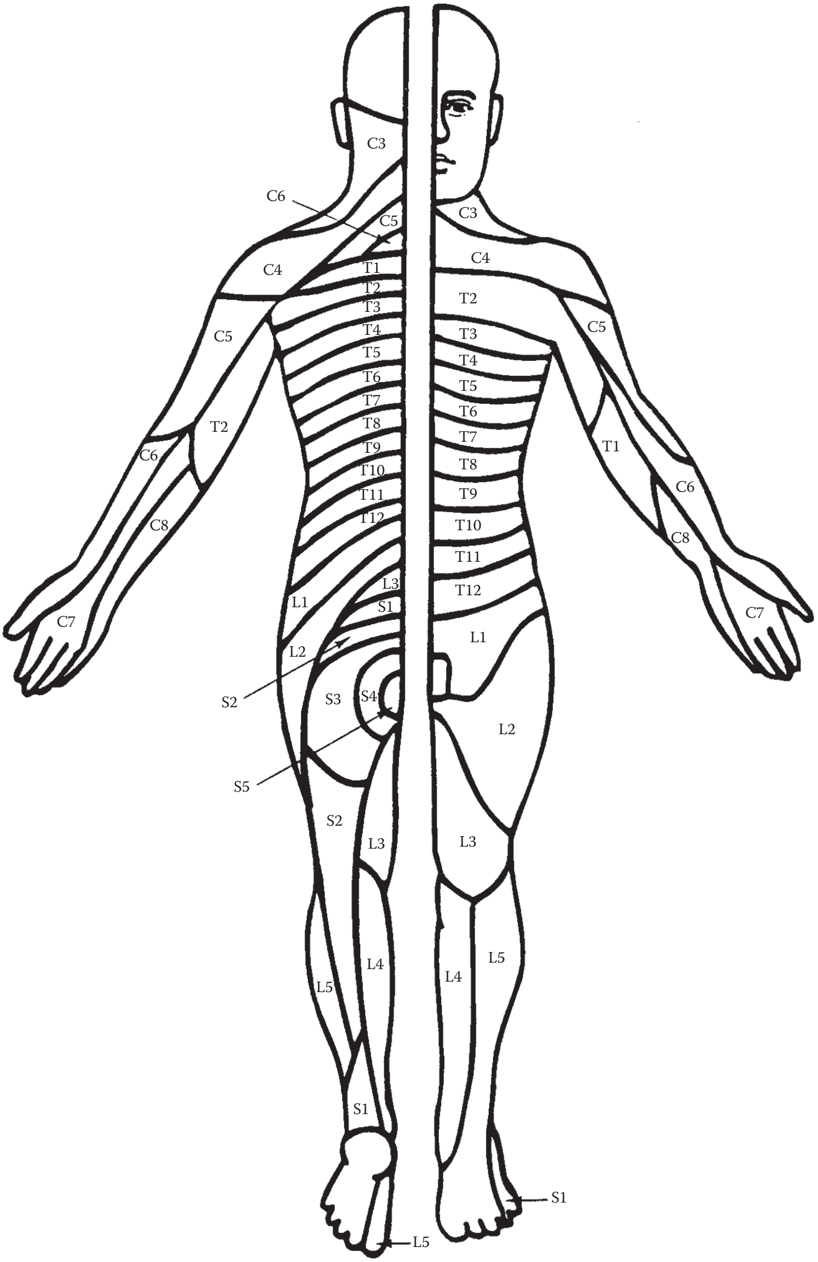

FIGURE 9.8 Sensory dermatomes identified by their nerve roots (C: cervical; T: thoracic; L: lumbar) at the spinal column. (Modified from Jarrett, A., ed., *The Physiology and Pathology of the Skin*, Academic Press, London, 1973; Kroemer, K. H. E., Kroemer, H. J., and Kroemer-Elbert, K. E., *Engineering Physiology: Bases of Human Factors/Ergonomics*, fourth ed., Springer, Heidelberg, Germany, 2010.)

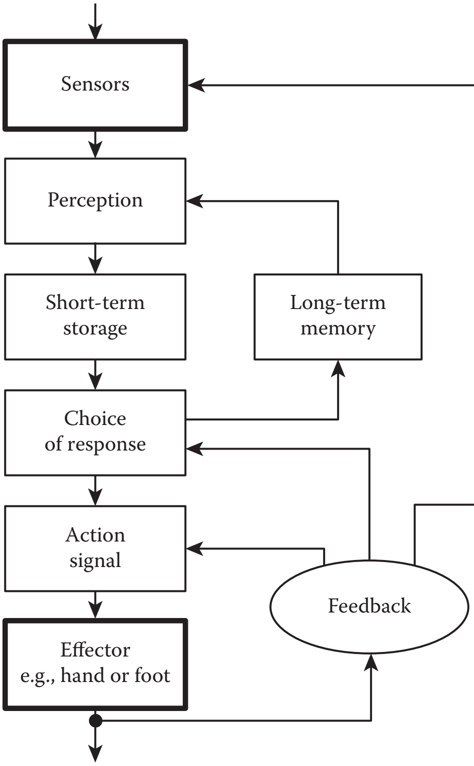

FIGURE 9.9 Model of human information processing. (From Kroemer, K. H. E., *"Extra-Ordinary" Ergonomics: How to Accommodate Small and Big Persons, the Disabled and Elderly, Expectant Mothers and Children*, CRC, Boca Raton, Florida, 2006c.)

and sends related impulses along the sensory pathways of the PNS to the central processor in the CNS. It interprets the information and chooses an action (which may include "no action"). Then the CNS generates appropriate feedforward impulses and sends these along the motor pathways of the PNS to the effectors, usually the voice or the muscles in the hand or the foot. A sensory feedback loop serves to compare the output of the system with the desired performance. If the comparison between actual and intended performance shows a difference, that disparity gives rise to revised action.

Sensors inside the body

Interoceptors are sensors inside the body; they include the Golgi organs and spindles, associated with muscle, already mentioned. Ruffini organs are receptors in the body joints where they inform on their angulation. Other sensors are in the semicircular canals of the ears: these vestibular receptors detect and report the position of the head in space, as already alluded to. Still other interoceptors respond to events within the internal organs, such as in the abdomen, the chest, and the head. They relay such sensations as pain and pressure.

Sensors near the surface

Exteroceptors provide information about the outside. They are involved in sight, sound, taste, smell, and touch. Some of these senses are of particular importance for the control of body activities; the sensations of touch, pressure, and pain provide feedback to the body regarding the direction and the intensity of muscular activities transmitted to an outside object. The receptors are located throughout the skin of the body, although in different densities; see the dermatomes shown in Figure 9.8. The sensors are mostly free nerve endings, Meissner and Pacinian corpuscles. Since the PNS nerve pathways leading to the CNS interconnect extensively in the PNS, the reported sensations are not always specific to a given input; for example, very hot or very cold sensations can be associated with pain, which itself can be caused also by hard pressure on the skin.

Adaptation and speed

Almost all sensors respond vigorously to a change in the stimulus, but they will report less and less when the load stays constant. This adaptation makes it possible to live with continuously present but unimportant stimuli, such as the pressure of clothing. The speed of adaptation varies with different sensors. Furthermore, the velocities of transmitting sensations to the CNS are quite different for diverse sense pathways: light and sound, for example, are reported quickly but pain appears rather slowly.

Modifying input signals

The human has a wide range of sensations; yet there are signals that we cannot naturally perceive. For example, we cannot hear ultra- and infrasounds, frequencies that are of great importance to many animals such as dogs and elephants. Another case is the presence of X-rays, for which our body has no sense organs. One of the major tasks of the ergonomist is to modify physical properties of external signals, which we are not able to sense but that are important to us, so that we become aware of them. If the signal is altogether not within the bandwidth of the human senses, the engineer must change the nature of the signal. Examples of technical solutions are generating a buzzing sound or flashing light to make the presence of radiating energy known.

Providing proper input signals

In other cases, we adjust the signal or the environment so that the signal can penetrate the clutter of the surroundings. Examples are on/off blinking of signals, changes in the light colors of an emergency vehicle, modulation of the sound of its sirens, or adjustment of the qualities of a loudspeaker system. Computer offices provide more examples: here, the overall illumination level is often kept low to avoid glare on the computer screen or washing out the image on it; yet, in spots, we increase the illumination by separate task lights to make the reading of

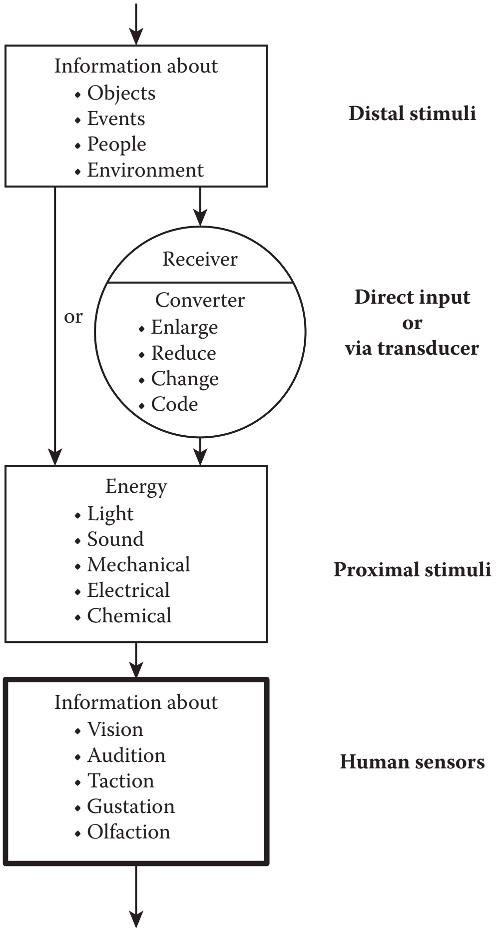

FIGURE 9.10 Transforming distal signals into proximal stimuli that can serve as inputs to the human processor. (From Kroemer, K. H. E., *"Extra-Ordinary" Ergonomics: How to Accommodate Small and Big Persons, the Disabled and Elderly, Expectant Mothers and Children*, CRC, Boca Raton, Florida, 2006c.)

paper documents easier, especially for older persons, which in turn might generate glare. Providing proper input signals can be a daunting ergonomic task. Figure 9.10 presents a schematic that shows how we can transduce external signals so that the human senses may perceive them.

9.3 Making decisions

Models of information processing

Traditional models of information processing (IP) show a sequence of stages (like flowcharts used in industrial engineering) through which information passes. The simplest model of mental work has two distinct phases: first, the evaluation of occurring events and, then bringing about changes, the execution. The resulting new environment is then evaluated again, and so begins a new sequence of phases.

Parallel IP

A refinement of this single linear model recognizes that multiple sources of information are present simultaneously, which we evaluate using multiple processing facilities. In each stage, our mind filters and transforms information from previous stages, then integrates and compares it with information from memory° before it passes to the next stage. By this model, the overall cognitive performance of a person depends on (a) the number and the type of stages required and (b) the efficiency with which the operations proceed at each stage.

Channel capacity

Some models of IP emphasize the limits in the amount of information, channel capacity, which can be processed. For the human factors engineer, awareness of channel capacity often leads to the conclusion that systems may be best designed when they pose the least possible amount of input information and have the lowest possible demands on processing.

Perception of sensory signals

In the first stage of IP, we select for further processing the information from the overall onslaught of sensory signals that is important. The brain does this by comparing the new inputs with information stored in our memory and searching for and recognizing familiar features. This means that our past experiences generate expectations, which we then use to guide perception and selection of information. New, surprising incoming sensory information may either be rejected, or, in contrast, it may easily penetrate our expectation-based barriers, but then we may not know what to make of the unfamiliar inputs.

Short-term memory

Apparently, humans have a short-term and a long-term memory capacity. Short-term (or working) memory keeps registered information for a brief duration, such as a second, in mind to freeze a picture of the rapidly changing world around us that can serve as a comparison and a filtering frame. Another example is looking up a phone number and keeping the number active in memory until dialing it. The working memory seems to have a very limited capacity, both in duration and channel capacity. One theory is that the boundaries of the short-term memory may be the limiting capacities in information processing.

Long-term memory

In contrast, long-term memory has a much larger capacity and no obvious duration constraints. Common distinctions describing memory are those that involve general knowledge, called *semantic memory*, or specific events, referred to as *events memory*. Quite often, these are linked, such as by an episode in our past, for example an accident. The ability to remember (to find and call up) essential information in our long-term memory is important for many tasks. Forgetting information may be due to never having successfully encoded and engraved it in the memory bank, or one may be unable to retrieve it from the buffer because we may lack memory queues or present yet irrelevant information may clutter it.

Information stored in chunks

To interpret information, such as that shown on a display, and then to choose an appropriate response requires us to call up stored task-relevant information. The activation of related knowledge stored in our long-term memory may be triggered by recalling events or actions taken in the past in similar conditions. Two major factors influence the availability of information and its reactivation from long-term memory. One is the strength of the information trace, determined by its initial importance, the number of times it has been activated, and how recently that occurred. The other factor is its association with related items and events, such as the illumination of the workplace when an accident occurred. Such associated links mean that we store much information in chunks, not in isolated pieces.

Making decisions

Our brain must integrate incoming sensory stimuli with other relevant information and then process that knowledge in order to select a suitable response: this part of our mental work is often called *central processing*°, *consciousness*, or *thinking*. Of course, it requires keeping the overall goal of the task in mind in order to select the proper response from all possible ones. Thus, decision-making and response selection include the essential necessity of understanding the outcomes of several possible responses and recognizing which activities are needed to execute the proper response.

Limiting IP requirements

The thinking process must integrate many pieces of information, some newly acquired, most already engraved in the long-term memory. Many of our daily tasks involve this kind of central processing. Shrinking the IP requirements, using limited inputs and integration needs, makes the task easier. One example is driving an automobile in dense traffic where one might decide to follow a preceding car or to turn into another lane to overtake it. Following the car by accelerating and braking is usually easier and less dangerous than passing it; overtaking requires checking whether a neighboring lane is open, turning the wheel one way and the other way, and at the same time carefully regulating the speed of one's own car.

Fitting the human to the job

A traditional model of human information processing appears in Figure 9.9. It shows that, in the CNS, the signal transmitted from the sensors is perceived, decoded, interpreted, and processed, using sequential stages. Little is known specifically about how this complicated procedure actually develops; yet it obviously involves a comparison with previous experiences by pairing the current information with related knowledge stored in the long-term memory. Such experience comes naturally with aging and intentionally with teaching and training. That need for teaching and training of novices in decision-making is an example of fitting the human to the job—as opposed to fitting the job to the human.

New models of IP

The currently predominant premise in cognitive psychology (originally developed in the second half of the last century) is that the brain can be interpreted as a complex computing system. The computer metaphor still provides the basis for most current concepts of human mental work: they rely on the assumption that our brain functions in ways similar to how computers process information—although, naturally, a comparison between a living organism and a technical product is always imperfect. For example, computers have specialized input and output devices; this is somewhat similar to the specialized sensory and response modality of humans. However, they and we have different types of memory stores that can be accessed or searched in different ways; searches, evaluations, and decisions follow hierarchies of importance, and capacities are often limited in amount and function time.

Advanced concepts° include models based on new findings in neurophysiology, for example, using multiple and parallel feedforward and feedback paths together with distributed processing in neural networks. Such models would overcome the limitations of the serial-stage models with discrete processing in each stage; they should provide a more detailed and realistic description of how information storage and processing actually functions. Nevertheless, for the time being, the traditional stage-based concept still provides a useful framework and supplies guidance for the human factors engineer.

9.4 Actions and reactions

Transducers

After the CNS has chosen a response to the received signals, the CNS generates action signals, often to an effector such as the hand or the foot, to activate muscles in order to fight or run. With today's technology, that usually means that the body applies force to a handle or a pedal or other input control element of machinery, be it a simple hand tool or a motorcycle or an airplane. If the effector tool is a hammer or a screwdriver, the task is direct. If there is a more complex piece of machinery, such as an airplane or a ship, so-called transducers are involved, which modify the action of the human body, as Figure 9.11 illustrates. For example, in a bicycle or a small boat, turning the steering wheel creates immediate conversion of human movement into vehicle motion by means of mechanical gears, hydraulic transmissions, or electric/electronic commands. In complex human-operated systems, such as in a large ship or a space vehicle, the response to the action of the human master is commonly slow and takes time to materialize. In this case, a computerized system may be useful, which can predict the future results of the current action.

The design of the transducers and of their feedback signals is a challenge to the human factors engineer. No particular device is needed to assess the effect of swinging a hammer: the result of the first blow is immediately apparent and serves to redirect the next stroke in order to achieve the goal of hammering a nail deeply into a wooden beam while avoiding hitting one's other hand. However, for complicated human–machine interactions, it is useful to distinguish among specific aspects of human actions and reactions.

Response time

The time from the appearance of a stimulus (such as a light) to the beginning of an effector action (for example, movement of a foot) is called *reaction time*. Then, motion time follows. Both combined results in response time°:

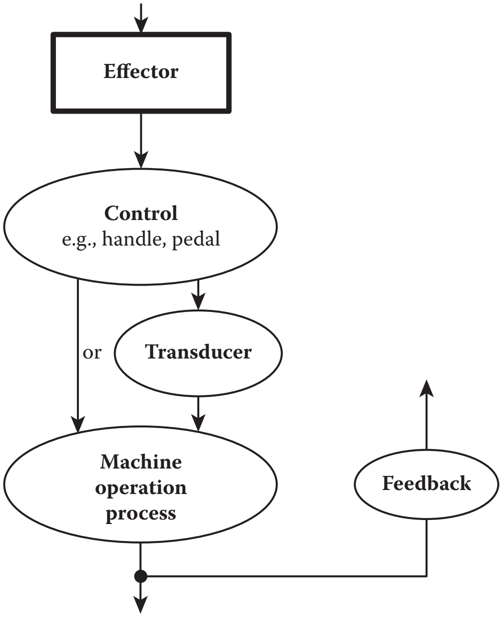

FIGURE 9.11 Transformation of effector output for machine operation. (From Kroemer, K. H. E., *"Extra-Ordinary" Ergonomics: How to Accommodate Small and Big Persons, the Disabled and Elderly, Expectant Mothers and Children*, CRC, Boca Raton, Florida, 2006c.)

Response time = reaction time + motion time.

Reaction time

Time passes between the appearance of a signal on the sensory input side of the nervous system and the emergence of a (re)action on the output side. Time delays occur at the sensor, in afferent signal transmission along the PNS, in processing by the CNS, in efferent signal transmission in the PNS, and in muscle activation. Estimates of the time delays are as follows:

- At the receptor: 1 to 38 ms
- Along the afferent path: 2 to 90 ms
- In CNS processing: 70 to 90 ms
- Along the efferent path: 9 to 20 ms
- Muscle latency and contraction: 30 to 70 ms

Simply adding the shortest time delays leads to the theoretically shortest possible reaction times. In reality, there is little reason to expect that all the conditions are ideal and, hence, the times are shortest.

If a person knows that a particular stimulus will occur, is prepared for it, and knows how to react to it, the resulting time is called the *simple reaction time*. Its duration depends on the kind of stimulus and its intensity. Many different tables of reaction times have appeared in engineering handbooks, but how the original data were measured is no longer known. Although the following information is dubious and needs experimental reevaluation, the shortest possible reaction times (in milliseconds) that are generally quoted ° are as follows (as already listed in Table 7.1):

- Electric shock, touch, and sound: at least 130 ms
- Sight and temperature: at least 180 ms
- Smell: at least 300 ms
- Taste: at least 500 ms
- Pain: at least 700 ms

That listing shows practically no time difference in reactions to electrical, tactile, and sound stimuli. The slightly longer reaction times for sight and temperature stimuli may lie well within the range of measuring accuracy. However, the time following a smell stimulus appears distinctly longer and that for taste yet longer, whereas it takes by far the longest to react to the infliction of pain. The simple reaction times change little with age from about 15 to 60 years, but the reactions are substantially slower at younger ages and slow again as one grows older°.

Choosing between reactions

If a person has to choose among several feasible actions, *choice reaction time* is involved. It is longer than the simple reaction time and expands further if it is difficult to distinguish among several similar stimuli of which only one should trigger the response. The length of a choice reaction time is a logarithmic function of the number of alternative stimuli and responses. The mathematical formula is

$$\text{Choice reaction time} = a + b \log_2 N,$$

where a and b are empirical constants and N is the number of choices. N may be replaced by the probability of any particular alternative; this means $p = 1/N$, and the preceding equation changes to

$$\text{Choice reaction time} = a + b \log_2 (1/p).$$

Motion time

Motion time follows the reaction time. Movements may be simple, such as lifting a finger in response to a stimulus, or complex, such as swinging a tennis racket. Swinging the racket involves more intricate movement elements than lifting a finger, and it also engages larger body and object masses to be moved; all this requires more time.

Motion time depends on the distance of the movement and its required precision. This relationship, called Fitts' law, is

$$\text{Motion time} = a + b \log_2 (2D/W),$$

where D is the distance covered by the movement and W is the width of the target. The constants a and b depend on the particulars of the situation (such as the body parts involved, the masses moved, and the tools or the equipment used), the number of repetitive movements, and the skill (training and experience).

Response time

Minimizing the response time—the sum of the reaction and the motion lags—is often a goal of human factors engineering. Optimizing the stimulus and selecting the body part that is best suited to the task are among the obvious ergonomic choices. This usually requires both careful task selection (and choosing of equipment and procedures) and assessment of related capabilities of the prospective user. This is often an iterative process until the best match becomes apparent.

Summary

The center of the human nervous system is the brain. The central nervous system has the abilities to perceive and interpret afferent signals sent from body sensors, then to process that information by integrating it with knowledge culled from memory, and, finally, to make decisions about actions to be taken. Then signals are sent along the efferent pathways of the peripheral nervous system to the body organs, especially the muscles, to take action. Body sensors pick up the results of these actions, together with independent new information, and corresponding signals are sent along the afferent pathways of the peripheral nervous system to the brain for new decision-making.

Current concepts of the brain functions presume similarities between the ways the human brain and computers operate. Hence, the models depict information processing in sequential stages. We can look forward to the use of more realistic models and their practical applications. For the time being, however, we must make do with serial-stage models. These provide guidance to the ergonomist for the design of human-controlled systems.

Fitting steps

Step 1: Select external signals that human sensors accept easily and quickly.

Step 2: Plan for decisions that depend on the sensory inputs, which are familiar, secure, and fast to make.

Step 3: Design for appropriate quick reactions. Test the system and revise as needed.

Notes

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

Hope for more distinct information: Colapinto 2015.

Ability of the brain to modify° is called "neuroplasticity": Doidge 2007.

The PNS … delivers signals: The PNS was known to be "plastic" when the CNS was still thought to be "hardwired."

9.1 Taking up information:

Memory: Arswell and Stephens 2001; Stanton et al. 2005.

Central processing: Bailey 1996; Wickens, Lee, Liu 2004.

Advanced concepts: Arswell and Stephens 2001; Muchinsky and Culberson 2016.

9.4 Actions and reactions:

Response times, *simple reaction times*: Boff, Kaufman, and Thomas 1988; Boff and Lincoln 1986; Kroemer 2006c; Kroemer, Kroemer, and Kroemer-Elbert 2003; Swink 1966; Wargo 1967.

SECTION III

Body and mind working together

As we try to understand the human, we often consider certain characteristics separately, as if they function independently from each other. Of course, in most cases, there are strong interactions.

The first part of this book treated specific physical aspects of the human body, while, in the second part, the main issue was how we perceive our environment through the senses. In this section, such physiological and sensory aspects are merged with psychological facets to better represent the human where, indeed, the body and the mind work together.

Chapter 10 is concerned with hard labor; Chapter 11 addresses work that is less physically demanding; and Chapter 12 deals with task load and stress.

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CHAPTER TEN

Hard physical work

In many areas of our Earth, mechanization has reduced the demands for human labor. Nevertheless, heavy physical work still prevails in sections of agriculture and forestry. Demanding labor remains frequent in mining, in deep-sea fishing, in building construction, and in some industries; it exists even in recent jobs, for example, in baggage handling by airline personnel. Periods of heavy demands may alternate with times of light duty work.

10.1 Physiological principles

Hard labor is an activity that intensely employs skeletal muscles. These can convert chemical energy into work (physical energy) by moving body segments against internal and external resistances. From resting, the muscle can increase its energy generation up to 50-fold. Such enormous variation in metabolic rate not only requires quickly adapting supplies of nutrients and oxygen to the muscle but also generates large amounts of internal waste products, which need removal. The bloodstream, powered by the heart, provides the transport means for supply and removal.

The body's ability to maintain an internal equilibrium determines how much demanding work it can perform: that capacity largely depends on the proper functioning of the respiratory and circulatory systems to serve the involved muscles. The services are essentially the supply of energy carriers and oxygen and the removal of wastes and heat. Another major service is the control of body temperature, which is of special importance in hot and humid environments (see Chapter 8).

Assessing labor demands and worker's capacities

Heavy work calls for great physical exertion with high energy consumption; thus, it poses high demands on the worker's metabolic functions with consequent strains on the circulatory and respiratory functions of the body. Usually, energy consumption and cardiac effort set limits to the performance capability of an individual. Therefore, the measurement of the demands on metabolic and heart functions often serves to assess the severity of the physical task. Physiological measures of the worker's capacities° in metabolic, cardiovascular, and respiratory functions, together with strength and mobility assessments, serve to judge his or her ability to execute heavy physical work.

Assessing a person's physical fitness

The measurement of the maximal amount of oxygen an individual's body can use during a specified period (such as 1 minute) of intense exercise reflects the aerobic physical fitness of the person. That VO_2 max° is also used to predict endurance capacity during prolonged, submaximal exercise.

10.2 Energy consumption

The skeletal muscles make the body work by moving body segments against internal and external resistances. Muscles need energy for contraction. The mitochondria inside muscles can convert chemical energy into physical energy (see Chapter 3). Running this human energy machine involves a complex metabolic process that has similarities to the combustion of fuel in an engine:

- It yields energy to move parts.
- It needs fuel and oxygen to proceed.
- It produces heat and other by-products.

Comparing the combustion engine with the "human energy machine"

In the cylinder of the engine, an explosive combustion of a fuel–air mixture transforms chemically stored energy into physical kinetic energy and heat. The energy moves the pistons of the engine, and gears transfer their motion to the wheels of the vehicle. Cooling the engine is necessary to prevent overheating, and waste products need removal.

In the "human machine," muscle fibers are both cylinders and pistons: bones and joints are the gears. The fuel, mostly derivatives of carbohydrates and fats in the nutrients, needs oxygen to yield energy in a slow combustion. When the muscles work, they produce metabolic by-products, including heat, that need removal.

Figures 10.1 and 10.2 are diagrams that illustrate the sequence of events in the human body associated with the conversion of nutrients into mechanical energy and heat.

Metabolism

Metabolism is a fundamental biological process: the body takes in food and drink, which contain chemically stored energy, and converts them into mechanical energy. As Figures 10.1 and 10.2 illustrate, food passes from the mouth to the stomach, where it is liquefied; alcohol, when present, is absorbed in the stomach and passed from there into the bloodstream. The digestion of the major energy carriers in food and drink, carbohydrates, fats, and proteins, takes place in the intestines. Digestion means the chemical conversion of large complex molecules into smaller ones that can pass through the membranes of the intestine cells and then become absorbed into the blood and the lymph. The liver largely controls what happens to the absorbed energy

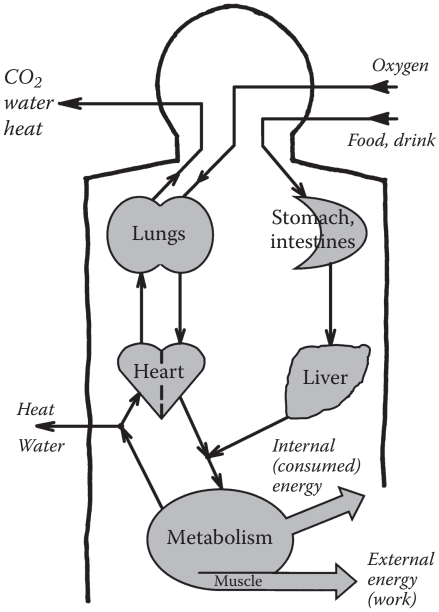

FIGURE 10.1 Diagram of the energy flow in and out of the human body. (Adapted from Kroemer, K. H. E., Kroemer, H. J., and Kroemer-Elbert, K. E., *Engineering Physiology: Bases of Human Factors/Ergonomics*, fourth ed., Springer, Heidelberg, Germany, 2010.)

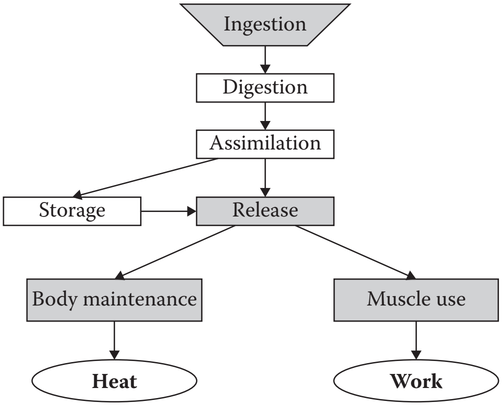

FIGURE 10.2 Diagram of the energy conversions from ingestion to heat and work. (Adapted from Kroemer, K. H. E., Kroemer, H. J., and Kroemer-Elbert, K. E., *Engineering Physiology: Bases of Human Factors/Ergonomics*, fourth ed., Springer, Heidelberg, Germany, 2010.)

carriers: they are assimilated (reassembled) into new molecules that can be

- Stored as energy reserves (mostly as fat—one can "get fat" without ever eating any°)
- Employed for body growth and repair with the rest converted into heat
- Degraded for use of their energy content (glucose and glycogen). When needed for doing work, first glucose and then glycogen serve as energy sources; stored fat provides the body's largest energy resource but is the last to be used.

Metabolic by-products

Human metabolism is a complicated process. Only part of the chemically stored energy is actually converted into mechanical work performed by the muscles; most serves to build and maintain structures of the human body and finally converts to heat. Since the human body core temperature must stay at 37°C (99°F), the excess heat must be dissipated to the environment, a task quite difficult to achieve in a hot climate (see Chapter 8). The heat is transported within the body by the bloodstream; some to the lungs, where it is dispersed into the air to be exhaled; some to the skin, where it is dispelled to the outside air, often with the help of evaporating sweat. Another by-product is water, which the blood also brings to the lungs and the skin for elimination there. A third by-product is carbon dioxide, which the blood transports to the lungs for dissipation. The proper management of these metabolic by-products is a major prerequisite for the body to be able to maintain energy generation and hence to be able to continue hard physical labor.

Energy units

The measuring units for energy (work) are joules (J) or calories (cal) with 4.19 J = 1 cal. [1 J = 1 Nm = 0.2389 cal = 10^7 ergs = 0.948×10^{-3} BTU = 0.7376 ft lb.]. The correct alternate expression for kcal is Cal. The units for power are watts, 1 W = 1 J/s, or 1 kcal/hour = 1.163 W.

Energy content of food and drink

The kilojoule (1 kJ = 1000 J) and the kilocalorie (1 Cal = 1 kcal = 1000 cal) commonly serve as measures of the energy content of food and drink. Their nutritionally usable energy contents per gram are, on average

- Alcohol: 30 kJ (7 Cal)
- Carbohydrate: 18 kJ (4.2 Cal)
- Protein: 19 kJ (4.5 Cal)
- Fat: 40 kJ (9.5 Cal)

Prepackaged food and drink usually carry labels that list the number of kilojoules or kilocalories (often misprinted as *CAL*, even falsely as *cal*) of its content and per serving size (which may be in rather fanciful amounts). The label also usually provides a breakdown of the energy content in terms of carbohydrates, fats, and proteins.

Basal metabolism

A minimal amount of energy is necessary to keep the body functioning even if a person does no activities at all. Under strict conditions (complete physical rest in a neutral ambient temperature, after fasting for 12 hours, with protein intake restricted for at least two days), one can measure the basic metabolism. The results show that the basal metabolic values depend primarily on age, gender, height, and weight—the last two variables occasionally expressed as body surface area. Among healthy adults, there is little variation; hence, a commonly used value is 1 kcal (4.2 kJ) per kg per hour, or 4.9 kJ/min for a person of 70 kg.

Resting metabolism

Often it is impractical to accomplish the highly controlled conditions needed to measure basal metabolism. Instead, one often measures the metabolism before the working day, with the subject as well at rest as possible. Depending on the given conditions, the resting metabolism is around 10–15% higher than the basal metabolism.

Work metabolism

The increase in metabolism from resting to working is called *work metabolism*. This increase above the resting level represents the amount of energy needed to perform the work. Often, to describe the demands of work, one measures the total amount of energy used by the body, which includes the resting or basal levels.

Measuring heaviness of work

One way to assess the heaviness of work is, simply, to ask the working person to describe how hard the effort feels. For standardization, it is advantageous to employ an established rating procedure, such as the Borg scale described in Chapter 12. However, in many cases, objective measurements are desired, and for this purpose, three different procedures are in common use. One procedure is to observe the energy supplied to the body over a given time, the second approach is to take account of the heart rate during work, and the third technique measures the volume of oxygen consumed during work°.

Energy supply to the body

Taking account of the energy input by observing what a person eats and drinks and weighs is one of the oldest techniques. The underlying assumption is that, after deducting what is needed to maintain the body, all surplus energy is used for doing work. Naturally, this approach requires long observation periods, days or weeks during which the observed person performs various kinds of physical activities, interspaced with resting periods. This method is notoriously inaccurate unless performed under strictly controlled conditions.

Oxygen consumption at work

When the body performs work, oxygen consumption (and carbon dioxide release as well) is a measure of the associated metabolic energy production. A variety of measurement techniques is at hand; they all rely on the principle that the differences in oxygen content between the exhaled and the inhaled air indicate the O_2 absorbed in the lungs. Assuming an overall average energy value of oxygen of 5 kcal (21 kJ) per liter of O_2, the volume of oxygen absorbed allows the calculation of the energy that the body converts doing an activity during the observation period.

Respiratory exchange quotient

The respiratory exchange quotient (RQ) provides a more detailed assessment of the nutrients actually metabolized. The RQ 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. Hence, for carbohydrates, the RQ is 1 (unit). The energy released is 18 kJ/g of O_2, 21.2 kJ/L of O_2. The RQ for protein conversion is 0.8; for fat and alcohol conversion, the RQ is about 0.7. Measuring the volumes of CO_2 and O_2 during work allows the determination of which energy carrier is metabolized.

10.3 Heart rate as a measure of work demands

Heart rate during work

Counting the heart rate during work is also a time-honored and widely used method. It relies on the knowledge that the metabolizing muscles require, for their proper functioning, a continuous supply of oxygen; also, metabolic by-products must be removed. The higher the energy requirements, the more blood flow is needed. To attain more blood flow, the heart must produce higher outputs, which it primarily achieves by increasing the number of heartbeats per minute. Thus, the heart's pulse rate varies in accordance with work demands.

Relations between heart rate and oxygen uptake

During dynamic work, a close relationship exists between metabolic processes and their circulatory support systems, as just mentioned. Consequently, the heart rate (as indicator of circulatory functions) and the oxygen consumption (indicating metabolic conversions) show correlated reactions to physical effort. (However, the specific relations differ among persons and may change with a person's physical training or deconditioning.) Therefore, one can often simply substitute heart rate counting for measurement of oxygen intake. This is a very attractive shortcut since the heart rate responds more quickly to changes in work demands. Furthermore, pulse counting is easier than measuring oxygen uptake.

Reactions of O_2 intake to work

As Figure 10.3 shows schematically, at the start of a strong physical effort with its sudden need for oxygen, the actual oxygen uptake lags behind the demand. After a slow onset, the O_2 intake rises rapidly and then levels off to meet the requirements of steady work. Thus, during the onset of labor, the body incurs a deficit in available oxygen due to the sluggish rise in oxygen supply. After work ends, the body's oxygen intake begins to decrease until it falls back to the resting level, but that return takes usually about twice the time it took to raise the O_2 uptake at the start of work.

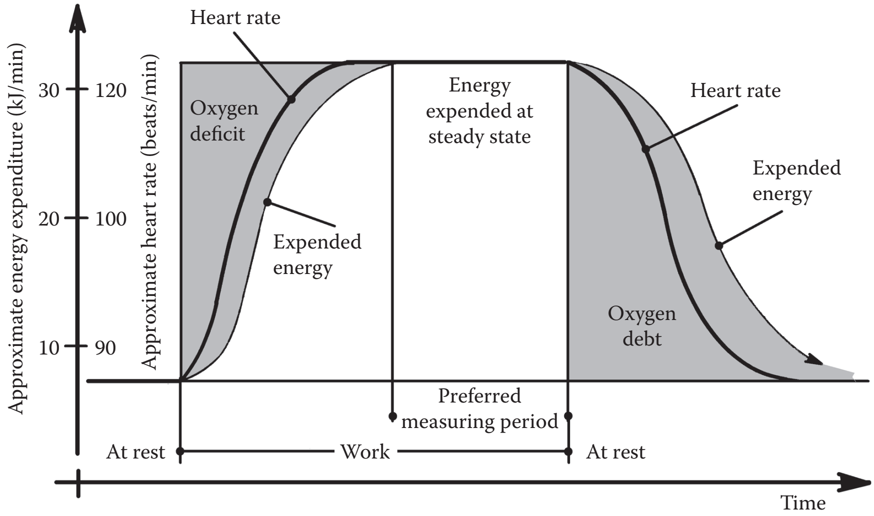

FIGURE 10.3 Schematic of energy liberation, energy expenditure, and heart rate before, during, and after steady-state work. (Modified from Kroemer, K. H. E., Kroemer, H. J., and Kroemer-Elbert, K. E., *Engineering Physiology: Bases of Human Factors/Ergonomics*, fourth ed., Springer, Heidelberg, Germany, 2010.)

Oxygen deficit and debt

The first burst of energy is mostly provided by degrading the energy carrier adenosine tri-phospate (ATP) to adenosine di-phosphate (ADP) and CP available in the body. During recovery, the body resynthesizes ATP and CP and replenishes O_2 stores in the hemoglobin in the blood and the myoglobin in the muscles. This requires elevated biochemical, cardiac, and respiratory functions and, correspondingly, enlarged oxygen intake: as a rule, the oxygen debt repaid is approximately twice as large as the oxygen deficit initially incurred.

Breathing hard

Our body's ability to develop an oxygen deficit explains why we can perform feats that require for a short time a tremendous amounts of energy that we could not sustain for long; and our body's need to repay the oxygen debt explains why we continue to breathe hard after a strenuous physical effort.

Reactions of heart rate to work

Of course, given the close interaction between the circulatory and metabolic systems, the heart rate reacts to bouts of work in similar ways as oxygen intake; yet the heart rate increases faster at the start of work than the O_2 uptake and during recovery also falls back to the resting level more quickly, as Figure 10.3 illustrates.

Table 10.1 Classification of work demands

Classification	By energy expenditure		By heart rate
Words	(kJ/min)	(kcal/min)	(beats/min)
Light, easy	10	2.5	90 or less
Medium, moderate	20	5	100
Heavy, hard	30	7.5	120
Very heavy	40	10	140
Extremely heavy	50	12.5	160 or more

Steady-state work

If a required work effort stays below a person's maximal capacity, then metabolic processes, oxygen supply, blood flow, and respiration can achieve and maintain their required levels. This condition of stabilized functions at work is called *steady state*; it is shown in Figure 10.3. Measurements of work demands on the body are reliably obtained during this state. Obviously, a physically fit person can attain this equilibrium between the demand and the supply at a relatively high workload, whereas an untrained or less fit person would be able to achieve a steady state only at a lower demand level.

Classifying work demands

Obviously, the expenditure of energy and the number of heart pulses during extended work are objective indicators of the heaviness of the demands of work done by a person. When asked for descriptive words, the worker might call some demands light or easy and others heavy or hard. However, such descriptions can vary with circumstances and experiences: some grandparents, for example, still used to physical labor, might call a certain level of work demand rather moderate, which their grandchildren might find rather heavy. Table 10.1 contains classifications of work demands. The energy values listed contain basal and resting metabolisms; all values are "unisex" so many men will call the work a bit easier and many women harder than the labels imply.

10.4 Limits of human labor capacity

A maximal effort raises many body functions considerably, as Table 10.2 shows. As long as the body can meet the work demands by staying at steady state, the work can continue, as Figure 10.3 indicates. However, if work demands exceed the

Table 10.2 Typical changes in physiological functions 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

Source: Kroemer, K. H. E., Kroemer, H. J., and Kroemer-Elbert, K. E., *Bases of Human Factors/Ergonomics*, fourth ed., Springer, Heidelberg, Germany, 2010.

body's capabilities, the heart rate and other supply functions cannot achieve a steady state but increase their activities until they reach their limits. This forces work stoppage; then heart rate and other functions slowly fall back to their resting levels, as Figure 10.4 illustrates. The level of demand that an individual can follow depends on the person's physical fitness and trained skill to do the job.

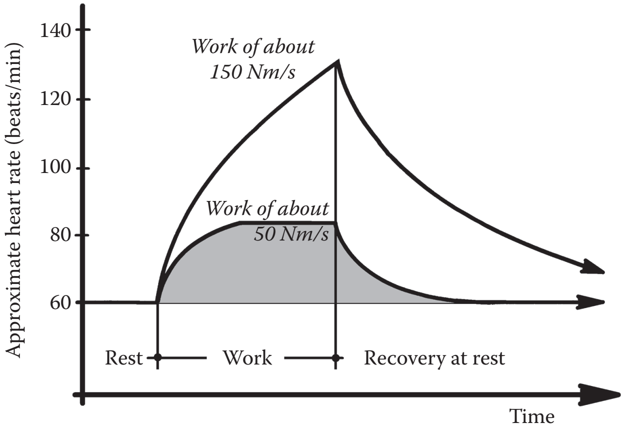

FIGURE 10.4 Heart rate increase in exhausting work versus heart rate at steady state during light physical work.

Measuring people's fitness to do heavy work

Most medical and physiological assessments of human energetic capabilities primarily rely on the measurement of oxygen consumption, with the heart rate as a secondary indicator. Standardized tests allow comparisons among persons' capacities. These tests employ generally accepted idealized forms of external work, often using bicycle ergometers, treadmills, or steps. Their use primarily stresses leg muscles. Since leg mass and musculature are substantial components of the body, their extensive exercising during a bicycle test also strains pulmonary, circulatory, and metabolic functions of the body, but not all of them. The treadmill primarily strains lower body capabilities as well, but in contrast to bicycling, the legs must support and propel the entire weight of the body. Hence, the treadmill test strains the body in a more complete manner than bicycling; however, both omit trunk and arm capabilities from consideration. These examples show that the selection of test equipment and procedure can lead to different evaluations of persons' physical fitness: for instance, the tryout outcomes of well-trained bicyclists and of well-trained long-distance runners would differ when done on either bicycles or treadmills. A major problem of all these tests is that they do not resemble actual work conditions. So the test results have only limited value for predicting the abilities of the subjects to perform physically demanding work tasks.

Selecting persons fit for heavy work

Health and fitness tests are important means to make sure that only persons who are fit to do heavy physical work are employed to do so. However, in the view of the ergonomist, it is better to design work tasks and equipment so that that they impose relatively small demands on human physical capabilities. This ensures not only that people do not get overtaxed by the work, but also that more persons, even those with less than superb physical capabilities, can do the job.

"Static work"

Maintaining a motionless posture requires that muscles generating the posture maintain continuous contraction. If such static (isometric) contraction° exceeds about 15% of the muscular strength, the blood flow through the muscle becomes reduced because the muscle compresses its own arteries and veins transversing the muscle tissue. Stronger compression, which comes with increased muscle tension, further reduces the blood flow and may even cut it off completely even though the heart tries to increase the blood pressure to overcome the flow obstruction. This leads to fatigue, which finally makes us abandon the tiring posture to relax and recover. The ability to endure a static contraction depends on the magnitude of contraction, as Figure 10.5 illustrates.

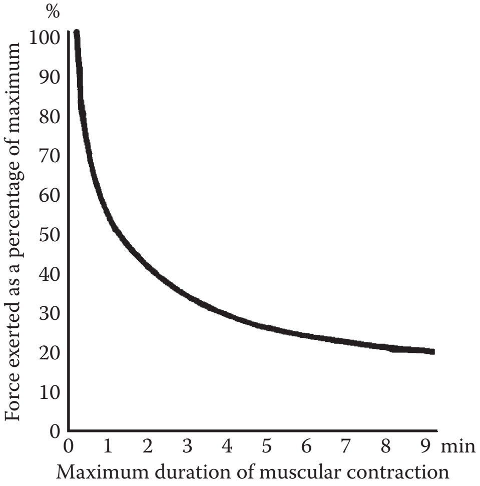

FIGURE 10.5 Maximal duration of static muscle contractions.

Static versus dynamic muscle effort

In suitable dynamic work, quite in contrast, rhythmic alterations between tension and relaxation in a muscle facilitate blood flow through its tissues—this has been called a *muscle pump*—as illustrated in Figure 10.6. Static effort increases the pulse rate as the heart strives to increase the blood pressure in order to overcome the flow resistance in compressed blood vessels within the straining muscle. Increased heart rate associated with a sustained static muscular effort is indeed an indicator of physical strain; however, since the blood flow is diminished, the metabolism is reduced as well. Therefore, in the case of static effort at work, the direct relation between heart rate and energy consumption, mentioned earlier, falls apart.

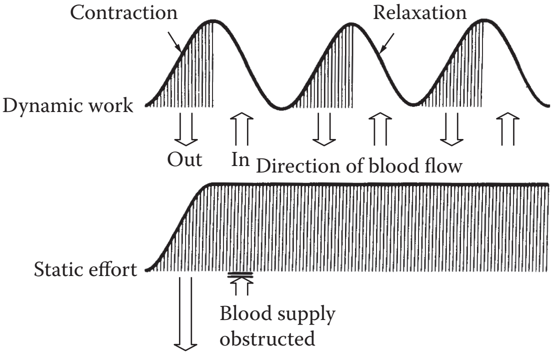

FIGURE 10.6 Blood flow through a muscle doing dynamic and static exertions.

10.5 Designing heavy human work

Human energy efficiency at work

Engineers and economists like to express work efficiency as the ratio of gain versus effort. If we assume that the energy storage in the body does not change (meaning that the observed person does not put on or lose weight) and that the body neither gathers heat from the environment nor loses any, we can state a simple energy balance equation as

$$I = H + W,$$

where I is the energy input, H is the heat developed, and W is the performed work.

Human energy efficiency (work efficiency) e is the ratio between the work performed and the energy input:

$$e\ (\%) = 100\ W/I.$$

In everyday activities, the human body is very inefficient in terms of energy usage. Only about 5% or less of the energy input converts into work, that is, energy usefully transmitted to outside objects; highly trained athletes may attain, under favorable circumstances, perhaps 25%. The remainder (that is, most) of the input converts into heat, usually at the end of a long chain of internal metabolic processes. Since humans are so inefficient, in energy terms, their capabilities are better used to think and manage or to control machinery and processes rather than to serve as physical movers.

Design work to fit the human

The engineer determines the work required and how it is to be done. To arrange for a suitable match between capabilities and demands, the engineer needs to adjust the work to be performed (and the work environment) to the body's energetic capabilities. These human capabilities are determined by the individual's capacity for energy output (physique, training, health), by the neuromuscular function characteristics (such as coordination of motion, muscle strength, etc.), and by psychological factors (such as motivation).

Avoid exhausting work

Coal miners and lumberjacks, doing their work with hand tools, are among the male workers with the highest energy consumption: about 19,000 kJ per day, measured in the 1960s. Such extreme efforts are probably becoming rare in many countries because mechanized tools and modern machinery can make work less demanding. The daily energy consumption for moderately demanding work is around 12,000–15,000 kJ for men and 10,000–12,000 kJ for women.

Provide rest breaks

Breaks in physical work provide recovery and rest. Providing breaks is essential in hard physical labor and desirable even at lighter work for physiological and psychological reasons. Providing many breaks of short duration is more beneficial than just allowing a few longer interruptions. The reason is that recovery is steepest at the beginning of a break in work, as the curves of energy and heart rate in Figures 10.3 and 10.4 illustrate.

No "static work"

As already mentioned, the standard understanding of physical work is that it consists of dynamic actions. Under these conditions, normally, the heart rate and the energy consumption are closely related. However, many actual work tasks include static efforts, where parts of the body must be kept in a frozen position for a while. Whereas static effort does not constitute work in physics terms, it nevertheless strains the body, especially its cardiovascular system: the heart rate increases, while the energy consumption does not. Static muscle efforts are often tiresome but not productive; therefore, they should be designed out by changing the process or replacing human effort by the use of mechanical solutions.

Summary

Figure 10.7 provides an overview of the human traits and the conditions at work that determine, by interacting with each other, how much hard work a person can do. The ergonomist exerts no power over individual characteristics but, in contrast, has latitude and responsibility for the layout of work task and schedule and, relatedly, for the equipment and tools used.

Fitting steps

Step 1: Determine whether it is indeed necessary for hard physical labor to be done by humans.

Step 2: Try to alleviate the workload.

Step 3: Provide rest breaks; encourage taking time off from work as needed.

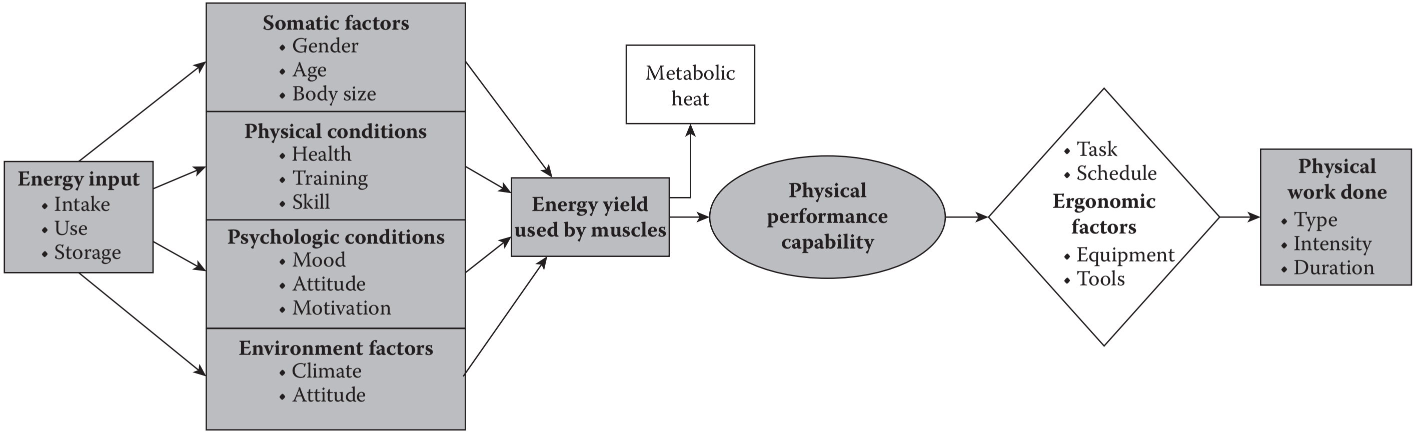

FIGURE 10.7 Traits of the human operator, the conditions, and the design of work interact and hence determine the person's ability to perform heavy physical work. (Adapted from Kroemer, K. H. E., Kroemer, H. B., and Kroemer-Elbert, K. E., *Ergonomics: How to Design for Ease and Efficiency*, second ed., Prentice-Hall/Pearson Education, Upper Saddle River, New Jersey, 2003, amended reprint.)

Notes

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

10.1 Physiological principles:

Physiological measures of the worker's capacities: Astrand, Rodahl, and Stromme 2004; Hall 2015; Kenny, Wilmore, and Costill 2015; Kroemer, Kroemer, and Kroemer-Elbert 2010; Rodahl 1989.

VO_2 max (max VO_2) is also called *maximal oxygen consumption*, *maximal oxygen uptake*, *peak oxygen uptake*, or *maximal aerobic capacity.*

10.2 Energy consumption:

Getting fat without eating fat: Flier and Maratos-Flier 2007.

Measure heaviness of work: Kroemer, Kroemer, and Kroemer-Elbert 2010.

Static contraction: Because there is no displacement in an isometric (static) muscle contraction, this muscular effort does not produce "work" in the definition of physics: work is the integral of force and displacement. So the term *static work* is a misnomer but often used.

CHAPTER ELEVEN

Light and moderate work

Even when we are at rest or when our work requires just a fairly light effort, the basic metabolic functions of our bodies run essentially the same as when supporting hard labor (see Chapter 10), but at a lower level: energy stored in chemical compounds in our food and drink is digested, then assimilated into simpler molecules. These serve to build and maintain our organs and to provide the energy that muscles need to function. The lungs collect oxygen and dissipate by-products of the metabolism (carbon dioxide, water, heat), while the skin exchanges heat. This loads the circulatory and respiratory body functions, but naturally less so than during heavy physical work.

Table 10.1 described light work as having energy demands below 10 kJ and causing less than 90 heart beats per minute and moderate work as below 20 kJ/min and 100 pulses/min. Therefore, in contrast to harder labor, during light and moderate work neither energy use nor blood flow limits our performance. The chief demands are on our willingness and ability to toil diligently with endurance and attention to detail.

The environment in which we work can strongly contribute to our perception of the work as being easy or demanding. In physics terms, the work environment primarily depends on air temperature and humidity, on surround sound and noise, and on lighting, already discussed in Section II of this book. Organizational conditions at work are of great importance: the "psycho-social environment" determines, for example, how we get along with our coworkers; feeling well at work also depends on the arrangement of our working hours, including work shifts—all discussed in Section IV.

11.1 Physiological and psychological principles

Most jobs in modern offices, or while driving vehicles, for example, are sedentary and require little physical effort, as listed in Table 11.1. Therefore, many persons with sit-down jobs try to bring up their daily expenditures by doing demanding leisure activities, workouts, and sports. Such exercise activities rev up otherwise idle body functions and help to compensate for unneeded intake of energy by food and drink, which otherwise might lead to excess weight. One simple way to exercise the body is to walk up and down the stairs instead of taking the elevator in tall buildings. Stair climbing demands heavy muscle use to lift the body and hence helps to keep the metabolic and circulatory systems fit. Figure 11.1 shows the energy expenditures in various activities.

Table 11.1 Energy expenditures at sample activities

Sedentary office work	About 2 kJ/min
General house work	5–20 kJ/min
Walking, on level ground at 4 km/h	About 14 kJ/min
Walking with 30 kg load on the back, on level ground at 4 km/h	About 23 kJ/min
Running, on level ground at 10 km/h	About 45 kJ/min
Climbing stairs, 30° incline, 100 steps/min gaining a height of 17 m/min	About 60 kJ/min

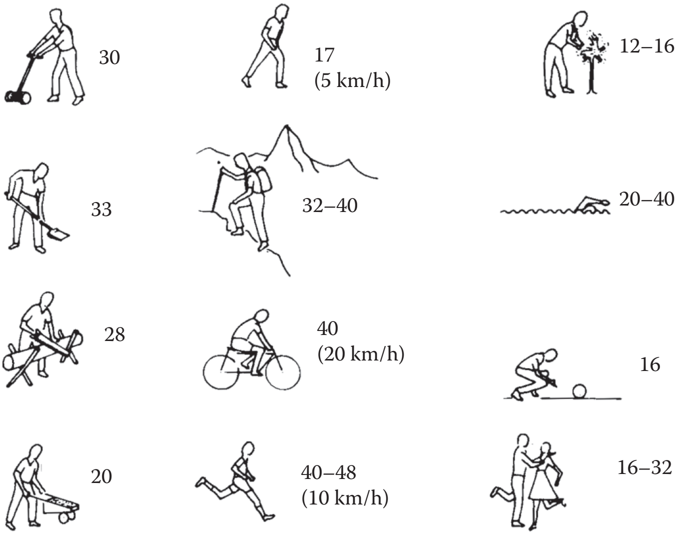

FIGURE 11.1 Energy consumption (kJ/min) in leisure activities.

Measuring work load effects

When the energy requirements of work are low, measuring the worker's oxygen consumption provides little useful information. However, the heart rate (HR)—which is easier to obtain—may be a useful indicator because it also responds to static muscle loading, such as when holding the body or its segments in one given position. This sensitivity of the HR may be an advantage over energy assessment, but the responsiveness also extends to mental reactions such as excitement or anger, so the reactions of HR may reflect not just loading by physical work. Other specific approaches to measure workload effects° rely on electrical events in the body, for example, related to muscle activation (EMGs) and brain activities (EEGs) and eyelid closure frequencies. Simply observing the general work output, especially as it fluctuates with changing working conditions, is also a realistic and nonintrusive yet nonspecific measure.

Scaled judgments

Another way to assess satisfaction or discontent with the conditions of work is to ask people for their opinions and judgments. This can be done informally or, more structured, by using prepared questionnaires. For example, a questionnaire might use the following pairings of descriptors:

Fresh———Weary
Sleepy———Wide awake
Vigorous———Exhausted
Weak———Strong
Energetic———Apathetic
Dull, indifferent———Ready for action
Interested———Bored
Attentive———Absent-minded

The person may be instructed to choose between one of the paired descriptors: this is called a *forced choice*. Or the person may put a mark on a line between two opposing statements to indicate how interested, or how bored, for example, one actually is. Of course, many other, often complicated questionnaires may be of value to assess the conditions of comfort or discomfort at work.

Three kinds of scales

Often responses are collected using one of three scales in common use. *Ordinal scales* arrange judgments in rank order; they allow only statements of "higher" or "lower." *Interval scales* require judgments set in steps that are at equal distances from each other. *Ratio scales* are interval scales that are anchored by an absolute zero; therefore, the numbered responses in ratio scales allow mathematical calculations. (Borg's rating of perceived exertion scale in Chapter 12, Table 12.2, is an interval scale, whereas the CR 10 scale is a ratio scale.)

Subjective versus objective appraisals

Because of the inherent difficulties related to obtaining objective numbers, many studies use subjective judgments (by the worker or by another expert) that assess an existing work situation. While the procedures vary widely among researchers, most rely on templates that ask for discomfort or pain statements. The manner of administering the survey may affect the outcome, but just being involved in such a study may generate a heightened awareness of problems at work that should be in everybody's interest, although management sometimes views this issue with apprehension.

The Nordic Questionnaire

An often-used, well-standardized inquiry tool is the Nordic Questionnaire, which invokes either forced binary or multiple-choice answers. It consists of two parts, one asking for general information and the other specifically focusing on regions of the body. This section uses a sketch of the body, divided into nine regions, shown in Figure 11.2. The interviewed person indicates

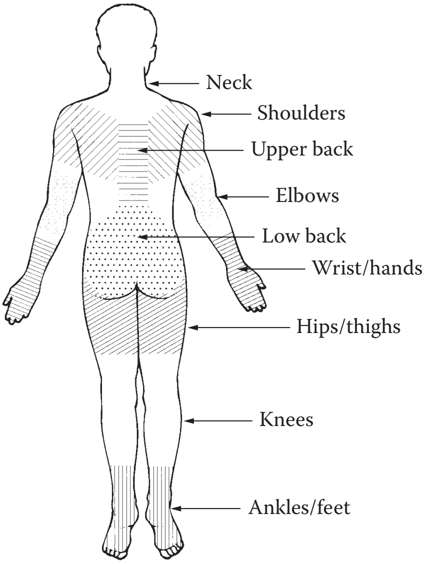

FIGURE 11.2 Body sketch in the Nordic Questionnaire. (Adapted from Kroemer, K. H. E., Kroemer, H. B., and Kroemer-Elbert, K. E., *Ergonomics: How to Design for Ease and Efficiency*, second ed., Prentice-Hall/Pearson Education, Upper Saddle River, New Jersey, 2003 amended reprint.)

whether she or he experiences any musculoskeletal problems in these areas. While a number of modifications to the Nordic Questionnaire have been proposed, it is widely administered, and it therefore provides internationally standardized information.

11.2 Tiredness, boredom, and alertness at work

Feelings of tiredness and boredom are familiar in everyday life. By strict definition, tiredness results from fatigue, the physiological effect of having spent our energy, of muscles overstrained, so that our body needs rest to recuperate from the preceding effort—as discussed in Chapter 3. In comparison, boredom is a psychological or emotional condition in which a lack of events lulls us into a state of indolence. However, in everyday parlance, we say that we are tired as a result of either (physical) fatigue or (psychological, emotional) boredom. So the "I am tired of …" and "I am bored by…" have become to mean almost the same: we take little interest in our present task and are disinclined, even feel unable, to continue what we were doing.

Diversity versus monotony

Some individuals enjoy a job that has diverse parts, tasks that change and therefore variously challenge mental and physical capabilities. The variety of demands keeps them interested, and they find satisfaction in successful solutions. However, other persons prefer a job that predictably presents the same tasks, or at least similar things to do. They may find satisfaction in skillful repetition, such as on an assembly line, while thinking, daydreaming, or conversing. So monotony, the lack of unusual stimuli, is something to loathe or to like, depending on one's inclinations. For most people, however, performance—and job satisfaction—is best with a job that is neither overly complex nor too simple, as depicted in Figure 11.3. However, any person's preferred spot on that mound-shaped curve° may change according to skill, health, and mood.

Vigilance and event frequency

Many jobs require alert watchfulness, vigilance, over long periods. The ability to sustain concentration turned out to be of special importance during World War II. Then it was noticed that the frequency at which radar observers reported submarines to appear on their screens diminished with the length of their watch. Half of all occurrences were reported during the first 30 minutes on duty; then the reports of sightings fell and ended up at 10% after two hours on duty. Obviously, alertness° deteriorated with time on watch.

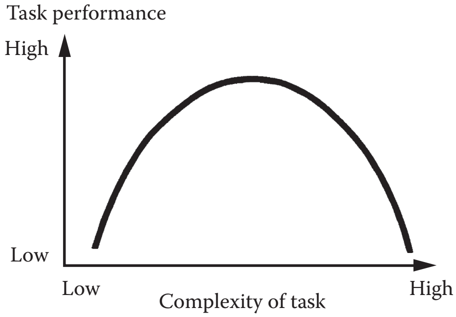

FIGURE 11.3 Conjectured relation between task complexity and performance.

Signal frequency

Other experiences showed that the frequency at which signals occur greatly influences the number of reported signals. If so few signals appear that the observer gets tired of waiting for them and therefore pays little attention, a signal may not even be recognized when it finally shows. On the other side, at very high frequencies of occurring signals, the observer may no longer be able to follow and report them. Between these extremes of too few and of too many signals is a broad range of signal frequencies in which the signal appearances are well reported. This finding lead to the hypothesis that, at very few events, the observer is underloaded, and so the mind drowsily wanders; conversely, with too many events, the observer is overloaded and hence fails in recognizing and reporting all of them. Figure 11.4 depicts these relations: it suggests that the observer's performance follows a "Mound" curve, also called "inverted U." (Note the similarity to Figure 11.3.)

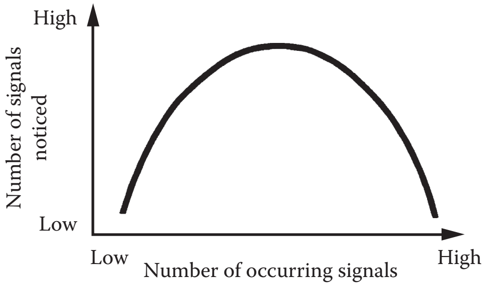

FIGURE 11.4 Mound curve depicting the number of signals occurring and noticed.

Operator performance

These observations opened an important field of research that generated extensive knowledge and many theories about vigilance and arousal: Performance decreases with time. Performance also worsens if the intervals between signals vary much, if the observer is fatigued or under mental stress or if the observer must perform in environments that are obnoxious, for instance, because of heat, noise, or vibration. On the other hand, strong signals at suitable frequencies, meaningful to the task, improve performance.

Monotonous jobs

In the 1920s, industrial managers thought it appropriate to split jobs, when possible, into a small number of identical tasks, which the operator was to repeat over and over. This approach, often traced to the early 1900s ideas of Frederick Taylor°, created monotonous and repetitive tasks with the same demands on the operator's dexterity. Consequently, after practice, the worker became highly skilled and could perform the tasks at high speed. There are, however, serious problems with this Tayloristic approach: while some people like to do repetitive work, others are bored by drudgery and monotony; furthermore, excess repetition can lead to injury of the human musculoskeletal system, as discussed below.

Satisfaction with one's work

Individuals' preferences and aspirations differ; yet just about every person wishes to have the satisfying experience of mastering the work task and exercising power over how to do the job, especially how it could be done more easily and the outcome improved. So-called detail (or instrumental) control is at the task level, including decisions regarding workplace arrangements, tools, and procedures, and the immediate environment. Conceptual (managerial) control is at a higher level: it may include decisions about general design, work organization, even administrative policies. Having control over the job provides feelings of power and importance, while the lack of control can deter performance and be a social stressor. Feedforward and feedback among workers and management are a vital part of participatory and teamwork, as discussed in some detail in Section IV of this book. Active communication can greatly improve job satisfaction and create a social climate conducive to high productivity. Recognition, rewards, and incentives that follow successful work create satisfaction, personal interest, and ego involvement°, which improve performance.

11.3 Suitable postures at work

No static work

In light and moderate work, fatigue often results from the requirement to maintain positions of the limbs, or the posture of the whole body, over considerable time°. Maintaining a posture often requires the involved muscles to keep up a constant contraction, which compresses its own tissues. That pressure hinders the flow of blood through the muscle (as discussed in Chapter 10), and the obstructed blood stream cannot remove all metabolic by-products. With accumulating metabolic by-products, the muscle fatigues and must relax to recover. During that time, the blood flow gets restored and the metabolic waste is removed. To avoid such fatiguing and debilitating postures, various—and often simple—ergonomic solutions are at hand.

Avoiding fatiguing body postures

Many tasks still contain requirements for tiring body postures°. Standing, stooping, and kneeling increase the metabolic cost over sitting, as Figure 11.5 shows. Other examples of fatiguing conditions are twisting the trunk, bending close to the ground, or reaching up; working with extended arms; standing for hours such as at sales counters; in computerized offices, long sitting with the eyes on displays and the hands on keys. Avoid severe twisting of the trunk, such as that shown in Figure 11.6, in order to move a heavy packet onto a shelf. Figure 11.7 illustrates that thoughtlessly putting a large box on the floor requires a person to bend into it in order to sort and take out the content. Simply putting the box on its side, atop a support, allows the worker to work in a more upright posture—see Chapter 21 for a discussion on material handling.

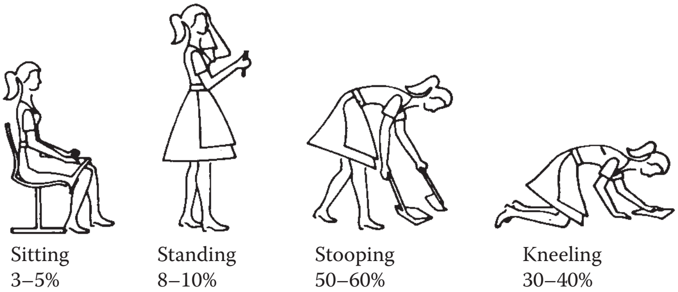

FIGURE 11.5 Increases in metabolic cost associated with body posture; the reference is lying down, resting.

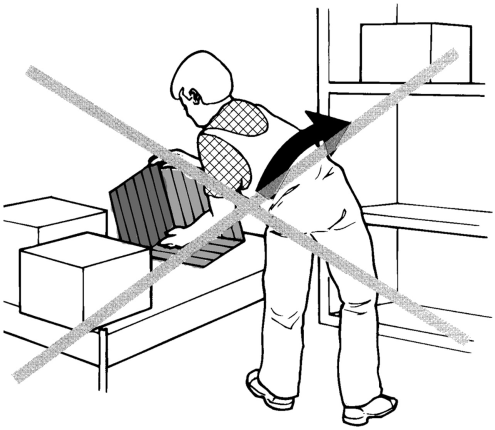

FIGURE 11.6 Avoid trunk twisting.

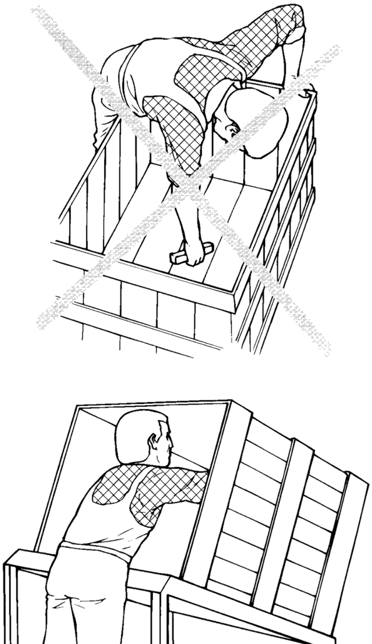

FIGURE 11.7 Putting a large box on its side, elevated, replaces "diving" into the container to take out its content.

Sitting at work

Sitting is less tiring than standing. However, the workstation should have space for the legs and a provision for effortless sitting; not every operator likes to fold the legs under his or her body, as the wood carver does in Figure 11.8. One could argue that carving in this way, where the toes actually serve to hold the work piece, is the traditional way to which local artisans have long been accustomed. However, no such excuse applies to the grinder workplaces in Figure 11.9. This drawing shows that the grinders must tuck their feet under, bend forward, and work with extended arms—we can just hope that at least proper safety provisions exist at these miserable workplaces. The operator shown in Figure 11.10 has better legroom, but an edge of the machine seems to press against her knees; furthermore, she must do much of her work with arms stretched upward and forward.

FIGURE 11.8 Wood carver sitting on his work piece.

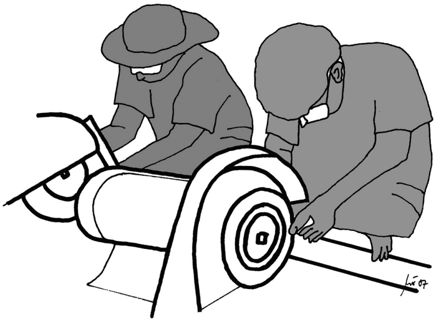

FIGURE 11.9 Grinding in miserable work postures.

FIGURE 11.10 Loading and unloading parts with extended arms.

Too much sitting

Cases of nearly intolerably long and immobile sitting occur in long-distance automobile driving and airplane flying. A truck driver who must cover a long distance may have to remain seated with hands on the wheel, feet on the pedals, and eyes on the road for many hours before getting up and stretching the body. A military pilot who has to fly a long mission is even worse off, because there is no way of getting up and out. The solution tried in World War II airplanes was to have separate, air-filled sections in the pilot seat that would automatically inflate and deflate. Such pulsating body support can provide some relief from constant pressure on the body. Persons who cannot move, such as some ill patients, often develop pressure ulcers (bedsores) on those body parts that transfer most weight. Moving about instead of remaining still is essential for well-being and well-feeling.

11.4 Accurate, fast, skillful activities

Exact manipulations

In light work, especially if it requires frequent and exact movements, the work area of the hands should be at about waist height, in front of the trunk. This preferred work area is shown in Figure 11.11. It allows fast and accurate hand motions,

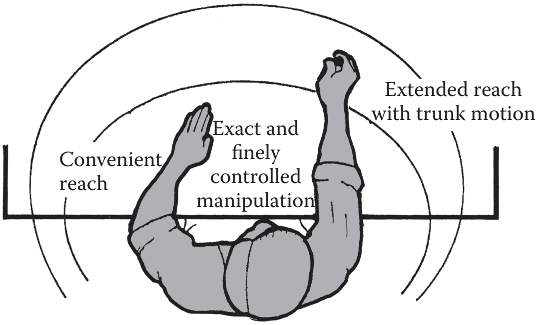

FIGURE 11.11 Space for fast and accurate light handwork. (Adapted from Proctor, R. W., and Van Zandt, T., *Human Factors in Simple and Complex Systems*, second ed., CRC, Boca Raton, Florida, 2008.)

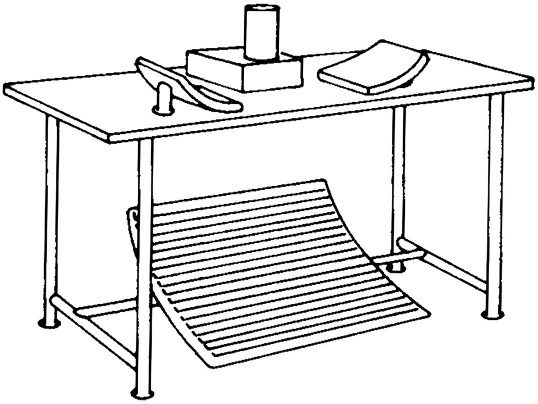

FIGURE 11.12 Workplace with supports for the elbows and the feet.

accomplished by inward rotation of the whole arm about the shoulder joint and by raising and lowering the forearm. If the work requires particularly exact manipulation, armrests as in Figure 11.12 might be helpful to stabilize the upper body.

Seeing what we are doing

Being forced to keep the neck bent or twisted can cause a real headache; such an unbecoming posture is often enforced by having to look at a work object that is not within easy view. Work with fixed loupes or microscopes has always been difficult because, in order to keep the eyes in their required positions at the ocular lenses, the neck and trunk muscles must maintain strict static contractions. Electronic devices can eliminate this problem because they project the image on a monitor, which the operator can view from various locations of the eyes and the head.

Describing head posture

Describing the head and neck postures with the so-called Frankfurt plane (still found in older textbooks) used to be a chore, but is easy when employing the ear–eye (EE) line, shown in Figure 11.13 (which repeats Figure 5.4). The EE line runs through two simple markers on the head, the ear hole and the meeting point of the eyelids. Its angle against horizontal defines the position of the head in the view from the side. The angle of the line of sight against the EE (LOSEE in Figure 11.13) defines the direction of the sight line.

Line of sight

The line of sight connects the eye with the visual targets. If the visual target is far ahead, most persons like to look slightly downward below the horizon; the favored angle of the sight line against the EE line, LOSEE in Figure 11.13, is about 15°; but that angle becomes larger as the object, upon which one must focus, gets closer. At reading distance, which is at about forearm length (around half a meter) from the eyes, the preferred angle is about 45°. However, there are large differences in the preferred angles and the distances from person to person, and wearing eye corrections can play a role as well. Eye movements within about 15° above and below, and to the sides, the average line of sight angle is still comfortable; that means that the common viewing task should be within a 30° cone around the normal line of sight, as shown in Figure 11.14.

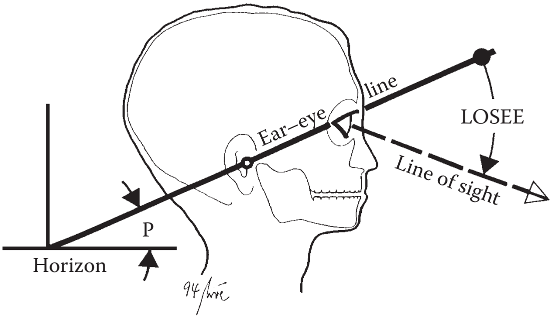

FIGURE 11.13 The EE line runs through the ear hole and the junction of the eyelids. It describes the posture of the head and serves as reference for the angle of the line of sight.

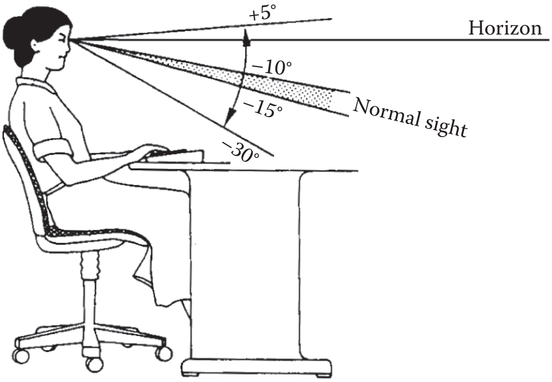

FIGURE 11.14 The cone of easy sight.

Better tools

Forcing the body into contorted, especially bent, and twisted positions is frequently the result of improper design, such as mispositioning the controls on machinery. Figure 11.5 illustrates such design flaws on machine tools, which are easy to avoid by considering body sizes and reaches. One can improve even such traditional tasks as gardening and fieldwork by simple means; Figure 11.16 shows an example for hand seeding and fertilizing. Variations in basic fieldworking tools such as handheld hoes can make work easier or harder: in loose soil, the open hoe, shown in Figure 11.17, needs less energy to use than a conventional blade, and it also works well in compacted Earth.

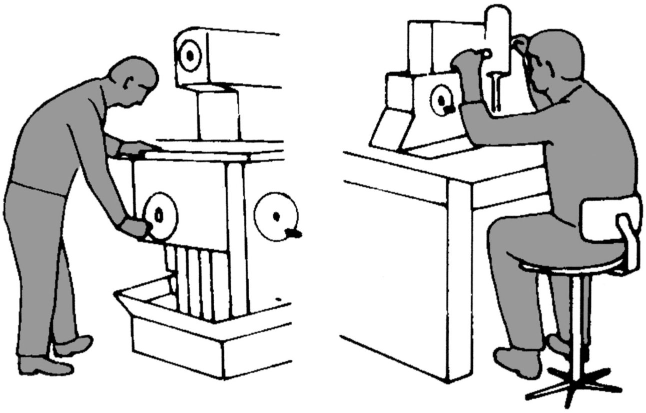

FIGURE 11.15 Improper machine tool design causes bent body postures.

FIGURE 11.16 Hand seeding or fertilizing.

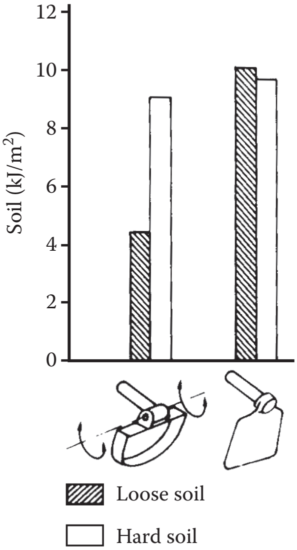

FIGURE 11.17 Energy use with two kinds of hoes.

Repetitive work

Much skillful work consists of often-practiced tasks. Repetition-caused injuries to muscle and other connective tissues, and to the joints of the human body, have recently become a major problem in occupational safety and health. This is surprising because, in 1713 already, Ramazzini° described occupation-related diseases and injuries that occurred in jobs with physical labor; he mentioned that even secretaries (scribes) suffered from muscle pains and cramps stemming from their repetitive tasks°. Even light work can bring about repetitive strain injuries but forceful exertions, hard physical contact, vibrations, and sustained or awkward postures can cause them as well. Even if each activity by itself does not cause an injury, repeating it frequently and over long periods can do harm. Since the accumulation of minitrauma adds up to a final injury, the term *cumulative trauma disorders* describes such excessive wear and tear on tendons, muscles, joints, and sensitive nerve tissue.

Apparently, the human body is not designed for overly repetitive actions, whether they occur at work or at leisure, as Table 11.2 illustrates. The underlying reasons for the listed health

Table 11.2 Descriptive names of repetition-related disorders

- Writer's cramp or scribe's palsy
- Telegraphist's or pianist's wrist
- Stitcher's or tobacco primer's or meat cutter's or washerwoman's wrist
- Goalkeeper's, seamstress', or tailor's finger
- Bowler's or gamekeeper's or jeweler's thumb
- Bricklayer's hand
- Jackhammerer's or carpenter's arm
- Carpenter's or jailer's or student's elbow
- Porter's neck
- Shoveller's hip
- Weaver's bottom
- Housemaid's or nun's knee

Twentieth- and twenty-first-century disorders

- Knitters or crocheter's wrist
- Ballet dancer's or nurse's foot
- Baseball catcher's hand
- Letter sorter's or yoga wrist
- Golfer's or tennis player's elbow
- Letter carrier's shoulder
- Nurses' back
- Carpet layer's knee
- Typist's or cashier's wrist
- Typist's myalgia
- Typist's tenosynovitis
- Keyboarder's mouse elbow
- Keyboarder's carpal tunnel syndrome
- Texters' thumb

Source: Kroemer, K. H. E., *International Journal Universal Access in the Information Society UAIS 1/2*, 99–160, 2001.

problems are plainly obvious from the descriptive names of the injuries. Hands, wrists, elbows, shoulders, and low back are predominant locations for repetition-caused overuse disorders.

Rest breaks

Breaks in physical work provide time for rest and recovery. They are beneficial for both physiological and psychological reasons. Providing many breaks of short duration is more helpful than just allowing a few longer interruptions. The reason is that recovery is steepest at the beginning of a break in work. Interrupting the flow of work, especially if it is repetitive, monotonous, or otherwise demanding in either the mechanical or the psychological sense, helps to prevent overload. Furthermore, it gives opportunity to engage in social interaction with others, often while the energy supplies of the body are replenished by food and drink. Thus, generous provision of frequent rest breaks, freely selected by the worker if at all possible, can be an important means to improve well-being, job-related attitude, and hence performance in all kinds of work, mental and physical, heavy and light.

Summary

Light and moderate works do not impose heavy burdens on our physical capabilities; instead, the chief demands are to toil diligently with attention to detail. Therefore, many persons with sit-down jobs choose to bring up their daily expenditures by doing demanding leisure activities and sports.

Measuring heart rate—which is easy to do—can be a useful indicator of a person's work strain because it responds both to dynamic work and to static muscle loading, such as when holding the body or its segments in one given position. This sensitivity of the HR also extends to mental reactions such as excitement or frustration: so the reactions of HR may reflect more than the loading by physical work. Another way to assess the conditions of work is to ask people for their opinions and judgments. This can be done either in an informal manner or, more frequently, by using prepared questionnaires and scaled responses.

Many individuals enjoy a job that has diverse tasks which challenge mental and physical capabilities. However, to others, there is appeal in a job that consists of the same or similar tasks to do. For most people, performance—and job satisfaction—is best with a job that is neither overly complex nor too simple and that allows them some control over task execution, workplace arrangements, and immediate environment.

Physical fatigue can result from the requirement to maintain the positions of limbs or the posture of the whole body, over considerable time. While sitting is, as a general rule, less tiring than standing, nearly intolerably long and immobile sitting occurs in some jobs, in long-distance driving and flying. Moving about instead of remaining still is essential for well-being and well-feeling.

Work that requires frequent and exact movements of the hands should be done at about waist height, in front of the trunk. Being forced to keep the neck bent or twisted can cause a real headache; such an unbecoming posture is often enforced by having to look at a work object that is not within easy view. Commonly, a viewing task should be within a narrow cone around the normal line of sight, which is inclined forward–downward. However, there are large differences in preferred viewing angles and distances from person to person.

Some skillful work consists of often-practiced tasks. However, doing the same activity over and over, using the same muscles, tendons, and joints, often harms them, whether at work or at leisure.

Breaks in physical work provide time for rest and recovery. They are beneficial for both physiological and psychological reasons.

Fitting steps

Step 1: Make work easy to do; avoid fatiguing postures and highly repetitive tasks.

Step 2: Ask people for their opinions and judgments of the conditions of their work.

Step 3: Strive to improve.

Notes

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

11.1 Physiological and psychological principles:

Measuring workload effects: Karwowski 2006a; Kumar 2007; Kumar and Mital 1996; Stanton et al. 2005.

11.2 Tiredness, boredom, and alertness at work:

Alertness etc: Proctor and Van Zandt 2008; Stanton et al. 2005; Wickens et al. 2004.

Mound (inverted U) curve: This up–down curve (and its mirror image, the down-up valley or *U*) is often employed to describe human physical and physiological behavior—for example, see Figure 8.7.

Frederick Taylor: *(1856–1915) Taylorism: Ruthlessly cutting cost and effort by planned management engineering*: Bjoerkman 1996; Lepore 2009.

Ego involvement, work performance: Bailey 1996; Kroemer, Kroemer, and Kroemer-Elbert 2003.

11.3 Suitable body postures:

Static work: Because there is no displacement in an isometric (static) muscle contraction, this muscular effort does not produce work in the definition of physics: work is the integral of force and displacement. So the term *static work* is a misnomer but often used to refer to fatiguing maintained body posture.

Tiring body postures: Chaffin, Andersson, and Martin 2006; Delleman, Haslegrave, and Chaffin 2006; Kroemer 2001.

Ramazzini: Wright 1993 (translated the Latin text into modern English).

Repetitive work: Kroemer 2001; Kroemer, Kroemer, and Kroemer-Elbert 2003; Kumar 2001, 2004, 2007.

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CHAPTER TWELVE

Task load and stress

What is stress?

The physician Hans Selye° (1907–1982) introduced the term *stress* in the 1930s. He described it as the reactions of the human to good situations, *eustress*, and to bad situations, *distress*. Today, the emphasis is almost completely on the negative condition: for example, we feel “stressed out” by a stressor.

Stressor causes stress

Selye’s choice of terms was unfortunate: he did not realize that engineers consider stress an external load or a thrust or an impact (such as from a heavy truck on a bridge or from a sudden blow on the back) that causes strain in the receiving structure (in the framework of the bridge; in the musculoskeletal components of the trunk). These two conflicting meanings of stress, either considered the “cause” (in engineering) or the “result” (in psychology), have led to much confusion. This book uses the convention that a *stressor causes stress.*

12.1 Task load

Human reactions to task loads

Heavy physical work regularly brings with it high energy consumption and severe demands on the heart and the lungs. Energy consumption and cardiac effort often set limits for the capability to perform hard work (see Chapter 10); therefore, these body functions can serve to describe the severity of a physical task load. Similarly, the severity of a mental task load is commonly assessed by the demands that the associated stressors put on the human mind in terms of stress.

Blue- and white-collar work?

Well into the middle of the twentieth century, the working population was often labeled either blue-collar workers, who performed physical work, or white-collar workers who primarily used their brains for work. Today, that simplistic division no longer exists because work tasks and job requirements have changed, as did clothing habits. An example of those changes is the wide use of electronic devices, computers, for information retrieval and storage even in work categories that were commonly associated with physical efforts, such as automobile repair. However, there are occupations that mostly rely on the use of mental capabilities; pilots, medical personnel, process control operators, teachers, and journalists come to mind as do most office workers. It is reasonable to assume that such jobs pose special demands on mental capabilities; therefore, one should be able to measure both the mental task load and the related mental capabilities.

Computer adaptation syndrome

The introduction of computers into offices in the late 1900s provides an example of stress felt by a large group of people. Many experienced office workers were concerned about their ability to handle the new requirements of using computers, especially if they expected that lack of performance might lead to job insecurity. It was feared that computers required an extraordinary technical knowledge; in addition, there were concerns about radiation health risks associated with the cathode ray tubes in the monitors. Fortunately, the computer-use stress problem° ceased to exist within a rather short time. One main reason was that smarter software, and well-designed training and instructions made it easier than anticipated to become familiar with computer use. As many of the older office workers became proficient, they found that computers in fact made certain tasks easier, and others more interesting and challenging. Younger office personnel grew up with computerized electronic devices as everyday gadgets, so they had no qualms about using computers at work. Thus, the computer adaptation syndrome completely vanished within a decade.

What is mental task load?

Surprisingly, a generally accepted definition of mental workload does not exist. In 2006, Megaw repeated the 1989 statement by Linton et al.: “The simple fact of the matter is that nobody seems to know what workload is. Numerous definitions have been proposed, and many of them seem complete and intuitively ‘right.’ Nevertheless, current definitions of workload all fail to stand the test of widespread acceptance or quantitative validation.” Even ISO Standard 10075, which deals with mental workload, does not provide a convincing definition.

Demand and resource

To understand the concept of workload, we can use the resource construct: it assumes a certain quantity of human capability of which the task demands a portion. Figure 12.1 sketches a "partially filled cup" analogy. Workload is the portion of resource that is expended in performing the given task. If less is required than available, a reserve remains. If more is demanded than provided, an overload exists.

Overload versus underload

In the case of an overload, the performance of the task remains incomplete or even impossible and the operator is likely to suffer, physically or psychologically or both, from overload stress. The measurement of the performance outcome provides clues for the type and the quantity of overload. In contrast, if underloaded, the operator is capable of performing more, or better, according to the remaining reserve capability; satisfactory performance of the primary task does not require all the operator's capabilities, and so the person is able to perform a secondary task simultaneously. Measuring the performance on the secondary task is one way to assess the workload posed by the primary task; more about this will be discussed in the following.

Task performance

Figure 12.2 shows, schematically, the relations between task demands, operator workload, and task performance. The task demands may be defined in terms of intensity, complexity, time, or other measures of difficulty. The operator's workload depends on the person's task-related capabilities that exist at the moment of demand.

"Multitasking" often allows assessing task demands and operator workload: simultaneous performance on a secondary task can be a measure of how much of the operator's capabilities the primary task requires. A problem with this procedure is that performing the secondary task may affect the execution of the primary task.

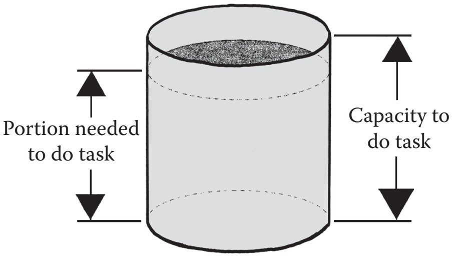

FIGURE 12.1 Resource model.

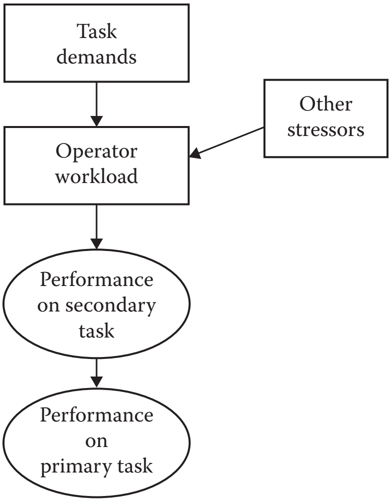

FIGURE 12.2 Workload and task performance.

Of course, these simple concepts only hint at the complexity of many real situations. Workload stress not only is a direct result of task demands but also relies on how the operator perceives the task, which, in turn, depends on the operator's skill and experience. These circumstances may determine the strategies that the operator adopts; the most effectual strategy is reducing the task load, which diminishes the stressor per se, and hence the stress. However, the individual perception of task load (and the person's task performance) depends on the individual's task-related capabilities, aptitude, attitude, motivation, arousal, or fatigue. While working, the operator may gain skill and simplify the task; both outcomes modify the resulting task load.

12.2 Mental workload

Mental task load causes physiological reactions

Selye° discovered that physiological responses to stress are particular in such that both a good situation (eustress) and a bad situation (distress) can cause similar reactions in the autonomic nervous and in the endocrine systems. Typical responses increased the secretion of hormones in the adrenal glands, especially of adrenalin and noradrenalin, which put the whole organism in a state of heightened alertness.

Stress at work and leisure

The mind–body interaction works both ways: psychological factors can contribute to the onset or the aggravation of a wide variety of physical disorders, and, conversely, physical problems can affect a person's thinking or mood. At work, the intensity of stress and its effects depend on how the individual responds to the specific conditions of the work environment; of course, it can make it more difficult for the person to deal with work-related stress if there are also problems outside work. The emotional responses of individuals to the same stressors are different, and so are their bodily reactions.

Is stress always harmful?

Obviously, stress is part and parcel of our life; it is a necessary condition for all living creatures who must react to new situations in an appropriate way. Life without stressors would not only be unnatural but also boring as well. Paracelsus, a physician in the sixteenth century, said that it is only the dosage that determines whether something is toxic or not. That also seems true for stress: the amount of stress determines whether it has adverse effects on well-being or whether it increases a person's ability to cope with life events. Where the boundary is between healthy and pathological stress varies from one individual and one situation to another. Often, challenging tasks appear captivating and interesting, and we feel satisfied when we succeed to meet the challenge: awards, promotions, rewards for accomplishments, compliments, pleasant surprises, joyful events, comical situations, unexpected good deeds, and friendly words make us feel alive and perky. Thus, good stress is part of a good life.

12.3 Distress

Stress is an emotion

Today psychologists assert that the basic experience of stress is emotional°. One's state of mind can cause joy or anxiety, both of which can trigger the body's endocrine and autonomic nervous systems. Emotions provoked by distress can cause muscle tension, which may lead to pain in the head, the neck, the back, or elsewhere. Healthwise, distress may bring about disturbed sleep, gastrointestinal complaints, cardiovascular diseases, musculoskeletal impairments, and weakened immune functions.

Behavior under stress

Intensive or sustained stress often changes the ways in which people behave and feel. Irritability, general dissatisfaction, impaired attention, damaged interpersonal relations, anxiety, and depression are common symptoms. Stress may also lead to maladapted behaviors such as excessive smoking and alcohol and drug abuse. Work-related stress of employees may also affect the organization negatively and lower its functioning through increased staff absence, poor work attitude, and reduced productivity and quality of work. Hence, stress can make an individual suffer and may be costly to the employing organization°.

Coping with stress

Distress, anger, anxiety, and even depression may arise when the person cannot adequately cope with the demanding conditions. Because stress is a subjective experience, stress management techniques must be tailored to each individual case. To deal with stress means to activate individual cognitive and behavioral strategies. They may aim directly at the causes by eliminating stressors (see the following) or by altering the stressors and their perceived demands by such strategies as time management, work style adaptation, assertive communications, and setting of limits. Coping strategies may focus on individual emotions, such as by the cognitive reevaluation of the situation (reframing the problem) and the use of humor, relaxation exercises, off-work activities, and hobbies. The person's physical health, nutrition, and habits (including smoking or drinking) may require attention, even a change in lifestyle. A radical solution is to quit the stressful job and look for work that is more suitable; this is feasible if another better job is at hand.

Eliminating stressors at work

Job stress is primarily a mismatch between the demands and a person's ability to meet them. Instead of trying to adapt the person, it often makes more sense to eliminate stressors at work. The following list contains examples of stressors in the work environment:

1. Job content
2. Demand intensity
3. Task load complexity
4. Repetitive, monotonous tasks
5. Deficient control over one's job
6. Excessive responsibility
7. Lack of recognition or insufficient rewards for achievement

8. Environmental circumstances such as noise, unpleasant climate (indoor or outdoor), crowded office space, and technical problems like frequent equipment malfunctions
9. Lack of job security or fear of losing job
10. Lack of social support from supervisors and peers
11. Unreasonable, unfriendly supervisor
12. Threats or bullying from the boss or coworkers.

Stress metrics

Workload as a general term for "stressor(s)" defies psychometric definition—but a variety of techniques is available to categorize a person's perception of stressful workloads and to scale the resulting stress. Physiological stress metrics have been derived from electroencephalogram (EEG), electrocardiogram (ECG), transcranial Doppler sonography, eye tracking, and heart rate variability. In the medical domain, several health assessments exist, as do various approaches in the industrial engineering and management disciplines.

Psychologic metrics

Among the most used psychologic metrics for perceived mental task load are the NASA (NASA-TLX), the Subjective Workload Assessment Technique (SWAT), the Multiple Resource Questionnaire (MRQ), and several task load indices, which combine specific measures. Further assessments include well-being surveys, stress arousal checklists, mood assessments, emotional intelligence questionnaires, and assessments of coping capabilities; psychosocial literature continually reports on more refined approaches. The sensitivity of workload indices to cognitive demands of tasks is quite variable, as are the relationships between indices. Usually, stress indices are specific to the task and to the person. Clearly, such measurements require that well-trained experts take the lead in selecting stress metrics° and in evaluating the test results and choosing stress relief strategies—this is not for laypersons.

12.4 Underload and overload

Too little, too much

Most people feel stressed because of a task overload, which requires too much from them in terms of task intensity, complexity, diversity, time pressure, and such. However, some jobs demand too little effort, which leaves persons idle, bored, and their capabilities underused. This experience has led to the notion than one can describe the relations between the task

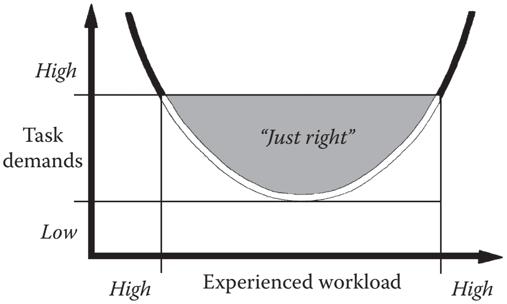

FIGURE 12.3 Assumed U-function (Valley function) between task demands and experienced workload.

demands and the experienced workload as a "Valley" function° that looks like the letter *U*: in its center part, a balance exists between demand and load that is just right. However, either requiring too high a task load or not demanding enough leads to worker overload or underload, respectively. Task performance suffers under both overload and underload conditions. Figure 12.3 shows a postulated U-function; other theories use an S-shaped (sigmoid) relationship. Of course, what is fitting depends on the situation and the individual operator.

Monotony and boredom

Monotony is the property of an environment that does not change over time, or where changes occur in repetitive and predictable fashion over which the operator has no or little control. A varied environment usually provokes interest and even excitement; in contrast, monotonous conditions produce boredom. Boredom at work is a state of human emotion produced by a dull, uninteresting job environment. A bored person often complains of feeling tired or fatigue, regularly accompanied by yawning, which one would expect from a person worn out by heavy physical work.

12.5 Psychophysical assessments of task loads

The understanding and definition of task load depends on two factors: one is the intensity of the task, and the other, the related capability of the person to perform the job. That relationship between demand and ability is further modified by the person's perceived stress and willingness to perform. There are some simple cases where one is able to measure both the load and the operator's resulting physical strain: consider a baggage handler loading an airplane cargo hold, or a mason carrying bricks up a ladder at a building site. Here, an investigator may determine, in physics terms, what energy the job requires; and in physiological terms, how this loads the person's metabolism and circulation, as already discussed in Chapter 10.

Complex jobs, complex assessments

However, such simple cases with only a few and easily assessable components are rare. Usually, the task demands are complex, and environmental conditions often contribute intricately to the demands. Furthermore, it is often impossible to measure the responses of a person's body and mind to the demands by using just a few established physiological techniques, which assess only one of several strains on the body (via oxygen uptake, for example) and whose apparatus often hinders task performance. The literature reflects a long-ranging discussion° about the usefulness of the so-called objective (analytical, quantitative) measures, compared to assessments that rely on subjective (qualitative, empirical) judgments, made by either an observer or the worker. Table 12.1 lists a sampling of methods useful for task load assessments.

Listen to the worker

The last entry in Table 12.1 mentions psychophysical measures. These integrate elements of biomechanical, physiological, and psychological assessments in the form of subjective judgments, made either by an observer or by the operator. The underlying premise is that an experienced person can perceive and fuse all existing loadings and then summarize their combined effects in form of a judgment. That concept appears plausible.

Table 12.1 Typical methods of workload assessments

Methods	Techniques; examples
Archives and records	Description, statistics, trend
Indirect observations	Interview, discussion, survey
Direct observations	Chart, checklist, critical incidents
Expert analyses	Walk-through, judgment, scoring
Task analysis	Flow/time chart, time-and-motion study
Simulation	Mathematical/physical mock-up
Modeling	Task network, control processing
Performance measures	Work rate, output in amount, and quality
Biomechanical measures	Posture, force/moment/work analysis
Physiological measures	Oxygen consumption, heart rate
Psychological measures	Perceived exertion, attitude, rating
Psychophysical measures	Subjective assessments—see below

The reliability of judgments should increase when they are formulated within a standardized and controlled framework, for example, in preselected words or in numbers that reflect rankings (less than, more than) or mathematical relations, for example, double or triple as much as a reference.

Borg scales

Borg's psychometric scales° incorporate such organized judgments. Table 12.2 contains the ratings of perceived exertions and the category ratio 10 (CR 10) scales. The steps are "verbally anchored" and arranged to follow mathematical formulas. The RPE ratings are in equidistant steps, which are numbered so that when multiplied by 10, they correspond to heart rates measured at these work levels. The CR 10 scale has ratings in steps set to constant ratios.

Just as with any other measurements, these Borg scales need rigidly controlled procedures to yield credible results. For example, his CR 10 scale, from Table 12.2, is put 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 a 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 claimed 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.

Such psychophysical assessments (and there are many more complicated ones°) have several practical advantages: they are relatively easy and inexpensive to carry out, do not usually interfere with task performance, and provide a comprehensive summary of the effects of all stressors at work. However, they need to be administered carefully, or their results may be very misleading.

Table 12.2 Borg scales

Borg RPE scale

Number	Wording
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

Borg CR 10 scale

Number	Wording
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

Source: Adapted from Borg, G., Rating scales for perceived physical effort and exertion, pp. 358–541. In Karwowski, W. (ed.), *International Encyclopedia of Ergonomics and Human*. London: Taylor & Francis, 2001; Borg, G., Scaling experiences during work: Perceived exertion and difficulty, pp. 11-1–11-7. In Stanton, N., Hedge, A., Brookhuis, K., Salas, E., and Hendrick, H. (eds.), *Handbook of Human Factors and Ergonomics Methods*. Boca Raton, FL: CRC, 2005.

Summary

Work-related stress is an individual's emotional reaction to aspects of work demands, work environments, and work organizations that the person feels adverse and noxious. While people react differently to job conditions, in general, stress results from a mismatch between the demands and a person's ability to meet them. Instead of trying to adapt the person, it often makes more sense to change the demands.

Fitting steps

Step 1: When setting up a new task, carefully design out excessive task demands and adverse conditions.

Step 2: When people complain of overloading, or of a boring task, rearrange to their satisfaction.

Step 3: Listen to the working people. They can tell you what is good and what needs improvement.

Notes

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

Hans Selye wrote *The Stress of Life* (1956, 1978) and *Stress without Distress* (1974).

12.1 Task Load

Computer-use stress problem: Grandjean 1987.

12.2 Mental Workload

Stress is an emotion: Cox and Griffiths 2005; Carayon and Lim 2006.

12.3 Distress

Stress is costly to the organization: Cox and Griffiths 2005.

Stress metrics: Rubio et al. 2004; Megaw 2005; Finomore et al. 2013; Matthews et al. 2015.

"Valley" function: The inverse is the "Mound" function discussed in Chapter 11.

12.5 Psychophysical assessments of workloads:

Discussion of measures: in *J. Ergonomics*, Volume 45, Number 14, 2002; Finomore et al. 2013; Matthews et al. 2015; Wilson and Corlett 2005.

Borg Scales: Borg 2001, 2005.

Complicated scales: Wilson & Corlett 2005.

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SECTION IV

Organizing and managing work

This section of *Fitting the Human* first addresses the issues that primarily determine how people get along with each other at work and, as one of the consequences, how much effort they put into their work.

How individuals feel about their company, and hence about their work, depends to a large extent on the organizational setup. The design of the work organization, and the manner in which the organization is run, may be labeled macroergonomic issues, in contrast to the concerns about human factors details, for example, the workspace of the hands.

Section IV deals with another set of managerial responsibilities that concerns the organization of the work itself: how many hours of work per day; what is the best time for work during the day; how to organize shift work suitably.

- Chapter 13 Working with others
- Chapter 14 The organization and you
- Chapter 15 Working hours and sleep
- Chapter 16 Night and shift work

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CHAPTER THIRTEEN

Working with others

A large Chicago-based professional services company moved from an older office tower downtown into a newly built building. The company, a venerable institution with a rich 60-year history, employed thousands of people. Employees often described themselves as part of a family, with extensive interaction among all levels of the corporate hierarchy and a strong prevailing team spirit.

The old offices had sentimental value for many employees; this is where many had begun their careers. However, the new office building was easier to access via public transportation, allowed for increased company growth, and was more reflective of the company's success, with luxurious interior appointments.

Once the relocation was complete, many company members soon regretted it. The move carried with it some unintended and unfortunate consequences. The configuration of the new space was different: in the former building, executives' offices and cubicles were interspersed among staff cubicles, whereas in the new space all executives' offices were located on two separate floors. Initially, the concept behind establishing executive floors centered on easier communications among the directors; additionally, the company wanted to reward executives' performance by providing them with especially posh suites. However, some of the effects of the new configuration on the corporate culture were utterly unforeseen and, in the long run, damaging. The new configuration sharply reduced the casual interaction between executives and employees that had existed before, when many of the managers followed the strategy descriptively known as *management by walking around*. Employees and executives interfaced daily at the old building, meeting routinely at the coffee machines, in the hallways, and in the cubicles and

> offices; now, interaction was reduced to business-only discussions at formal meetings. Where before employees welcomed the executives' casual visits and drop-ins in their cubicles, inviting the friendly and open banter, they now felt anxious and vaguely frightened during formal business meetings.
>
> After some time in the new space, employees felt disconnected from company leadership, even disenfranchised from the company as a whole. There was now far less of a team atmosphere and more of a "them versus us" philosophy. Interestingly, executives too felt out of the loop with the employees, sensing a formidable new barrier between themselves and the staff. The team spirit that had once prevailed was sharply and unexpectedly curtailed by the office move; an important part of the company culture had been inadvertently and irrevocably destroyed.

This example° shows how the setup of the whole organization, including the layout of the workspace for individuals and work teams, can strongly affect people's work attitudes and output. The topic of organizational design is treated in some detail in Chapter 14.

13.1 Getting along with others

The example refers to many kinds of personal interactions: "Employees and executives interfaced daily …, meeting routinely at the coffee machines, in the hallways, and in the cubicles and offices [for] … friendly and open banter …" Indeed, the most basic and perhaps most important everyday interactions take place between individuals, often informally.

Distances between persons

The expectations for personal interactions differ in different regions of the Earth, in different populations with differing traditions; yet in the old world of Europe and North America, social relationships between individuals generally take place at certain distances which persons preserve between them. How people maintain and use the personal space around them, especially the distances they keep from other people, conveys psychological and social messages.

Personal space

Most of us feel that we have a certain volume around us that we consider our own sphere. When another person enters that space, this can give rise to strong emotions. The whole so-called social distance extends out to three/four meters. Where within the personal space° people locate themselves to deal with you reflects the nature of your relationship.

Distances in personal relationships

Most personal interactions take place within about an extended arm's length, whereas a narrower intimate distance often involves body contact. Friends and good acquaintances usually move in closely, within about a meter. Interactions between unacquainted persons and business transactions often occur within a distance of about two meters. Beyond about that distance, the interactions are typically formal. The public distance is beyond about four meters, where voices may have to be raised for communication. Of course, local customs determine all these metered distances.

Use of personal space

When somebody who, for personal or social reasons, is not supposed to be close but nevertheless invades a person's personal space, the owner of that space usually experiences arousal and discomfort. However, if coworkers, good acquaintances, and friends stay too far away, disappointment and alienation are likely and formerly close relationships may deteriorate. At work, when group members are expected to cooperate as teams, performance should be best if they are in close proximity. Competition, however, is fiercer when persons remain outside the distances of personal relationships.

Owning an area

Some persons display behavior patterns called *territoriality*, which is the inclination to occupy and control a defined physical space, such as property, a workplace, or just a section of a workbench. Preventive or reactive defenses may keep intruders at bay; an invader may be met with offensive behavior or the space may be abandoned. Often the owner of an area personalizes it and demarcates it in some ways, for example, with flowers or photographs; these measures convey the feeling of control and security.

Crowding

Crowding is the negative experience of too many people within a given space. As do the other feelings associated with personal space, the perception of crowding depends on individual characteristics, on the assessment of one's coping capabilities and, of course, on the physical and social settings. Individual reactions to crowding may be aggression or withdrawal.

Teamwork

Working in groups is a common requirement in offices, in planning and design, in production and assembly, and in maintenance and repair tasks. It is a necessity in such threatening situations as rescue, fire fighting, and military operations. Teams are two or more individuals who pursue a common goal by performing their tasks in interdependent, complementary, or distinct manners°. Team members must communicate with each other, adapt, and adjust their work to perform their tasks in a timely and integrated fashion. At the core of teamwork are sets of interrelated kinds of knowledge, skills, attitudes, and behaviors, including formal or informal organizational aspects. In general, team members must be willing to communicate and to be flexible in adapting to the changing allocations of functions within the team. Not all individuals are able and eager to subordinate their individual work habits and specific skills to the rules of teamwork; furthermore, certain regional cultures emphasize working together, while other social environments further individual work.

13.2 Motivation and behavior

The field of study that helps to understand and deal with interpersonal and managerial challenges in the workplace is called *organizational behavior*°. The recent lean and mean years made many employees in North America fear for their jobs and feel uncertain about their professional futures. Instead, other companies are trying again to keep their employees happy, satisfied, and motivated. The reason is not sheer altruism but the recognition that improving employee satisfaction will improve profit.

Happy employees

Happy employees are productive; they treat customers better, work harder, and take fewer sick days. Moreover, they tend to stay with the organization, which reduces one of the most significant costs—employee turnover related to dissatisfied employees. Employee attrition often generates huge expenses for recruiting and training new employees: the outright expense of replacing a valuable employee can range from half to several times a year's pay. A newly hired employee initially accomplishes less than an experienced worker. Finally, there is the less tangible cost of unhappy employees who stay on the job: they are likely to show low productivity and poor customer service, but they also personally suffer from stress (see Chapter 12) and, potentially, from serious stress-related illnesses as they trudge through a dreary work routine.

Psychosocial work factors

How we feel about ourselves as members of a work organization depends on a variety of psychosocial work factors°, listed in Table 13.1. These relate to the demands of the job, what we have to do and how we do it, how we feel about our cooperation with peers and superiors in the organization, and what we expect in terms of our professional and employment future.

Division of labor

Even Frederick Taylor's° frequently (and often appropriately) maligned concept of division of labor, which from the early 1900s lead to work mechanization and specialization, promoted motivating the individual and sharing responsibilities between management and labor. He claimed to place the worker's interest as high as the employer's. Taylor's approach generated efficient work systems by time studies, careful design of work, provision of the right tools, and selection of able persons. In this course, unfortunately, a worker's task was often cut into small components, which reduced skill requirements and facilitated performance evaluations. Thus, many jobs became simplified and standardized, repetitive, and monotonous.

Table 13.1 Psychosocial job factors

Job demands	Physical workload
	Variations in workload
	Work pressure
	Cognitive demands
Job content	Challenges, interest
	Repetitiveness, monotony
	Development and use of personal skills
Job control	Control over work pace
	Control over physical environment
	Task/instrumental control
	Organizational control
Social interaction	Interactions with colleagues
	Interactions with supervisors
	Dealing with clients and customers
Job future and career issues	Ambiguity about job future
	Fear of losing job
Organizational and management issues	Employee participation
	Management style

Source: Carayon, P., and Lim, S. Y., Psychosocial work factors, Chapter 5 in Marras, W.S., and Karwowski, K., eds, *The Occupational Ergonomics Handbook: Interventions, Controls, and Applications in Occupational Ergonomics*, CRC, Boca Raton, Florida, 2006.

Quality of work life

Half a century later, an educated and liberated workforce became more aware of the working conditions and environment and the quality of work life. This raised the issues of recognition of personal value and improvement of working conditions. Consequently, theories were developed about individual worker's motivation, productivity, and well-being. Individual needs and wants were emphasized, and workers' behavior and their attitudes toward work were considered important.

Motivation and performance

Motivation° incites, directs, and maintains behavior toward goals. Motivation and job performance are, of course, related; a motivated person who desires do well at work is willing to expend effort to do so. One might say, "Performance is the product of motivation and ability." Performance is moderated by situational constraints at work, which are factors that can stymie or enhance performance; examples are the climate (both psychological and physical) and up-to-date equipment.

Maslow's Needs Hierarchy

In the 1950s, Maslow and then his disciples developed a so-called Needs Hierarchy°, sketched in Figure 13.1. According to this model, motivation is a function of meeting personal needs, which start at basic physiological necessities and then step up to higher-order aspirations. First, we must meet basic needs such as food and shelter. With this achieved, we strive to meet our safety needs, which focus on economic and physical security. The next step up concerns our social needs; above these are our wants for esteem, where we gain self-confidence through recognition, appreciation, and respect. The fifth step gains our highest-order needs: self-actualization, where we achieve our full potential and esteem.

Needs may change

The Maslow theory says that behavior is motivated by the urge to satisfy the needs and the wants of increasingly higher orders. This tenet has been modified in various ways to explain such observations as people moving forth and back among needs:

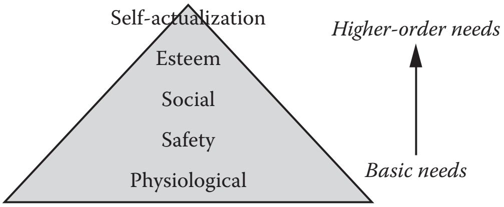

FIGURE 13.1 Maslow's Needs Hierarchy.

what are steps according to Maslow may in fact be a continuum where needs and desires change, overlap, and merge. This concept explains shifts among our concerns that relate to

- Existence: Food and essential supplies, compensation, working conditions
- Relatedness: Relationships and interactions with family, friends, colleagues
- Personal growth: Desire for personal development, advancement, recognition

Job satisfaction

Satisfaction with one's job, or dissatisfaction, can greatly influence motivation and task performance. As usual, there are large differences in individual perceptions of what makes a job satisfying or not. For example, somebody might value personal growth and recognition at work over monetary rewards; this person would be satisfied with a rather low-paying job as long as there was appreciation of performance and success in professional challenges. Another person, however, might be mostly interested in job security and good pay and be satisfied even if the position is seen as being of low rank.

Herzberg's two-factor theory

In 1966, Herzberg explained his concept of job satisfaction with his so-called two-factor° theory. It assumes that positive *content* factors of a job mostly explain satisfaction, while negative *context* factors lead to dissatisfaction. As Figure 13.2 illustrates,

Content factors when positive **promoting satisfaction and motivation**	Promotion chances
	Personal growth chances
	Recognition
	Responsibility
	Achievement

Context factors when positive **preventing dissatisfaction**	Supervision quality
	Pay
	Company policies
	Relations with others
	Working conditions
	Job security

FIGURE 13.2 Herzberg's two-factors theory: content satisfiers and context dissatisfiers.

Herzberg and his disciples isolated five *content* factors that act as satisfiers or motivators:

1. Achievement
2. Recognition
3. The work itself
4. Responsibility
5. Advancement

If these factors are present, they can create job satisfaction and motivation to strive at work; their absence would make an employee feel neutral or indifferent. On the opposite side are *context* factors (also called *hygiene* factors):

6. Company policies and administration
7. Compensation
8. Supervision and management
9. Interpersonal relationships
10. Physical conditions at work
11. Job security

If these context factors are negative, an employee becomes dissatisfied and lacks motivation. (Chapter 14 addresses some of these issues.)

APCFB model

Alderfer in 1969 and other researchers developed models to explain the cognitive processes that link external events to employee behavior. The APCFB model posits that a person's closely held *assumptions* color the *perceptions* of a given event, leading to highly individual *conclusions*; these in turn cause *feelings*, which result in *behaviors*. Since everyone has a different set of assumptions, individual behaviors or reactions even to one common event can be widely divergent.

Basic understanding

The groundbreaking concepts of Maslow and Herzberg about behavior, motivation, and satisfaction provided basic insights into why people act the way they do on the job. Newer research has refined and redirected our knowledge.

13.3 Task demands, job rewards

Work conditions that motivate

Theorists have thought about many work conditions that motivate people to perform their tasks efficiently. The past has shown that under austere conditions and for short periods, even such negative factors as fear, or greed, can drive people to outstanding task performance. However, as a society of valuable humans, we strive for a high quality of work life; everyone has a right to a fulfilling, rewarding, safe, and secure job. This goal matches well with the business intent to prosper because job satisfaction is associated with critical revenue-impacting variables like turnover, absenteeism, and job performance.

Job enlargement and enrichment

In contrast to earlier work specialization that evolved from Tayloristic principles, the ideas of job enlargement and job enrichment form the basis for many current job design theories. Job enlargement means a larger variety of tasks and activities, usually at about the same professional level; job enrichment means expanding work skills and increasing work responsibility, often taking in tasks at higher professional levels. Job design, in general and in details, can strongly affect our attitudes and hence our performance.

The Hawthorne effect

Sociologists and industrial psychologists have performed innumerable experiments in which they changed working conditions and observed their effects, if any, on work attitude and output. Among the best-known experiments are those done in the 1920s in the Hawthorne° Works near Chicago. There the intervention consisted of improving the lighting conditions in a manufacturing/assembly task. Each rise in the lighting level brought about improved output; but when the illumination level was finally lowered, surprisingly, performance still improved. The explanation was, in somewhat simplified terms, that paying attention to the workers, taking their comments and activities seriously into account, and listening to them—in short, treating them as important—led to improved output regardless of the magnitude, even the direction, of the overt work intervention taken.

The term *Hawthorne effect* has become proverbial: it describes a work situation where an introduced change triggers an increase in productivity, not because of the change itself but because the participating workers find themselves in the spotlight of attention, which encourages strong motivation and extra effort. These effects usually wear off and are no longer present later on. Even though short-lived, they point to the effectiveness of positive engineering and managerial measures.

Goal setting and rewards

Obviously, the rewards inherent in a job must be meaningful and valuable to the employee, and, with individuals being so different, no universal reward system exists. Goal-setting theories posit that people set targets and then purposefully pursue them; their premise is that conscious ideas underlie our actions, and the goals that we have set motivate us, direct our behavior, and help us decide how much effort to put into our work. Within limits, the more difficult goals foster higher levels of commitment; and the more specific the goal, the more focused the efforts of the individual to attain it.

Motivation and work behavior

In spite of how compelling these and other existing theories are, there is no clear-cut correct answer to the question of what motivates people. Instead, bits of theories apply to different people, under different circumstances. Motivation is both intrinsic and extrinsic: the factors within us and external to us drive our behavior. What most likely occurs is that we consider our own needs and wants, and either consciously or subconsciously determines our goals; then we act to increase the chances of obtaining what we want. We do know from Maslow's, Herzberg's, and others' theories that we will strive first to fulfill basic survival needs like securing food and shelter; beyond this, needs are still real but vary widely among individuals in terms of priority and strength. People around us influence and shape our motivation and behavior because we are all, to some degree, social creatures. How hard we work depends on what our work will bring us: if we feel rewarded in ways that are meaningful and valuable to us, and if we perceive a definite link between the strength of our efforts and performance, we will work strenuously to perform well and gain those desired rewards.

Motivators other than money

What motivates people can shift. In Europe and North America, for example, pay and stability used to be among the most important motivators in a job; now, with an increasingly diverse, lifestyle-conscious workforce, there are many other nonfinancial ways to reward employees and keep them motivated and happy. On-site childcare and flexible work hours and vacation time are a few examples of the benefits that employees might seek; most people put high value on having friendly coworkers and a nurturing corporate atmosphere: my company is "a good place to work" and "my buddies on the job are like family."

Summary

Today's educated and liberated persons seek pleasant conditions at work in which they can use and expand their skills; they consider work as an important part of their quality of life. Careful design of work, provision of the right tools, and a suitable work environment are basic ergonomic measures, which must be augmented by an "organizational culture" (see Chapter 14) that encourages personal development.

An individual's motivation, productivity, and well-being are linked; performance is a product of motivation and ability. How hard a person works depends on what that effort yields: if there is a definite link between exertion and performance, and if one feels rewarded in ways that are meaningful and valuable, individuals will work strenuously to perform well and gain those desired rewards.

Fitting steps

Step 1: Carefully design work; provide the right tools and a suitable work environment.

Step 2: Provide opportunities for developing individual skills and fulfill aspirations.

Step 3: Be innovative, flexible, and adaptive.

Notes

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

13.1 Working with others:

Example: Adapted from Chapter 2 in Kroemer and Kroemer (2001). See also the 2017 2nd edition.

Personal space: Proctor and Van Zandt 2008.

Teamwork: Muchinsky and Culberson 2016; Stanton et al. 2005.

13.2 Motivation and behavior:

Frederick Taylor (1856–1915): *The Principles of Scientific Management* (1911).

Psychosocial work factors: Smith 2007.

Motivation: See Landy and Conte (2006), Muchinsky and Culberson (2016), and many other related books.

Maslow's needs hierarchy: Maslow 1943, 1954.

Herzberg's two-factor theory: Herzberg 1966, 1968.

13.3 Task demands, job rewards:

Hawthorne effect: Roethlisberger and Dickson 1943; Parsons 1974.

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CHAPTER FOURTEEN

The organization and you

For smooth and successful operation of any business, a good fit is necessary between not only worker and work, but also among workers and their employing organization as well. Organizations are networks of related elements that all must work together to enable the whole organization to function well. Of course, a family running a small farm requires much less of an organization than setting up a manufacturing business, or managing a firefighting or a military team. This chapter discusses various kinds of organizations.

Human system integration

Macroergonomics° is a sociotechnical approach that takes into account that the value system of workforces is shifting: in North America and western Europe, for example, people now expect to have control over the planning and the pacing of their work, and they want to exercise decision-making responsibilities. Many employees enjoy broadly defined jobs that provide the feelings of responsibility and accomplishment. The so-called human system integration encompasses the acknowledgment that, compared to conventional organizations, new work structures are less formalized and less controlled by solid procedures, rules, and detailed job descriptions; and they are less centralized than traditional bureaucracies because tactical decisions are delegated to lower-level supervisors and workers. These are profound changes from traditional work systems.

14.1 The human is in the center

Fitting together employees, work, and organization make for smooth efficient performance. The human is at the center of the organization's operations, because, ultimately, companies cannot exist by their strategy, structure, and machinery, but rather rely on living, working, and interacting people. Without humans, the organization is dead. People affect the organization and the way it functions, and, in turn, the organization affects these individuals. Why people act the way they do—and what can be done to keep them satisfied and interacting fruitfully with each other at work—is a fascinating puzzle that has kept psychologists and behaviorists° busy for many decades. Some explanations came into view in Chapter 13; others follow here in this chapter.

The individual in the organization

The individual is the innermost and most important asset of an organization. When a company's stock market value is determined, hard assets like property, plant, and equipment generally make up one third to one half of its value. The remainder consists of soft human attributes such as customer base and, of particular importance, employee involvement. Human resources are a company's most valuable assets. However, the workforce consists of unique individuals. Familial upbringing, social environment, life experiences, and personalities all make every one special. It is a complex proposition to assemble individuals into groups in a work environment and to expect that all work together, according to company directives, given the tensions inherent in a job: hard or monotonous duties, long hours, and imposed relationships with other people. The organization has limited possibilities to select persons and to train them so that, as employees, they will fit in; selection and training are common tasks of industrial psychology. Instead of relying solely on those individual approaches, greater success should result from laying out the organization, and designing work tasks and conditions therein, in such ways that they accommodate and utilize various individual capabilities and aspirations.

Social contracts

Throughout history, the relations between individual workers and the organizations employing them have vacillated between extremes: from "I'll work hard for them until I die" to "good enough for government work" on one side, and from heartless exploitation to near-parental care on the other side. These social contracts, usually not in writing but well understood nevertheless, included appropriate pay, a secure workplace, as well as health and retirement care in exchange for reliable, thorough, and

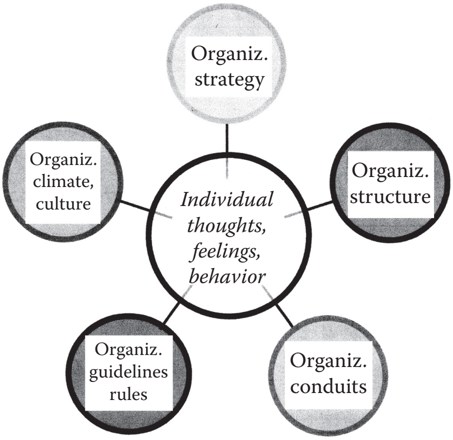

FIGURE 14.1 A basic human-centered organization. (Adapted from Kroemer, K. H. E., and Kroemer, A. D., *Office Ergonomics*, Korean edition, Kukje Publishing, Seoul, South Korea, 2006.)

hard work, once proverbial among employees as in “A Krupp man forever” or “Once IBM, always IBM.” To the employees, these conditions provided the feel of security and belonging, and of recognition and appreciation, which, in turn, generated interest in doing their work well, toiling carefully and thoughtfully in the interest of the company. On the other hand, care for the employees, especially in the case of illness and after their working years, was costly to the organization but rewarded loyalty: unfortunately, some employees took advantage of the goodwill.

Organizational components

The schematic° shown in Figure 14.1 depicts the basic components of the organization that determine the roles of its human players. In this case, five main elements interact to define a company: its *strategy* (the company’s plan for success), its *structure* (corporate hierarchies), its *conduits* (channels for allocating, controlling, and tracking corporate resources), its *guidelines and rules including policies and procedures*, its *social climate* (employees’ feelings about the company) and its *culture* (behaviors and feelings within the company). All affect one another, and as one changes, the others too must adapt.

14.2 Organizational strategy

The diagram in Figure 14.1 shows *strategy* as one of the main components of an organization. Strategy is the plan—stated or implicit—that the company has adopted to succeed in achieving its goals. It guides the company's operations and determines specific tactics that the company will use. Examples include the repair service that pledges to dispatch a plumber within two hours of a request, the grocery store that wants to offer a wider selection of fresh produce and gourmet items than its competitors, and the manufacturer intending to produce the best airplanes.

14.3 Organizational structure

Structures outline the hierarchies within an organization. In larger traditional companies, they are usually depicted in detailed diagrams linking the elements in the organizational chart. An organization's structure determines accountability and authority within its ranks; essentially, it defines the official relationships that exist between employees. Each level in a structured organization has its own degree of authority and responsibility; moving up in the hierarchy increases one's authority and responsibility.

Down/up/sideways relations

Obviously, the structure of an organization determines each employee's position, the ways in which instructions come from the top down, reports travel upwards, and how persons at the same level communicate with each other. In a "mom and pop" shop or in other small groups, formal organizational structures are usually unnecessary because the divisions of labor and of responsibilities develop naturally according to personal preferences and skills. However, formal down/up/sideways relations are of utmost importance in most more complex organizations, such as manufacturing plants, airlines, big-city firefighter companies, or local police department.

Fixed structure

Volumes have been written on organizational designs°, which run from rigid structures (traditional in the military) to loose conglomerates. The simplest and clearest structure follows the so-called unity of command principle where each employee is only accountable to one boss. Figure 14.2 shows a basic example of such a conventional layered organizational chart. It depicts an organizational structure with several divisions or departments, which commonly contain persons at the same hierarchical level who perform specific tasks. Each department is headed by one person; department bosses report to division heads; and finally all division chiefs report to the *capo dei capi*. Among the main advantages of this rigid structure is the clarity of communication down and up. However, employees and work projects may not succeed in this firm hierarchical structure, but do better in a more flexible network.

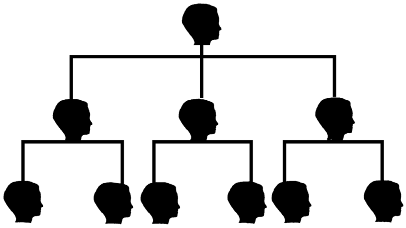

FIGURE 14.2 Chart of a basic layered organization.

Overlapping assignments

Teamwork that includes job enlargement and enrichment (see Chapter 13) often does not flourish under the conventional rigid setup. For example, originally, an electrician was responsible exclusively for the maintenance of all electrical equipment; but in a new, flexible, team-oriented organization, the electrician acquired additional tasks such as testing and designing new equipment, developing software, planning work, and even doing some financial accounting. Similarly, other employees also have multiple roles that overlap the formerly separate areas of production, equipment, maintenance, delivery, strategic forethought, and funds allocation. Overlapping and multiple tasks can lead to a complicated amoeba-type organizational structure, sketched in Figure 14.3, which provides flexibility but is complicated in supervisory assignments.

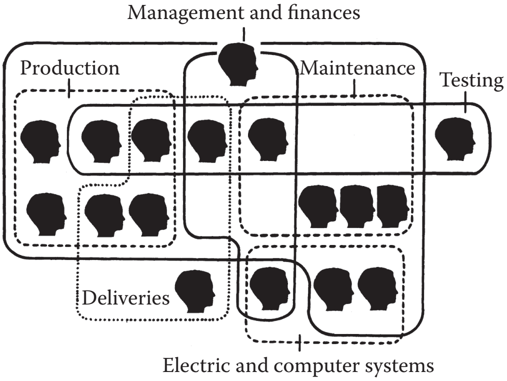

FIGURE 14.3 A flexible work organization with overlapping worker teams. (Adapted from Nagamachi M., Relationship among Job Design, Macroergonomics, and Productivity, Chapter 6 in Hendrick H. W. and Kleiner B. M., eds, *Macroergonomics: Theory, Methods, and Applications*, Erlbaum, Mahwah, New Jersey, 2001.)

Flexible organization

Loose and flexible organizational setups are necessary for autonomous teams, which self-organize to solve varying problems and to meet changing tasks. Such employee empowerment can largely dissolve the traditional organization, abolish managers, and eliminate job titles. Self-governance° can be a radical new system by transferring substantial authority to each employee who must be well informed, knowledgeable, and skillful and engaged to follow the organizational strategy set by the "big boss."

Employee self-governance

Few companies in the United States have tried to introduce comprehensive self-governance (occasionally called "holacracy"), which creates fresh challenges; for example, among disenfranchised managers, especially of the middle level, and among employees who are uncertain about what to do with their new authority. New issues need to be solved: how to establish, communicate, administer, and implement company goals; how to prevent task overload; how to evaluate performance; how to compensate each employee.

14.4 Organizational conduits

Conduits are the dispatch systems by which information travels within the organization; in theory, these pipelines follow the official structures that provide the ducts by which people, money, and things (machines, equipment, supplies) are properly allocated, controlled, and tracked. Conventional organizations have firmly defined conduits; obviously, these pipes are more likely to become loose channels (occasionally grapevines) as the company structure dissolves. For example, in a self-governed business, who assesses employee performance and accordingly allocates travel funds?

14.5 Organizational guidelines and rules

Policies and procedures govern an organization's conduct. Examples of policies include the amount of medical benefits a company provides, the retirement plans available, or the number of paid vacation days an employee receives. Procedures and rules prescribe the ways by which employees and supervisors interact. In larger companies, policies appear written up in an employee handbook, but the details of guidelines and practices are often not documented yet nevertheless widely understood;

for example, how often e-mails are checked every day or whether employees may on occasion arrive late or depart early.

Conduits and rules interact

Breaking the organizational structure into components, as done in this chapter, helps to specify topics and allows considering them separately; yet, in reality, they all interact. This is particularly true for organizational conduits and rules. The tighter the organization, the more regulated are the communications and the procedures, especially up and down within the organizational hierarchy. Furthermore, the available means to interact also affect how much interaction takes place and how it is done. Consider the shift from yesterday to today: then, a carefully edited written report formally delivered to the *Herr Direktor* by an appropriately dressed underling who had attained passage through the antechamber of the almighty Executive Secretary: today, an electronic memo, complete with inputs from involved colleagues and updated with the newest data, sent with the push of a button to all who need to know, who can ask and comment immediately. Momentous changes came with portable computers and especially via the always-available phones enabling, even provoking, incessant use of information media. Intraorganizational conduct is, formally as well as behind the scene, largely determined by the available means.

14.6 Organizational culture

The norms, beliefs, unwritten rules, rites and rituals, behavior, and practices among the members of an organization establish the organizational climate and culture. They are created by underlying values that commonly remain submerged but surface in the behaviors of the system members. Friendly social climate and culture have become very important, especially in bureaucracies, as major determinants of the employees' overall happiness and of the organization's performance. (That was well known but then often disregarded by the lean and mean management in the United States around the 2000s.) Now, at this time of casual work environments, telecommuting, job sharing, and emphases on both individuality and participatory work, companies' cultures vary widely—and are apparently more important to people than ever before.

How do you feel about your company?

The structural design of a company has strong effects on its social climate and culture. That is a group phenomenon that relates to the behaviors, the beliefs, the values, the customs, and the ideas that the employees as a group hold. This, in turn, affects the emotional state of the individuals and how they feel about the company, their coworkers, and their jobs.

> Consider two advertising agencies°: one a large and highly traditional company headquartered in a metropolis; the other a small, boutique agency in a smaller town. Here are some of the characteristics of each: the first agency is 60 years old, has many long-standing blue-chip clients, and is highly structured, with formal dress codes, office procedure manuals, and written policies for all conceivable situations. Internal memos follow a set format and are heavily scrutinized by several administrative levels before they are issued; annual retreats and parties are scheduled and planned many months in advance. The second agency is 10 years old, with only a handful of young partners who employ highly creative individuals in an entirely unstructured office. Shorts and baseball caps are standard attire, no handbooks exist, and decisions are made quickly and with virtually no bureaucracy.
>
> Clearly, each of these companies—although both operate in the same industry—have very different cultures, with widely diverse values and behavior, and hence with different climates. Employees starting to work in an organization quickly learn about its culture and climate; over time, they become socialized into the broader group by interacting with its members—or they become outsiders, perhaps outcasts, and usually leave the company.

One might be inclined to believe that under harsh conditions such as working in a foundry or when fighting a fire, social climate and culture would be of no importance—however, while the term seems improper, there are still social rules that govern how to behave, how to work with others, and how to perform individual and team tasks. Under loose and friendly conditions, naturally, the social interactions are different but still of eminent importance to the individual's feelings toward the organization in general, to the individual's assessment of the working conditions, and, consequently, to the individual's motivation to work.

14.7 Individual thoughts, feelings, and behavior

Chapter 13 contains a discussion of the basic concepts of individual job behavior, motivation, and satisfaction. Maslow, Herzberg, Alderfer, and many following researchers provide insights into why people act the way they do on the job. This understanding provides pointers to create organizational conditions that are conducive to generate positive attitudes and behaviors—which benefit both the individual and the company.

Motivation and performance

Every person holds beliefs about the way the employer ought to be. We each have our own value system, and we think that a suitable job should meet our corresponding expectations. While we are willing to make some adjustments, to satisfy us the job should motivate us to attain personal professional goals. Behavior theories hold that individuals strive to satisfy certain needs, and that this quest in turn drives our behavior. Expectancy theories posit that an individual's motivation (and resulting satisfaction) depends on the difference between what the work environment offers versus what the worker expects. Motivation incites, directs, and maintains behavior toward goals. Motivation and job performance are, of course, related; a motivated person who desires to do well at work is willing to expend effort to do so. Performance is moderated by situational constraints at work, which are factors that can stymie or enhance performance; examples are an organization's climate (both psychological and physical) and up-to-date equipment.

Satisfaction

Job satisfaction closely correlates with motivation, and, naturally, several theories exist to explain the degree of pleasure an employee derives from his or her job. Some approaches postulate that job satisfaction is determined within the individual, achieved when a person's physical and physiological needs are met; other concepts center on the external factors of social comparison. Work conditions are likely to strongly influence job satisfaction; Herzberg's two-factor theory (see Chapter 13) postulated that certain job conditions (context or hygiene factors) such as pay and the work environment could generate dissatisfaction if perceived as negative. However, in Hertzberg's opinion, simply making these factors positive (good pay, for example) would not result in satisfaction; only positive work content factors such as achievement (and subsequent recognition and pay increase) produce job satisfaction.

Stress

In Selye's original theory° (discussed in Chapter 12), stress had a positive side: on the job, it was a condition in which a person felt compelled to better a situation, improve one's performance, and achieve a higher degree of satisfaction. In today's parlance, we usually mean *dis-stress*, as Selye called it: a strained personal condition, nerve-racking and exhausting caused by demands at or beyond our means to cope. Such stressors and resulting stress can appear on all organizational levels and in all jobs. Stress can stem from situations outside work and interact with job-related stress.

Stress is an individual's psychological and physiological response to excessive demands; it can carry severe consequences in terms of both physical and mental health. Avoiding such stress is critical for the well-being of employees and accordingly for the continued operational soundness of an organization.

Stressors

Since individuals react in different ways to demands, stressors vary in terms of the severity of their impact on people. In general, however, the biggest organizational stressors include task attributes, work environment, lack of recognition and support from supervisors, and unfair or bullying peers and bosses—as listed in Chapter 12. Proper organizational policies and prudent actions by those carrying responsibilities in the organization can eliminate many stress producers.

14.8 A good place to work

As discussed in Chapter 13, need- or value-based theories posit that job satisfaction is an attitude that is specific to each individual. Every person has physical and physiological needs that one strives to fill in order to obtain satisfaction. A satisfying job meets physical needs (such as food and shelter), through appropriate income, and meets psychological needs (such as self-esteem and intellectual stimulation), through job opportunities and professional recognition.

Other theories focus on social comparison. They postulate that people assess their own feelings of job satisfaction in relation to other persons; by inferring their feelings about their jobs, they compare themselves to the other people who work in similar capacities. Work conditions are the focus of the third group of theories that attempt to explain job satisfaction; Herzberg's two-factor theory is the best known.

Ultimately, various theories contribute to an overall understanding of what kind of job it takes to keep employees satisfied.

The best place to work

As a summary statement of the various factors underlying motivation and job satisfaction, we might do best to take comments from the trenches. One of the U.S. companies that continually made the list of “100 Best Companies to Work For” offered these reasons for its success: “This is a positive place. People are friendly … they feel challenged. They feel respected and valued. And they respond with loyalty.” The company’s philosophy included “Treat others the way they want to be treated. Strive for mutual respect and for an atmosphere that makes people proud to work here. Provide career opportunities. Say thank you for a job well done.”

Quality of life at and off work

Striking a balance between life at work and life outside the job is, of course, of primary importance to the individual; but this has become an issue to the employer as well. A leanly staffed company in a tight labor market is likely to set up a situation in which the employees are overloaded with work. Technological developments that connect employees to work around the clock, like cell phones and handheld computers, also influence the burden many employees feel. Employers realize that overtaxing employees may lead to reduced productivity and employee exodus; consequently, organizations may well take measures to keep their employees from feeling overwhelmed by work. These measures include limited hours of work; off-time free of work tasks and phone calls; lengthy and uninterrupted vacations; employee sabbaticals; limited meetings; and flexible schedules. A rested employee is essential to a company’s business.

Summary

An organization cannot function by its strategy, structure, and machinery alone; it is powered by its working, thinking, aspiring, and interacting employees. People affect the organization; they determine the way it functions—yet, in turn, the organization affects these individuals. “Good fit” between individuals, work, and organization makes the system run smoothly.

Motivating employees is a complex yet, of course, highly desirable goal. Many theories exist that try to explain motivation; they can be roughly divided into two categories. The first group focuses on the individual and inherent traits; the second group particularly considers the immediate environment and the overall work organization.

Taylorism° and mechanization, and then automation, changed many jobs into monotonous and deskilling drudgery; organizations became sectional, hierarchical, and stuck in bureaucracy. These trends deprive humans of outcomes such as expertise, autonomy, and self-fulfillment.

Today's educated and informed employees expect to be recognized at work as skillful and resourceful individuals. They expect respect and recognition for their efforts. They expect better-designed jobs, greater participation in decision-making, and freedom to work in a less formal organization. They expect a pleasing environment; they expect to work with pleasant people as colleagues besides, below, and above in the system. These expectations translate into a human-system integration that is less hierarchical than it was in the past, less formalized and less centralized in its organizational structures.

The human-centered layout of the whole organization and the ergonomic design of the work environment can lead away from the aloof "I don't know what I'm doing, I just work here" to the interested participation expressed by "If I don't show up, this place will come to a standstill."

Here is a voice from Japan°:

- Body movement and thinking on the job stimulate alertness.
- A complex job enriches skill and motivation and generates satisfaction when completed.
- Flexibility and freedom of choice in the execution of a task result in efficiency and productivity.
- Opportunities for decision-making provide a feeling of responsibility that leads to performance-directed motivation and satisfaction.
- The organization that promotes participation enhances its members' self-development and self-realization and furthers its own success.

Fitting steps

Step 1: Lay out the organization to utilize people's skills and aspirations.

Step 2: Encourage the members of the organization to work the way they "like to do" as this furthers the strategic goals.

Step 3: Be innovative, flexible, and adaptive.

Notes

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

Macroergonomics: Hendrick and Kleiner 2005.

14.1 The human is in the center:

Schematic in Figure 14.1: This text uses some material from Kroemer and Kroemer (2017).

Psychologists and behaviorists: Greenberg 2010; Landy and Conte 2006; Stanton et al. 2005; Vercruyssen and Hendrick 2011; Wilson and Corlett 2005; Wilson and Sharples 2015.

14.2 Organizational strategy:

Organizational designs: Booher 2003; Pew and Mavor 2007.

14.3 Organizational structure:

Comprehensive self-governance: Useem 2015.

14.6 Organizational culture:

Advertising agencies: example from Kroemer and Kroemer 2001.

Selye's original stress theory: Selye 1956, 1974.

Summary:

Taylorism: Lepore 2009.

Voice from Japan: Paraphrased from Nagamachi 2001.

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CHAPTER FIFTEEN

Working hours and sleep

Mothers of young children are busy all day long, often even during the night. Farm work has always been associated with long working hours, often starting at sunrise and ending at sunset. During the so-called Industrial Revolution, around 1800, in Europe, home-based handwork as well as factory work often lasted 10 to 12 hours a day, six or even seven days a week. Today, in cities, firefighters and ambulance personnel can be on call 12 hours a day, but much of that time is—they hope—just waiting time; yet they are ready for any emergency.

The human body changes its physiological functions throughout the 24-hour day. In the waking hours, the body is naturally ready for physical and mental work; during the night, it relaxes and sleeps. Attitudes and behavior also change regularly during the day. New time signals and unusual periods of activity and rest (such as when starting shift work; see Chapter 16) can upset the daily rhythm and have performance and health consequences.

15.1 Circadian body rhythms

Body rhythms

Daily rhythms are natural temporal programs controlling the life of animals and plants. In humans, functions such as body temperature, heart rate, blood pressure, and hormone excretion, follow a set of daily recurring fluctuations, called *circadian*° (or *diurnal*) rhythms, as sketched in Figure 15.1. Several programs intertwine with each other: core temperature, blood pressure, and sleepiness, for example.

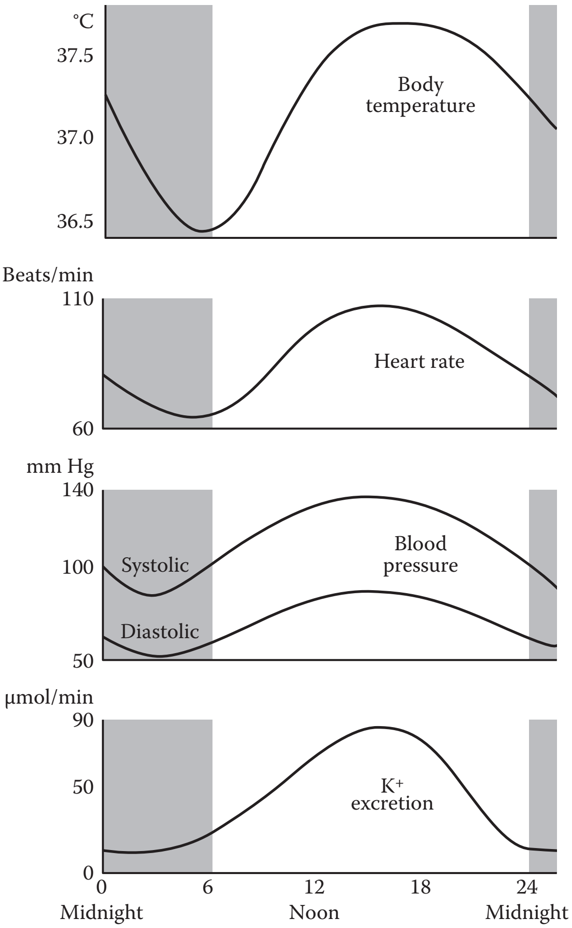

FIGURE 15.1 Typical variations in body functions over the day. (Adapted from Kroemer, K. H. E., Kroemer, H. J., and Kroemer-Elbert, K. E., *Engineering Physiology: Bases of Human Factors/Ergonomics*, fourth ed., Springer, Heidelberg, Germany, 2010.)

Daily rhythms

During daylight, we are awake, active and we eat and drink; at night, we fast and sleep. Physiological events do not exactly follow that general pattern. For example, the body core temperature falls even after the body has been sleeping for several hours; it is usually lowest around six o'clock in the morning. The core temperature then quickly rises when one gets up. It continues to increase, with some variations, until late in the evening. Thus, body temperature is not just a passive response to our regular daily behavior, such as getting up, eating meals, performing work, and doing social activities. This circadian physiological rhythm of the body is solid and self-regulated. Another example is skin temperature, which increases with the onset of sleep, regardless of when this occurs.

Twenty-four-hour cycles

When a person is completely isolated from external time markers and events such as night darkness and daylight, and no regular activities are set, the internal body rhythms are running free, under internal control° only. Many experiments have consistently shown that circadian rhythms continue when running free, but, curiously, their time periods are slightly different from the regular 24-hour duration: most rhythms run freely at about 25 hours; some take longer. This experience indicates that body rhythms can persist independently from external stimuli and follow their own built-in clocks. However, when subjected to daily 24-hour activities and associated time markers, the internal rhythms synchronize at a common 24-hour cycle.

Individual differences

Some people have consistently shorter (or longer) free-running circadian rhythm periods than others. Statistically, those with short periods are likely to be "morning types" who get up early from sleep, while those with longer internal rhythms are probably "evening types" who stay up into the late hours of the day. Rhythm amplitudes, for instance of body temperature, usually reduce with increasing age, which could explain a shift toward early morning activity among the elderly. Also, oscillatory controls seem to lose some of their power as one ages: this would indicate a greater susceptibility to rhythm disturbances with increasing age.

Internal and external events

Under regular circumstances, there is a well-established phase coincidence between external activities and the internal circadian events. For example, during the night, the low values of physiological functions, such as of core temperature and heart rate, are primarily due to the diurnal rhythm of the body; however, they are further helped by the body's nighttime inactivity and fasting. During the day, the peak activity usually coincides with high values of the internal functions. Thus, normally, the observed diurnal rhythm is the result of internal (endogenous) and external (exogenous) events, which concur. If that balance of concurrent events is severely disturbed, well-being, health, and performance decline.

Synchronized biological clocks

The regulation of alertness, wakefulness, sleepiness, sleep, and many physiological functions appears to be under the control of two internal clocks of the body°: one controls sleep and wakefulness; the other, physiological functions, such as body temperature. Under normal conditions, the internal clocks are linked together so that body temperature and other physiological activities increase during wakefulness and decline during sleep. However, this congruence of the two rhythms may be disturbed by night-shift work, for instance, where one must be active during nighttime and sleep during the day. (More on shift work in Chapter 16.) As such patterns continue, the physiological clocks adjust to the external requirements of the new sleep/wake regimen. This means that the formerly well-established physiological rhythm flattens out and, within a period of up to two weeks, reestablishes itself according to the new sleep/wake schedule.

Resetting biological clocks

Strong and persistent external events can put the regular circadian rhythms into a new order. This happens commonly when we travel fast and far to the east or the west. Upon arrival at the new location, we experience jet lag at first: our body still functions at its normal timing, which now differs from the local time settings of day light and night darkness, of waking up and seeking sleep, of working hours and meal times. These events and activities act as time markers. Their regular repetition resets our internal biological clocks, which regulate our diurnal rhythms.

Airline crews and other short-time visitors to a different times zone may decide to simply stay on their home time setting until they return to their regular time zone. Of course, this is not practical for long-term moves to a new time zone, where it is better to realign. That rearrangement usually takes at least three days: the larger the jumps in time, the longer the adjustment time to overcome the rhythm lag.

15.2 Sleep

The body needs sleep

While it is obvious that humans need sleep, exactly why their body needs sleep is not clear°. There is the general opinion that sleep has recuperative benefits, allowing some sort of restitution or repair of tissue or brain following the wear and tear of wakeful activities. However, what is meant by restitution or repair is usually not clearly expressed, nor fully understood. Certainly, sleep is accompanied by rest and, consequently, by energy conservation. But, when not forced to be active, a human can attain similar relaxation during wakefulness. Regarding the restitution of the body, it is an everyday experience that muscle ache resulting from a day's effort is gone the next morning; yet it might go away just as well during a long rest while being awake. Limited sleep deprivation does not impair the physiological ability to perform physical work. Apparent reductions in physical capability, blamed on sleep deprivation, may be mostly due to reduced psychological motivation. The lack of experimental findings regarding the physical benefits of sleep is somewhat surprising because this challenges common experience.

The brain needs sleep

In contrast, the restorative benefits of sleep for the brain are well established. 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, slurred speech, lack of attention, drowsiness, memory problems, and other performance reductions. As mentioned in Chapter 10, mental performance is less diminished on stimulating and motivating tasks than on boring, repetitive, and unrewarding tasks. More than two nights of sleep deprivation reduce all task performances. These performance degradations indicate function impairments of the central nervous system owing to sleep deprivation, hence a need for the brain to sleep.

Observing sleep phases

The brain and the muscles are the human organs that show the largest changes from sleep to wakefulness: their electrical activities have allowed for well-established techniques of observation. Electrodes attached to the surface of the scalp can pick up electrical activities of the brain, encephalon. Thus, the name of this measuring technique is electroencephalography (EEG). The EEG signals provide some general information about brain activities. The other common technique records the electrical activities associated with the muscles that move the eyes and those in the chin and neck regions. The recording of eye activities is called electro-oculography (EOG). Both techniques (already mentioned in Chapter 9) are often applied together to record and describe events during sleep.

EEG signals during sleep

The amplitude of EEG signals is measured in microvolts; the amplitude rises as consciousness falls from alert wakefulness through drowsiness to deep sleep. EEG frequency is measured in Hertz; the frequencies observed in human EEGs range from 0.5 to 25 Hz. Fast waves are frequencies above 15 Hz; frequencies under 3.5 Hz are slow waves. Frequency falls as sleep deepens; slow-wave sleep is of particular interest to researchers.

Certain frequency bands are labeled with Greek letters.

- Beta, above 15 Hz: These fast waves of low amplitude (under 10 μV) 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 μV, and occur more often as sleep becomes deeper.

Also, certain occurrences in the EEG waves have descriptive names, such as vertices, spindles, and complexes, which appear to be regularly associated with certain sleep characteristics.

REM and non-REM sleep phases

EOG outputs of the eye muscles often serve as the main descriptors of sleep episodes. Accordingly, sleep is divided into periods associated with rapid eye movements (REMs); the other phases are called non-REM. Non-REM conditions are further subdivided into four stages according to their associated EEG characteristics. Table 15.1 lists these.

Table 15.1 Sleep stages

Condition	Sleep stage	Muscle EMG	Brain EEG	Sleep percentage (approximate) (%)
Awake	–	Active	Active; alpha and beta	–
Drowsy, transitional light sleep	1 Non-REM	Eyelids open and close; eyes roll	Theta; loss of alpha; sharp vertex waves	5
True sleep	2 Non-REM		Theta; few delta; sleep spindles; k-complexes	45
Transitional true sleep	3 Non-REM		More delta; slow wave sleep	7
Deep true sleep	4 Non-REM		Predominant delta slow wave sleep	13
Sleeping	REM	Rapid eye movements; other muscles relaxed	Alert; much dreaming; alpha and delta	30

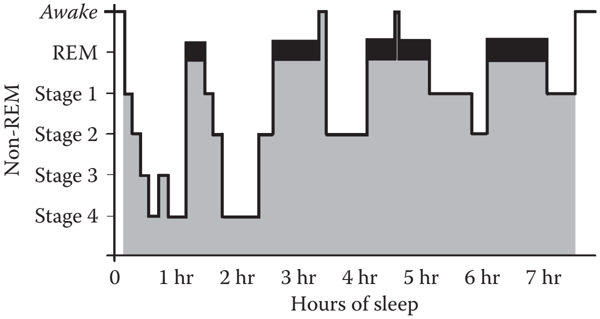

FIGURE 15.2 Typical phases during undisturbed night sleep. W indicates wakefulness; the black bars represent REM sleep. (Adapted from Kroemer, K. H. E., Kroemer, H. J., and Kroemer-Elbert, K. E., *Engineering Physiology: Bases of Human Factors/Ergonomics*, fourth ed., Springer, Heidelberg, Germany, 2010.)

The REM sleep phase shows irregular breathing and heart rate, as well as low-voltage, fast brain activities visible in the EEG. During the non-REM stages, regular and slow breathing and heart rates occur, and the EEG activity is slow but shows high voltage. These phases change cyclically during sleep. The REM/non-REM cycles occur in roughly hour and one half timings; however, this duration has large within- and between-subject variability and appears to shorten in the course of a night's sleep, accompanied by a lengthening of the REM portion. Figure 15.2 depicts a diagram of typical sleep phases during the night.

Normal sleep requirements

Certain age groups in the western world show rather regular sleeping hours; young adults sleep, on average, about seven and one half hours; yet some people are well rested after about six hours of sleep, while others habitually take nine hours and more. 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 five hours of sleep per day, with even shorter periods still being somewhat useful. The amount of slow-wave sleep in both short and long sleepers is about the same, but the amounts of REM and non-REM sleep periods differ considerably. Individuals naturally sleeping less than three and one half hours are very rare among middle-aged people; no true nonsleepers have ever been found among healthy persons.

Sleep loss and tiredness

Apparently, only the brain assumes a physiological state during sleep that is unique to sleep and cannot be attained during wakefulness. Muscles, for example, can rest during relaxed wakefulness, 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 seems to be functionally disconnected from subcortical mechanisms. The brain needs sleep to restitute, a process that cannot sufficiently take place during waking relaxation. It appears that not all the regular full sleep time is essential for brain restitution. Following sleep deprivation, usually not all lost sleep is reclaimed; a sleep period that is up to two hours shorter than usual can be endured for many months without negative consequences. Evidently, the first five to six hours of regular sleep (which happens 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°.

Sleep deprivation

Traveling through several time zones, then being ready to get some sleep but forced to stay awake, can put us into a difficult situation: we need sleep. Why sleep is necessary°, and precisely what it does to our body and mind, is—surprisingly—still a topic of much discussion among researchers. Whatever the reason, we all know that performing everyday tasks can be very difficult while being deprived of sleep.

There are occasions that demand continuing work for long periods, such as a full day or longer. This not only means being busy for long periods but also encompasses loss of sleep. Hence, negative effects on operator well-being and performance associated with such extended working spells result partly from the long-time work itself, but they are also due to the lack of sleep.

Performing tasks while sleep-deprived

Sleepiness and wakefulness appear in unpredictable waves, so work performance may be fine for a while and then become difficult and faulty. Sleepiness has little effect on the performance of demanding work tasks that are interesting and appealing, especially if they last less than half an hour, even if they include making complex decisions. Accuracy in performing a job may still be quite good even after losing sleep, but it takes longer to perform the job. Self-paced work deteriorates less with sleepiness than externally paced tasks.

However, sleep loss negatively affects the performance of work to be done over longer periods, particularly so if the task is repetitive, monotonous, or complex. Decision-making takes longer if the task is disliked and unappealing. Long-term and short-term memories degrade when people are required to stay awake for long periods.

15.3 Rest pauses and time off work

Given the natural circadian rhythms in physiological functions, one expects corresponding changes in attitudes and activities during the day. Of course, the daily organization of getting up, working, eating, relaxing, and sleeping also affects, strongly so, attitudes and work habits and work performance. In experiments, it is possible to separate the effects of internal and external daily rhythms. For practical purposes, it is reasonable to look at the overall results of the combined internal and external factors as they affect work load and work output.

Performance changes during daylong work

For many people, the morning hours seem be best for strenuous activities, mental and physical, because "fatigue" arising from work already performed may reduce performance over the course of the day. Often, performance shows a pronounced decrease early in the afternoon: this is often called the *post-lunch dip*. However, there seem to be no similar changes in physiological functions; for example, the body temperature remains unchanged at that time of the day. Hence, it appears reasonable to speculate that the interruption of the activities by a noon meal and the following digestive activities of the body, together with reduced psychological arousal and expectation and habits, would bring about this reduction in performance. However, in medium to heavy physical work, such lunch dip does not occur except when the food and beverage ingestion was very heavy and if true physiological fatigue had built up during the premeal activities.

Stress of long working hours

Some individuals are capable of continued heavy physical labor and, in fact, enjoy doing it while others prefer lighter physical tasks or mental activities; the types and the intensities of activities pose varying demands on the worker. Section III of this book contains discussions on how to assess the actual workloads and, consequently, how long persons can perform such work. If metabolic, circulatory, or respiratory labor demands exceed sustainable limits even with interspaced rest periods, the work must be terminated; at lower physical demand levels, work can continue smoothly, even over extended periods, if pauses can be freely chosen.

Breaks needed

Mental activities such as visual searches or information processing, and tasks requiring concentrated attention, may be interesting and generate alertness—or they may be overtaxing and fatiguing—depending on their intensity and duration and how they comply with individual traits and motivation. Persons expected to perform monotonous mental tasks, which are low in novelty, interest, and incentive or that are high in complexity, need breaks every half an hour or so; otherwise, performance falls off severely. Accordingly, tasks that are monotonous or complex should not be requested from persons over long periods. Varying or new tasks are more resistant to deterioration if they require decision-making or problem-solving or deal with information that is highly interesting or rewarding.

Rest pauses

In both physical work and mental activities, suitable breaks permit us to, literally, “catch my breath” or “take my mind off the task”; pauses and off-work time allow relaxation, recovery, reloading. The working human body needs to maintain a balance between energy consumption and energy replacement: put simply, between work and rest. This supply–use–supply process is an integral part of the operation of muscles, of the heart, and of the organism as a whole. Rest pauses are indispensable physiological and psychological requirements if performance must be maintained.

There are four types of work pauses:

1. Spontaneous pauses
2. Disguised causes
3. Work-caused pauses
4. Pauses prescribed by management

Spontaneous pauses are taken by workers on their own initiative to interrupt the flow of work in order to take a break and recharge; that may include napping°. These pauses are in response to the effort; they are needed to recuperate. As discussed in Chapter 11, as a rule, many short pauses have greater recuperative value than a few long ones.

Disguised pauses are those where the worker takes up an activity other than the main job; examples are replacing work tools or tidying the workplace. Many of these disguises serve to cover a necessary spontaneous pause. It would be better to take these pauses openly, so that the necessary recovery from the work can be fully realized.

Work-caused pauses are interruptions that arise from the work itself, such as waiting for a machine to complete an operation or for a tool to cool down, or they may be caused by a breakdown in the flow of work. These breaks are beyond the worker's control, yet they provide time to recuperate.

Management-prescribed pauses are wisely provided so that workers can get away from the job and rest openly, to have time for eating and for other personal needs. As a rule, during shifts lasting up to eight hours, one long pause of 30 minutes or longer should be provided somewhere during the middle of the work, and two shorter pauses, say of 15 minutes each, should break up the two halves of the working time.

Pauses are physically or psychologically helpful, often needed, to maintain performance during the full work shift. Taking spontaneous pauses should be encouraged by the management; disguising a pause with another activity reduces the recovery value of the break.

15.4 Daily and weekly working time

One prerequisite for our well-being is the maintenance of our circadian rhythms in spite of external disturbances. This state of balanced control, called *homeostasis*, regulates our body functions, makes us sleepy or awake, enables us to work, establishes our inclinations to do certain activities, and determines our social behavior.

Days on/off work

Most persons are used to working during daylight. Physiologically, we should be able to do so every single day, provided that we have suitable conditions of work, including rest breaks. However, tradition and societal customs have made us expect to have days free of work regularly°: in many regions, this is every seventh day. In most of Europe, for example, Sundays have been the day off work since at least the mid-1800s; free Saturdays followed in the mid-1900s; since then, a four-day workweek has been widely discussed. The conventions of certain sequences of days with work, followed by days off work, have lead to many theories and experiments° to determine the suitable numbers of working hours during the day in relation to working days during the week (discussed in the following) and of shift work (discussed in Chapter 16).

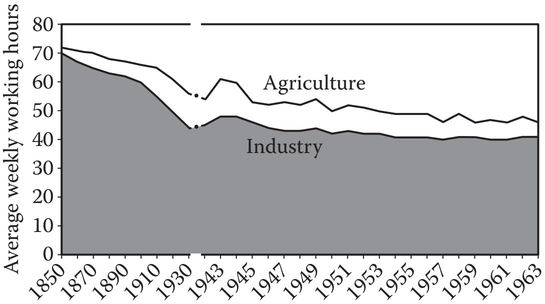

FIGURE 15.3 Weekly working hours in the United States.

History of working time

Weekly and daily working times are closely related. In Switzerland, the Factory Act of 1877 stipulated a 65-hours workweek, with 11 hours of work each weekday and 10 hours on Saturday. In 1914, a legal amendment shortened the weekly work to 48 hours. Figure 15.3 shows the history of working hours in the United States from 1850 to 1963. In 1850, outside agriculture, the average working time was about 70 hours per week, which, around 1940, had decreased to about 50 hours. In 1963, the working time per week was around 40 hours in industry, where it has stayed, with little change, until now. In the United States, nearly 20% of working adults work for 48 hours, or more, per week; 7% spend at least 60 hours at work, per week°. About 40 hours of working time per week is common in most industrialized regions on Earth.

Forty-hour workweek

The reduction of the weekly working time to 40 hours, to even less in some countries, was often associated with a changeover from a six-day workweek to five days of work each week. Employees and employers generally both welcomed that reduction in workdays; it often came with a slight increase in productivity and reduction in absenteeism°. It is of socioeconomic interest that this reduction in work hours and workdays allowed, in some countries, to hire more workers and thus reduce widespread unemployment.

Eight-hour workday

Apparently, the division of 24 hours into three about equal sections fits the current lifestyle in many societies. That setup is commonly acceptable because it offers about eight hours for family and social interactions, reserves eight hours for sleep, and still provides eight hours for work. As mentioned earlier, it is appropriate to interrupt the work shift of eight hours about halfway with a long break of at least 30 minutes, commonly used for taking in a meal. A truly long break could be used for an extended siesta around noon, as is traditional in hot climates. Each of the two blocks of working time should be split by another scheduled break, lasting perhaps 15 minutes, and workers should be encouraged to take additional pauses as desired and needed.

The work shift of eight hours has become widespread: it suits organizational purposes in trade and industry, especially because the eight hours work period allows establishing a three-shift schedule that covers the 24-hour day; however, one could also do a two-shift arrangement with 12-hour work; more about shift arrangements in Chapter 16.

Brief work periods Work that is very demanding, mentally or physically, may be impossible to maintain for the customary eight hours of working time a day, even with suitable breaks for recovery: instead, six hours of work may be more acceptable. Even in such shortened work arrangements, a substantial break at about mid-time is generally required, and each of the two halves of working time should be interrupted by one scheduled break, with additional pauses taken as needed.

Long work periods Long work shifts may be scheduled for a variety of reasons: for example, big-city firefighters spend much of their 10- or 12-hour work schedules waiting for the call of duty. In automated plants, supervisory presence makes sure that the process runs smoothly with occasional human interference as needed. Twelve-hour shifts may be desired to fill the 24-hour day—more about shift arrangements in Chapter 16. However, working periods of 10 or 12 hours is not suitable if they require continual effort from the worker. Humans cannot perform physical nor mental work at a continuing high rate over long periods without physical or mental fatigue with its accompanying resulting negative effects on well-being and work performance: lapses in attention are unavoidable, mistakes are likely, and accidents are possible.

Flextime Flexible working hours are a recent form of work organization. Its specific feature is that a person can distribute the required work time, say 40 hours per week, over the official work days as long as certain requirements are met, such as full presence on certain days or during a core time of the day, for example from 10 to 12 in the morning. *Sliding time* (or *gliding time*) is a subgroup of flexible work hours where, instead of weekly working hours, the daily working hours can be slid (floated) over the day. As with weekly flextime, usually certain requirements must be met, such as being present at set times. Both arrangements have been generally popular with employees and employers, although not all kinds of work are suitable for flexible arrangements. Furthermore, in nearly every organization, there are groups of employees who must be present during all the conventional hours, such as receptionists or cafeteria workers, or assembly workers organized in groups.

Emphasis on performance

Working at home, especially in the home office usually associated with computer use, has the most flexible arrangements. The control of the number of working hours, and their scheduling, is on the individual; the overriding requirement is to get work done on time. All these flextime arrangements abolish much of the traditional control over working time by the employer and put more responsibility on the individual worker. The emphasis

Table 15.2 Comments on flextime

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

Source: Knauth, P., Extended work periods, *Industrial Health*, 45, 125–136, 2007a; Kroemer, K. H. E., Kroemer, H. B., and Kroemer-Elbert, K. E., *Ergonomics: How to Design for Ease and Efficiency*, second ed., Prentice Hall/Pearson, Upper Saddle River, New Jersey, 2003.

is on performance, not on hours spent on the job. Yet overly ambitious persons might spend more time working on their own than they would do if they were on regular schedules.

Compressed workweek

Flextime is often, although not necessarily, associated with compressed work weeks that have more working hours per day, but fewer workdays per week. For example, the customary numbers of weekly work hours is 40, divided into eight hours of daily work. This can be consolidated into four days per week, where each day has 10 hours of work. This allows the worker to have three instead of two free days each week. Apparently, this is attractive to many employees and employers for reasons such as these: There are more work-free days, best if together in one block; the number of trips to and from work is reduced, and there are fewer setups and closedowns at work. However, there are also concerns about increased fatigue due to long workdays and reduced performance and safety—see Tables 15.2 and 15.3.

Work performed in compressed workweeks

The type of work to be performed mostly determines whether compressed workweeks can and should be used. Thus, long

Table 15.3 Comments on extended workdays/compressed workweeks

Positive
Appeals generally to employees and employers
Makes available more work-free days for family and social life
Provides more time per day for scheduling meetings or training sessions
Generates fewer start-up and warm-up expenses
Does not result in reduced employee pay
Reduces commuting traffic problems
Negative
Decreases job performance
Requires overtime pay
Tends to fatigue workers
Increases tardiness and early departure from work
Increases absenteeism
Increases on-the-job and off-the-job accidents
Increases energy and maintenance cost

Source: Adapted from Knauth, P., Extended work periods, *Industrial Health*, 45, 125–136, 2007a; Kroemer, K. H. E., Kroemer, H. B., and Kroemer-Elbert, K. E., *Ergonomics: How to Design for Ease and Efficiency*, second ed., Prentice Hall/Pearson, Upper Saddle River, New Jersey, 2003.

shifts have been mostly employed in cases where one is on standby much of the time. Also, activities that require only few or small physical efforts, especially if they are diverse and interesting yet fall into routines, have been done in long shifts. Examples are nursing, clerical and administrative work, technical maintenance, computer supply operations, and supervision of automated processes. Little experience exists from long shifts that include manufacturing, assembly, and machine operations. Furthermore, information stems mostly from subjective statements of employees, results of psychological tests, and scrutinizing performance and safety records in industry.

Twelve-hour workdays

Working very long work shifts, such as 12 hours, is likely to lead to fatigue, to cause drowsiness and bring with it reductions in cognitive abilities and motor skills, and to generally reduce performance during the course of the work shift, which becomes more pronounced as the workweek progresses. There is the potential that a fatigued worker takes careless shortcuts to complete a job; and work practices become less safe in tasks that are tedious because of high cognitive or information-processing demands, or in highly repetitive work.

Summary

Human physical and psychological functions as well as behaviors follow a set of regular daily fluctuations, the circadian (diurnal) rhythm. Under regular living conditions, this temporal program is well established and persistent. Upsetting the rhythm by strong external time markers and events, such as work in a different time zone, can lead to reduced performance and well-being.

Regular work shifts should be done during daylight. The suitable length of the working time per day primarily depends on

- The type and intensity of work and how these relate to worker capacities
- The ways work is organized within societal and social customs

A working time of eight hours a day is generally acceptable for psychological, physiological, social, and organizational reasons; yet scheduled and freely taken rest periods are necessary. Under certain circumstances, shorter or longer daily work times are reasonable.

Apparently, the common division of the 24-hour day into three approximately equal sections fits the current lifestyle in many societies because it reserves about eight hours for family and social interactions, eight hours for sleep, and still leaves eight hours for work.

Fitting steps

Step 1: Determine the suitable length of the workday with rest pauses.

Step 2: Establish whether fixed or flexible arrangements are desirable.

Step 3: Rearrange as experiences suggest.

Further reading

Czeisler, C. A., and Gooley, J. J. (2007) Sleep and circadian rhythms in humans. *Cold Spring Harb Symp Quant Biol.* 72: 579–597.

Refinetti, R. (2016) *Circadian Physiology*, third ed., CRC Press, Boca Raton, FL.

Notes

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

15.1 Circadian body rhythms:

Daily rhythms called *circadian* from the Latin *circa*, which means “about,” and *dies*, which means “day”; *diurnal* from *diurnus*, which means “of the day.”

Rhythms running free under internal control: Folkard and Monk 1985.

Model of two internal clocks: Horne 1988, 2006; Foster and Kreitzman 2004.

15.2 Sleep:

Why we need sleep is not clear: Horne 2006; Siegel 2003.

Importance of REM and non-REM sleep: Horne 1988, 2006.

15.3 Rest pauses and time off work:

Napping: Driskell and Mullen 2005.

15.4 Daily and weekly working time:

Have days free of work regularly: From a formal/decimal point of view, there is little sense in such numerical arrangements as 12 months a year, 7 days a week, 24 hours a day, 60 minutes per hour.

Theories and experiments to determine suitable working hours: discussed by Hornberger et al. 2000; Folkard, Lombardi, and Tucker 2005; Foster and Kreitzman 2004; Popkin, Howarth, and Tepas 2006; Refinetti 2016.

Weekly working hours in the USA: National Institute of Occupational Health and Safety (NIOSH) 2015.

CHAPTER SIXTEEN

Night and shift work

Physiological functions of the human body wax and wane rhythmically throughout the 24-hour day, as described in Chapter 15. During daylight, the body is prepared for work; sleep is normal at night. Our attitudes and behavior fluctuate accordingly and so does our social life. A new set of time signals, of activity and rest, such as those associated with shifting work schedules, can upset the normal daily rhythms. Work schedules should be arranged to least disturb physiological, psychological, and behavioral rhythms to avoid negative health and social effects and to prevent reduced work performance.

Physiological and psychological functions of the human follow daily fluctuations, called *circadian rhythms*. They are easy to observe in body temperature, heart rate, blood pressure, and hormone excretion, as sketched in Figure 15.1 in the preceding chapter. These natural temporal programs keep our body and mind healthy°, they make us able to work and to function in our social environment. The circadian programs intertwine: for example, core temperature and blood pressure are coupled with sleepiness and wakefulness. Self-sustained internal clocks control the rhythms, which run on a 24-hour cycle synchronized by our daily time markers: real clocks, getting up, eating, working, going to sleep.

The circadian rhythms show a high persistence under varying external conditions. However, strong and repeated external events and time markers can upset the regular circadian rhythms and disturb the daily balance of wakefulness and sleep, activities and rest, alertness and drowsiness. Such balance is a prerequisite for human performance and individual health, physical and mental. Getting enough sleep is part of that requirement, as discussed in Chapter 15.

Job performance at night

Performance levels are generally lower during nighttime activities, when the body and the brain usually rest, than during daylight time. This has long been known. Figure 16.1 shows a summary graph of reading errors recorded between 1912 and 1931. During that time, about 175,000 readings of gas meters were taken around the clock. The number of errors was by far highest around two o'clock in the morning. Another peak in errors, although noticeably lower, happened after lunch. Similar relations between mishaps and time of the day have been reported ever since. Figure 16.2, with data from the mid-1950s, illustrates the frequency at which truck drivers fell asleep while driving. That occurred most often after midnight and, again, around lunchtime. Sleep loss and its resulting sleepiness are likely to aggravate such naturally occurring fluctuations in performance.

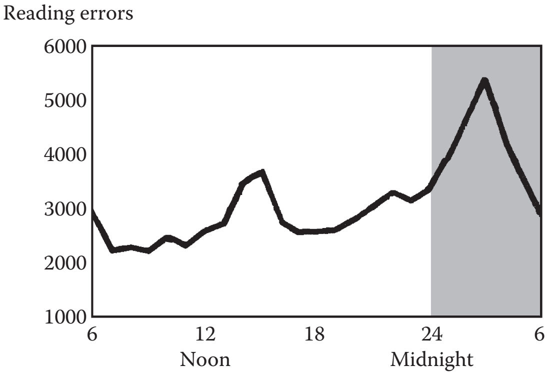

FIGURE 16.1 Frequencies of errors in gas meter readings. (Adapted from Lehmann, G., *Praktische Arbeitsphysiologie*, Thieme, Stuttgart, Germany, 1953.)

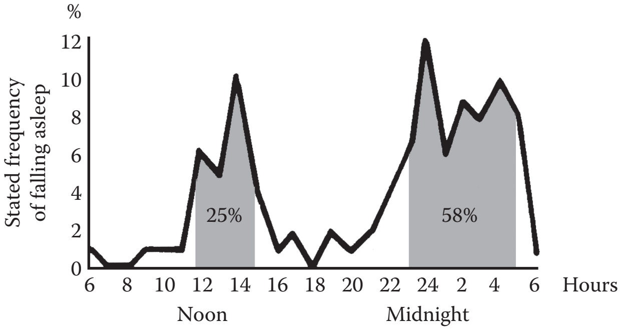

FIGURE 16.2 Frequencies at which truck drivers fell asleep while driving. (Adapted from Lehmann, G., *Praktische Arbeitsphysiologie*, second ed., Thieme, Stuttgart, Germany, 1962.)

16.1 Organizing shift work

Defining 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 means either attending the same workplace regularly at the same time (continual shift work) or at regularly recurring times (discontinuous, rotating shift work).

Other important identifiers of shifts and shift patterns° are the starting and ending times of a shift; the number of workdays in each week; the hours of work in each week; the number of free days per week or per rotation cycle; the number of consecutive days on the same shift (cycle length), which may be a fixed or variable number; the schedule by which an individual worker either works or has a free day or free days; the number of free days per week and year; and the number of shift teams.

History of shift work

Shift work is not new. In ancient Rome, a decree required that deliveries were to be done at night to relieve street congestion. Bakers have traditionally worked through the late night and early morning hours. Guards and firefighters always did night shifts. With 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-hour period with either two 12-hour work shifts, or with three eight-hour work shifts, became common practice. In the first part of the twentieth century, the then traditional six-day workweeks with 10-hour shifts were shortened, as shown in the preceding chapter in Figure 15.3. Since the middle of the twentieth century, many work systems use a shift arrangement of eight-hour per day on five workdays per week. Data from the U.S. Bureau of Labor Statistics indicate that, in 2004, almost 15 million Americans worked full time on evening shifts, night shifts, rotating shifts, or on other employer-arranged irregular schedules.

Circadian rhythm and shift work

With the increase in shift work, the matter of circadian rhythm adjustments and the fear of consequent negative health outcomes became an important topic in industrial medicine. The first large surveys came from Norway, around 1960. They showed that shift workers had significantly more digestive ailments and nervous disorders than their colleagues on regular day shifts. Many workers disliked shift arrangements and tried to return to regular day work.

Health concerns

Half a century later, these early concerns about negative health effects of shift work are still valid. Working at unusual times, especially during the night; working long shifts, such as 10 or 12 hours; and changing the timings of work, especially when they lead to sleep loss, can all cause health problems especially if these shift work conditions combine to cause extraordinarily long working times and large deficits in rest and sleep. Prominent on the list of concerns for human well-being are the following:

- Interruption of natural physiological and psychological rhythms
- Fatigue, drowsiness, sleepiness
- Increased accident risks, both on and off the job
- Sleep disorders
- Gastrointestinal disorders
- Cardiovascular diseases
- Nervous disorders
- Cognitive decrements
- Disturbances of family and social life

Obviously, the main problems are physiological and psychosocial: *physiological* in that such work needs to be performed at times when the body is set to sleep and rest, and *psychosocial* because work must be done at times that are commonly employed for family and social interaction and for leisure activities.

Societal expectations of free time

Persons working on permanent evening or night shifts set up their own personal schedules for sleep, leisure times, and social networking, possibly at odds with the habits of a society that values free time in the evening and on weekends more highly than free time at other times of the day or the week. In a theoretical view, the societal expectation of free time especially on weekends generates a major hindrance for permanent readjustment of daily rhythms because if shift workers return to their ingrained temporal societal customs and expectations over the weekend, they fall out of sync with their work shift rhythm. That phenomenon seems to underlie the widespread organizational preference for starting new shift schedules after the weekend.

16.2 Three basic solutions for shift work

There are three basic solutions that help to avoid serious complications that can result from doing shift work during the evening or the night, or at other unusual timings. Their common aim is not to upset the circadian rhythm.

Just one odd shift The first solution is to insert just one odd work shift and then return to the normal schedule. This means muddling through the one unusual work shift (perhaps two shifts) and thereafter taking a good rest, and then returning to the regular work schedule. However, as discussed in Chapter 15, getting through the unusual work period is fatiguing and strenuous and may seriously reduce work performance.

Permanent shift assignments The second solution is to adopt a permanent work arrangement at the "unusual" time. Often, there are persons who volunteer to continually work evening or night shifts; they are willing to readjust their circadian rhythms and their habits of private and social interactions permanently. Such volunteers were, for example, bakers and night guards of olden times; today they are firefighters, nurses, and physicians; drivers of trains, buses, trucks, and taxis; workers on offshore oil rigs, and others who agree to be on evening or night shifts for weeks, months, or even years on end. These persons readjust their physiological and social rhythms fully and permanently; therefore, they are not likely to suffer from disorders related to rhythm disturbances. Figure 16.3 sketches the schedules on permanent shifts starting in the morning or the evening or at night.

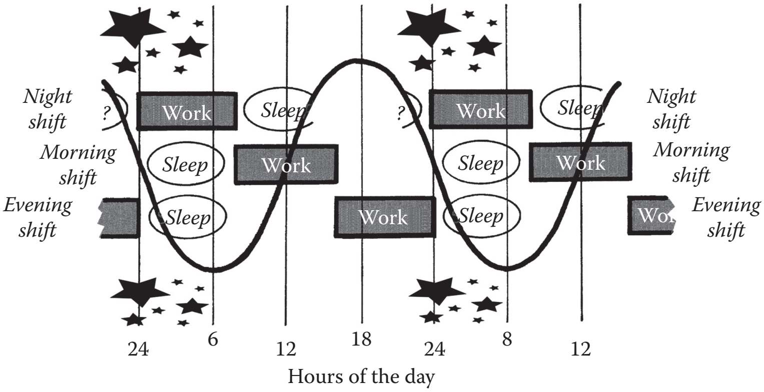

FIGURE 16.3 Typical work and sleep patterns with permanent shifts. (Adapted from Kroemer, K. H. E., Kroemer, H. J., and Kroemer-Elbert, K. E., *Engineering Physiology: Bases of Human Factors/Ergonomics*, fourth ed., Springer, Heidelberg, Germany, 2010.)

Shift–pause–shift The third solution entails a limited number of work shifts (say, five workdays of a week) at the odd time, followed by an interruption (often the weekend), and then continues again with a limited number of work shifts at the same or at another timing. Although this schedule is often used, it has two major repeating disadvantages: the interruption is likely to destroy the adjustments in body rhythms and individual habits attained during the foregoing work period and the following new setup requires upsetting new adjustments. So while seemingly “fair” when all involved workers are being shifted in the same manner, every one of them suffers the same negative consequences.

16.3 Shift patterns

For practical reasons, shift work seems to be unavoidable in many organizations. Shift work appears in several basic patterns, but any selected shift system may comprise aspects of several patterns. Five particularly important features are the following: Do shifts extend into hours that would normally be spent asleep? Do shifts cover the entire seven-day week? What days of rest, such as free weekends, do shifts include? How long is each shift? Do shift crews rotate or do they work the same shift permanently?

All these aspects are of concern regarding the welfare of the shift workers, their work performance, and they affect organizational scheduling.

Shift rotations In terms of organizing the schedule, it is easiest to establish a permanent setup or a schedule that rotates weekly. The literature discusses many such solutions, most of which rely on traditional societal expectations, especially regarding weekends, that originated in Europe and North America. In most systems used there today, the same eight-hour shift is being worked for five days, usually followed by two free days during the weekend. This regimen, however, does not cover all 21 (7 × 3) shift periods of the week, thus additional crews are needed to work on weekends.

If one uses three shifts a day (day, D; evening, E; night, N) with four teams, the shift system (for each team) is D–D–E–E–N–N–free–free with a ratio of six work/two free days and a cycle length of eight days; this is called the *metropolitan rotation*. The *continental rotation*, which also assumes three shifts per day and four crews, has the sequence D–D–E–E–N–N–N, free–free–D–D–E–E–E, N–N–free–free–D–D–D, E–E–N–N–free–free–free; its work/free day ratio is 21/7, its cycle length is four weeks, and free days follow each set of night shifts.

Table 16.1 Proposed 6:4 rotation shift schedule

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	D	E	E	N	N	Free			

Source: Knauth, P. 2007b. Schicht- und Nachtarbeit (shift work and night work) in Landau, K., Ed., *Lexikon Arbeitsgestaltung*, Stuttgart, DE, Gentner.

Note: D: Day (morning) shift; E: Evening shift; N: Night shift.

Table 16.1 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 for two periods, then rotates forward again to the next set of two shifts. Then four free days follow, which, however, do not always include weekend days. The system has a work/free day ratio of 6/4, its cycle length is exactly 10 weeks; on average, each week has 33.6 work hours.

16.4 Selecting suitable shift systems

Two sets of criteria exist by which to judge the suitability of shift plans: one set focuses on the worker and the other, on the organization. The human is by nature used to daylight activity, with the night reserved for rest. Working evenings or during the night (and possibly working on weekends and holidays) generates physical and psychosocial stress, which may be light or severe, depending on the circumstances and the person. Organizational criteria include the number of shifts per day, the length of every shift, the coverage of the day and week by shifts, work on holidays, and the performance of work. Obviously, any shift work schedule is a compromise among various, occasionally contradicting expectations.

Shift selection

The consideration of the following points is part of the decision to select one of the many possible shift plans:

- Daily work duration should normally not be more than eight hours.
- 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 suitable solution is to stay permanently on the same late shift.)

- A full day of free time should follow every single night shift or a series of night shifts.
- Each shift plan should contain consecutive work-free days, preferably including the weekend.

Making late shifts easier

During evening or night shifts, the management should provide high illumination levels at the workplace to suppress the production of the hormone melatonin, which causes drowsiness. Furthermore, environmental stimuli can help keep the worker alert and awake, such as occasional stirring music, provision of snacks and (possibly caffeinated) beverages. Interaction with coworkers, even taking short naps, should be encouraged as the type of work allows. The work task should be interesting and rewarding since boring and routine tasks are difficult to perform efficiently and safely during the night hours.

Coping strategies

The shift worker can use coping strategies for setting the biological clock, obtaining restful sleep, and maintaining satisfying social and domestic interactions. For example, sleep should be taken directly after a night shift, not in the afternoon. Sleep time should be regular and kept free from interruptions. Shift workers should seek to gain their family's and friends' understanding of their rest needs. Certain times of the day should be set aside specifically and regularly to be spent with family and friends.

Summary

Human body functions and human social behavior follow circadian rhythms. Shift work required at unusual times can put these synchronized rhythms and the associated behavior of sleep (usually during the night) and of activities (usually during the day) out of order. Resulting sleep loss and tiredness usually have negative health effects on the shift worker, diminish family and social life, and reduce work performance.

Shift work is often desired for organizational/economic reasons. Rules for acceptable regimes of shift work include the following:

- Job activities should follow entrained body rhythms.
- It is best to work during the daylight hours.

- Evening shifts are preferred to night shifts.
- If evening or night shifts are necessary, two opposing recommendations apply: either work only one evening or night shift then return to day work or stay permanently on the same shift, whichever that is.

Task performance is influenced by four major interrelated factors: the internal diurnal rhythm of the body; the external daily organization of work activities; the subjective motivation and interest in the work; and the type and conditions of work. Physical and mental performances are particularly weak during low periods of the circadian cycle such as in the early morning hours. Performance deteriorates during long-continued work, especially when accompanied by sleep loss. Deterioration can be counteracted by interesting and rewarding work, interaction with coworkers, breaks (naps) and snacks and beverages, and by environmental stimuli such as bright illumination.

One long night's sleep usually restores performance to a normal level, even after extensive sleep deprivation.

Fitting steps

Step 1: Seek to work only in day shifts.

Step 2: If two or three shifts a day are necessary, attempt to find volunteers for permanent assignments.

Step 3: If shift rotations are necessary, carefully lay out schedules that suit workers' preferences.

Notes

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

These natural temporal programs keep our body and mind healthy: Costa 2010; Folkard, Lombardi, and Tucker 2005; Folkard and Tucker 2003; Foster and Kreitzman 2004; Monk 2006; Refinetti 2016.

16.1 Organizing shift work:

Other important identifiers of shifts and shift patterns: Costa 2010; Folkard and Tucker 2003; Knauth 2006, 2007a,b; Popkin, Howarth, and Tepas 2006.

Cognitive impairments: Marquie et al. 2013.

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SECTION V

Human engineering

The previous sections of this book dealt with specific categories of knowledge about the human body and mind, about abilities and limitations. In many cases, the discussions also concerned the effects of the environment on the human ability to perform.

This section of the book assembles detailed knowledge, taken from the foregoing chapters in this book, and applies it to several examples of intricate *multipart designs*, such as of homes and work places. These are typical cases of human engineering (occasionally called *human factors engineering*), which require gathering and using information from many special knowledge areas:

- Chapter 17 Designing the home
- Chapter 18 Office design
- Chapter 19 Computer design and use
- Chapter 20 Workplace design
- Chapter 21 Load handling
- Chapter 22 Healthcare for patients and providers
- Chapter 23 Autonomous automobiles: Emerging ergonomic issues
- Chapter 24 Making work efficient and pleasant

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CHAPTER SEVENTEEN

Designing the home

A home suitable for living in Norway would not serve its purpose well in Egypt; a community house from Fiji would look strange in Turkey. Different house designs provide shelter from different climates; their occupants may have rather divergent opinions about comfort and privacy. Accordingly, there is not just one type of dwelling that is right from the ergonomic point of view; instead, there are many good solutions, depending on climate, availability of materials, and societal expectations.

The following text discusses human engineering solutions for homes suitable for moderate climates. Most of the concepts to make living easy and safe grew from the habits originally developed in Europe and reflect western architectural traditions, expectations, and lifestyles. Climates, living conditions, and customs are quite different in the many regions and cultures on Earth. Still, some or many ideas presented here may have universal appeal.

The main purpose of having a home is to be sheltered from unpleasant features of the environment. With this achieved, other attributes come to the forefront; they include privacy, safety, comfort, convenience, pleasure, and aesthetics. Different inhabitants are likely to have dissimilar opinions about the importance of these attributes, but from an ergonomic point of view, the usability of the design of the home is very important. For young and healthy persons, rather unusual designs might be quite attractive, for example, spiral staircases and lofts—but such features may be difficult to use and laborious to maintain, even dangerous for pregnant women and children, and impractical for elderly and impaired persons.

17.1 Designing for mother and child

"Child-proofing"

Most homes serve, usually for many years, as a safe haven for children and their mothers. This requires the design of the interior to be child-friendly, mostly in terms of safety for young children. Examples of "child-proofing" are not having stairs, or at least blocking them off; not having protruding hard and sharp objects; avoiding hot items that can burn skin, like a stove surface in the kitchen, or scalding hot water in the bath—all measures that make the home safe for everybody else.

Design for pregnancy

During pregnancy, many everyday tasks become more difficult for the mother-to-be. Most of the difficulties derive from reduced reach and mobility, often related to back pain. Owing to the increasing bulk of the trunk with pregnancy, objects on the ground near the feet are hard to see, and stumbles and falls are feared dangers, especially if the sense of balance is affected. Frequent urination is a common symptom of pregnancy, which requires convenient access to a toilet and washroom.

What is difficult to do

With advancing pregnancy, in general, come decreases in the ability to perform work that requires great exertions, extends over long periods, and involves a great deal of mobility, such as low bending and far reaches. The following are typical responses to a survey in which pregnant women listed their most difficult activities:

- Picking objects up from the floor
- Walking upstairs
- Driving a car
- Getting in and out of a car
- Using seat belts in a car
- Ironing
- Reaching high shelves
- Getting in and out of bed
- Using public toilets

Overall, the answers (not counting those referring to car use) indicate that the proper overall layout of the home, and the specific design measures already mentioned, contributes to achieving a design that helps pregnant women and suits all inhabitants.

17.2 Designing for impaired and elderly persons

During a resident‘s illness or recuperation from an injury, the home serves as a temporary care facility, which may have to accommodate a wheelchair, possibly even a gurney. Such use makes thoughtful layout and detail design highly important, especially of the bedroom, the toilet and bath, and the hallways. The same carefully incorporated design features also accommodate aging occupants° who are losing some of the physical and mental abilities that they had in younger years. Continuing to live in one’s own home has the major advantage of being in a familiar setting with all its physical and emotional implications. These include feeling at home, being comfortable, enjoying privacy, and having the satisfaction of self-sufficiency and independence.

Remodeling

Unless designed with prudent foresight, private homes are commonly ill-suited for the aging resident; so alterations are usually necessary to passage areas, kitchen, bathroom, and bedroom. Future-looking carefulness when building or acquiring a house can save much effort and huge expenses because the reworking of an existing residence can be substantial and costly.

17.3 Access, walkways, steps, and stairs

In the United States, perhaps the best-known house expressly built for use by a person with restricted mobility is the Top Cottage in Hyde Park, New York, which President Franklin Roosevelt designed to accommodate himself in his wheelchair. Fortunately, most persons can walk about freely, but designing a house for a wheelchair user will certainly make it convenient for every inhabitant, even if disabled, including aging persons who are no longer as agile and powerful as in their youth. Thus, a (real or imaginary) wheelchair is a good instrument to assess the suitability of passageways.

Passageways

Passages to and from a dwelling and within it must be safe and comfortable to use even for a frail person. The walking surface should be flat, without barriers such as stairs or thresholds, and best not sloped. Doors and passageways should be wide enough to allow a wheelchair to pass and turn, and flooring should provide enough friction for safe stepping even when wet. Straight hallways are easier to pass through than passages with turns and corners. Passages must be well illuminated, as should be all other rooms of the dwelling.

No steps

Flights of stairs, steps, and thresholds often make it impossible for wheelchair users to roll up or down; they make moving difficult for everybody and cause many falls, often resulting in serious injuries. Even low sills at doorways or shower stalls can be a nuisance and cause stumbling, as do the rims of carpets and loose rugs. Lifts and elevators facilitate moving about if a residence spans several stories. Elevators connecting the ground floor with the next one are fairly simple and relatively inexpensive to set up, especially when the dwelling is planned to accommodate them and installation is done early during construction or remodeling°.

Doors and windows

Doors and windows must be easy to open and close, even when an additional insect screen or storm door is present. They require clear space in front to provide access. All exterior doors should open to the outside to make for a quick escape in case of a fire. Controls must be handy and require little strength to operate yet provide security. Push bars and lever handles are easier to operate than round knobs. A transparent or translucent curtain can replace some interiors doors.

17.4 Kitchen

Work flow in the kitchen

The kitchen is one of the most frequently used and important rooms of the house for many people. This is often a gathering room, a social place, and a communication and message center; although, basically, it is the location to prepare, serve, and store food. Many design concepts° follow the idea of a "work triangle." Its corners are the three areas of primary activity: storing (refrigerator, cabinets, etc.), preparing (gas or electric burners, conventional or microwave oven, coffee/tea maker), and cleaning (sink, dishwasher, garbage disposal). Several classic human factors principles, augmented by newer ergonomic findings and changing with new ways of living, apply to kitchen design:

1. Kitchen design and components should facilitate the flow of work at the most used activity areas, among these areas, and for serving the prepared food and taking care of used utensils.
2. Items should be stored near the point of use.
3. Cabinets and other storage facilities should be within comfortable reach. The contents should be in sight; therefore, shelves should be at or below eye height and not so deep that items located in front obscure those at the back.

4. Items on storage shelves and in cabinets should be easy to reach. For this, shallow shelves are beneficial.
5. Retrieving items should be easy, not requiring excessive body bending, stretching, or twisting. Rollout shelves are advantageous at low height.
6. The workspace for the hands, at counters and sinks, should be at about or slightly below elbow height. This facilitates manipulation and visual control. The counter and the sink may be put lower than usual for wheelchair-bound persons.
7. Stove, oven, refrigerator, and dishwasher openings should be at no-bend heights.
8. All counters should have a work surface that extends about 10 cm into the room, or at least have a recessed toe space, so that one can step close in.
9. Traffic by others should not cut through the patterns of workflow.

17.5 Bedroom, bath, and toilet

Bedroom

Most of us stay about one-third of the day in the bedroom, and weak or ill persons spend even more time in it. Hence, it is important to pay attention to its ergonomic features. The bed should be at a height that makes lying down and getting up comfortable. In the past, many different mattress properties have been promoted, especially for people with back problems, ranging from hard through pliant to soft; when no objective criteria appear convincing, users select the support that pleases their individual preferences.

The bedroom must be spacious enough to allow maneuvering space. It should supply easily reachable shelving and hanging for clothing, linen, and bedding. It should contain direct-access storage for medical supplies. It should allow emergency access and have an emergency exit. As a rule, the bedroom must provide privacy and be near a bathroom.

Bathroom

Bathrooms deserve particular ergonomic attention because they are essential for healthy living. Basic equipment includes bathtub and/or shower, washbasin, and toilet. Additionally, bathrooms usually contain storage facilities for toiletries, towels, and other supplies. Unfortunately, many traditional bathroom designs in the United States are difficult to use for aged people and persons with disabilities. The major problems are narrow doors and tight space so that users who need canes, walkers, and especially wheelchairs find it difficult to move about.

Tub and shower

The bathtub and the shower, the two main areas for cleansing the whole body, are sites of numerous accidents. Most danger stems from the slipperiness of wet surfaces against the skin, including bare feet. The most hazardous is a bathtub with slanted slick surfaces. Arising from it and stepping over its high sides are not easy for most people and particularly difficult for people who have balance and mobility deficiencies. Proper handrails and grab bars within easy reach can be of great help when getting in and out.

A shower stall is easier to use because its low enclosure rim at the floor poses little hindrance to walking in and out. A rimless walk-in design usually takes more floor space but is the best solution for a wheelchair user.

Control handles

Using the control handles for hot and cold water is often difficult for impaired persons, particularly when they have to reach across a tub or a shower basin to access them. In some setups, both controls for hot and cold water move in the same direction while in other designs the faucets turn in opposite directions; the standardization of human-engineered solutions would be advantageous. To prevent scalding, thermostatically adjusting the water temperature is a good ergonomic solution, helpful to all users.

Washbasin

The proper height of the washbasin is important. The basin may be difficult to use if it is too far away such as when inserted in a cabinet so that one cannot step close to it but must lean forward over it. Big faucets and outlets should not reduce the usable open area of the washbasin.

Toilet

Throughout the world, different customs and installations prevail for the designs used for the elimination of alimentary wastes while keeping the body clean. For western-style toilets, substantial literature exists about suitable design, sizing, shaping, height, location, and function. Proper handrails and grab bars aid persons with mobility problems, such as caused by back pain, in sitting down and getting up. Personal hygiene systems such as a water shower installed in the toilet bowel can be of great help.

17.6 Lighting, heating, and cooling

Windows are important to many persons: not only do they deliver light to the inside of the house, but they also provide visual and emotional connections with the outside. If natural light fails, electrical lamps supply illumination, so arranged that they light up what must be seen, yet not producing deep shadows or glare that can blind the eye.

Automatic lights are advisable in passageways, bathrooms, and bedrooms. Manual switches and all other controls as well as electrical outlets should be located at about hip height so that persons both standing and sitting can reach them naturally. They should be easy to operate, at best by a simple push and not require fine fingering.

In North America, many table and floor lamps provide stunning examples of how to make it difficult, instead of easy, to turn lights on and off; they have push–pull or turn switches at the socket of the light bulb, hidden high up inside the lampshade so that one cannot see them. Due to their location, they are hard to find by groping, and they are tricky to operate due to the required arm bending and the awkward switch design.

Houses of the affluent usually have electric or gas-fired heating systems, called *air-conditioning* or *climate control* when combined with features for cooling and regulating humidity. Automatic settings for climate control are desirable because they require no judgment, decision, or action by the person. Many people prefer a floor-heating system with its uniform warmth to the often drafty and loud forced-air arrangement common in North America.

17.7 Home office

Working from home

New work technologies usually bring along changes in work practices. A striking example is the recent appearance of the “instant office”: wireless and portable computers, lap-placed or hand-held, even wrist-mounted, and especially mobile phones enable us to communicate and write and record anywhere—including, obviously, our home. Such home offices can be a curse if they tie us continuously to work, or they can be a blessing when we do not have to spend time working in a tiny cubicle inside a beehive office° but, instead, can follow our own work schedule while checking on our children.

Setting up your computer workplace

Computer work in the home often starts with the occasional use of the kitchen table, a space in the den, or a spare room in the home, for talking with colleagues and customers, writing letters and memos, producing brochures and articles, drawing and inventing, ordering wares, and sending bills.

The more frequent and intensive working at home becomes, the more important it gets to apply ergonomic thinking to the layout of the home office°. Wherever the office workplace, the same human engineering principles apply. Provide the following:

1. Furniture that comfortably supports body movements and postures
2. Work tools and equipment that facilitate execution of the tasks without overloading human capabilities, particularly regarding repetitive movements
3. Lighting at the workplace that is suitable for the task, which does not produce direct or indirect glare
4. Suitable thermal climate and acoustic environment
5. Comfortable and appealing work surroundings

Chapter 18, next in this book, deals with these issues in detail.

Your choice

While arranging our home office, we can discard the ballast of old habits and conventions about how to sit at work that governs us in the company office. If you work only occasionally in your home, then the old dining table and the odd kitchen chair probably will not harm you, but stuffing an old cabinet with your equipment—as in Figure 17.1—is not a suitable solution. As you begin working in your home office for hours and hours, you should become very conscious about the conditions there: in principle, everything discussed in Chapter 18 applies to the home office. So equip your office with carefully selected furniture, where the components of the workstation fit each other well—and, most importantly, fit you well.

Sit on a comfortable office chair such as sketched in Figure 17.2 (even if it is expensive), semi-sit perched on a kneeling chair as in Figure 17.3, or lounge on an easy chair as shown in Figures 17.4 and 17.5. Choose whatever feels good to you, what supports your body well over long periods. Perhaps you want to work standing up, at least when you take notes or make phone calls, for example. Some people walk on a treadmill or ride an exercise bike as they work. This is your own workspace, which you put together for your comfort and ease at work, and it does not have to be similar to anybody else's setup, nor does it have to be expensive, because some simple furniture on the market is well designed.

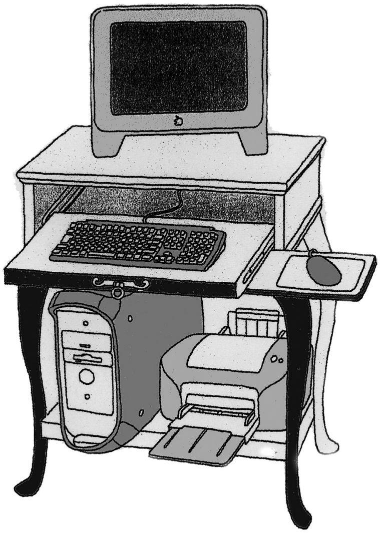


FIGURE 17.1 About everything is wrong in this improvised setup: The display is too high on the top shelf. The keyboard occupies nearly all the work surface, which has a sharp front edge that is likely to squeeze the undersides of the user's wrists. The mouse pad is too far to the side. The bottom shelf leaves no room for human legs. (Adapted from Kroemer, K. H. E., and Kroemer, A. D., *Office Ergonomics*, Taylor & Francis, 2001, London.)

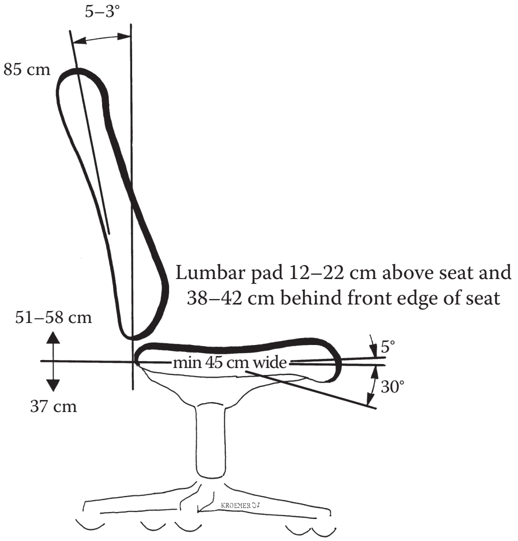


FIGURE 17.2 Dimensions and adjustments of a conventional office chair.

FIGURE 17.3 Semi-sitting. (Adapted from Kroemer, K. H. E., and Kroemer, A. D., *Office Ergonomics*, Korean edition, Kukje Publishing, Seoul, South Korea, 2006.)

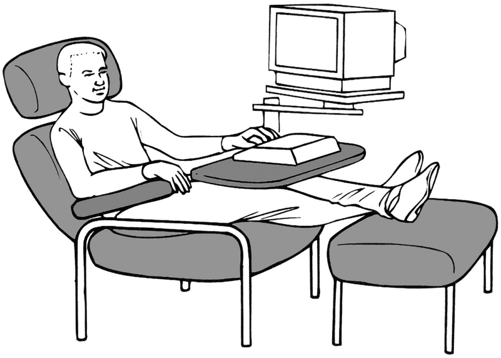


FIGURE 17.4 Niels Diffrient's circa 1984 "executive workstation."

Get a quality computer with an up-to-date display and with suitable input devices. Select a keyboard that feels comfortable to you (see Chapter 19) but consider voice input that might work for you. If you travel much with your portable computer, consider using it in your office as well. Select a room with good lighting that is separate, quiet, and well heated and cooled (Chapters 5, 6, and 8). You will probably work in your home office longer than you expected, and your well-being is worth the effort and the money that you spend on it.

FIGURE 17.5 2015 home office.

Summary

Laying out and arranging a dwelling must be one of the oldest tasks for humankind. One should think that modern design procedures and building techniques incorporate, at a basic level, knowledge on how to lay out a home to accommodate the inhabitants in terms of ease of use and safety, especially when they are not agile because of pregnancy, age, or disability—however, such human factors design is not common in the European/American tradition.

Numerous publications provide advice on how to design homes that suit pregnant women and children and accommodate disabled and older persons. This chapter summarizes much of this ergonomic information and applies it primarily to the topics of access, walkways, steps, and stairs; lighting, heating and cooling; and rooms of special importance, namely, the kitchen, the bedroom, and the bath and toilet.

With computer work done increasingly from home, the layout of the home office becomes important for many people with regard to their well-being and work performance.

Notes and more information

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

17.1 Designing for mother and child: Kroemer 2006a,b; Kroemer, Kroemer, and Kroemer-Elbert 2003; Lueder and Rice 2007.

17.2 Designing for impaired and elderly persons: Kroemer 2006c.

Remodeling: Richard Atcheson describes the renovation needs of a home to accommodate older residents in vivid detail in his article "Our Old House" in *Modern Maturity* (November–December 2000, issue 43R: 6, 62–71.) Reprinted in a book by Kroemer (2006c).

In the United States, the American Association of Retired Persons (http://www.aarp.org) provides free brochures on age-friendly buildings and modifications of habitats.

17.4 Kitchen: Lillian Gilbreth and her husband Frank developed, in the 1920s, the initial idea of the "work triangle" in the kitchen from their time-and-motion studies: Lepore 2009.

17.7 Home office: *Beehive office; ergonomic layout of the home office*: Kroemer and Kroemer 2017.

CHAPTER EIGHTEEN

Office design

The *uffici* (offices) in Florence, Italy, are probably the best-known classic office building. Finished in 1581, seen from above the structure is the shape of the letter U around an open court so that every room has a window to the outside, providing natural light and ventilation. Heating was done, if needed, by coal fires and stoves in the rooms, and bad odors abounded when the windows had to be kept closed. Into the 1900s, large office buildings°, and the arrangement of the offices within, still followed that example. Then, new technology in lighting and air-conditioning allowed radically different designs.

The layout, the equipment, and the decor of our office can affect our quality of work life; our feelings of well-being, or of not being comfortable, can also appreciably influence our productivity at work. Consequently, there are both ergonomic and economic reasons to design offices to truly fit their human occupants so that they work efficiently and effectively.

Around the year 2000, the novel technology of wireless and portable computers profoundly changed many working habits and consequently altered the appearance of the office workspace. Large stationary desktop computers were increasingly displaced by movable notebooks and laptops. Easily portable cell phones and handheld and wrist- and head-mounted communication devices allow individuals to have “instant offices” wherever they happen to be, in waiting rooms, in cafes, on trains and planes, or at home. Whether the resulting continual office connection is a blessing or a curse can be debated, but it certainly made many “cube dwellers” into roaming workers.

18.1 Office spaces

Designs of conventional offices can vary from open plans to closed, walled-in individual rooms. Open plans include the stereotypical paperwork factory, taking up a vast room filled with straight rows and columns of desks and chairs. Figure 18.1 depicts an example of such a ca. 1990 layout with computers on the desks.

Office cubicles versus private offices

Often, low partitions subdivide large spaces into smaller semi-private cubicles. In spite of their popularity as the target of jibes and jokes, if done appropriately, partitioned cubicles can indeed help provide some privacy. At the other extreme of office layout are the separate, walled-in offices shared by a few employees or used by just one person, usually of some rank. In reality, many office buildings house various designs; they have some areas that feature open plans, while other departments or floors within the company may have contained spaces.

Office landscape

The idea of an "office landscape" originated in the 1960s. The basic concept was that a large office space can be made appealing by setting it up like a park or a large garden, done by irregular arrangements of furniture, office machines, and dividers among flowers, bushes, and small trees. This often resulted in rather pleasant office landscapes that could easily accommodate changes in interior arrangements. One popular draw was the use of plants: partly for their appearance and partly for their assumed abilities to prevent noise propagation and to absorb air contaminants; unfortunately, they do next to nothing in either respect. Still, they can be pleasing to the eye; aesthetics are important.

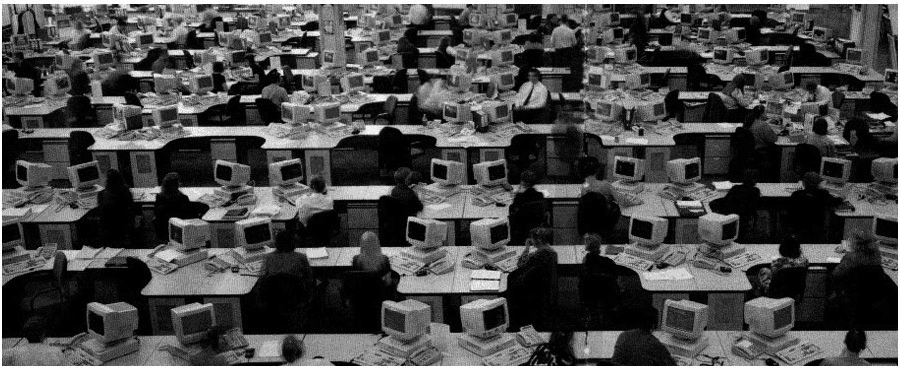


FIGURE 18.1 Computerized paperwork factory ca. 1990.

Cons of open designs

The disadvantages of open designs include lack of privacy, which is an issue when business requires the exchange of confidential information. Many organizations use a mixture of office designs: wide open spaces here, sections with shoulder-high cubicle dividers there, and closed-off individual offices in other parts. Another clear drawback of the wide office landscape is disruptive noise, from people and equipment, which may reduce performance (see Chapter 6) and job satisfaction.

Stepwise office design

The process of designing a new office or remodeling an existing facility involves several steps. The first step is evaluating the needs of the people who will inhabit the office, the tasks they will perform, the work tools and equipment they will use, and their preferences and work styles. Specific statements of these functional requirements guide the design concepts such as open plans or separate rooms. The next step is identifying a range of design options from which practical solutions can be chosen; this usually involves some compromises. The third step involves evaluating the candidate designs (more on this in the following). The last step is selecting the final design, followed by implementing it and putting it to use. Employees should be involved in all phases of the process so that their needs are truly met and they do not feel manipulated or ignored.

Evaluating different designs

A sample procedure to evaluate several candidates for a new (or updated) office involves four designs, layout # 1 through layout # 4. These candidate designs are to be evaluated along carefully selected criteria, which often include

- Construction cost (ConstrCost)
- Ability to expand when needed (Expand)
- Running costs (RunCost)
- Appeal to employees and clients (Appeal)
- Expected efficacy and effectiveness of use (EfficEffec),
- Time needed until the chosen layout can be occupied (Availability)

A panel of experts that includes managers and employees can do the scoring. Assume that the raters gave the scores (with 1 as the worst and 10 as the best) listed in Table 18.1.

Rating scores

According to the raw scores, office layout # 2 is the preferred solution while layout # 4 is a strong contender. However, applying weights to the ratings changes the outcome: with weighted criteria, layout # 4 becomes the preferred solution, with layout # 1 not far behind.

Table 18.1 Raw and weighted scores of four candidate office layouts

	Layout # 1	Layout # 2	Layout # 3	Layout # 4
Raw scores				
ConstCost	3	1	5	10
Expand	4	10	6	1
RunCost	9	10	1	5
Appeal	7	2	1	10
EfficEffec	8	10	5	1
Availability	1	5	8	10
Total	**32**	**38**	**26**	**37**
Weighted scores				
ConstCost (×8)	24	8	40	80
Expand (×3)	12	30	18	3
RunCost (×10)	90	100	10	50
Appeal (×7)	49	14	7	70
EfficEffec (×5)	40	50	25	5
Availability (1)	1	5	8	10
Total	**216**	**207**	**108**	**218**

Source: Kroemer, A. D., and Kroemer, K. H. E., *Office Ergonomics*, second ed., CRC, Boca Raton, Florida, 2017.

A clear approach Defining criteria for judging the candidate designs, including their weightings, eliminates irrational decision like the muddled “I like this better.” The process outlined above is logical and transparent and forces all decision makers to follow the same rules. Furthermore, this approach considers the human aspect of office design, not only the conventional monetary cost-benefit analysis°.

Flexibility with new technology Current architectural, engineering, and construction technology allows designing almost any office environment one might wish. Yesterday’s technology tied us to one office, and often to one place therein, because we were bound by wired phones and computers, cabled machines, and stationary equipment; now, most of us can be flexible in location, work schedules, and habits.

Looks good, feels good, makes for good work Pleasing office aesthetics convey an appealing image of the organization to the public; they contribute to attracting new employees and help in retaining them. However, to generate true and lasting positive attitudes of the workers requires more than just facility design; it necessitates treating persons as important contributors to the organization's aims; caring about employees' well-being, on and off the job; and understanding people's concerns about their professional future. In many successful organizations, employees feel they are part of a family with extensive interactions among all levels of the corporate hierarchy and a strong prevailing team spirit. They appreciate a supervisor's advice to stay home when one feels sick, to come in late or leave early for important personal reasons, and to switch the mobile phone off and to leave the portable computer at home when going on vacation.

Appreciation

Being personally and professionally appreciated is very important and makes employees feel engaged with their employer. People also enjoy job amenities that provide convenience, which can create an almost home-like atmosphere at the office. These features go well beyond the usual employee cafeteria and may include free coffee bars, fitness rooms, on-site laundry and dry-cleaning facilities, ability to shop and get haircuts, and—very important to young parents—on-site childcare. These factors work together to increase the employees' job satisfaction, to develop emotional ties to the company providing the job, and hence to enhance job performance. This is of importance to the employer, because ultimately the office is a place to work and perform. (Chapters 13 and 14 expanded on these aspects.)

18.2 The physical environment

The physical environment in the office, in terms of lighting (Chapter 5) and sound (Chapter 6) and climate (Chapter 8), generates conditions that affect the worker's health, comfort, and ability and willingness to perform. Providing the best possible work environment is among the top tasks in office design.

We need light to see

18.2.1 Office lighting We can see an object only if it sends light that strikes the cones and the rods located on the retina at the rear of our eyes. That light is usually reflected from surfaces of the object after it arrived there from a light source, such as the sun or a lamp.

Photometry

Illumination is the visible energy that radiates from the sun or a lamp or another light source. However, since we must not look into the sun and usually do not want to stare at a luminaire, what we "see" is *luminance*, the portion of illumination that objects reflect into our eyes. (Self-luminous electronic displays, such as computer monitors, present surfaces to the eye that have optical properties similar to the luminance coming from a reflecting surface.) Traditional photometry° commonly used measurements of incoming light, illumination, to describe the lighting conditions of our visual environment. The main reason for this procedure was the ease of measuring illumination even though only luminance is truly relevant for our everyday vision.

Luminance contrast

A strong luminance contrast between the visual target and its background allows us to see details well. Reading a printed text provides a typical example: the text is easy to read when it shows crisp black letters on a white background; if the letters fade into grey and the surface, on which they appear, is dirty, deciphering them might become very difficult especially if the letter's contours are unsharp. Colored objects, such as curves in charts, must show strong luminance contrasts because similar colors are difficult to discern. Computers around 1990 demonstrated that issue: their text displays commonly combined pale green with darker green, which made reading arduous.

Lighting affects our work

We want an office environment that pleases us in terms of contrast and colors, that allows us to see clearly and vividly what we wish to see. Many individuals value natural light that enters the office through windows because it provides a spacious and natural feel to the work place. However, to the lighting engineer, daylight has disadvantages: the natural illumination changes over time, and while spots near the windows can be lit glaringly, workplaces in the rear may be too dark. Well-placed luminaires can provide even lighting of the entire room. Task lights, lamps at the workstation, which the individual worker controls, allow fine adjustments of the local illumination.

Lighten up the office

One specific task encountered when setting up office lighting is to prevent glare and annoying bright spots in our visual field. Accountants usually like the use of direct lighting where rays from the source fall directly on the work area because this is most efficient in terms of illuminance gain per unit of consumed electrical power; unfortunately, direct light can produce high glare, poor contrast, and deep shadows. The alternative is to use indirect lighting, where a surface, often the ceiling of the office, reflects the rays from the light source in many different directions so that diffused light reaches the work area. This helps to provide an even illumination without shadows or glare, but is less efficient in terms of use of electrical power. A compromise

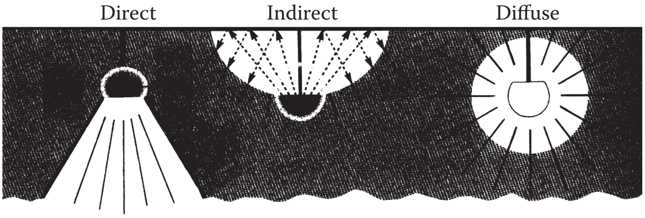


FIGURE 18.2 Direct, indirect, and diffused lighting. (Adapted from Kroemer, K. H. E., and Kroemer, A. D., *Office Ergonomics*, Taylor & Francis, London, 2001.)

is to use a large translucent bowl that encloses the light source and scatters the light before it is emitted from the bowl's surface. This can cause some glare and shadows, but is usually more efficient in terms of electrical power usage than indirect lighting. Figure 18.2 shows these kinds of room lighting.

Glare-free lighting

Glare is the experience of intense light that enters the eye and overpowers the ability of the cones and the rods in the retina to distinguish shades of gray and colors (see Chapter 5). An example of direct glare is light from a lamp shining straight into your eyes, whereas indirect glare occurs when the light rays are reflected from a shiny surface and from there enter the eye. Figure 18.3 shows these conditions. Strong glare temporally disables vision, while weak glare acts like a veil in the field of vision, making it difficult to see slight contrasts.

Avoiding glare

Placing the computer in front of a window can make it difficult to discern details on the screen when the strong light from the outside overwhelms the ability of the eyes to see subtle images at your workplace. Figure 18.4 shows direct glare, and Figure 18.5 illustrates indirect glare coming from a window or

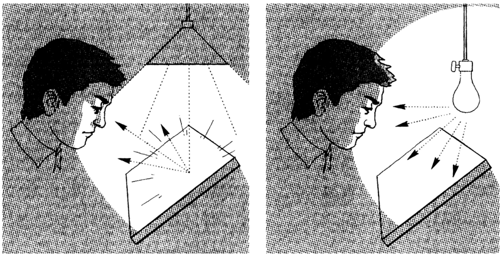


FIGURE 18.3 Indirect and direct glare. (Adapted from Kroemer, K. H. E., and Kroemer, A. D., *Office Ergonomics*, Korean edition, Kukje Publishing, Seoul, South Korea, 2006.)

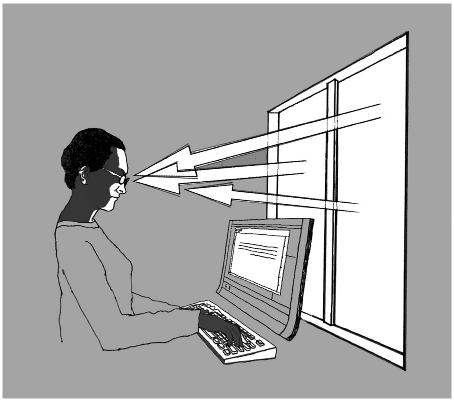


FIGURE 18.4 Direct glare in the office. (Adapted from Kroemer, K. H. E., and Kroemer, A. D., *Office Ergonomics*, Korean edition, Kukje Publishing, Seoul, South Korea, 2006.)

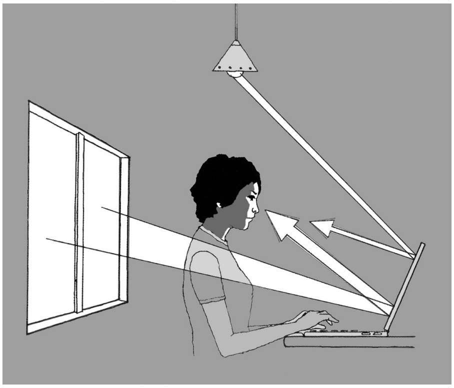


FIGURE 18.5 Indirect glare in the office. (Adapted from Kroemer, K. H. E., and Kroemer, A. D., *Office Ergonomics*, Korean edition, Kukje Publishing, Seoul, South Korea, 2006.)

a lamp. Obviously, repositioning the workplace so that the light sources are on the worker's left or right side remedies the glare situations, and reducing the intensity of the incoming light (turn off the lamp, draw a curtain across the window) would be helpful as well.

Room illumination

Lamps for general office illumination should be arranged so that they provide glare-free lighting. As the top part of Figure 18.6 shows, locations to the left and right sides of the operator are not likely to cause indirect glare. However, placing a lamp (or

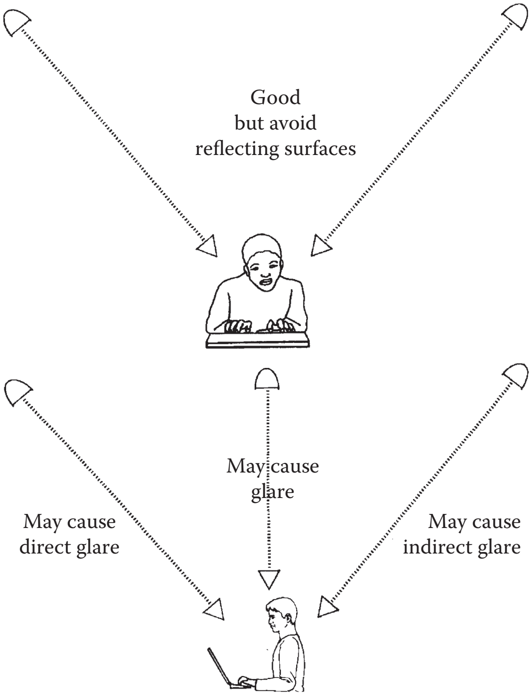


FIGURE 18.6 Placement of lamps. (Adapted from Kroemer, K. H. E., and Kroemer, A. D., *Office Ergonomics*, Taylor & Francis, London, 2001.)

a bright window) in front of a person can cause direct glare. To avoid indirect glare, do not place a light source above or behind a person because the light could be mirrored on the display surface.

Recommended office illumination

What is optimal lighting for good vision depends on many factors including the conditions of the eyes to be accommodated, the task at hand, and the objects to be seen. General office illumination is usually at about 500 lx, but it may be up to 1000 lx if there are many dark (light-absorbing) surfaces in the room. If cathode ray tube (CRT) displays are present, the overall illumination should be lower, between 200 and 500 lx. In rooms with light-emitting displays, illumination of 300–750 lx is suitable. The low illuminances may be a bit dim, especially for such tasks as reading text on a paper: so it can be helpful to turn on a task light directed at the visual target, which generates more luminance there without appreciably raising the overall lighting level in the office. Care must be taken, however, to avoid glare by shining that light, directly or by reflection, into one's eyes.

Table 18.2 Actions to alleviate vision problems in computer use

- *Stop and blink*: When you are working at the computer or reading, pause frequently—say, every 15 minutes—to close your eyes, or gaze away from the screen or page, and blink repeatedly.
- *Take a break*: Every 30 minutes or so, certainly every hour, get up and move about.
- *Keep your distance*: Position your eyes at the same distance from the screen as you would from a book. If you find that uncomfortable, buy a pair of glasses with a prescription designed for computer work, or use progressive-addition bifocals, which have gradually changing power from the top to the bottom of the lens.
- *Lower the screen*: Keep the top of the screen below eye level. Gazing upward can strain muscles in the eye and the neck.
- *Hold up the document*: Put a support for the reading matter next to the screen, at the same distance from your eyes.
- *Clean up*: Clean your screen and your glasses. Dust and grime can blur the images.
- *Lighten up*: Age tends to cloud the lens of the eye and shrink the pupil, sharply increasing the need for luminance. So if reading strains your eyes, consider installing brighter lights or at least moving the reading lamp closer to the page.
- *Cut the glare*: Position the reading lamp so that light shines from over your shoulder, but make sure it does not reflect into your eyes from the computer monitor. Do not read or do computer work while facing an unshaded window. Wear sunglasses if you are reading outside, but if you feel that you should have shades inside, then the setup of your visual environment is faulty.

If these actions do not reduce the strain from computer work or reading or writing, have an optometrist or an ophthalmologist check whether you need to start wearing glasses or to have your prescription changed.

Easy things to do

Often, some simple actions, listed in Table 18.2, can help to alleviate vision-related annoyances, which make us uncomfortable while working at the computer.

18.2.2 Office climate Control of the physical climate is important because it influences how the people in the office feel and how they execute their tasks; especially, air temperature and humidity affect well-being and performance. In our work environment, we also want fresh rather than stale air, but the airflow should not generate a strong draft.

Working when warm or cold

We are not “cold-blooded,” neither in the emotional nor the physical sense; instead, even while our skin temperatures may change, our body usually succeeds in maintaining a rather constant temperature of about 37°C in the brain and the chest cavity, regardless of the surrounding climate. Achieving a constant core temperature is a complex task for the human body’s temperature control system, as discussed in some detail in Chapter 8.

The body itself generates heat energy and at the same time exchanges energy with the environment. When our office surroundings are cool, we do not want to feel cold, so we need to prevent excessive heat loss, which we usually can do easily by choosing suitable clothing. When our environment is warm and it threatens to warm up our body core as well, we must get rid of body heat to prevent overheating. This is rather difficult to do, because we cannot reverse the natural heat flow, which is always from the warmer to the colder. The most efficient biological way to cool our body in a hot environment is to evaporate body water, particularly that contained in sweat on our skin—but the resultant odor is unpleasant for all in the office. So we resort to technical means; the most complete (and expensive) solution is "climatizing" the office environment by controlling its temperature, humidity, and air movement.

Feeling comfortable

For our well-being and comfort, the temperature difference between exposed skin and the environment is very important, but humidity and airflow also play major roles—as do our attitude and level of acclimatization. In a sheltered office environment, the human thermoregulatory system has no problem keeping the core close to constant 37°C. At the skin, in contrast, there are often large temperature differences among various regions. For example, at a given time, the toes may be at 25°C, the legs and the upper arms at 31°C, and the forehead at 34°C: for most of us, such combination feels comfortable.

Energy exchanges with the environment

In physics terms, heat energy exchange between our body and the environment takes place via four pathways: by convection, conduction, evaporation, and radiation (see Chapter 8 for more details). In each case, heat irreversibly flows from the warmer to the colder medium.

Convection and conduction can cool or warm

Both convection and conduction follow the same thermodynamic rules that govern heat exchange. In each case, skin contact makes for heat transfer: with air (or fluid) in convection, with a solid in conduction. The amount of transferred heat depends on the area of human skin that participates in the process, and on the temperature difference between the skin and the adjacent layer of the outside medium. An air draft, caused by an open window or a fan, can increase convective heat exchange as the air moves quickly along the skin surface, which helps maintain a temperature (and humidity) differential. Wood and some plastics on office furniture feel warm because their heat-conduction coefficients are below the coefficient of human tissue, so they keep the warmth close. Metal of the same temperature accepts body heat easily and conducts it away; therefore, it feels colder than wood even when both are at the same room temperature.

Evaporation cools the body

Heat exchange by evaporation is in only one direction: the human body loses heat. (There is never condensation of water on living skin, which would add heat.) Some water evaporates in the respiratory passages, but most appears as sweat on the skin. It requires energy to evaporate sweat water: about 2440 J (580 cal) per cm^3. This energy is mostly taken from the body and hence reduces the heat content of the body by that amount. Hence, evaporating sweat is very effective to cool the body and functions even in a hot environment. Even if we do not notice, there is always some perspiration and hence sweat evaporation going on; hence, our clothes smell when worn too long.

Radiation may cool or warm us

Radiation exchanges heat between two opposing surfaces, for example, between a windowpane and a person's skin. Hence, the human body can either lose or gain heat through radiation, depending on whether the skin is warmer (lose) or colder (gain) than the other surface. The amount of radiated heat depends on the temperature difference between the two surfaces, and on their sizes, but not on the temperature of the air between them.

Heat balance

Primarily, the actual amounts of heat exchanged with our surroundings depend, directly or indirectly, on the difference in temperature between the participating body surfaces and the environment. Secondarily, the magnitude of exchanged heat depends on the surface areas that participate; clothing determines how much skin we expose, hence has a great effect. (Clothing also has other heat transfer properties, such as insulation; see Chapter 8.) Humidity plays an appreciable role when it is very high or very low.

Over time, we feel well in a climate when our body can achieve heat balance, allowing the body to keep its temperatures at comfortable levels. The healthy body achieves this by (among other actions) responding to a cold environment by making its skin surface colder, and to a hot environment by making the skin warmer. (If that statement surprises, recall the fact that heat energy always moves from the warmer to the colder.)

Acclimation

We can help to achieve this state of balance by deliberately dressing more lightly in the heat or conversely, when our surroundings are frigid, by covering up in insulating layers.

Adjusting how we dress is partly a social action and hence intentional, but it is also a part of unconscious acclimating. We acclimate psychologically by simply expecting and accepting a hotter environment as summer comes and by getting mentally ready for colder conditions as fall arrives. We acclimate physiologically by continuous or repeated exposure to hot and (not as pronounced) to cold conditions, which brings about a gradual adjustment of body functions, resulting in a better tolerance of climate stresses.

There are no striking differences between females and males with respect to their ability to adapt to changing office climates. Any individual tendencies to feel too warm or too cool can be alleviated by using a portable fan or heater, but, usually, simply adjusting clothing habits is sufficient.

Figure 18.7 provides a summary overview of temperature ranges and their effects on the human. As discussed in more detail in Chapter 8, to convert temperature degree values from one scale to the other, one must consider the different settings for freezing and boiling temperatures of water as well as the number of degrees between freezing and boiling:

Fahrenheit to Celsius: (°F − 32) (5/9) = >°C

Celsius to Fahrenheit: [(9/5)°C] + 32 = >°F.

Effects of heat on mental performance

It is difficult to evaluate the effects of heat (or cold) on mental or intellectual performance. However, apparently the mental performance of a nonacclimatized person deteriorates when room temperatures rise above 25°C. That threshold rises to 30 or even 35°C if the individual has 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. These results stem from laboratory tests; in the office, such high temperatures are rare.

Good office climate

There are several technical ways to generate a thermal environment that suits the physiological needs of people as well as their individual preferences. The primary approach is to adjust the physical conditions of the climate (temperatures, humidity,

	°F	°C	K
Water boils	212	100	373.15
At about 85°C, skin burn damage occurs when touching wood or plastic for 4 s		90	363.15
		80	353.15
		70	343.15
At about 60°C, skin burn damage occurs when touching metal or water for 4 s	140	60	333.15
		50	323.15
About 40°C, temperature in the shade on a hot summer day in New York City 37°C, body core temperature	104	40	313.15
About 27°C, highest comfortable office temperature in the summer in New York City		30	303.15
		20	293.15
About 18°C, lowest comfortable office temperature in the winter in New York City	50	10	283.15
Water freezes	32	0	273.15

FIGURE 18.7 Temperatures between freezing and boiling of water in Kelvin and in Celsius and Fahrenheit degrees.

and air movement), usually done by automatic air-conditioning. The American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) recommendations in the United States, international standards by the International Organization for Standardization (ISO), and national regulations and regional recommendations and customs provide guidance°.

Too hot/too cold: What to do

If there is no way to control the climate in the office automatically, several time-honored means are at hand to counteract heat:

- Move air swiftly through the room. (This may require ye olde paperweights.)
- Stay away from warm surfaces, such as windowpanes, that radiate heat.
- Cool the air and hot surfaces by sprinkling water on warm surfaces.

- Rest during the hottest time of the day. (The siesta is an example.)
- Dress lightly.
- If you are cold, dress more warmly, get close to warm radiating surfaces, or sit in the sun.

18.3 Office furniture

Sitting at work

The concept of sitting has different meanings: In many regions on Earth, this does imply perching atop a stool or a chair, as became a tradition in ancient Egypt and Greece. But in other civilizations, people habitually rested their body on a carpet, mat, cushion, or on bare floor by kneeling, squatting, or sitting with the legs extended, or having a foot or both feet underneath the body. Around 1900, subordinates in European offices habitually stood while working while their superiors enjoyed sitting comfortably.

Sitting still

It is tiresome to maintain any body position unchanged over extended periods. This includes sitting still for hours on end. We would like to move about, but in the current computer office, we are doubly tied to our equipment: by our hands that must operate keys and by our eyes that must view screen, text, and keys. These two ties keep our hands and eyes and, through them, our whole body fixed at the workstation. We may try to ease the effort of maintaining the rigid posture by sitting on a chair as comfortably as practicable, shifting and slouching as needed, but our body keeps telling us to get up and walk and move around for a while.

Erect posture

A century or so ago, the office clerks were men who stood at their desks, using ink to write letters and make entries in ledgers. By the middle of the twentieth century, most office employees in subaltern positions now were females and the work posture had changed from standing to sitting.

In the late 1800s, body posture had become of great concern to some physiologists and orthopedists in Europe. In their opinion, the upright (erect) standing posture was balanced and healthy whereas curved and bent backs were unhealthy and therefore had to be avoided, especially in youngsters. Consequently, "straight" back and neck° became the recommended posture for both standing and sitting, and, logically, seats were designed to bring about such upright body position.

But that cliché applied only to lowly employees: managers habitually enjoyed an ample armchair with high back and comfortable upholstery, which allowed various body positions.

Sit as you like

The simplistic concept that sitting upright, with thighs horizontal and lower legs vertical, meant healthy sitting lasted, surprisingly, for about a hundred years. Finally, around the year 2000, it had become generally accepted that people sit any way they like—see Figure 18.8—apparently because freely choosing and changing their posture makes them feel comfortable.

Sitting versus standing

Sitting, as opposed to standing, is suitable when only a small workspace must be covered with the hands: this is typical for much of today's office work. Sitting keeps the upper body stable, which is helpful to execute finely controlled activities. Sitting supports the body at its midchapter; it requires less muscular effort than standing, which is important when it is to be maintained over long hours. Reduced muscular exercise contributes, unfortunately, to loss of physical fitness.

The human body is made for change

Of course, there is nothing wrong with upright sitting or standing at one's own will, but maintaining an erect back requires tensioning of muscles, as Figure 18.9 demonstrates for sitting without a backrest. Even when a backrest is present, it does not provide much support unless one presses the back against it,

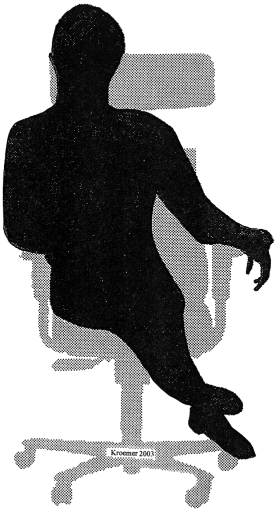


FIGURE 18.8 People sit any way they want to sit.

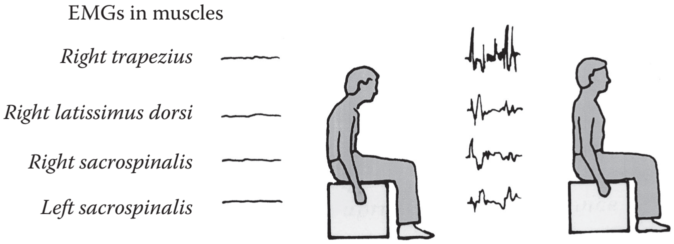


FIGURE 18.9 Activation of back muscles during upright and relaxed sitting without backrest. (Adapted from Grandjean, E., *Ergonomics in computerized offices*, Taylor & Francis, London, 1987; Lundervold, A. J. S., *Acta Physiol Scand*, 24, 1–171, 1951.)

which requires muscle effort. Slumping in the seat and moving the body are instinctive actions to take strain and tension away from muscles that would otherwise be working to maintain prolonged postures. Sitting (or standing) still for extended periods is uncomfortable; it leads to the compression of tissue, and it can hinder blood circulation and lead to the accumulation of extracellular fluid in the lower legs. Obviously, the human body is made for change, to move about, as discussed in Chapter 2 in this book.

Comfort and discomfort

Subjective judgments arise from physiological phenomena (such a tissue compression and circulatory events) and incorporate emotional components as well. This becomes obvious when one tries to assess the feeling of comfort, as it relates to sitting. One definition of *comfort* has long been, conveniently and misleadingly, the absence of discomfort°. However, these two aspects are not the opposite extremes on one single judgment scale. Instead, there appear to be two scales: one for the agreeable feelings that relate to comfort and the other scale for the unpleasant experiences of discomfort that relate to such sensations as fatiguing, straining, smarting, hurting, and not being at ease. Using the term *annoyance* (instead of discomfort) avoids the false concept of one scale that has comfort and discomfort as polar opposites. The two scales seem to overlap but they are not parallel to each other. Table 18.3 lists rating categories that distinguish chairs by comfort and annoyance.

Annoying seats

Feelings of annoyance when sitting are associated with such descriptors as stiff, strained, cramped, tingling, numbness, not supported, fatiguing, restless, soreness, hurting, and pain. Some of these attributes can be explained in terms of circulatory, metabolic, or mechanical events in the body; others go

Table 18.3 Rating of chairs by comfort or annoyance

Comfort statements

1. I feel relaxed.
2. I feel refreshed.
3. The chair feels soft.
4. The chair is spacious.
5. The chair looks nice.
6. I like the chair.

I feel comfortable.

Annoyance (discomfort) statements

1. I have sore muscles.
2. I have heavy legs.
3. I feel uneven pressure.
4. I feel stiff.
5. I feel restless.
6. I feel tired.

I feel annoyed.

Note: Helander and Zhang (1997) used six specific statements about chair comfort or annoyance, followed by one general statement. Each ranking employed nine steps from *not at all* to *extremely*.

beyond such physiological and biomechanical phenomena. Users can rather easily describe design features that result in feelings of annoyance such as chairs in wrong sizes, too high or too low, with hard surfaces or sharp edges; but avoiding these mistakes, per se, does not make a chair comfortable.

Comfortable seats

Feelings of comfort when sitting associate with such descriptive words as *warm*, *soft*, *plush*, *spacious*, *supported*, *safe*, *pleased*, *relaxed*, and *restful*. However, exactly what feels comfortable depends very much on the individual and his or her habits, on the environment and the task at hand, and on the passage of time. Aesthetics play a role: if we like the appearance, the color, and the ambience, we are inclined to feel comfortable. Appealing upholstery, for example, can strongly contribute to the feeling of comfort, especially when it is neither too soft nor too stiff but distributes body pressure along the contact area. Mesh fabric, often used on the seat surface and on the back support instead of traditional cushion upholstery, breathes by letting heat and humidity escape as it supports the body—and it can look fashionable and sleek.

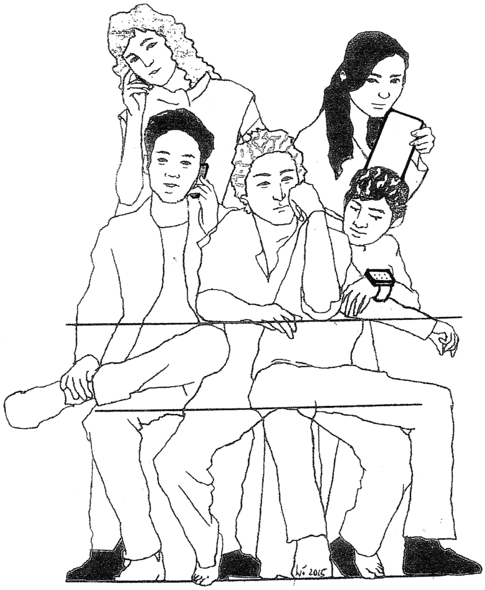


FIGURE 18.10 People sit as they want. (Adapted from Kroemer, K. H. E., and Kroemer, A. D., *Office Ergonomics*, Korean edition, Kukje Publishing, Seoul, South Korea, 2006.)

Dynamic design

In the early 2000s, *dynamics* was a key word in the design of office chairs, as opposed to the statics of maintained posture. People do move about as they please. Design should encourage and support free-flowing motions, as sketched in Figure 18.10, with opportunities for transitory postures at the whim of the person.

18.4 Ergonomic design of the office workstation

Successful ergonomic design of the office workstation depends on proper consideration of several interrelated aspects: work tasks, work movements, and work activities. All these must fit the person to achieve individual well-being and foster high work output. Of course, job content and demands, control over one's job, and many other social and organizational factors also influence feelings, attitudes, and performance at work, as discussed in Sections III and IV of this book.

Office furniture should accommodate the full range of body sizes, varying body postures, and diverse activities; it should further task performance; it should be appealing and help make people feel well in their work environment. At conventional computer workstations, the furniture consists primarily of the seat and a working surface, usually a table (or a desk), which serves as a support for data entry devices and displays. It is best, although expensive, to have all these independently adjustable, as explained in the following.

Links between person and task

For the proper layout of a workstation, it helps to consider three main links between a person and the task.

1. Visual interface: One must look at the keyboard, the computer screen or the printed output, and source documents.
2. Manipulation: The hands operate the keys, a mouse, or other input devices; they manipulate pen, paper, and telephone.
3. Body support: The seat pan supports the body at the undersides of the thighs and buttocks, and the backrest supports the back. Armrests or a wrist rest may serve as further support links.

Design for vision

The location of visual targets can greatly affect the body position of the computer operator, as shown in Figures 18.11 and 18.12. Objects upon which we focus our eyesight should be located directly in front, at a convenient distance and height from the eyes. If one is forced to tilt the head up to view the

FIGURE 18.11 The monitor is set up too far from the eyes and too high, so the operator arches his back and neck in trying to get the image into focus. (Adapted from Kroemer, K. H. E., and Kroemer, A. D., *Office Ergonomics*, Taylor & Francis, London, 2001.)

FIGURE 18.12 A document placed to the side causes a twisted upper body posture. (Adapted from Kroemer, K. H. E., and Kroemer, A. D., *Office Ergonomics*, Taylor & Francis, London, 2001.)

computer screen or to turn it to the side to read a document, eye strain is commonly experienced, often together with pain in the neck, the shoulders, and the back.

As a rule, the display or a source document should be at the proper viewing distance for the operator, which is about half a meter from the eyes, the reading distance for which corrective eye lenses are usually ground. A convenient procedure is to place the screen° and the source document at slightly less than an arm's length, best perpendicular to the line of sight (so a document holder may be helpful). Of course, proper lighting is necessary on documents to be read and other objects to be seen distinctly, as discussed earlier.

Design for manipulation

In addition to the eyes, our hands are usually very busy doing various office tasks: punching keys, grasping and moving papers, taking notes. If our hands are engaged in many different activities, the varied manipulation is likely to keep our arms and the upper body moving around in our workspace. Motion is desirable—in contrast to maintaining a fixed posture, such as when tapping on the keyboard over an extended time.

When sitting, sweeping our hands at extended arms provides a fairly large manipulation area, even larger when we move the upper body and, of course, we can cover even space when standing up. However, we prefer the space on the front of chest and belly for finely controlled hand and forearm motions°; see Figure 11.11. We can also acutely see there because objects are at a suitable distance from the eyes and so low as to fit the natural downward direction of gaze, as discussed in Chapter 5.

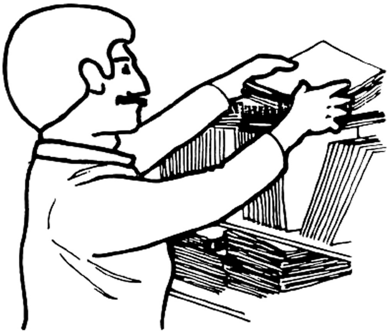


FIGURE 18.13 Get up and stretch the body. (Adapted from Kroemer, K. H. E., and Kroemer, A. D., *Office Ergonomics*, Taylor & Francis, London, 2001.)

Design for body motion and support

Our body is built to move about, not to hold still. It is uncomfortable and tiresome to maintain a body position without change over extended periods. We experience this while driving a car and sitting at workstations with immovable desktop computers (where the chair is often much less comfortable than our car seat). But, unlike when driving, we can get up and move around at will in our office. It is a good practice to get up and stretch the body while talking with a colleague, getting some papers or other supplies—see Figure 18.13.

Active sitting

Design for motion means that the office chair should be comfortable for relaxed and upright sitting, for leaning backward and forward, and for getting in and out. In some chairs, both the seat pan and the backrest follow the motions of the sitting person and provide support throughout the range. Other designs start from the premise that the seat must not be a passive device but an active one: the chair as a whole, or its pan or backrest separately, can automatically change the configuration slightly over time, perhaps in response to certain sitting postures maintained by the person. The change can be in the angles, or in the stiffness of the material. Seat and back cushions that pulsate were tried in the 1950s to alleviate the strain that military aircrews felt when they had to fly extended missions, sitting in the same posture for hours on end. Should an "intelligent seat" or our computer remind us to get up, move about, stretch, walk, after we sat in a static position for too long a time?

Design for diversity

For decades, the illusion ruled western office design that one could establish strict norms for dimensions of office furniture that would fit (nearly) everybody. The globalization of trade and the recognition that people are diverse (in sizes, habits, behavior, and preferences) have finished off the one-design-fits-all idea. Instead, the diversity of use has lead to diversity in design.

Design for body sizes

The size of office furniture derives essentially from the body dimensions, the work tasks, and the working habits of the people in the office. Main vertical anthropometric determiners of height requirements are lower leg (popliteal and knee) heights, thigh thickness, and heights of elbow and eye: see Chapter 1 for explanations and data.

Design ranges

As listed in Table 18.4, essential furniture dimensions depend on the body dimensions of the user(s); for example, the height of the seat pan is determined by the user's lower leg length, with expected shoe-heel height added. For designing the adjustment range of the seat, the tallest user's lower leg length (plus shoe-heel height) identifies the highest seat setting. The lowest adjustment would be for the person with the shortest lower legs. Obviously, these highest and lowest settings, and the adjustment range between them, would be different for different user populations and possibly need modifications for differing sitting habits.

Fitting everybody

Some relations between furniture and body dimensions are loose; for example, commonly, the location of the display is not tightly linked to the location of the eyes. Other relations are definite: The clearance height under a desk or a table may not be less than the knee height of the tallest user. Since that clearance height is usually fixed, even a small user is likely to perch on a high-adjusted seat in order to work at the given

Table 18.4 Relations between furniture dimensions and measurements of the user's body

Furniture dimension	Body size of user	Reference numbers shown in Figure 1.1 and Table 1.3
Display height	Eye height above seat pan	#9
Work surface height	Elbow height above seat pan	#11
Seat pan height	Popliteal height plus shoe heel height	#14
Clearance height under table or desk	Thigh height above seat pan or knee height plus shoe heel height	#12 or #13
Seat pan depth	Buttock–popliteal depth	#25
Seat pan width	Hip breadth	#28

(high) work surface; such a high seat pan would cause the user's feet to not be able to reach the floor, and so employing a foot rest is appropriate.

Seat slope affects pelvis and spine position

Since connective tissue links the bones of the pelvic girdle to the lumbar spine, the rotation of the pelvis affects the posture of the lower spinal column. When one sits down on a hard flat surface, not using a backrest, the lowest protrusions of the pelvic bones (the ischial tuberosities) act as fulcra around which the pelvic girdle rotates under the weight of the upper body. Figure 18.14 illustrates that, if the rear edge of the seat pan is elevated, the resulting slope makes the pelvis rotate forward which, in turn, tilts the lower spine into its natural lordosis; a lumbar pad on the backrest can be helpful as well. Furthermore, the angles at the hip and the knee affect the position of pelvis and hence the curvature of the lumbar spine because leg muscles run from the pelvic area across the hip and the knee joints to the lower legs.

Seat pan variations

The curvature of the spinal column, especially in the lumbar area, has been of a major concern for orthopedists and seat designers. Their ideas about proper posture and body support have generated innumerable designs for the seat pan: high and low, hard and cushioned, tilted fore and aft, contoured and flat, saddle-shaped, and otherwise curved: all associated with hopes and claims of healthy sitting. However shaped, the surface of the seat pan must support the weight of the upper body

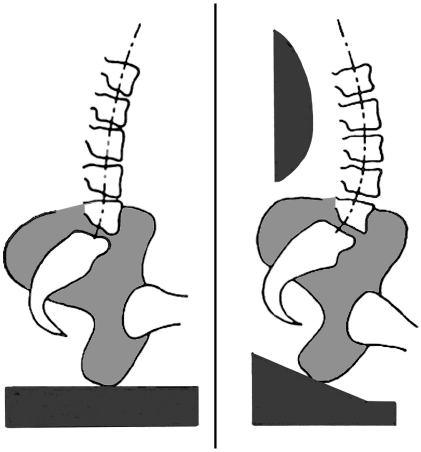


FIGURE 18.14 Rotation of the pelvic bone on flat or sloped seat surface.

comfortably and securely. Hard surfaces generate pressure points, which can be avoided by suitable upholstery, cushions, or other surface materials that elastically or plastically adjust to body contours.

Is a backrest necessary?

Some people think that a backrest is not necessary when sitting because, without it, back muscles act to stabilize the trunk, which, supposedly, is good muscle exercise. Figure 18.15 depicts "semi-sitting" without backrest. However, most people find that a backrest is desirable for several reasons. One is that a back support can carry some of the weight of the upper body, which reduces the load that the spinal column must otherwise transmit to the seat pan. A second reason is that a lumbar pad, protruding slightly in the lumbar area, helps to maintain lumbar lordosis, believed to be beneficial. A third related reason is that leaning against a suitably formed backrest allows muscles to relax. Figure 18.16 illustrates the concept of relaxed supported sitting.

Chair shapes

Notice in Figure 18.16 that the neck region is not well supported: a better fit could be achieved if the headrest was separately adjustable up/down and forth/back, or if an adjustable neck cushion were used.

Of course, the backrest should be shaped to support the back comfortably. Around 1960, Ridder in the United States and Grandjean in Switzerland found in experiments that their subjects preferred similar backrest shapes, as depicted in Figure 18.17. In essence, these shapes follow the curvature of the rear side of the human body. At the top, the backrest is convex to follow the curve of the cervical lordosis; below, it is nearly straight but tilted backward to support the thoracic area; in the

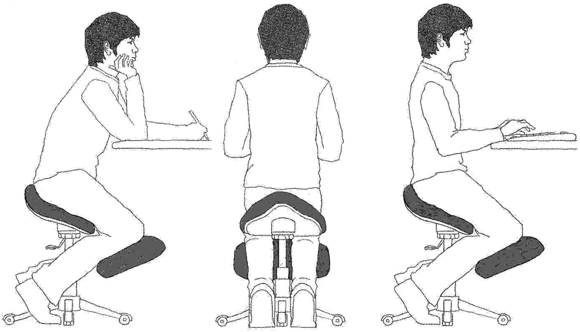


FIGURE 18.15 Semi-sitting. (Adapted from Kroemer, K. H. E., and Kroemer, A. D., *Office Ergonomics*, Korean edition, Kukje Publishing, Seoul, South Korea, 2006.)

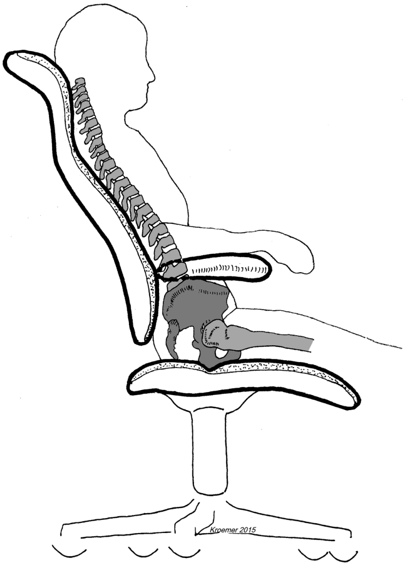


FIGURE 18.16 Relaxed sitting on a supportive seat.

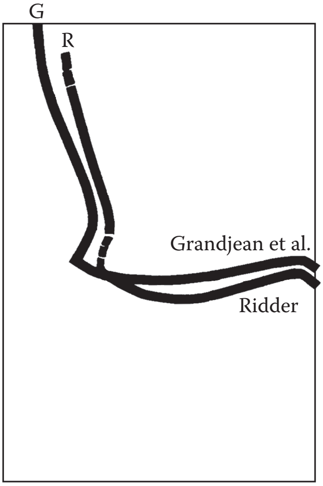


FIGURE 18.17 Ridder's 1959 and Grandjean's 1963 preferred contours of seat pan and backrest. (Adapted from Kroemer, K. H. E., and Kroemer, A. D., *Office Ergonomics*, Taylor & Francis, London, 2001.)

lumbar region, the backrest has a slightly protruding pad accommodating lumbar lordosis; at the bottom, the backrest is concave or open to provide room for the buttocks. The seat pan has some depression (possibly created by deformable material) to accommodate the ischial tuberosities; its front is well rounded. Shapes such as these have been successfully used for seats in automobiles, aircraft, passenger trains and for office chairs.

Seat measures and adjustments

The only inherent limitation to the size of the seat for western-style sitting is that its pan should be so short that the front edge does not press into the leg's sensitive tissues behind the knees. A seat pan with a well-rounded front edge, between 38 and 42 cm deep and at least 45 cm wide, fits most western bodies. The height of the seat pan must be widely adjustable, preferably down to about 37 cm and up to 58 cm to accommodate persons with short and long lower legs. It is very important that the person, while seated on the chair, can easily do all adjustments, especially in height. Figure 18.18 illustrates desirable adjustments of seat pan and backrest, together with other workstation features.

Work surface and keyboard support

The height of the workstation depends largely on the activities to be performed with the hands, and how well and exactly the work must be viewed. Thus, the main reference points for ergonomic workstations are the elbow height of the person and the location of the eyes. Both depend on how one sits or stands, upright or slumped, and how one alternates among postures. For western users, the table or other work surface of a sit-down

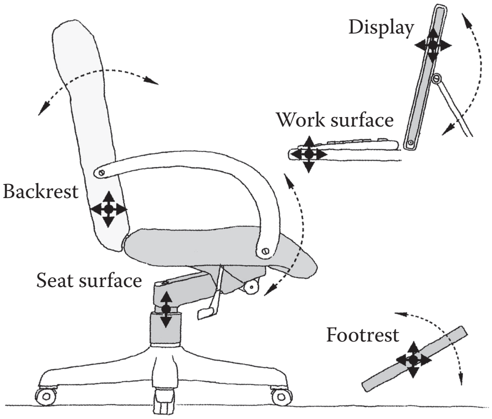


FIGURE 18.18 Adjustments of office furniture. (Adapted from Kroemer, K. H. E., and Kroemer, A. D., *Office Ergonomics*, Korean edition, Kukje Publishing, Seoul, South Korea, 2006.)

workplace should be adjustable in height between about 53 and 70 cm, even a bit higher for very tall persons, to permit proper hand/arm and eye locations. As mentioned, a fixed high work surface, high because of the desire to provide leg clearance for long-legged persons, generates the need to provide footrests for shorter persons perched on a tall seat.

Adjustability

Fixing the height of just the tables (or of desks or of all seats) reduces the price of office furniture but causes uncomfortable body postures for many users. It is best, although expensive, to have all be independently adjustable, which allows an ergonomic fit for all. If technology and working habits continue toward the dominant use of small portable computers and possibly of virtual displays, old-fashioned desks and tables might not be in much need anymore—which could revolutionize furniture and appearance of office spaces.

Fitting it all together

The first responsibility for proper office design goes to managers, architects, interior designers, and human factors engineers. They determine the overall layout and other important general conditions such as lighting and climatization. However, within the overall boundaries of design, there is much freedom for specific workplace arrangements by the section manager, the supervisor, and especially by the individual office holder. Table 18.5 summarizes what the individual can do to make office work agreeable.

Summary

Designs of traditional offices vary from open plans to closed, walled-in individual rooms. The disadvantages of open designs include the lack of privacy and the propagation of disruptive sound and noise. Many organizations use a mixture of office designs; some wide-open spaces, sections with shoulder-high cubicle dividers, closed-off individual offices in other parts.

The details of suitable office illumination depend on the tasks at hand, the objects to be seen, and the conditions of the eyes to be accommodated. General recommendations for office illumination are about 500 lx but, if CRT displays are present, the overall illumination could be as low as 200 lx, while in rooms with light-emitting displays, illumination of up 750 lx is suitable. For such tasks as reading text on a paper, it can be helpful to use a task light; however, care is necessary to avoid glare.

Neither theories nor practical experiences endorse the idea of one single proper, healthy, comfortable position, such as erect

Table 18.5 Ergonomic recommendations for your office setup

This feels good

- Place all the things you must operate with your hands (keyboard, mouse, trackball, pen, paper, telephone)
  - Directly in front of you
  - At elbow height
  - Within easy reach.
- Place the display and the keyboard directly in front of you, at your best viewing/reading distance.
- Place the monitor low behind your keyboard. (Do not put it on a tall stand or on the central processing unit [CPU] box.)
- Sit on a seat so designed that you can change your posture frequently. If long-time sitting is required, then a tall backrest that can recline helps support the back and the head.
- Change your body position often. Change helps avoid the continued compression of tissues, especially of the spinal column, facilitates blood circulation, and counteracts muscular fatigue—and it breaks boredom.
- Support your arms and hands by resting them, as often as feasible, on soft arm rests attached to the seat, and/or on padded wrist rests at the keyboard—but avoid hard surfaces and, worse, rigid corners and edges that compress the skin tissues.
- Keep the shoulders relaxed, the upper arms hanging down, the forearms horizontal, and the wrists straight.

What to do if you are not comfortable

If your eyes are tired, or hurt, or feel teary or dry

- Place all the things you must clearly see (display, source document, writing pad, template, keyboard) directly in front of you, to the best viewing/reading distance (which is probably shorter than you have now).
- Place your monitor low behind your keyboard. (Take it off from a tall stand or the CPU unit.)
- Make sure you do not have light (from a window or from lamps) reflected in the display or shine directly into your eyes.
- Talk with your supervisor and, if the condition does not go away, have your eyes checked by an ophthalmologist or optometrist.

If your back hurts

- Take a break at least every 30 minutes; walk and move your body.
- Make sure that you lean against the backrest of your seat.
- Get a seat that fits your body and accommodates your sitting habits better than your current chair.
- Place all the things you must clearly see (display, source document, writing pad, template, keyboard) directly in front of you, to the best viewing/reading distance (which is probably shorter than you have now).
- Place your monitor low behind your keyboard. (Take it off from a tall stand or the CPU unit.)

(*Continued*)

Table 18.5 (Continued) Ergonomic recommendations for your office setup

- Place all the things you must operate with your hands (keyboard, mouse, trackball, pen, paper, telephone)
  - Directly in front of you
  - At elbow height
  - Within easy reach.
- Talk with your supervisor and get a medical evaluation if the condition does not abate.

If your neck or your back hurts

- Take a break at least every 30 minutes; walk and move your body.
- Place all the things you must clearly see (display, source document, writing pad, template, keyboard)
  - Directly in front of you, at your best viewing/reading distance (which is probably shorter than you have now)
  - Low behind your keyboard (do not use a tall tilt stand, or the CPU unit, under the monitor).
- Place all the things you must operate with your hands (keyboard, mouse, trackball, pen, paper, telephone)
  - Directly in front of you
  - At elbow height
  - Within easy reach.
- Talk with your supervisor and get a medical evaluation if the condition does not go away.

If your shoulder hurts

- Take a break at least every 30 minutes; walk and move your body.
- Put the mouse or trackball next to the keyboard, all at elbow height.
- Operate the mouse or other input device with the other hand. (Yes, you can do so well after just a few minutes.)
  - Use armrest and wrist rest often.
- Talk with your supervisor and get a medical evaluation if the condition does not go away.

If your wrist or hand or arm hurts

- Take a break at least every 30 minutes; walk and move your body.
  - Make sure that your wrist remains straight while working the keyboard or other input device.
- Strike keys very lightly.
- Use armrest and wrist rest often.
- Put the mouse or trackball next to the keyboard.
- Talk with your supervisor and get a medical evaluation if the condition does not go away.

If your leg hurts

- Take a break at least every 30 minutes; walk and move your body
- Make sure that you have ample room at your workstation to position and move your feet freely

(*Continued*)

Table 18.5 (Continued) Ergonomic recommendations for your office setup

- If the front portion of your seat presses on the underside of your thighs, lower the seat. (Probably, you must also lower the keyboard and the monitor, the table or the desk, or other work surface accordingly.)
- Get another seat that has a soft waterfall shape at its front.
- Use a wide and deep footrest.
- Talk with your supervisor and get a medical evaluation if the condition does not improve.

sitting. Instead, many motions and postures may be subjectively comfortable (healthy, preferred, suitable) for short periods, depending on one's body, habits, and work activities. Changing from one posture to another one, moving freely among all the comfortable poses, is important. Consequently, furniture should allow for body movements among various postures by easy or automatic adjustments in its main features, especially in seat height and seat pan angle and backrest position. The entire computer workstation should permit easy variations, for example, in the location (especially height) of the input devices and the height and the distance of the display.

Within given overall boundaries, there is usually freedom for specific workplace arrangements that fit the task and suit the individual. This is particularly true for the setup of personal home offices. Individual arrangements can be essential to achieve ease of work.

Notes and more information

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

Office buildings: Detailed discussions by Kroemer and Kroemer (2017) and Saval (2014).

18.1 Office spaces:

A clear approach, cost-benefit analysis: Mishan and Quah 2007.

18.2 The physical environment:

Photometry in office illumination: In traditional photometry, the apparent reason for measuring illuminance was the ease of doing so. Instruments to measure luminance, which determines how well we can see objects and distinguish their details, are more complex and expensive and harder to use—see Rea 2005.

The traditional relations between lighting and human vision primarily concerned two elements in the visual environment: the objects being viewed, such as print on paper; and their illumination, such as by daylight or electrical lamps. However, the widespread use of self-luminous sources, as on television and computer monitors, has lead to some change in emphasis because the visual characteristics of these light-emitting objects are not dependent on illuminating light. For more on this topic, check Howarth (2005).

Good office climate: For listings and discussions of ASHRAE recommendations in the United States, of international standards especially by ISO, and of national regulations and regional recommendations and customs, see Parsons 2003, 2005, 2014.

18.3 Office furniture:

In the late 1800s, body posture had become of great concern: In 1884, the orthopedist Staffel had publicized theories about "hygienic" sitting postures. He recommended holding the trunk, the neck, and the head erect, similar to what he advocated for standing. In 1889, it was reported that farmers and laborers often had back curvatures, which were either too flat or overly bent. Staffel and his colleagues were also concerned about the postural health of children and recommended that all be exhorted to maintain an erect posture of the back, the neck, and the head. Starting in the late 1880s, a great number of "hygienic and healthy" designs for school furniture were proposed. These ideas were also applied to office furniture with the intent to make office personnel sit correctly upright (Kroemer, Kroemer, and Kroemer-Elbert 2003; Kroemer and Kroemer 2017).

Straight back and neck: Seen from the side, a healthy spinal column is not straight but slightly bent forward in the neck and lower back regions and bent backward in between—see Chapter 2.

Comfort and discomfort: Corlett 2005; Helander 2003.

18.4 Ergonomic design of the office workstation:

Place the screen: Rempel et al. 2007.

Space … for finely controlled hand and forearm motions: Kroemer 1965.

CHAPTER NINETEEN

Computer design and use

Within just a few decades, computers became essential work tools, much-used leisure gadgets, and toys of many kinds. Computer technology made long-distance interaction easy. Much of business communication, formerly done by mail and telephone, is now wireless. Computers opened the world for many persons, especially those who are sick or elderly, who would otherwise feel shut in; electronics allow them to communicate directly with others, to shop and bank, to get the news. The Internet provides an abundance of information to anybody with just a few key strokes.

QWERTY keyboards on computers

However, even current computer keyboards are not well human-engineered but, instead, still follow essentially an 1878 typewriter design, although now often miniaturized. The QWERTY layout makes keying unnecessarily difficult and time-consuming and can even cause repetitive injuries to the hands and the arms of keyers. For more than a century, inventors have made many proposals for new devices replacing the keys and the keyboards of the old typewriter design; yet so far no novel solutions have been successful.

This chapter discusses ergonomic aspects of computer design and operation and derives suggestions for better, user-friendly designs. This review shows a typical process of solving a technical problem; starting with a hardly workable design, then improving it incrementally and, ultimately, seeking a fundamentally different, truly good solution.

19.1 Sholes' "typewriting machine" with its QWERTY keyboard

Throughout the 1800s, numerous inventors proposed a great variety of typographical devices on which the manipulation of an input device (usually with keys of some sort) generated imprints of letters on paper. Given the technology available at that time, the innards of these typewriting machines relied on complex mechanical lever setups. Apparently, the overriding technical challenge was to find workable mechanisms, so the inventors of these machines seem to have paid little attention to the usability of the input side, the design of keys and their arrangements.

Sholes' type-writing machines

One of these inventors, Christopher Latham Sholes, from 1868 on was granted eight U.S. patents for various designs of a typewriting machine: two patents in 1868, both with Glidden and Soulé; then one patent in 1876 with Schwalbach. In 1878, he obtained five patents: 199,382, followed by 200,351 (with Glidden), then 207,557 and 207,558, and finally, on August 27, 207,559.

Sholes' keyboards

The two first patents, both in 1868, have rectilinear rows of keys: the first patent, 79,265, shows 21 unmarked keys, described (on page 1) as "similar to the keyboard of a piano" with 10 shorter keys atop 11 longer keys, akin to the white and black clavier keys. The 36 keys in patent 79,868 are also (as said on page 2) "similar to the keys of a piano or melodeon," but they all lie in one plane, side by side, alternating in length. The keys on the left side, as the operator sees them, show numbers in increasing order while the other keys, in the middle and on the right side, carry alphabetic letters. Neither patent contains any explanation for the choice of the respective key layout beyond the just quoted statements.

The following 1876 patent (182,511) and the first four patents of 1878 all exhibit arrays of three straight rows of button-like keys affixed to lever-type bars: 32 keys in the 1876 patent and 21 keys in the 1878 patents. No labels with letters or numbers are on the buttons, and the texts of the patents provide no explanation or description of any kind.

QWERTY keyboard

Sholes' last patent, 207,559, contains 14 specific technical claims, but none refers to the key layout. One drawing in this patent shows a frontal view of four straight and horizontal rows of key tops. The rows are staggered in height so that the row

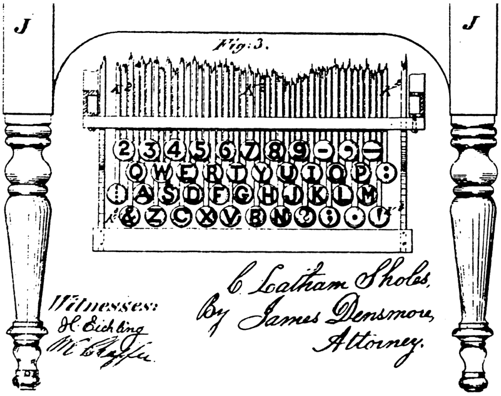


FIGURE 19.1 The QWERTY keyboard in C. Latham Sholes' 1878 U.S. patent 207,559.

closest to the operator is the lowest and the farthest row is the highest. Another drawing depicts a top view of the four straight rows, each with 11 round keys, for a total of 44 keys—see Figure 19.1. The key tops carry inscribed numerals, letters, and signs.

Why QWERTY?

We know of no statements by Sholes or by his co-inventors or contemporaries, either in their patents or reported elsewhere, that explain why the specific keyboard layouts were chosen in the patents. However, one can observe that the final 1878 patent 207,559 layout shows some remnants of an alphabetic arrangement. Sholes was a printer by trade, and so we may surmise similarities to the arrangement of the printer's type cases in which, presumably, pieces were assorted according to convenience of use instead of just alphabetically. Another possible reason for the arrangement of the characters and the keys may have been the intent to avoid that type bars (in the then-used mechanical lever mechanisms) collide or stick together when activated in quick sequence. This may have lead to a separation of certain bars and, hence, a separation of keys on the keyboard. However, there is no contemporaneous evidence for any of these speculations.

19.2 From typewriter to computer keyboard

Sholes' 1878 invention became a global success, and his puzzling layout of the keyboard is still in general use, with only the positions of X and *C* exchanged and the *M* moved to the first row in the English language versions. The six leftmost keys on the third row, counted from the operator, carry the letters Q, W, E, R, T, Y. Even on today's computers, the term *QWERTY keyboard* serves as a short name for any arrangement in which the letter keys essentially follow Sholes' keyboard layout.

Twentieth century typewriters

None of the numerous patents and proposals for alternate key and keyboard designs° were commercially successful. Changes within the Sholes layout were technically difficult as long as the mechanism relied on mechanical levers. The first significant change to typewriter designs was the introduction of electric motors in the 1950s, which supplied auxiliary energy to strike the type bar (later, a type ball on some machines) on the inked tape to make the imprint on paper; until then, the typist's hands had provided that energy. In the 1960s, fingertip-operated switches controlling electric and then electronic circuitry began to replace the lever mechanisms of the keys. This drastically reduced both the finger force needed to actuate the key and the key displacement, diminishing the dynamic work (force-displacement integral) required from the operator's fingers for every keystroke—but it did not reduce the keying rate.

Typewriters morphing into computers

Starting in the 1960s, electronics replaced the mechanical innards: typewriters transformed into personal computers. The new technology would have allowed to easily relocate keys and redesign the entire keyboard. However, instead of creating novel solutions, keys were simply added to the original keyboard. These were mostly "function" keys, placed to the left, behind and especially to the right of the QWERTY set. With an extra numeric key pad and a further cursor control key pad (both commonly on the right-hand side), in the 1980s, the total number of keys was customarily just over one hundred, in some case about 125—more than double as many keys as on the old Sholes typewriter. So many keys took much keyboard space and the big keyboard required large finger and hand movements. Mouse, trackball, touch pad, and other accessories generated new tasks and required new body motions from the keyboarder.

The 1980s saw a wave of computers entering modern offices, sweeping out the remaining mechanical and even the newer "electric" typewriters. For example, IBM introduced its first personal computer in 1981; only 10 years later, it stopped producing typewriters. Two decades further on, IBM sold its whole personal computer business to a Chinese firm.

From around 2000 on, wireless telephones became immensely popular. They are often used for texting done on miniature keyboards, which still largely follow Shole's key layout.

19.3 Human factor considerations for keyboarding

Obviously, the keyboards on early typographic devices, including Sholes' 1878 invention, were not "human-engineered." Nevertheless, his QWERTY layout became by default the most commonly manufactured keyboard when his typewriting machine became a global success.

Body posture and effort

Current desktop computer technology poses two postural requirements on the user, which are similar to what the typist had to do: focus the eyes on the display while keeping the hands on the keyboard. Such prescribed locations of the eyes and the hands fixate the overall positions of the head and the upper body and hence allow little variation of body posture. Even movable laptop and tablet computers impose similar posture requirements on their users.

Overloading typists

The spatial arrangement of the keyboard itself, and of the keys on it as per Sholes' design, forced typists' arms into strong inward twist (pronation) and the hands into lateral bend (ulnar deviation) at the wrist, and it required complex motions between the ill-located keys. The unfortunate combination of forced posture and hard effort overloaded many typists' hands, wrists, arms, shoulders, and necks.

1920s typists

Klockenberg (1926) provided an illustration, reproduced as Figure 19.2, of a typical typist. In a moving narrative, Klockenberg described how young women, who had chosen typing as their profession, after just a few years on the job found themselves with painful hands, unable to do typing or to perform everyday tasks with their hands, incapable even of lifting their small children. Obviously, the reason for the typists' musculoskeletal injuries was the heavy repetitive work required to operate their typewriters in unsuitable body postures. Today, the posture of a keyboarder is usually much less contorted but still bound by the needs to keep the fingertips on the keys and the eyes directed at the display.

FIGURE 19.2 Klockenberg's illustration of the posture of a 1920s typist.

Heidner's 1915 keyboard designs

Among the early proposals of improved keyboards, one stands out: In 1915, Heidner received U.S. patent 1,138,474 for his novel layouts. In his patent, he wrote that his keyboard designs allowed "… to write with greater ease, in a less cramped position … in accordance with the natural form of the hand … and there being thus much less strain … writing is rendered considerably less fatiguing." Figure 19.3 illustrates how Heidner divided the keyboard into left and right halves; on them, he arranged the keys in various layouts, which predate many ergonomic recommendations that inventors have proposed since 1915; surprisingly, his patent was apparently forgotten or overlooked until the 1980s.

Repositioning keys

Keying performance° has been an issue since the early years of keyboarding. Measures of performance commonly focus on the total number of keystrokes done during a certain time and on the ratio between correct and incorrect strokes. Starting in the early 1900s, several patents for new key arrangements appeared that were meant to improve typing performance by overcoming problems of the QWERTY layout. These new designs usually relocated keys° but kept Sholes' original layout of bent columns and straight rows of keys. Dvorak's (1936, 1943) simplified keyboard (SK) is probably the best known and most long-lived of all these plans. However, in 1956, a comparative test showed that it took a long time to retrain typists to become proficient on the SK, yet they still made more errors on it than on their customary QWERTY keyboard, and they gained less improvement

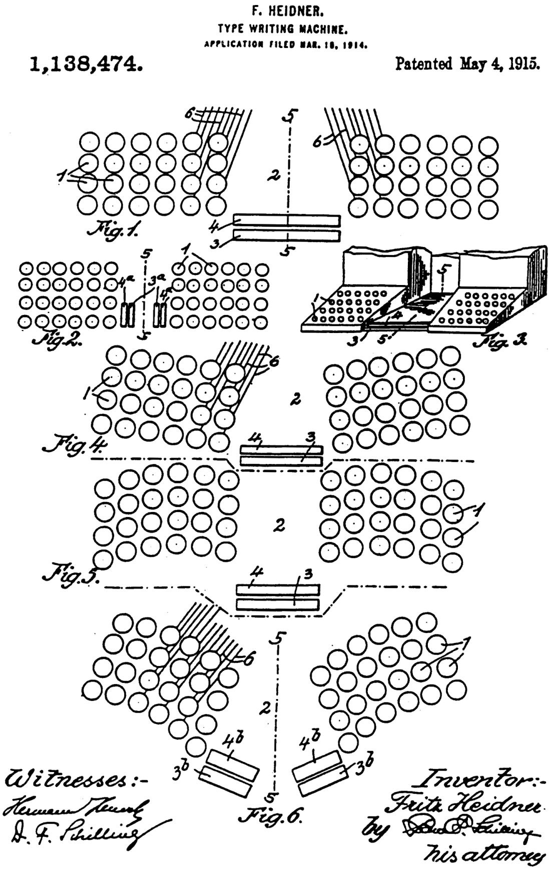


FIGURE 19.3 Heidner's keyboards in his 1915 U.S. patent 1,138,474.

in typing rate with ongoing training. These findings apparently discouraged further attempts to reposition certain keys on the regular key pad; several well-reasoned proposals to use alphabetic layouts° did not find wide acceptance.

Repetitive injuries during the 1800s

The physician Poore stated in 1872 and 1887 that he and other authors, following Ramazzini's° much earlier lead, had traced writers' cramp to "muscular impotence" and "spasms" caused by often repeated use of the same muscles. Poore said that this health problem was not limited to writers, but also occurred in tailors, cobblers, fencing masters, and musicians. He wrote that one might speak of *pianists' cramp* because this overuse disorder occurred so frequently among pianists. In 1892, Osler also associated these spasms “with continuous and excessive use of muscles in performing a certain movement” in writers and musicians and in operators of the Morse key apparatus who suffered from a disabling injury then called *telegraphist’s wrist*.

Keying “myalgia”

Evidently, since the second half of the 1800s, the associations of repetitive strain disorders with repetitive muscle overuses in certain occupations were well established. It was common knowledge that players of keyboard instruments are in danger of developing chronic musculoskeletal disorders. After Sholes’ typewriter became widely used, the same “myalgia” also appeared in typists.

Muscles used in typewriting

In 1951, Lundervold published the first report of his groundbreaking studies to attain knowledge about the use of individual muscles while typewriting. He measured electromyographic signals on 47 healthy typists and 88 patients, most of them suffering from occupation myalgia in muscles that had been overstrained during repetitive typewriting. Lundervold demonstrated that changes in the EMG records reflected the actual muscle activity and the status of muscle fatigue. His experiments provided support for the long-held opinion that repetitive typing can lead to a cumulative overexertion injury even when doing single key strokes is not harmful by itself.

Occupational overuse disorders

In Europe, ailments such as tendinitis, tenosynovitis, and tendovaginitis of the upper extremities became recognized as occupational repetition-related musculoskeletal diseases° of typists in the late 1950s. Researching the reasons for cumulative trauma disorders, especially of the carpal tunnel syndrome (CTS), associated with repetitive keyboarding activities, turned into topics of engineering and medical concern. In the late 1990s, the (U.S.) National Research Council (NRC) convened a workshop on work-related musculoskeletal disorders. In the summary of its findings, the NRC (1999, p. 59) stated that musculoskeletal disorders are multifactorial since individual, social, and organizational factors can contribute to their appearance; however, the biomechanical demands of work constitute the most important risk factors.

Overuse pathomechanics

A slow operator, tapping just 20 words per minute (with five letters per word), performs 12,000 key strokes (20 × 5 × 60 × 2) during a two-hour work session. A fast keyer, doing 100 words per minute over six hours, performs 180,000 keystrokes. Each stroke requires a digit flexion followed by a digit extension. So many motions can create pathomechanical conditions°.

The biomechanical stresses that generate cumulative trauma disorders, especially the CTS, had become well researched in the 1980s and 1990s. The anatomy of the human hand and wrist and its kinematics° while keyboarding explain the overuse conditions that especially afflict the flexor tendons° of the digits in the carpal tunnel: see Figure 2.6 in Chapter 2. Forces in the flexor tendons are often more than three times stronger than the impulses that the fingertips transmit to the key tops. The longitudinal travel of the tendons can be up to 2 cm; the wrist position strongly affects the ease of their gliding within synovial sheaths. The inflammation of the tendons and their sheaths causes swelling of the tissues within the limited space of the carpal tunnel. The resulting pressure can damage the median nerve, causing the CTS that affects hand functioning.

19.4 Input-related anthromechanical issues

Sholes' keyboard concept with its mechanical keys required efforts from the typists that often exceeded their musculoskeletal capacities. The underlying biomechanical problems arose from several categories of work demands: the physical energy to accelerate the masses of the typewriting mechanisms; the postures of hands, arms, upper body, and neck; the extensive use of mainly the flexor muscles and tendons of the typists' hands; and the rate and the repetitiveness of muscle contractions and tendon motions.

Human factors design recommendations

Attempts to lighten the typist's load resulted in many proposals and patents from the early 1900s on; yet the mechanical nature of the then available machinery severely hindered new design solutions. In the 1960s, the terms *ergonomics* and *human* (*factors*) *engineering* were emerging. Consequently, the importance of fitting task and equipment to the human became widely recognized; reconfiguring the keyboard to suit the size and the mobility of the hand became an important challenge. In 1969, Remington and Rogers compiled more than 300 publications on keyboard entry devices. In the same year, Kincaid and Gonzalez formulated "human factors design recommendations for touch-operated keyboards." The emerging use of electric and then electronic circuitry would have allowed radically new designs; yet U.S. standards° in 1968 and 1988 still incorporated the QWERTY layout while adding more keys on its sides. Reviews of the issues of keyboard design and novel solutions for operator-centered designs of keys, keyboards, and keyboarding workstations, and for proper ergonomic ways to perform keying work, appeared in the international literature°.

19.5 Possible design solutions

Customary computer keyboards

Neither the original QWERTY keyboard nor its derivatives have been truly human reengineered in spite of Heidner's 1915 proposals and many other designs that followed. Even on today's customary computer keyboards, all keys are arranged side by side in straight rows (while fingertips are not). The columns of keys follow two different design rules: on the QWERTY set, the columns zigzag slanted to the left (as seen by the operator); on additional key sets, however, the columns are usually straight. That irrational design was largely transferred to portable computers, then miniaturized and applied even to cell phones where the smallness of keys and keypads seems to intensify the old QWERTY layout problem even if the columns of keys are stratified.

Designing for "big changes"

Design issues intermingle with existing technology, with user expectations and practices, and with marketing. In spite of these interactions, in the following discussion, improvement ideas will be assigned to certain categories, for clarity's sake. Obviously, solutions can combine aspects from two or more categories, such as design of keys, design of keyboards, and design of alternate input devices.

A major argument for not changing the basic QWERTY design of the keyboard is the expectation that altering the layout would require retraining the operators and hence would slow keying performance, at least initially. This reasoning is probably true for most minor changes, such as exchanging the letter designations of certain keys (as in Dvorak's proposal). In these cases, apparently the new skills are so close to the old habits that confusion is indeed likely. However, if there is a basic change in design, such as when relocating large sets of keys, or employing keys that have a clearly different operation mode (ternary keys or joysticks instead of binary keys, for example), then the new procedure is distinctively dissimilar from the old ways and there may be little or no interference by carryover from previous practices. Apparently, the human is amazingly fast in acquiring novel keyboarding skills as demonstrated by research° and by the phenomenally fast spread, across the globe, of texting on miniature keyboards, which, according to tests, should be practically unusable°.

Redesigning the key

Changing the basic key design can have major consequences for the user's efforts and performance. The traditional mechanical binary key has two activation states: *off* when up and *on* when tapped down. However, electrical switch and electronics technology would make it easy to replace tap-down binary keys by devices that can establish or break connections by different actions. Just a few examples: We may use a ternary device (having three states); or a device that responds to movements in many directions other than just down (like a joystick); or a force controller that does not need appreciable displacement for activation; or a multifunction gadget that can react to combinations of positions, displacements, and contact modes; or a sensor that responds to user body motion or to sound.

Redesigning the keyboard

Heidner's 1915 patent included several significantly improved designs; numerous later proposals in essence repeated Heidner's ideas to rearrange the angles of slope, tilt, and the slant of key sets, to change key spacing and to split° the key pad into left and right sections in order to make keying less strenuous and to improve typing performance—see Figure 19.4. In 1962, U.S. patent 3,022,878, assigned to IBM, placed the keys like a glove around the hands°. Several keyboards, commercially available since the 1900s, have similar features, in some cases with adjustable arrangements.

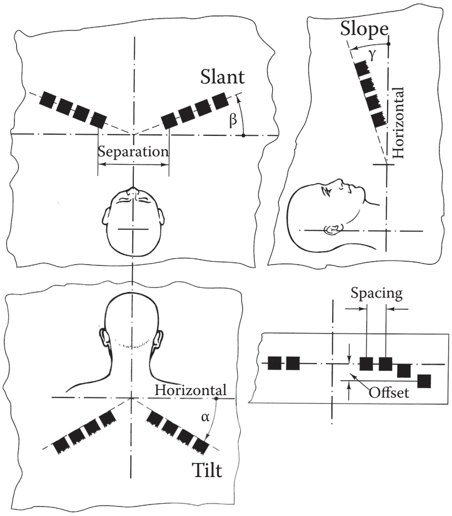


FIGURE 19.4 Terms describing keyboard angles and key positions. (Adapted from Kroemer, K. H. E., *Int J Univers Access Information Society*, 1/2, 99–160, 2001.)

Ternary instead of binary keys

Keyboard design decisively depends on the keys used. The choice of ternary instead of binary keys in Langley's 1988 U.S. patent 4,775,255 provides a good example. Each toggle key can assume three different positions: *off* when in its center position, *1st on* when pulled from there, and *2nd on* when pushed. Langley used chorded activation: the simultaneous activation of two or more keys generates the desired letter or other character. Accordingly, his keyboard needs only eight keys, four for each hand, as illustrated in Figure 19.5. The fingers do not have to move from one key to another but stay on their one assigned key; this allows each hand to rest on its support pad. Evidently, choosing other keys types can result in other keyboards.

Repositioning the keyboard

The old-time piano keyboard, which served as the model key set for many early typographic machines including those in Sholes' early patents, can be divided into several sections to be arranged side by side or elevated in different steps as in organs and modern electronic music keyboards. Although without explaining why he did so, Sholes used in his final 1889 patent a keyboard with the keys arranged in a 4 × 11 pattern: four straight horizontal rows of keys, 11 columns of zigzagging and rising keys. Tiring arm positions and complex finger movements (and the large energy that the typist had to exert on the keys) caused postural problems in combination with repetitive musculoskeletal trauma. Heidner, in 1915, was apparently the first patent holder who attempted to address the postural problems by dividing the one keyboard into sections and repositioning them into locations and angles that are more suitable for the operator. Many subsequent proposals and patents presented similar ideas°, some with adjustment features. So far, the more radical designs have not conquered the market.

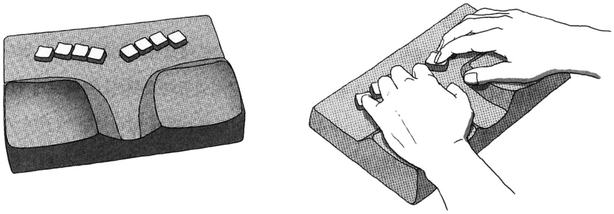


FIGURE 19.5 Langley's 1988 ternary keyboard with four keys for each hand, US patent 4,775,255.

Resizing keys and keyboard

Recent electronic, easy-touch, lightweight, and wireless keyboards allow the user to place them in various locations on a support surface or on one's lap, and one can alter locations at one's whim: this alleviates many of past postural problems associated with stationary keyboards. However, one problem is new: current cell phones have extremely small keypads that many users are tempted to operate them with one or two thumbs while the other hand digits hold the phone. *Texter's thumb* is the descriptive common name for the resulting overuse disorder.

19.6 Design alternatives for keyboards

There is no overwhelming reason for using the principle of "one keystroke for every bit (letter, numeral, sign) of input." That idea follows the tradition of Western writing; it is exact but also inefficient and can cause repetitive strain injuries to the users' hands and arms. Using fewer keys, moveable keys, virtual keys, or no keys at all would alleviate, even completely avoid, the past and current overexertion problems and facilitate body movements instead of the fixed posture caused by "hands on keys, eyes on display." Ways to communicate with the computer without manipulating keys are of great interest for everyday use, especially so to persons with physical disabilities. Several avenues are at hand.

Alternative keys and keyboards

Chords, traditionally used by pianists and other musicians, combine single tones to convey complex sounds, generated by simultaneously triggering several keys instead of activating them sequentially. Chording by simultaneous activation of two or more keys was proposed repeatedly for typewriter and computer operation to replace the sequential "one key for one character" procedure. Langley's 1988 U.S. patent, already mentioned, is a recent example for chording design, which can simplify keyboards, cut the number of keys, reduce hand digit movements from key to key, and, altogether, make key input faster while relieving some hand strain.

Speech and sound recognition

There are means to generate inputs to the computer that require no keys of any kind. We already try to communicate by voice, using speech recognition programs that work reasonably well within confined topic areas, for example, in computer control commands, medical evaluations, or music composition—but for general text, speed and especially recognition accuracy still leave much to be desired. If the impediments were finally overcome, conversing with the computer would be a natural solution. Of course, many other sounds could transfer information to the computer: whistles, grunts, and groans readily come to mind.

Nonverbal communication

Another set of solutions employs the recognition of body movements°. Examples are

- Hands and fingers for sign language and gestures in addition to activating control devices
- Arms for gestures, making signs, actuating control devices
- Torso for positioning and operating actions
- Legs for gestures, moving or pressing devices
- Feet for motions and gestures, for moving and actuating devices
- Head for positioning
- Mouth for lip movement, use of the tongue or of a blow/suck tube
- Face for grimaces and other expressions
- Eyes for tracking

These design solutions require sensors that respond to positions, movements, and forces of the operator's body: cameras, force platforms, motions sensors, instrumented gloves, and similar devices are among long-established technologies. Other approaches might use surface EMGs associated with muscle actions°; at the moment, employing neural signals such as EEGs related with brain activities still appears wishful thinking. However, certainly there are many thus far unexploited possibilities: nanoergonomics° may make it possible to access the human CNS and integrate important features of human cognition into computers, thus allowing direct interaction.

19.7 Designing for new syntax and diction

Klemmer (1950) and Lockhead and Klemmer (1959) recognized how changes in syntax and diction, new abbreviations, words, and phrases can interact with changes in key and keyboard technology. Stenographers and court reporters have long demonstrated that using shorthand code for words and parts of sentences, chunking, batch processing, and related techniques save time and effort. The telegram style in the middle of the last century created a new shortened mode of written expression; in recent times, e-mailing and text messaging have been changing communication manners, word-writing mode, spelling and punctuation: *thru* largely replaced *through*, *u r r8* and *rgds* exemplify that most text is decipherable without vowels. Emojis can convey complex messages.

Language changes constantly. New technologies bring shifts in communication; conversely, transformations in our language can also give designers opportunities for creating novel devices for communicating with computers.

19.8 Designing smart software

Cleverly designed software facilitates work with computers by reducing the demands on manipulative skills and short-term memory°. Software can use context to distinguish between *mail* and *male* and *then* and *than*; it can complete words after the input of only a few first letters; it can provide a set of stock responses to given circumstances; it can anticipate the use of certain words; and it can correct sentence structure and insert punctuation. With further advances in artificial intelligence, the auspices seem unlimited.

19.9 Designs that combine solutions

Today's electronics and tomorrow's novel technologies provide fundamentally new alternatives to Shole's design. We may sort these into certain categories, as done earlier; yet overreaching combinations are most likely to succeed. A current example is the blending of traditional keys with speech recognition and smart software. However, this approach still essentially employs the long outdated QWERTY key arrangement, which makes its use hard for persons with disabilities and, in fact, everybody else because it requires repetitive manipulation and constrains the operator's body posture via "hands on keys, eyes on monitor."

One essential decision is about abolishing the predominant principle of "for each input bit (letter, number, sign), strike one dedicated binary key" and instead use some sort of code or shorthand supported by smart software. The general acceptance of innovative mobile phones and tablets, and of gaming devices, for example, shows that the general public is willing to accept, even embrace, fundamental new techniques in human–computer interaction. These are likely to come together with technology-related neologisms in our language. Ergonomic innovations will address both input and display to improve the whole loop of feedforward and feedback between computer and human.

Summary

The current challenge for "human engineering" the stationary computer workplace is specific to the existing computer technology. Prescribed locations of the eyes and the hands fixate the overall position of head and the upper body, which does not allow much variation of the body position over time. New human–device interface technology can release the user from these binds and allow more freely chosen body postures.

Since the nature of repetitive trauma disorders and, hence, means to avoid them were well documented even in the 1960s, one should have expected that key and keyboard designs for typewriters and then for computers would have been accordingly improved. However, no new input concepts took hold. Instead, even current electronic devices essentially follow the established paths; while they created novel uses, they perpetuated the old key-related overuse problems. New technologies, at hand and emerging, allow the designer to establish innovative solutions for human–computer interfaces that make communication easier and more efficient.

One argument against changing the basic QWERTY design of the keyboard has been that an alteration of the layout would require retraining the operators and hence would slow their keying performance, at least initially. This reasoning is probably true for most minor changes, such as exchanging the letter designations of keys, or repositioning them slightly. In such cases, carry-over confusion is indeed likely because the new uses are close to the old habits. However, fundamental changes in keys and keyboards design, or even abandoning these altogether, create distinctively novel use procedures, which, because dissimilar from the old ways, do not suffer from interference by crossover from previous practices.

We humans are amazingly willing to quickly acquire novel keyboarding skills; a striking recent demonstration is the phenomenally fast spread, across the globe, of texting via miniature keys and keyboards and of associated new use procedures.

Notes and more information

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

19.2 From typewriter to computer keyboard:

Patents and proposals for alternate key and keyboard designs: Compiled by Kroemer (2001, 2010) and Kroemer and Kroemer (2017).

19.3 Human factor considerations for keyboarding:

Repetitive injuries during the 1800s: Osler 1892; Poore 1872, 1887.

Keying performance: Pereira et al. 2014.

Proposals to use alphabetic layouts°: Kroemer 2001, 2010.

Relocated keys: Dvorak's "Simplified Keyboard" of 1936 and 1943 and Strong's 1956 report.

Ramazzini reported in 1700 and 1713 on overuse diseases: See pages 43 and 254 in Wright's 1993 translation of the Latin text.

Occupational repetition-related diseases: Arndt and Putz-Anderson 2006; Garg and Marras 2014; Kroemer 2001, 2010; National Research Council 1999.

Pathomechanical conditions: Armstrong 2006; Arndt and Putz-Anderson 2006; Kumar 2001; Marras and Karwowski 2006; Putz-Anderson 1988.

Anatomy of the human hand and wrist and its kinematics: Baker et al. 2007; Freivalds 2006; Hughes and An 2007; Lee and Healy 2005; Marras and Radwin 2006.

Overexertion conditions that especially afflict flexor tendons: Ettema et al. 2007; Goodman and Choueka 2005; Dennerlein 2005, 2006; Freivalds 2006, 2011; Ugbolue et al. 2005; Zhao et al. 2007.

19.4 Input-related anthromechanical issues:

US Standards: 1968, Proposed US Standard for a General-purpose Keyboard; 1988, ANSI/HFS 100-1988 Standard.

Reviews... in the international literature: Marklin and Simoneau 2004; Kincaid and Gonzalez 1969;

Klemmer 1958; Kroemer 2001, 2010; Noyes 1983a,b; Remington and Rogers 1969.

19.5 Possible design solutions:

Subsequent proposals and patents presented similar ideas: Dennerlein 2006; Kroemer 2001, 2010; Noyes 1983b; Rempel 2008.

Acquiring novel keyboarding skills as demonstrated by research: Anderson et al. 2009; McMulkin and Kroemer 1994; Kroemer 2001; Marklin and Simoneau 2004.

Miniature keyboards … should be practically unusable: Pereira et al. 2014.

19.6 Design alternatives for keyboards:

Split the key pad: Rempel 2008.

Placing the keys around the hands: Noyes (1983a) and Rempel (2008) compiled information and commented on new designs.

Recognition of body movements: Kroemer 2001; McMillan 2001; McMillan and Calhoun 2001; Pereira et al. 2015.

Use …EMGs: Reddy and Gupta 2007.

Nanoergonomics: Karwowski 2006b.

19.8 Designing smart software:

Reducing the demands on manipulative skills and short-term memory: Fisk et al. 2009.

CHAPTER TWENTY

Workplace design

The driver's workspace in a 2015 motor vehicle provides examples of good and bad design. Overall, the driver's workspace is a bad design because it forces the driver to maintain the same body position over long periods in order to keep the feet at the pedals, the hands on the steering wheel, and the eyes focused on the road ahead. The good examples generally relate to a supportive and comfortable seat and to suitable designs and arrangements of displays. Most arrangements of hand controls also belong to the good examples; in contrast, the usual arrangement of the foot-operated controls illustrates just about the worst design thinkable. The driver cannot see the pedals but must move the foot quickly and exactly between the accelerator and the brake. These pedals are both operated in similar forward direction, although they cause exactly the opposite effect: making the vehicle move faster by one kind of forward push (on the accelerator pedal), but making it slow down by another push (on the brake).

20.1 Sizing the workplace to fit the body

Consider the design of the 1960 space capsules: they were small, for technical reasons. This required the selection of fairly small astronauts who could fit in. The workspace around them, the controls and the gauges, were carefully arranged for reach and vision. The shell and the seat supported high accelerations. Well, to be fair, we must say that comfort and previous fashions from Model Ts to Rolls-Royces were not on the human engineering to-do list—just get the people up, around, and down, as safely as possible.

One of the classic examples of equipment designed without paying proper attention to the human operator appears in Figure 20.1. It shows a lathe, which, after a long technological development, is one of the machines that functions reliably well—but it needs an operator who should be built much shorter and much wider than natural to easily attend the machine. Of course, it should be the other way around; all the controls to be manipulated, and the cutting tools to be observed, should be arranged in size and location to fit the actual human body.

Obviously, body dimensions are of importance for the design of large pieces of equipment and of workspaces, especially those data° that describe the overall size (stature, for example) and which identify the eye location as well as hand height and location, because they indicate where objects should be placed that need to be seen and manipulated.

The worker's body size plays a major role in determining the working height of a workbench, for example. The work task is another major determinant of the proper work height: Figure 20.2 illustrates that different jobs are best done at distinct heights with elbow height as a suitable anthropometric

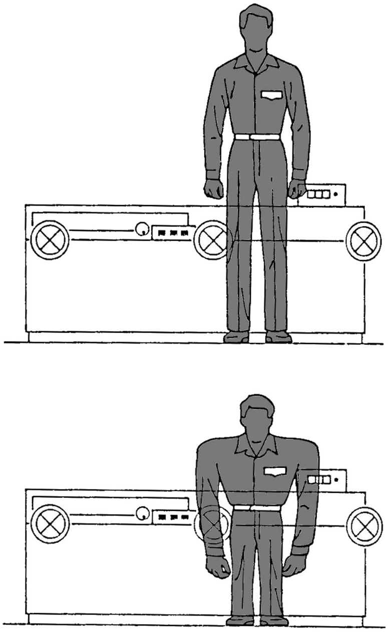


FIGURE 20.1 A lathe with a real and an imagined operator. (Adapted from Eastman Kodak Company, *Ergonomic Design for People at Work*, Van Nostrand Reinhold, New York, 1983.)

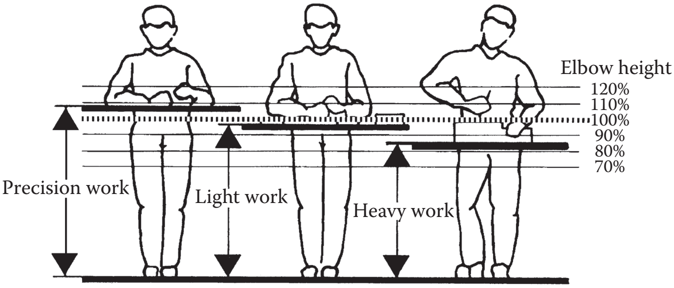


FIGURE 20.2 Elbow height is a suitable reference to determine the heights of working surfaces for different tasks.

reference. If a workplace cannot be adjusted for alternating use by small and big persons, than such a simple means as a platform can provide help by raising a short person, as shown in Figure 20.3; however, an elevated platform may become a stumbling hazard.

Another example of simultaneously considering several human engineering aspects is the design of consoles, where instruments and hand controls are arranged around the upper body of the operator, as shown in Figure 20.4. Such design allows both quick reaches to controls and good viewing of

FIGURE 20.3 Use of a platform to stand on can be of help to a shorter person to operate a machine designed for a taller operator. (Adapted from International Labour Office, *Introduction to Work Study*, third ed., International Labour Office, Geneva, Switzerland, 1986.)

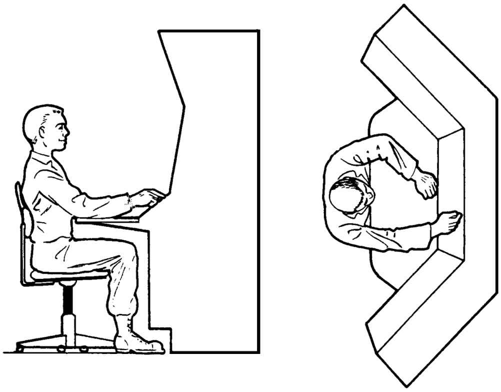


FIGURE 20.4 A console arranged around the operator. (Adapted from Kroemer, K. H. E., Kroemer, H. B., and Kroemer-Elbert, K. E., *Ergonomics: How to Design for Ease and Efficiency*, second ed., Prentice-Hall/Pearson Education, Upper Saddle River, New Jersey, 2003 amended reprint.)

instruments, all at about an extended arm's length from the operator.

20.2 On the feet or sitting down?

There are tasks that require walking about, for example, to pick up material, take it to the workbench, and, after the work is done, return it to another spot; moving around like that can be quite healthy for a fit person. In this case, the workbench is probably best a bit below elbow height, as shown in Figure 20.5. There may also be periods in which the worker does best while sitting: for this, a tall seat is appropriate, as also shown in Figure 20.5. In either case, the work surface should extend out some distance beyond the vertical front panel of the workbench so that one can step up close to it, or extend the legs under it when sitting. If such legroom is missing, as shown in Figure 20.6, sitting becomes very awkward.

On the shop floor, elaborate seats are usually not suitable. Instead, simple designs, robust and easy to clean, are of use. Various kinds of stools and lean-ons, such as shown in Figure 20.7, can take some load off the operator's feet, at least temporarily.

As mentioned, requiring a person to maintain the same position over long hours is not a good human factors solution: we humans need to move our bodies, not maintain the same posture. Keeping the same posture is particularly tiring if that

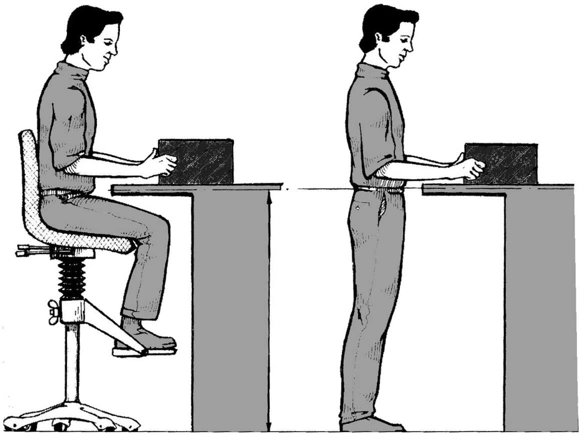


FIGURE 20.5 Work place suitable for sitting and standing. (Adapted from International Labour Office, *Introduction to Work Study*, third ed., International Labour Office, Geneva, Switzerland, 1986.)

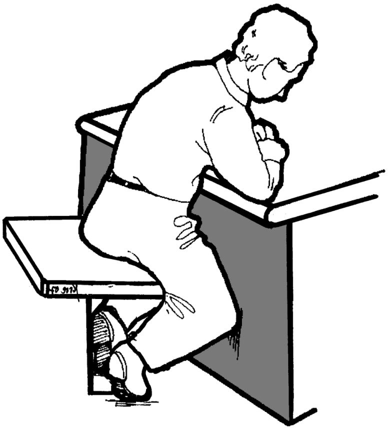


FIGURE 20.6 Missing legroom makes sitting awkward.

involves standing on one foot, as shown in Figure 20.8 (same as Figure 2.19) where, in order to operate a pedal with the right foot, the operator has to support his whole body weight on his or her left foot. Birds can stand on one leg for a long time, but people find that very tiring.

Even when we have a chair to sit on, we should not sit still. However, this does not mean that we should do awkward and possibly harmful motions, such as shown in Figure 20.9: the workplace is so badly set up that the operator has to bend over to the right side to place items into a container.

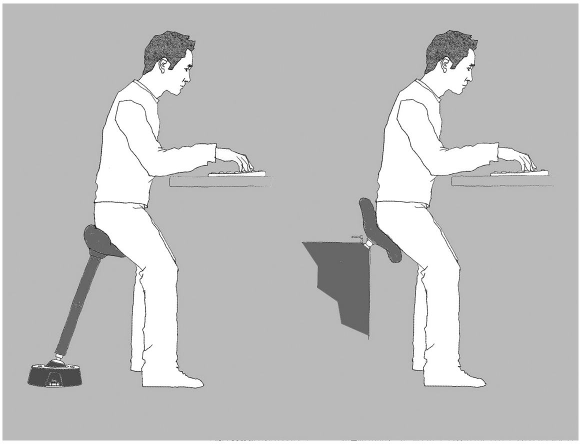


FIGURE 20.7 Examples of stools and lean-ons. (Adapted from Kroemer, K. H. E., and Kroemer, A. D., *Office Ergonomics*, Korean edition, Kukje Publishing, Seoul, South Korea, 2006.)

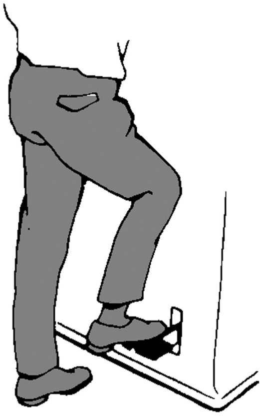


FIGURE 20.8 Standing on one foot in order to operate a pedal with the other foot.

Modern technology has generated many tasks and jobs that require sitting, for example, in airplanes and land vehicles and in conventional offices. Many automobile seats are quite comfortable and supportive—so some of them are available for use in the office. The times of the hard-surfaced primitive task chair are largely over; now office chairs on the market are well designed yet inexpensive. They provide such features° as sketched in Figures 20.10 (see also Figures 18.16 through 18.18): a contoured and padded seat pan with a smooth waterfall

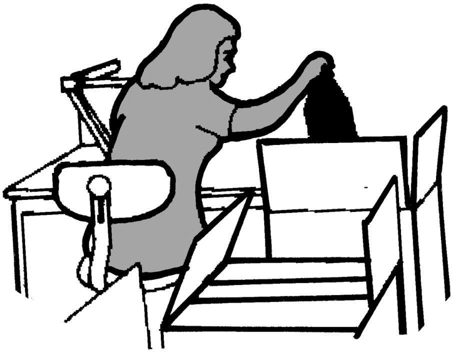


FIGURE 20.9 Packing arrangement that requires bending the body to the right.

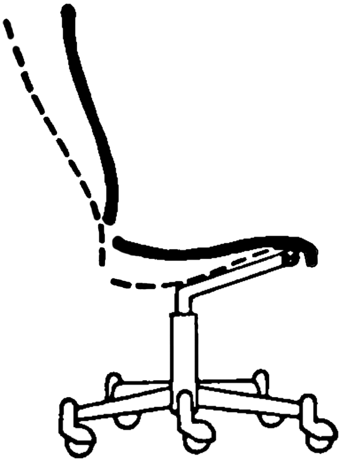


FIGURE 20.10 Essential features of a supportive work seat.

contour at the front, which avoids pressure behind the knee; a high backrest that conforms to the shape of the back and even provides a head rest. Both seat pan and backrest can incline and decline, independently or together.

20.3 Manipulating, reaching, grasping

The work task together with the worker's body size determine the necessary sizes of openings, such as of doors and hatches°, that must allow passing through them, often with equipment worn that makes the body more bulky. Bulk caused by gloves and clothing may also play a role, together with the need to move the tools, for determining the size of openings in machinery or enclosures to provide access for the hand to do repairs and adjustments: Figure 20.11 shows examples.

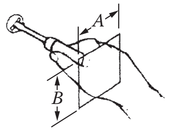
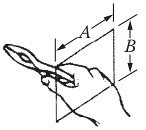
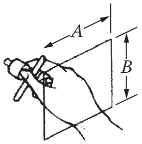
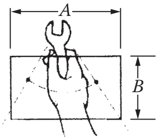
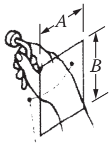
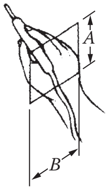
		Approximate dimensions in (cm)	
		A	B
For screwdriver use so that hand can turn up to 180°		11	12
For use of pliers and similar tools		13	12
For turning T-handle wrench up to 180°		14	16
For turning open-end wrench up to 60°		27	20
For turning Allen-type wrench up to 60°		12	16
For using test probe and similar devices		9	9

FIGURE 20.11 Minimal opening sizes (in centimeters) that allow one hand to pass when holding a tool. (Adapted from Kroemer, K. H. E., Kroemer, H. B., and Kroemer-Elbert, K. E., *Ergonomics: How to Design for Ease and Efficiency*, second ed., Prentice-Hall/Pearson Education, Upper Saddle River, New Jersey, 2003 amended reprint.)

Quite a few work tasks require finely controlled handling of delicate objects and instruments, such as in repair and assembly work. Exact manipulations are done most easily at about elbow height, in front of the chest and close to the body, which allows steady and secure arm and hand motions; see Figure 20.12. Also, this location facilitates good visual control because it is at a close viewing distance with at a well-declined angle of the line of sight.

Repeated reaches, such as in assembly work, are easy if the supply bins are carefully set along the periphery of hand–arm movements, as shown in Figure 20.13. In addition to the bin, tools needed for the job may be hung close by, as Figure 20.14 illustrates, so that the worker can pull them in and simply release them when no longer needed.

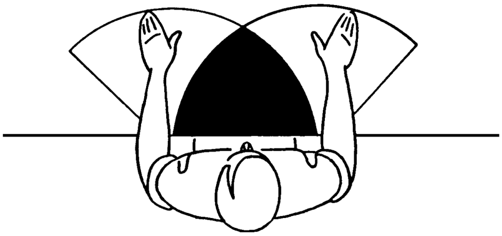


FIGURE 20.12 Work area suitable for finely controlled manipulation. (Adapted from International Labour Office, *Introduction to Work Study*, third ed., International Labour Office, Geneva, Switzerland, 1986.)

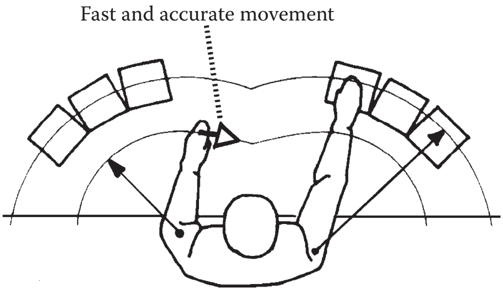


FIGURE 20.13 Supply bins placed along the area of easy reach.

FIGURE 20.14 Workplace arrangement of tools and bins. (Adapted from International Labour Office, *Introduction to Work Study*, third ed., International Labour Office, Geneva, Switzerland, 1986.)

20.4 Displays and controls

Most of us have learned, through trial and error, to steer a bicycle where we want to go. It is easy to control its direction by simply turning the handlebar to make the front wheel point to where we want to be; it is easy to control its speed by pedaling faster or more slowly; and it is easy to see the path that we are going to take. The relations between the control and the surrounding are more complicated in most technical systems. In an automobile, for example, there are several controls to determine its movement, and the results of our control actions show on gauges and through the windows. It takes much longer to learn how to drive a car than to ride a bicycle, and the results of faulty control actions or misreading a display can be severe. Other human–machine systems are even more convoluted, such as guiding a large ship into a tight harbor. A power plant is run from the control room in abstract ways by pushing buttons and turning knobs, and its functioning is solely displayed via gauges, as Figure 20.15 illustrates. Aircraft cockpits are among the most complex human factors design tasks since they involve many controls and displays. Figure 20.16 sketches the multitude of controls and displays in a large airplane; not surprisingly, the pilots have found ingeniously simple ways to mark objects of specific concern.

Coding° of controls helps to identify them, to point out how to operate them, to indicate the effects of their activation, and to show their status. The major coding practices employ

- Shape: Appeals to both vision and touch—see Figure 20.17
- Location: Indicates importance and sequence of operation
- Size: Makes operation fast and easy

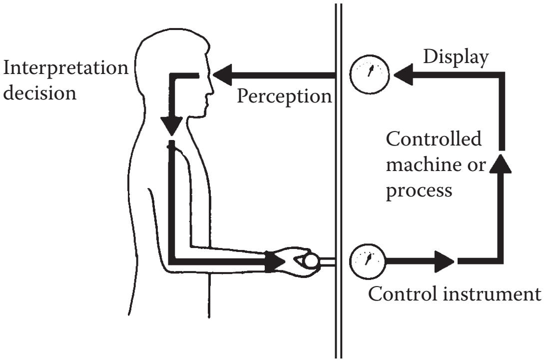


FIGURE 20.15 Operating a system through activating a control and reading a display.

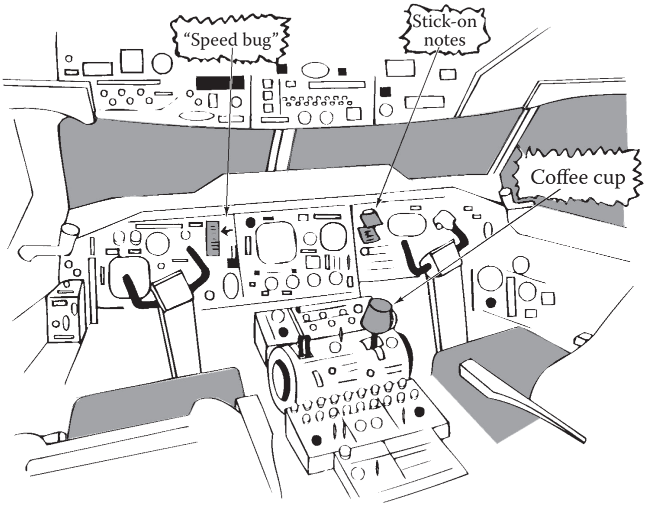


FIGURE 20.16 Aircraft cockpit with improvised markers. (Adapted from Kroemer, K. H. E., Kroemer, H. B., and Kroemer-Elbert, K. E., *Ergonomics: How to Design for Ease and Efficiency*, second ed., Prentice-Hall/Pearson Education, Upper Saddle River, New Jersey, 2003 amended reprint.)

- Mode of operation: Such as pushing, turning, or sliding
- Color: Effective when lit
- Labeling: Effective when read

Often, several of these coding techniques are used together. In a car familiar to the driver, one is used to finding controls by their location and by their feel (produced by shape and size);

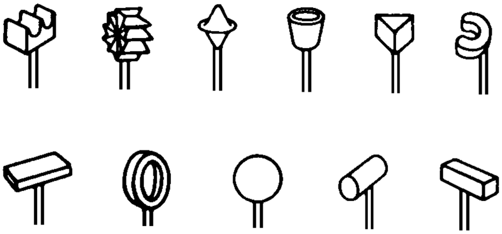


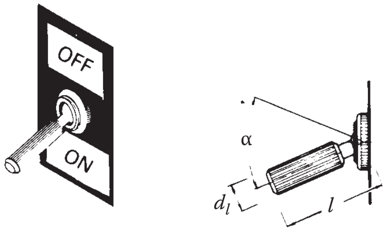
FIGURE 20.17 Easily distinguished control shapes. (Adapted from Kroemer, K. H. E., Kroemer, H. B., and Kroemer-Elbert, K. E., *Ergonomics: How to Design for Ease and Efficiency*, second ed., Prentice-Hall/Pearson Education, Upper Saddle River, New Jersey, 2003 amended reprint.)

having to look for them means wasting attention that should be paid to the road and the traffic.

A bar knob, shown in Figure 20.18, is easy to grasp and operate (if of proper dimensions) and by, virtue of its shape, indicates its setting. A toggle switch, shown in Figure 20.19, is also easy to grasp and operate, but it has only two or three possible settings. A rotating knob, shown in Figure 20.20, is handy as well, but its setting is not obvious unless a special indicator points it out. It can have more settings than a toggle or a bar

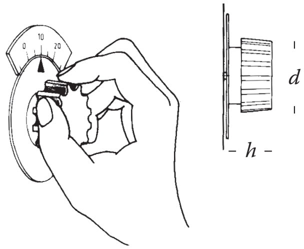
l = minimum 25 mm
b = maximum 25 mm
h = 12–70 mm
Resistance 13–18 N

FIGURE 20.18 Bar knob.



α = 45°
d = 3–25 mm
l = 12–50 mm
Resistance to operation
2.5–15 N

FIGURE 20.19 Toggle switch.



d = 35–75 mm
h = 20–50 mm
Max. torque = 320 N cm
Resistance 12–18 N
Angle for each step 15–40°

FIGURE 20.20 Rotary knob.

control, and the settings can be continuous or in steps. Push buttons are fast-operated controls, but they usually have only two settings, which may be difficult to distinguish.

Altimeters, instruments in aircraft to indicate the flying height, have been notorious for being difficult to read, for being easily misread, and for causing numerous emergencies and crashes. Figure 20.21 shows a 1960 model, improved from previous designs: it is still complex, and the pointer can still cover the counter windows.

Figure 20.22 lists the use characteristics of three indicator techniques: moving pointer over fixed scale, fixed pointer over moving scale, and digital counter. The main advantage of the moving pointer is that its motion catches the eye and conveys information about both the magnitude and the direction of change. The advantage of a fixed marker over a moving scale is that a large range can be covered, with only the currently used section appearing in the window. The digital counter is particularly good for exact readings, as Figure 20.23 shows.

When comparing moving-pointer displays, such as in Figure 20.24, the location of numbers and scale marks can make a

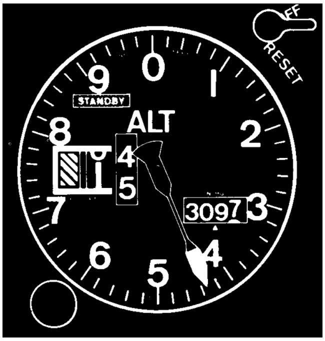


FIGURE 20.21 Aircraft altimeter, 1960 model.

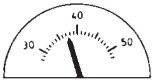
Type of display	 Moving pointer	 Fixed marker moving scale	 Counter
Ease of reading	Acceptable	Acceptable	Very good
Detection of change	Very good	Acceptable	Poor
Setting to a reading: controlling a process	Very good	Acceptable	Acceptable

FIGURE 20.22 Pointer and counter displays.

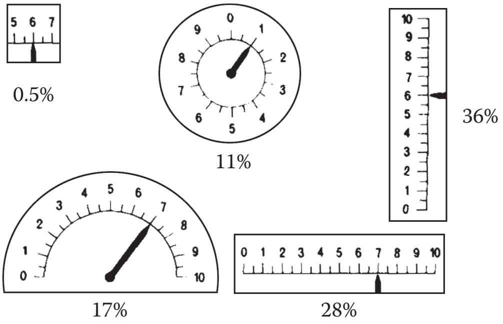


FIGURE 20.23 Reading errors with counter and pointer displays.

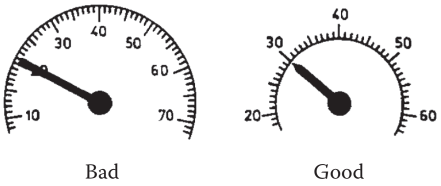


FIGURE 20.24 Two designs of a moving-pointer display.

big difference: in a bad design, the pointer obscures numbers and scale indications, whereas in a better design, numbers and marks are outside the field over which the pointer moves, and the tip of the pointer just touches the scale markers.

Often, exact information, such as a numerical dial presents, is not needed; all the observer has to know is whether

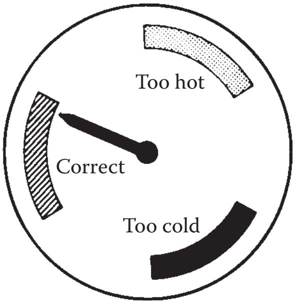


FIGURE 20.25 Status display: too hot, correct, too cold.

a condition is normal or either below or above. Figure 20.25 presents such a simple but effective gauge. The display may be made even more effective with signal colors, such as green for normal, blue for cold, and red for hot. The designer must keep in mind, however, that the meanings of colors may be different for persons with various cultural roots. Humans do differ; that fact makes ergonomic research exciting and human factors engineering interesting.

Summary

Human-centered design follows these guidelines°:

Consider	In order to
Human body size	Establish the dimensions of workspace, equipment, and tools to accommodate the human body.
Human strength	Facilitate exertion of strength (work, power) by object location and orientation.
Human speed	Place items so that they can be reached and manipulated quickly.
Human effort	Arrange work so that it can be performed with least effort.
Human accuracy	Select and position objects so that they can be manipulated and seen with ease.
Importance	Place the most important items in the most accessible locations.
Frequency of use	Place the most frequently used items in the most accessible locations.
Function	Group items with similar functions together.

Sequence of use	Lay out items that are regularly used one after the other in that sequence.
Human safety and comfort	Arrange all details to assure that the human will not be injured, will not suffer health consequences, but instead will be secure and feel comfortable.

Notes

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

20.1 Sizing the workplace to fit the body:

Anthropometric data: See Chapter 1 of this book.

20.2 On the feet or sitting down:

Seat features: See Chapter 18 of this book.

20.3 Manipulating, reaching, grasping: sizes of the following:

Doors, hatches, passageways: Kroemer, Kroemer, and Kroemer-Elbert 2003.

Line of sight: Discussed in Chapters 5 and 11 of this book.

20.4 Displays and controls

Coding of controls: Freivalds 1999; Kroemer, Kroemer, and Kroemer-Elbert 2003; MIL.-Std 759, 1472, and others.

Human-centered design, guidelines: More conceptual information in handbooks such as the following:

- Human Factors and Ergonomics Society 2004
- Karwowski, Soares, and Stanton 2011
- Marras and Karwowski 2006a
- Kroemer 2006c
- Kroemer, Kroemer, and Kroemer-Elbert 2003
- Nagamachi 2011
- NASA 2015
- Pew and Mavor 2007
- Salvendy 2012
- Stanton et al. 2005
- Wilson and Sharples 2015

Ergonomics books with practical orientation are listed at the end of Chapter 24.

CHAPTER TWENTY-ONE

Load handling

We all "handle" loads daily. While packing, moving, and storing objects we lift, lower, hold, carry, push, pull, drag them. The load may be soft or solid, bulky or small; it may come as bags, boxes, containers. We handle objects occasionally or repeatedly during leisure activities, but often as part of our occupational work. On the job, the ergonomic design of loads, containers, and workstations can help to avoid overexertions and injuries, as instructions should do and training on how to lift properly. For some jobs, the selection of persons who are physically capable of strenuous material handling may be considered.

If done on the job, the activities are often labeled *manual material(s) handling*—an exemplary tautology because the Latin *manus* means "hand."

21.1 Material handling strains the body

Material handling is among the most frequent and often severe causes of injury all over the world, with strains in the low back prevalent°. The direct and indirect costs are enormous, and the human suffering associated with, for example, back injuries, is immeasurable.

Stress by material handling

Bending, stretching, reaching, or otherwise moving just our own body requires muscle tensions and loads body joints. The manipulation of even lightweight and small objects adds strain especially if done often. Heavy and bulky loads pose additional strain on the body because moving more mass requires more force from us (Newton's second law°), which is even more demanding if we must do so in awkward body configurations.

External and internal forces

Exerting force and energy for moving an object with the hand(s) strains the hands, the arms, the shoulders, the trunk, and often the legs. Lifting or lowering, pushing or pulling, or carrying loads essentially stresses the same parts of the musculoskeletal system, but obviously the directions and the magnitudes of the external and internal force vectors are different.

Pains related to lifting

The primary area of physiological and anthromechanical concern is the back, particularly the lumbar spine area. Any contraction of the longitudinal trunk muscles compresses the spinal column, the only load-bearing structure of the trunk (see Chapter 2). This strains the spine, primarily its disks and facet joints of the vertebrae; yet all spinal connective tissues (ligaments and cartilage as well as muscles with their tendons) may experience insults, sprains, or trauma. Therefore, references to "low back pain after lifting" appear often in conversations and in writings.

Strainful activities

Weight lifting generates such musculoskeletal strain, but it also occurs in other sports and in many leisure and occupational activities. Most of the time, we exert energy intentionally toward an outside object, but our body may be subjected to external energy unexpectedly, such as when we catch an object or catch ourselves if we are about to slip or fall. The strain can be static, when we hold a load and keep our body still, or it may be dynamic with fast or slow onset and of short or long duration. The strain may be single or consist of several events; if the same or similar strains reoccur, that repetition may lead to cumulative trauma disorders, discussed in Chapter 11.

21.2 Body capabilities related to load handling

Strength is individual and situational

Material handling, such as lifting and lowering, pushing and pulling, requires our body to exert energy. The energy needed to do these tasks must be generated within the body by its musculature and then exerted in terms of force or torque over time to the outside object. Such strength capabilities depend on our individual fitness and on situational conditions° like body stance, as discussed in Chapters 3 and 4. Figures 3.7 and 3.8 in Chapter 3 show examples of static push and pull forces measured under experimental conditions set up so that the subjects kept their bodies still while they exerted one-time maximal efforts. In reality, however, usually people actually move their bodies and external loads dynamically, often repeatedly.

Back overexertions

The exertion of muscle strength while lifting, lowering, pushing, pulling, carrying, and dragging loads are dynamic efforts, often in the form of heavy work (see Chapter 10). A major concern is the associated wear and tear on the back, which can overexert spinal structures, especially of the lumbar intervertebral disks. Low back pain° (LBP) reduces one's mobility and vitality; it often leads to long absences from work and appears in North American and European statistics as one of the main causes of early disability. LBP is common even in younger age groups, and certain occupations are particularly prone to suffer from it: nurses, laborers, farmers, baggage handlers, and warehouse workers frequently suffer from back disabilities. Overexertion injuries, especially in the lower back, account for about one-quarter of all reported occupational disabling cases in the United States; some industries report that more than half of all injuries are due to overexertion. Accident and health statistics in the United Kingdom and Germany, for example, show similar figures. Clearly, low back strain is among the most common causes of injury and disability in many industrial populations.

Spinal loading

Many LBP victims cannot pinpoint when their back problems started: there was not a certain moment or a specific action when pain appeared; rather, it developed slowly until it was strong enough to be troublesome, even to disable. As we look at a person freely standing, the healthy spinal column has a slim S shape when upright, seen from the side, as shown earlier in Chapter 2. The spinal facet joints provide bone-on-bone mobility and sturdy load transmission; the intervertebral disks provide both elasticity and mobility. As we consider the body weight from the head down, it becomes obvious that the loading of spinal segments increases from the neck downward; it is greatest near the bottom, in the lumbar area. Just keeping the upper body in balance requires tensioning the muscle in the trunk, which compresses the spine. Weights carried, hand/arm/shoulder/trunk forces, and motions intensify compression, bending, and twisting strains of the spinal column.

Slipped disk

The spinal disks separate the vertebrae and provide shock absorption and flexibility. Disk degeneration occurs with aging and from repeated motions: A sudden overload can easily lead to an acute injury, especially when aging and wear come together. Disk degeneration primarily affects the outer layers; fluid loss can make the fibrous ring brittle and fragile. At first, the degenerative changes mostly make the disk flatter, which reduces shock absorption and mobility of the spine. In this case, even small actions such as lifting just one's own body or a light load or a slight stumble or a similar incident may bring disk injury and severe back pain. The progressive degeneration of the disk and/or a sudden load can cause disk herniation, when a rupture of its fibrous ring allows a bit of the gel-like nucleus to seep through under a sudden compression force. Such damage narrows the space between vertebrae and generates tension in muscles and ligaments of the spine, and the deformed part can generate pressure on spinal nerves. These occurrences can bring about a variety of discomforts, of pains and aches, and may result in such disabling health problems as lumbago and sciatica.

Biomechanics of disk loading

Figure 21.1 illustrates, in simple terms, a biomechanical approach° to approximate the conditions of disk pressure:

> The external load L pulls downward. The (upper) body weight W acts downward as well. The distances l and w are the lever arms of load and weight to the point of support (the fulcrum of the system) at a disk of the spinal column. The forces L and W exert the moments $L \times l$ and $W \times w$. Counteraction comes mostly from muscles that attach to the spinous processes of vertebrae: together they produce force M. It uses its lever arm m to the fulcrum to generate the moment $-M \times m$. (The minus sign indicates torque in the direction opposite to the torques due to W and L.) The upright force C at the spinal column keeps the system in place.
>
> The system is in balance when these descriptive equations apply:
>
> Sum of moments: $M \times m = L \times l + W \times w$; therefore
>
> $M = (L \times l + W \times w) / m$.
>
> Sum of forces: $C = L + W + M$.
>
> Assume the external load L to be 100 N, and its lever arm, 25 cm; the upper body W, at 500 N with a lever of 15 cm; the lever arm m of the muscle force is five cm: With these assumptions
>
> the muscle force M is 2000 N and
> the column force C is 2600 N.

In this example, the relatively large muscle force M (here: 20 times the external load) and the huge column compression force C (26 times the external load) primarily result from

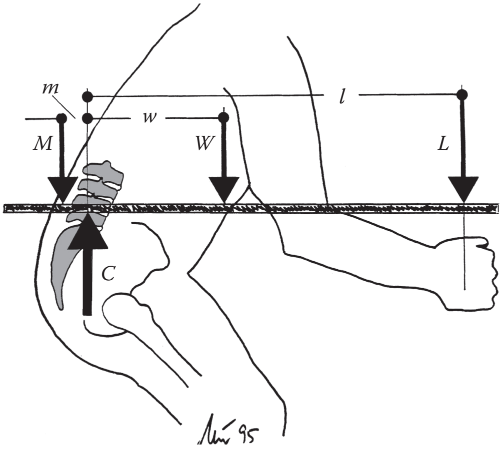


FIGURE 21.1 Anthromechanical model for calculating musculoskeletal back loading due to lifting.

the disadvantageously short lever arm *m* of the muscle *M*. That lever is anatomically determined, so we cannot change it—but the external load *L* is under our control, both in magnitude and in location relative to the body.

Both back muscle force *M* and column compression force *C* diminish as *L* and *l* get smaller—so *reduce the external load and keep it close*. *M* and *C* get even smaller if we *keep the body more upright* (which reduces *w* and also *l*) and if we decrease upper body weight *W*—so *slim down that belly*.

Such simple anthromechanical° considerations demonstrate that the following admonitions decrease the risks to connective spinal tissues and to the column:

- Keep the external load small.
- Keep the external load close to the body.
- Keep the upper body upright.
- Get rid of excess upper body weight, including belly protrusion°.

21.3 Assessing load handling capabilities

Everyday experience and formal epidemiological studies have long demonstrated the expected relations: the level and the dose of strain caused by load handling determine incidence and severity of injuries. Naturally, the abilities to tolerate load handling strain differ among individuals. Physiology, biomechanics, and psychophysiology provide disciplinary approaches that can be used, often in combination°, for assessing individual and population capabilities.

Intervertebral disk loading

Around 1970, researchers were able to measure the pressure inside intervertebral disks as affected by body postures and holding loads. Figure 21.2, based on one of the early studies, illustrates the changes in strain on the disk between the third and fourth lumbar vertebrae in various postures. Compared to no-load upright standing, standing straight with 10 kg of weights in each hand naturally increases the disk pressure; holding the weights while standing with bent knees and a bend in the back further increases disk loading. Yet the largest pressure occurs when the 20 kg are held with locked legs and a round back. Other researchers repeated theses studies and found essentially the same result: a bent or a twisted back causes higher and possibly dangerous pressure on the intervertebral disks° than a straight back. Bending the back leads to heavy pressure on the front edge of the disk where it also

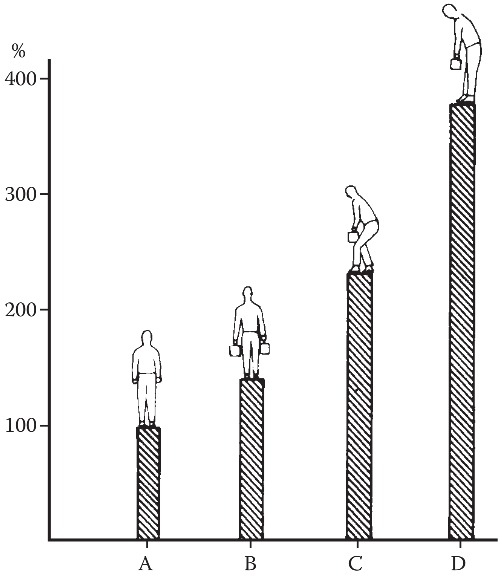


FIGURE 21.2 Strain on the disk between the third and fourth lumbar vertebrae with the body in various postures without weights and while holding weights of 20 kg. (Adapted from Nachemson, A., and Elfstroem, G., *Scand J Rehabil Med*, 1, 1–40, 1970.)

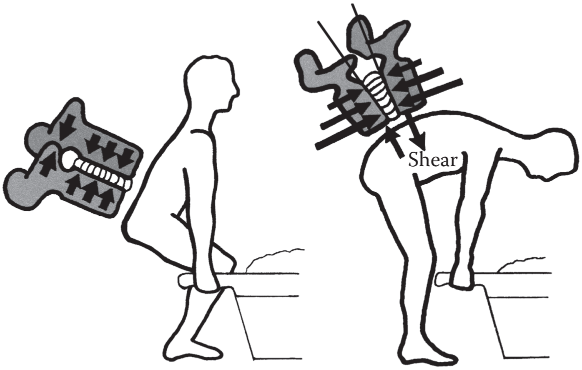


FIGURE 21.3 Diagram of typical spinal loading when lifting with straight and bent back.

generates shear, as Figure 21.3 illustrates. Straightening the back eliminates shear, makes the facet joints carry some of the compressive load, and distributes the compression forces more evenly over the disk surface, all of which reduce the risk of damage.

Lift strength

While measuring a person's lift strength, we must make sure that the person fully cooperates but is not in danger of an injury during the test. (The concept of a "maximal voluntary contraction" is discussed in Chapter 3.) Chapter 4 explains that strength capabilities are both individual and situational. Until about the middle of the twentieth century, information about human lifting capabilities relied largely on measurements of static (isometric) "upward" body strength. Into the 1980s, such static "lift" assessments were the basis for rather simplistic (and in some cases surprising) statements about loads which, supposedly, men, women, and even children (!) could lift safely°.

Psychophysiology

Compared to static tests, designing and controlling experiments with realistic dynamic strength exertions is much more complicated°. In these tests, the subject decides how much effort to exert; this includes the complex task of judging° (often unconsciously) the perception of how strenuous the test is. This judgment relies partly on experience and mostly on integrating internal feedback about various physiological (muscular, circulatory, metabolic, etc.) body functions° involved in the effort. Based on this assessment, the subject decides what amount of strength or energy she/he is willing to exercise over a given time, say 10 minutes or eight hours, without endangering or exhausting oneself. Such "psychophysical" experiments have been conducted to assess tasks done particularly in industrial material handling° and by firefighters and soldiers and nurses.

21.4 NIOSH's lifting and lowering guidelines

Starting in the late 1970s, the U.S. National Institute of Occupational Safety and Health (NIOSH)° began developing guidelines for lifting and lowering. The NIOSH combined several disciplinary approaches:

Biomechanics Biomechanical criteria are based on muscle strength and tissue tolerances. They include assessments of load-bearing capabilities of spinal joints (see Chapter 2) and of static and dynamic strength (see Chapters 3 and 4). Prominent among the physical criteria used to develop guidelines was the highest acceptable disk compression in the lumbar spine—see the anthromechanical case discussed earlier. NIOSH uses 3.4 kN as the maximally allowable disk compression force.

Physiology NIOSH used physiological criteria primarily to prevent whole body strain and fatigue. Important task characteristics concern the location of the external load and the duration of the work, especially the frequency of work and the work/rest pattern. NIOSH uses the following limits for energy expenditure (see Chapter 10): 50% of VO_2max for up to one hour of continued work; 40% of VO_2max for one to two hours of continued work; 33% of VO_2max for two to eight hours of continued work.

Psychophysiology Human perception appears to be able to integrate anthromechanical and physiological demands. Based on psychophysical studies conducted in the United States, NIOSH recommends that the job should be acceptable to most of the exposed population.

In summary, the limiting criteria used by NIOSH are:

- Biomechanical for high loads and low handling frequency
- Psychophysiological for moderate loads and low to moderate handling frequency
- Physiological for low loads and high handling frequency

NIOSH weight limits

The NIOSH guidelines apply to the following:

- Smooth lift (no jerking)
- Two-handed lift
- Load width below 75 cm
- Unrestricted posture
- Good foot traction
- Suitable environment with low humidity, appropriate temperature, good lighting

The latest NIOSH° guidelines contain recommended weight limits (RWLs) that 90% of U.S. industrial workers, male or female, may lift or lower. The maximal weight is 23 kg, under optimal conditions. However, optimal conditions are rare; therefore, the load should usually be lower, as determined by several factors, which include:

- The start and end points of the paths of the hands
- Whether or not the action is in front of the body
- The frequency of the lifting and lowering actions
- The quality of coupling between hand and load

These and some other factors become multipliers in an equation by which one calculates the RWL that applies under the given conditions°.

21.5 Liberty Mutual's material handling guidelines

At about the same time when NIOSH developed its guidelines, Snook and Ciriello at Liberty Mutual Insurance Company conducted psychophysical tests with U.S. workers to determine the efforts that they were willing to exert in pushing and pulling, in carrying and in lifting and lowering loads.

Acceptable forces and weights

The research primarily used psychophysical methodology but also included measurements of oxygen consumption, heart rate, and anthropometric characteristics. The subjects controlled either the weight of the objects or the force that they applied; all other task variables, such as frequency, size, height, distance, etc., were selected by the experimenter. During the experiments, the subjects monitored their own feelings of exertion or fatigue; accordingly, they adjusted the weight or force so that they would work as hard as they could without straining themselves, without becoming unusually tired, weakened, overheated, or out of breath. The results of the tests were compiled into tables of maximal weights and forces acceptable to 10%, 25%, 50%, 75%, 90% of the male and female U.S. population°.

Females versus males handling loads

The Liberty Mutual tables on lifting, lowering, pushing, pulling, and carrying provide data about the capability and the limitations of U.S. workers, grouped by females and male (available at http://www.libertymmhtables.libertymutual.com).

Some related findings are as follows:

- Bending—Any task that begins or ends with the hands below knuckle height presents some risk. The deeper the bending motion, the greater is the physical stress on the low back. Frequent bending regardless of weight is not recommended.
- Twisting—This motion puts uneven forces on the back, generating additional physical stress. The greater the twist, the more physically stressful the task.
- Reaching—The distance away from the body that a load is held greatly affects the forces on the back, the shoulders, and the arms. The farther the reach, the more physically stressful the task.
- One-handed lifts—The tables cannot be used to evaluate one-handed tasks. By nature, these tasks place uneven loads on the back and present a greater physical stress than two-handed lifts.
- Catching or throwing items—The tables cannot be used to evaluate these types of tasks. Any tasks involving catching or throwing items are physically stressful and, therefore, are good candidates for redesign.

Comparing NIOSH and Liberty Mutual guidelines

Altogether, there is a good overlap and fair agreement between the recommendations for lifting and lowering. If there is a difference, a prudent choice is to use the lower value. The NIOSH values are unisex, while Snook and Ciriello at Liberty Mutual considered female and male workers separately. Both sets of recommendations indicate, as to be expected, that high loads, far reaches, repetition, and deep bending or twisting of the body reduce the acceptable efforts. Both sets of recommendations indicate that the way of coupling between hand and load codetermines how much people are willing to exert. Missing handles, sharp edges, or objects that are so wide that they are difficult to grasp° reduce the acceptable load values.

The recommendations compiled by NIOSH and Liberty Mutual Insurance Company apply to North Americans. Other populations may have different body builds and strength characteristics; their work tasks, their customs and procedures at work, and their working conditions are possibly quite different. Consider these circumstances and local/regional/national codes, standards, or regulations.

21.6 Designing for easy load handling

The spinal column is the only solid structure in the upright human rump that keeps the rib cage from falling into the pelvis. Even without external load, a bent back generates shear in the disks and heavy pressure on their front edge and so creates the risk of damage, even rupture of the disk. Furthermore, bending and twisting the body increases the strain on the spinal column and its connective tissues. Straightening the back to its natural curves (see Figure 2.8) eliminates shear, makes the facet joints carry some of the compressive load, and distributes the compression forces more evenly over the disk surface, all of which reduce the risk of injury.

Intraabdominal pressure and lift belts

Lifting, lowering, or carrying commonly produces considerable increases in the pressure within the abdominal cavity, naturally accompanied by contraction of the abdominal muscles. The resulting intraabdominal pressure° helps to stabilize the trunk and reduces the loading of the spinal column and its supporting structures. That observation of increased intraabdominal pressure led to the idea to put a stiff belt around the trunk, with the purpose of helping competitive weight lifters and material handlers to avoid back problems. However, investigations have shown that the back belts are often ineffective°: they cannot replace proper ergonomic solutions that, at best, avert the need for material handling, or at least, make it easier. Incidentally, even weight lifters who wear belts often suffer injuries.

Making load handling easy

Machines do not have backs to hurt; therefore, load handling, especially lifting and lowering, is better performed by machinery than by people, as sketched in Figures 21.4 and 21.5. If humans must do the job, the most effective way to avoid lifting and lowering is to convert those activities into carrying, or even better, into pushing and pulling. Carrying is best done on both

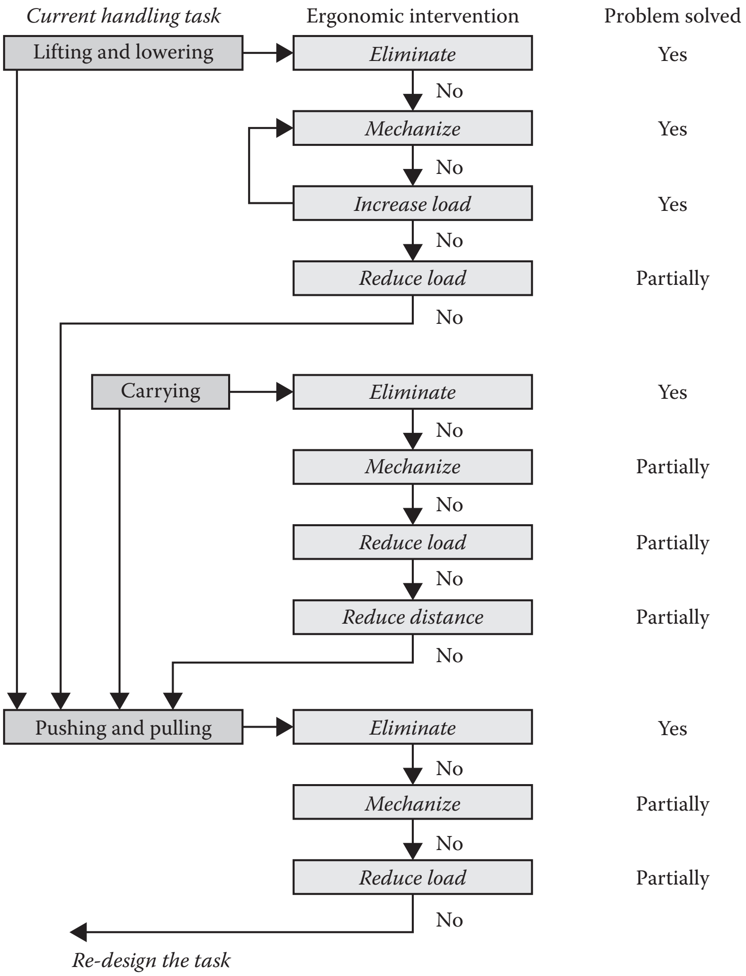


FIGURE 21.4 Convert lifting to carrying or, better, pushing or pulling. (Adapted from Kroemer, K. H. E., *Ergonomic Design of Material Handling Systems*, CRC, Boca Raton, FL, 1997.)

shoulders with a yoke, depicted in Figure 21.6. Of course, dollies or carts, as in Figure 21.7, can take over the carrying job, converting it into the least risky load-handling category, pushing and pulling. If a person has to generate the needed push or pull, rollers as shown in Figure 21.8, conveyors or similar ways to facilitate the motion are among the technical solutions of choice.

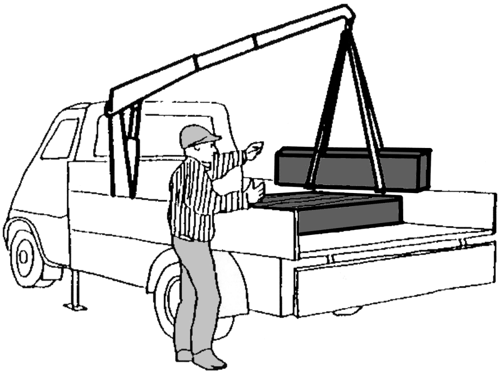


FIGURE 21.5 Let machines lift loads.

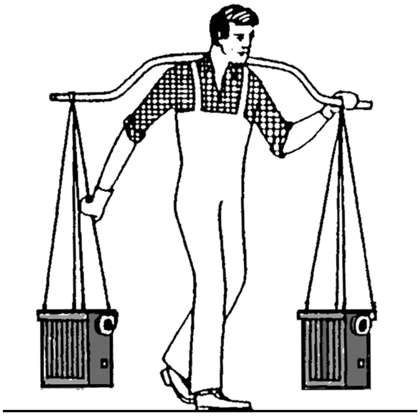


FIGURE 21.6 Carrying is best done with a yoke on the shoulders. (Adapted from International Labour Office, *Maximum Weights in Load Lifting and Carrying, Occupational Safety and Health Series #59*, International Labour Office, Geneva, Switzerland, 1988.)

Learning to lift safely?

It seems that one should be able to learn not to awkwardly lift objects from the floor (as in Figure 21.9) but more safely between one's legs (as shown in Figure 21.10) or, better still, pick them up from an elevated storage place (as in Figure 21.11). Likewise, it should be possible to learn to do lowering, carrying, pushing and pulling, and other manual material handling in safe ways. For example, one should learn not to exert strong force with the body twisted or the trunk severely bent, or in

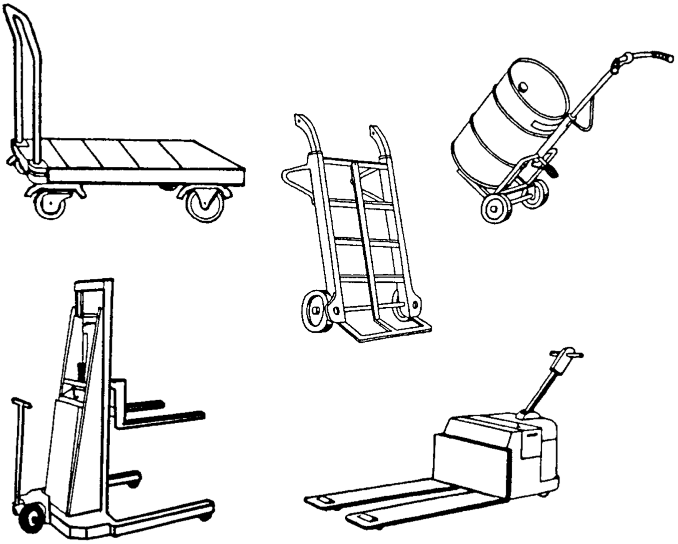


FIGURE 21.7 Using dollies and carts instead of carrying loads.

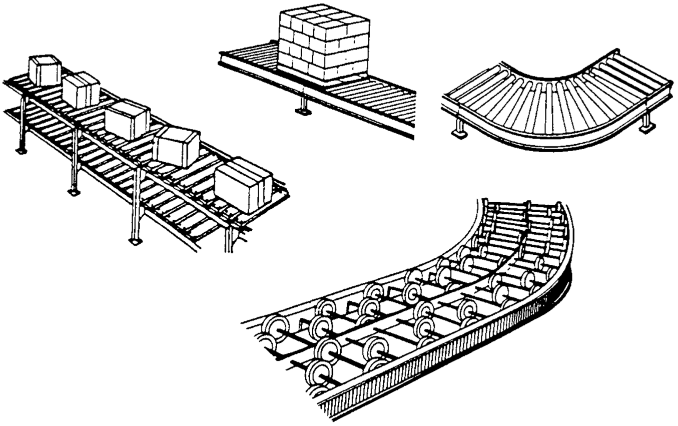


FIGURE 21.8 Rollers and conveyors make load moving easy.

sudden movements. It should be natural to use such simple advice, but apparently, it is also human nature to not always follow the proper ways. Numerous agencies and commercial outfits have developed systematic and often rather sophisticated courses for instructing nurses, warehouse workers, miners, and masons, to mention a few, to perform material handling in safe ways. Unfortunately, many surveys and systematic evaluations of the outcomes of such instructions have shown that a

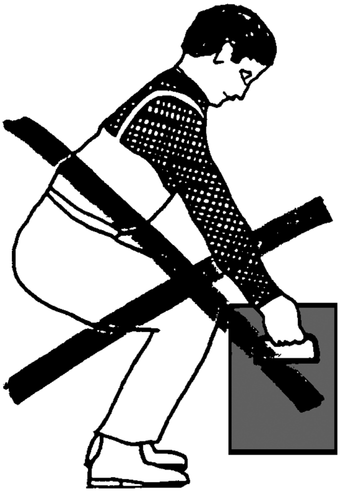


FIGURE 21.9 Do not lift while awkwardly bending.

FIGURE 21.10 Try to lift a load between your legs. (Adapted from International Labour Office, *Maximum Weights in Load Lifting and Carrying, Occupational Safety and Health Series #59,* International Labour Office, Geneva, Switzerland, 1988.)

large number of injuries occur even after proper load handling techniques were taught. Hence, it appears that instructions and training are much less effective, if they are successful at all°, than proper task engineering° to totally eliminate risks of overexertion and injury. Therefore, "take the hands out of load handling" is good advice.

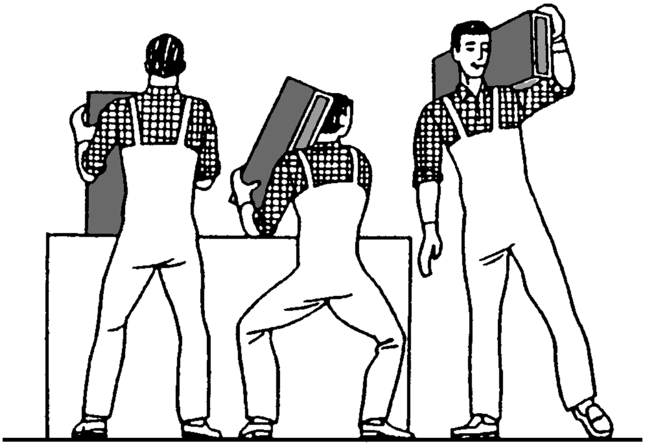


FIGURE 21.11 Take loads from an elevated location, not from the floor. (Adapted from International Labour Office, *Maximum Weights in Load Lifting and Carrying, Occupational Safety and Health Series #59*, International Labour Office, Geneva, Switzerland, 1988.)

Summary

The human body is vulnerable to overexertion and injury by load handling. Damage often occurs to the musculoskeletal elements of the lower back. Efforts to educate load handlers in proper and safe procedures are commonly less effective than desired. The only truly successful way to avoid human injury is to design out the risk as Figure 21.12 shows schematically.

Lifting and lowering, usually the most risky activities, should best be eliminated altogether. If that is impossible, mechanization of the task avoids human involvement; mechanization might become economically attractive if the load is increased, for example, by packaging several heavy items together. The opposite action, reducing the load, is appropriate if human involvement cannot be avoided.

Carrying is also likely to lead to injuries. It is best to totally eliminate the task; if that is not possible, the mechanization of the transporting might be feasible (possibly also with bundled loads). If humans must do the carrying, the load and the distance should be kept minimal.

Pushing and pulling are better techniques than lifting, lowering, and carrying loads; yet even pushes and pulls can still cause overexertions and should therefore be eliminated or at least done by machinery. If humans must push and pull, the loads should be kept low.

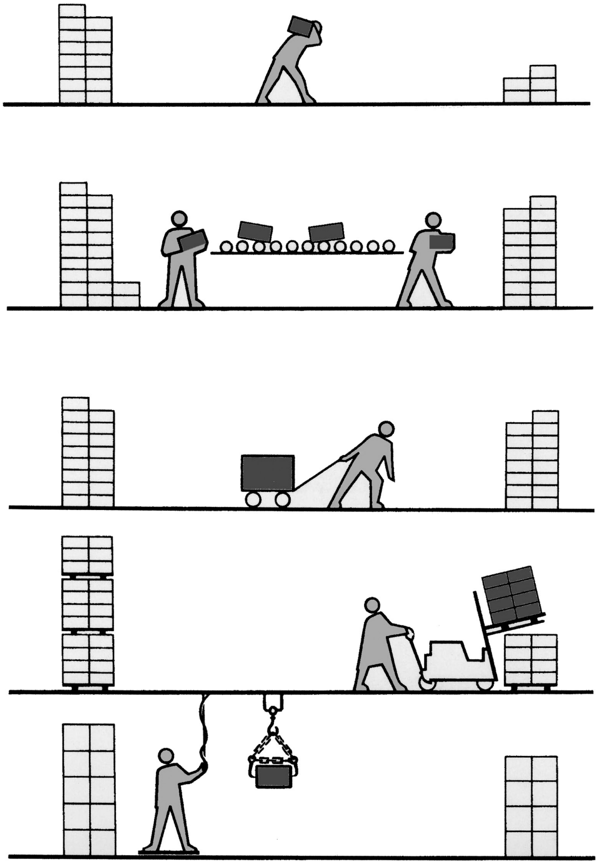


FIGURE 21.12 Let machinery do the heavy work—otherwise, make handling tasks easier.

Notes

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

21.1 Material handling strains the body:

Strains in the low back area most frequent: Garg and Marras 2014; Marras and Karwowski 2006b; Snook 2000.

Leading causes of workplace injuries: Liberty Mutual Insurance Company Newsletter Winter 2013/14. www.libertymutual.com.

Newton's second law: Force = mass × acceleration.

Low back pain: Deyo and Weinstein 2001; Marras 2008; Snook 2000; Violante, Armstrong, and Kilbom 2000.

Anthromechanical consideration: Kroemer 2007.

Belly protusion: Marras 2008.

21.2 Body capabilities related to load handling:

Individual and situational strength: Daams 1993, 2001; Kumar 2004, 2007.

Low back pain: Deyo and Weinstein 2001; Snook 2000; Violante, Armstrong, and Kilbom 2000.

Biomechanical approach: Chaffin, Andersson, and Martin 2006; Kroemer 2010; Kumar 2004; Marras and Karwowski 2006a; Oezkaya et al. 2012; Zhang and Chaffin 2006.

21.3 Assessing load handling capabilities:

Combinations of measurement methods: Dempsey 1998, 2006; Kumar 2004; Stanton et al. 2005.

Disk pressure: Chaffin, Andersson, and Martin 2006; Kumar 2004; Marras and Karwowski 2006.

Loads that, supposedly, men, women, and even children could lift safely: International Labour Office 1988.

Dynamic tests are more complicated than static tests: Astrand et al. 2004; Kroemer 1974, 1999; Marras and Karwowski 2006a; Winter 2009.

Judging the strenuousness of the task: Dempsey 1998, 2006; Snook 2005; Snook and Ciriello 1991.

Industrial material handling: Kroemer 1985.

Physiological body functions involved: Mostly metabolic and circulatory events, see Chapter 10 of this book.

21.4 NIOSH's lifting and lowering guidelines:

NIOSH: Colombini et al. 2012; Lu 2012; NIOSH 1981; Waters 2006; Waters and Putz-Anderson 1999.

RWL that applies under the given conditions: Since the guidelines are subject to updating, check the newest NIOSH and Occupational Safety and Health Administration information.

21.5 Liberty Mutual's material handling guidelines:

Acceptable to … percentage of the male and female U.S. population: Ciriello 2001, 2007; Ciriello et al. 1999;

Liberty Mutual regularly updated on http://www.libertymutual.com; Snook 2005; Snook and Ciriello 1991.

Objects that are difficult to grasp: Ciriello 2001, 2007; Kroemer 1997.

21.6 Designing for easy load handling:

Intraabdominal pressure°: Easily measured by swallowing a capsule that contains a pressure-sensitive element.

Back belts are often ineffective: McGill 2006.

Instructions and training: Black et al. 2011; Kroemer 1997; Kroemer, Kroemer, and Kroemer-Elbert 2003; Kurowski, Buchholz, and Punnett 2014; Lavender 2006; Martimo et al. 2008.

Proper task engineering: Ramsey et al. 2014.

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CHAPTER TWENTY-TWO

Healthcare for patients and providers

In recent years, great advances have been made in understanding, diagnosing, and treating health disorders and the effects of accidents and aging. This progress goes hand in hand with headway in medical technology and management of emergency and routine healthcare procedures.

In the United States, nearly 5,700 hospitals° were registered in 2013 with more than 900,000 beds, down from 1.5 million in 1975. These hospitals had about 75 million patient admissions per year and about 5 million employees. In addition, 21,000 nursing homes and residential care facilities employed approximately 2.8 million workers.

Healthcare has traditionally adopted roles and rules° that differ from those of other businesses; above all, there is the overriding mission of helping people in need; such ethical concern can create the conviction of knowing best what is good for others regardless of cost, and it may result in the attitude that achieving these goals justifies work practices for care providers, which exceed or disregard accepted rules elsewhere. However, during the last decade, it became increasingly recognized that even the "semi-gods in white and their assisting angels" should limit their working hours for their own sake and for the good of their clients, count their work tools at the conclusion of an operation to make sure that no items are left where they should not be, use checklists to make sure that hygienic procedures are followed, and employ managing procedures commonplace in other professions.

Consequently, special emphasis is placed on the contributions of specialists in ergonomics/human factors engineering to the improvement of patients' quality of care and their safety, as well as to the improvement of care providers' working conditions and their safety at work. The field of applications is wide and the development is in flux, so the following text contains lists of topics, long but certainly still incomplete, and comments as well as proposed solutions that may serve as examples of progressive procedures°.

22.1 Patient care and safety

It is particularly in the interest of patients to have ergonomics/human factors inputs regarding

- Ambulatory care
- Emergency medical services (EMS)
- Emergency room treatment
- Operating room procedures
- Intensive care provisions
- Patient handover
- Recovery and stay room care
- Beds, wheelchairs, and other equipment
- Nursing home care
- Patient handling
- Care environments
- Home healthcare

22.2 Care staff performance and safety

Of course, in each of the listed topics of patient care, care providers are at work—so their working conditions and safety need consideration as well. In addition, there are topics that are of specific concern to providers:

- Medical decision-making
- Predictive modeling and data mining
- Scheduling of treatments
- Emergency procedures
- Hygiene, cleanliness, sanitation
- Drug handling and exposure
- Medication alerts
- E-prescription technology

- Manuals, checklists, and questionnaires
- Electronic medical records
- Training by simulation
- Healthcare information technology
- Medical information technology
- Workplace design
- Disinfection and sterilization
- Design of operating theaters
- Design of operating devices
- Technology of medical and drug-delivery devices
- Usability of medicine/drug-delivery devices
- Healthcare supply logistics
- Organizational and management issues
- Handling of noncooperating patients
- Boredom and fatigue during long shifts
- Stress management
- Work schedules
- Error recovery
- Workflow analysis
- Safety guidelines, standards, laws
- Public health

Several of these topics are treated in other chapters in this book: making decisions in Chapter 9, boredom and fatigue in Chapter 11, workload and stress in Chapter 12, organizational and management issues in Chapters 13 and 14, work schedules in Chapters 15 and 16, computer use in Chapter 19, workplace design in Chapter 20, load handling in Chapter 21. Of course, the specific conditions associated with healthcare require special considerations and applications that go beyond the discussions in previous chapters. In the following, several of the topics listed earlier will be discussed in more detail to serve as examples for ergonomic approaches.

22.3 Emergency medical services (EMS), paramedics, first aid physicians, ambulances

EMS is an often life-saving component of public safety, such as when accidents occur in transport and industry or when catastrophic events happen, earthquakes or brush fires, for examples. The victims' survival or impact of injury depends on the speed at which emergency helpers arrive, on their ability to judge what to do, on their skill to administer in situ mechanical and/or medical treatment. The working environment of emergency personnel is unusually complex, fast paced, high stress, and often physically dangerous for all involved. It requires that first aiders make decisions quickly and take actions swiftly at a high level of competence. Interventions performed by EMS paramedics and physicians often involve procedures that, if performed incorrectly or at the wrong time, can cause serious harm to patients.

Ergonomic assistance to emergency services can be at several levels. The proper size, design, and content of the paramedics' response bag° with its medications, bandages, instruments, and tools is essential; and so is the training of first aiders in correct and efficient treatment of victims and in assuring their own safety because they are at high risk for both acute and chronic injuries.

Human factors engineering can also help in selecting and equipping ambulances and other vehicles needed to get EMS personnel to the accident site. One major point of concern is the intensity and quality of emergency treatment: is an experienced physician needed to perform life-saving intervention on the spot? What does that mean for the equipment of the ambulance? What kinds of apparatus for life support of the patient are needed during transfer to the nearest hospital?

22.4 Design of wheelchairs and hospital beds

Wheelchair design has come a long way from the hurtful folding chairs that did not provide sufficiently firm support to the victim because the seat and the backrest both sagged under the weight of the body, which added painful discomfort to the distress already felt by the patient.

Solid construction can stabilize patients of various body sizes in various postures by adjustments in height and angles of the seat, the backrest, and the foot supports. For long-term sitting, these settings should be variable by the user to provide the necessary pressure relief to avoid bedsores, ulcerations of skin and subcutaneous tissue caused by poor circulation due to prolonged pressure on body parts, especially bony protuberances. Users of motorized wheelchairs° appreciate such abilities as lowering the seat for fitting the thighs under a table, or as lifting the seat so that the person can reach for a high shelf, or tilting the seat and back support to shift the user's body to help avoiding pressure sores.

Hospital beds have a number of adjustments, done by hand or motorized: usually height adjustments of the whole bed or just of the sections that support the head or the feet. The adjustment features are meant to allow the patients to assume different body postures, to relieve pressure points, and to make it easier for caregivers to turn patients and help them getting on and off the bed.

The selection and the arrangement of the controllers for adjustments can be a difficult human engineering ask, especially so on wheelchairs, because many patients have limited movement capabilities. On motorized chairs, the type of controls and their location are often customized to suit individual users.

22.5 Moving patients

Many tasks in caring for patients at home and in hospitals and nursing homes require considerable strenuous physical labor from caregivers, especially when transferring, lifting, sliding, and otherwise moving persons who cannot actively cooperate. Healthcare providers who handle patients suffer a high number of work-related back pain cases; overall, the injury rate° for caregivers is about double the rate for all full-time workers in other occupations. Beyond the pain to the person, the cost of lost workdays is of concern to the management because it impacts the quality and the expense of healthcare.

Ergonomic interventions help to reduce the risk of work-related strain injuries by designing patient handling devices and work procedures that can be performed safely. Certainly, persons are not "loads", but most of the biomechanical discussions in Chapter 21 regarding proper load handling help to avoid overexertions and injuries to the caregiver. Back injuries and shoulder strains often occur while lifting, transferring, and repositioning patients.

Several risk factors relate to different aspects of patient handling. *Risks related to the task:*

- Force: Amount of physical effort required to perform the task (such as heavy lifting, pulling, and pushing) or to maintain control of equipment and tools
- Repetition: Performing the same motion or series of motions continually or frequently during the work shift

- Awkward positions: Assuming positions that place stress on the body, such as leaning over a bed, kneeling, or twisting the trunk while lifting

Risks related to the patient: Patients cannot be lifted like loads, so the advice in Chapter 21 does not always apply.

- Patients often cannot be held close to the body.
- Patients have no handles.
- Patient may not be able or willing to cooperate.
- It is not possible to predict what will happen while handling a patient who is bulky or in pain or sedated.

Risks related to the environment:

- Slip, trip, and fall hazards
- Uneven and soft support surfaces
- Space limitations (small rooms, equipment in the way)
- Inadequate equipment
- Inadequate footwear and clothing
- Lack of knowledge or training

It is useful to distinguish three ways of patient handling:

1. Manual transfer: carried out by one or more caregivers using their own muscular force and, wherever possible, any residual movement capacity of the patient involved.
2. Transfer using small patient handling aids: carried out by means of specific aids such as low-friction fabric sheets, ergonomic belts, rotatable footboards, trapeze bar attached above the bed, etc.
3. Transfer using sophisticated patient handling aids: carried out by means of electromechanical lifting equipment.

The selection of the proper handling technique involves an assessment of the needs and the abilities of both the patient and of the caregiver(s):

- A patient who is able and willing to partially support his own weight may be able to move from his or her bed to a chair using a standing assistance device, whereas a person who is noncooperative needs a mechanical lift.
- A patient may be too large or too heavy for caregiver(s) to lift without mechanical assistance.

- Medical conditions such as pregnancy, wounds, tubes, or bandages may influence the choice of methods for lifting or repositioning.
- The physical environment may necessitate awkward positions and postures and create unsafe conditions for the patient and the caregiver(s).

Manual lifting of patients should be eliminated when feasible and be minimized in all other cases. A large offering from simple aid devices to advanced (and often expensive) technical patient handling aids is available and should be carefully considered.

If you are taking care of a patient° by yourself, you are at greatest risk for back pain when you

- Pull a person who is reclining in bed into a sitting position.
- Transfer a person from a bed to a chair.
- Lean over a person for long periods.

When you lift or move a person, reduce your risk of back pain by

- Maintaining proper alignment of your head and neck with your spine
- Maintaining the natural curve of your spine; do not bend at your waist
- Avoiding twisting your body when carrying a person
- Keeping the person who is being moved close to your body
- Having your feet to be shoulder width apart to maintain your balance
- Using the muscles in your legs to lift and/or pull

If the task is too straining, get help.

22.6 Medication alerts

The proper setup of electronic health records (EHRs)° can produce alerts when prescribing a particular medication that may produce a health risk to a patient. Several conditions can trigger alerts:

- Drug-drug alerts—The effects of one drug alter the effects of another drug when both are administered together.

- Drug-allergy alerts—There exists an allergy to a drug.
- Drug-disease alerts—A drug is already taken with a pre-existing medical condition.
- Drug-food alerts—The effects of a drug are altered by food when both are taken together.
- Overdose alerts—The dose exceeds standard dosing values.

It is a promising concept to automatically generate an alert of a risk when prescribing a particular medication to a particular patient—however, to be usable and be used, the software systems must be reliable and, in particular, not generate an overwhelming number of alerts, which may appear complex, unexplained, even cryptic to the prescriber. Such deficiency can cause so-called alert fatigue that makes physicians overlook or inadvertently ignore clinically useful warnings; both can lead to serious consequences for patients.

22.7 Electronic personal and health records

Electronic personal health records (PHRs) are now profusely used in ambulatory practices, healthcare facilities, and nursing homes. Although PHRs are in principle valuable tools, this is true only for those records that contain complete and correct information; incomplete and incorrect records can be dangerously misleading. Since new patients (and often their helping companions) are usually asked to fill in blank PHR forms as a requisite for medical treatment or admission, designing the forms requires careful consideration of the users' ability to understand the questions they are asked to answer. People in acute distress, with low literacy, with little knowledge about health-related medical terms, or with limited technical skills may find it difficult to furnish the asked-for information° and, especially if they cannot (or do not) obtain needed assistance, may provide false or misleadingly incomplete data.

One somewhat unexpected side effect of the widespread adoption of electronic medical records by healthcare organizations is an increase in musculoskeletal disorders among healthcare staff who use the computerized information. Pain and discomfort in neck, shoulder, upper and lower back, and right wrist are the most often reported repetitive strain injuries of medical computer users°—similar to what occurred several decades ago when large numbers of computers were introduced into regular offices.

22.8 Medical devices

> In 2015, a hospital in Roanoke, Virginia, agreed to pay nearly $1 million to the family of a patient who died after a routine hernia operation. As reported, a nurse mistakenly programmed an automatic medicine dispenser to supply five times the intended painkiller dose. The manufacturer of the dispenser agreed to pay nearly $1 million because the use instructions were not written clearly°.

Infusion pumps are among the widely used devices for continually delivering medications or fluids to the patient's body in predetermined controlled amounts. However, if the user interface is poorly designed or the use instructions are deficient, misuses can occur and may lead to serious medical errors.

It is simply amazing to still encounter medical instruments with badly designed interfaces° that are difficult to use, and even prone to misuse because of complicated or counterintuitive mechanics, controls, and displays. It is similarly astounding how user guidelines, instructions, warnings, and labels can still be badly written, difficult to understand, and even be misleading—useful information on design and wording of written documents° has been available for a long time to manufacturers and importers of equipment and medications.

22.9 Stress in the workplace

Patient care routinely requires the staff to cope with some of the most stressful situations° found in any workplace. The staff must care for dependent and often demanding patients, and they must deal with life-threatening injuries and illnesses of their patients and, often, with patient deaths; at the same time, their work is complicated by intricate and possibly malfunctioning equipment, tight schedules, understaffing, overwork, complex hierarchies of authority and skills; all these contribute to stress. Stress can affect caregivers' attitudes and behavior; frequently reported consequences of stress include difficulties in judging the seriousness of a potential emergency, communicating with very ill patients, and in maintaining pleasant relations with patients and coworkers. Stressed individuals report loss of appetite, ulcers, mental disorders, migraines, difficulty in sleeping, emotional instability, disruption of social and family life, and increased use of tobacco, alcohol, and drugs.

22.10 Safety guidelines, standards, and laws

A plethora of safety-related guidelines, requirements, and regulations exists in many countries and in specific localities. These documents are quite different from place to place—however, they are all meant to achieve a high level of safety and health for patients and caregivers. So, everybody responsible for setting up and managing care facilities has to be knowledgeable of and must obey the relevant safety guidelines and laws. The new ISO health and safety standard ISO 45001° will demonstrate the global importance of occupational health and safety management systems. The standard will be aligned with Occupational Health and Safety Advisory Services 18001, ISO 9001 (Quality Management), and ISO 14001 (Environmental Management), which themselves are undergoing revision.

Specific to California, since 2012, a law (the "Hospital Patient and Health Care Worker Injury Protection Act") is in effect; its intent is to assure injury protection to patients and to healthcare providers. To this end, the law requires that care staff must be trained in safe patient handling (lifting, positioning, transferring, sliding) and that manual patient procedures be replaced, as appropriate, with powered patient transfer devices, lifting devices, and lift teams. Another important effort concerns the prevention of falls in nursing homes; they cause about 1800 deaths each year in the United States°.

Summary

Patients in acute care in hospitals and residents in nursing homes depend partially, often completely, on care staff members to provide medications and general nursing assistance; they also need help in daily living tasks such as dressing, bathing, feeding, and toileting. Each of these activities involves multiple person-to-person interactions, often with handling or transferring of patients/residents, which can result in injuries to either or both parties. Possible solutions include the appropriate design of facilities, installations, and devices according to human factors principles and practices; and the training of staff in the proper use of these implements.

If there is a mismatch between the physical requirements of the job and the physical capacity of the worker, work-related disorders, overexertions, and accidents, often trips and falls and back injuries, can result. Ergonomic interventions can adjust work demands and work practices to prevent such incidents.

Ergonomic contributions to the interface design of medical devices and to the wording of written use instructions, and to user training can contribute essentially to the safe and successful use of medical instruments and of automated drug delivery.

Workplace analyses and reviews of accident reports by management and employees provide directions for ergonomic efforts to reduce stressors for both patients and care staff and guide in the proper selection and use training of facilities and equipment.

The shift from paper to electronic records in the healthcare profession has brought similar human factors problems as seen earlier when other businesses made that transition. Imperfect questionnaires and data supply sheets lead to incomplete and incorrect information input; for example, upon first admission, patients may not supply sufficient information about their medical history. The following step, data management, needs appropriate software algorithms in order to detect, for example, medication interactions to which the prescribing physician should be alerted. If that purpose is not met, vital information may be overlooked, which can have dire consequences.

Training programs, carefully designed and implemented, should be in place to provide continual education and training about hazards and ergonomic controls to managers, supervisors, and all healthcare providers, including new employee orientation. Training should be updated as changes occur at the workplace.

Notes

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

Hospitals, nursing homes, and residential care facilities: Data retrieved in December 2015 from the websites of the American Hospital Association, the Bureau of Labor Statistics, and the Occupational Safety and Health Administration.

Roles and rules in healthcare: Brill 2013; Carayon 2011; Charney 2010; Dillon 2008; Gawande 2015; Waterson 2014.

Progressive procedures: For examples, see the *Proceedings of the Annual International Symposium on Human Factors and Ergonomics in Health Care.*

22.3 Emergency medical services, paramedics, first aid physicians, ambulances:

Paramedics' response bag: Bitan et al. 2015.

22.4 Design of wheelchairs and hospital beds:

Motorized wheelchairs: Williges, R. C. (personal communication July 8, 2015).

Selection of controls … is often customized: Chapter 10 in the book by Kroemer, Kroemer, and Kroemer-Elbert (2003).

22.5 Moving patients:

Injury rate for caregivers: Data retrieved in December 2015 from the website of the Occupational Safety and Health Administration. Kurowski, Buchholz, and Punnett 2014; Waters 2010.

Handling dear loads: Guidelines for patient handling, for example, from the European Agency for Safety and Health at Work (http://osha.europa.eu), the American Nurses Association Handle With Care Campaign fact sheet (http://www.nursingworld.org/handlewithcare/), and U.S. Occupational and Safety Health Agency (http://www.osha.gov/ergonomics/guidelines/nursinghome/index.html).

If you are the sole caregiver: Information retrieved December 2015 from the website of the American Academy of Orthopedic Surgeons.

22.6 Medication alerts:

Electronic health records and alerts: Mauney, Furlough, and Barnes 2015; Patterson et al. 2015.

22.7 Electronic personal and health records:

Furnish the asked-for information: Czaja et al. 2015.

Repetitive strain injuries of medical computer users: Hedge and James 2012.

22.8 Medical devices:

Use instructions were not written clearly: Reported by *The Roanoke Times* on December 30, 2014 and October 11, 2015.

Medical instruments with badly designed interfaces: Ali, Li, and Lisbon 2015; Weinger, Wiklund, and Gardner-Bonneau 2010.

Design and text of written documents: Robinson 2009.

22.10 Safety guidelines, standards, and laws:

ISO 45001: ISO Project Committee 283 intends publication in October 2016.

Prevention of falls in nursing homes … causing about 1800 deaths each year in the United States: Li and Ali 2015.

CHAPTER TWENTY-THREE

Autonomous automobiles

Emerging ergonomic issues

This chapter differs from most others in this book because it points out developing ergonomic challenges that come with emerging technologies. Therefore, this chapter does not present solutions but rather discusses issues of concern; how people might deal with changes in technology and organization, and what may be suitable ways to accommodate people under these new conditions. So, this chapter is an example of previewing and planning ergonomic progress in a changing world.

> Which current behavior will be most unthinkable 100 years hence? … Self-operating a 4000 pound motor vehicle at 80 miles an hour, surrounded by other humans doing the same. (The Atlantic, July/August Issue 2015, p. 11)

New technologies—New challenges

This chapter focusses on a technology of the near future that means going from

- Assisting the driver to
- Driverless traveling to
- Autonomous automobiles navigating within an automated control system.

An automated control system links vehicle and roadway instrumentation to provide hands-off/feet-off navigation where the road infrastructure and traffic control, instead of the driver, guide the vehicle automatically. Such systems can connect many vehicles via an “electronic drawbar” to accelerate or brake simultaneously and to follow each other with small distances, like a train of cars.

Numerous challenges stem from a vast conglomerate of issues/interests/aspirations inherent to the topic; there is the pure size of the project, its future importance; there will be technical difficulties to overcome as well as the effects of setbacks and possible failures; there are concerns about the safety of the participants; there is uncertainty about the willingness of the public to go along with the monetary, political, ecologic, and economic consequences. So there is a vast array of human factors issues: psychological, sociological, physiological, and anthromechanical. Ergonomists working on special projects within this developing technology have to be aware of the multifaceted context.

23.1 Road travel by automobile

Early automobiles In 1768, Nicolas-Joseph Cugnot built the first steam-powered automobile. In 1807, François Isaac de Rivaz designed the first car propelled by an internal combustion engine running on hydrogen. In 1886, Karl Benz designed a reliable gasoline-powered automobile and produced several identical copies of his Patent Motorwagen. Motorized wagons soon replaced animal-pulled carriages because automobiles became affordable for many people; the mass production of Henry Ford's Model T began around 1908.

Traffic speed In 1901, Connecticut apparently became the first U.S. state to regulate how fast motor vehicles may go, limiting them in cities to 19 km/h (12 mph) and in the country to 24 km/h (15 mph). This was, in fact, about as fast as horseless carriages could go then, powered by steam, gas, gasoline, or electric engines. Such vehicles were still rare so there was little need for new roads, and air pollution was not yet an issue. Furthermore, the likelihood of personal injury in a crash was slight because the kinetic energy of a moving body depends on the square of velocity; at 24 km/h, the kinetic energy is about 1/18 of that at 100 km/h.

23.2 Reasons for reengineering road traffic

Cost in human life Now, in the twenty-first century, road traffic by individual automobiles is in urgent need of radical improvement. The urgency arises primarily from the moral requirement to end the carnage inflicted on people (both inside vehicles and outside) by our current driving conditions: during each year since

2009, in the United States, around 33,000 people died in automobile crashes°. Of the annual victims, about half were drivers, 6000 were passengers, and another 6000 were nonmotorists. Definitions of human error° differ, but the massive majority of crashes appear to result from drivers' actions.

Cost to humans

Further reasons for changing the way we use automobiles include the reduction of the time wasted on overly long traveling, often prolonged by clogged traffic conditions, and the reduction of combustion products that poison the environment.

23.3 Better ergonomics

Outdated vehicle design

Facilitating the drivers' tasks was for decades a favored topic for assigning student class work—but essentially nothing changed during the twentieth century (except that the clutch pedal mostly disappeared). Several factors contributed to the lack of progress, chiefly probably the intent to proliferate the then existing technology—in other words, the unwillingness to "make big steps forward."

Immobile driver

In conventional road vehicles, the driver is fixed in the seat by the resolute requirements to (1) keep the foot on the pedal, (2) keep the hands on the steering wheel, and (3) keep the eyes on the road. The driver's body position cannot change appreciably; any sudden body movement (sneezing, reaching for a distant control) can dramatically affect navigation in direction and velocity.

Pedals

The traditional pedal arrangement° is truly astonishing: the driver's foot must move quickly and accurately between pedals that are invisible to the driver. Pushing on one pedal accelerates, but a similar push on another pedal brakes the vehicle. These actions require delicate control and are often critical to avoid damage and injury, even death. Yet each pedal is operated by a forward motion of the foot, which, depending on the pedal beneath the foot, has opposing results.

Current human factors problems

These basic problems, together with many other technical and operational flaws, can be explained—but not justified—as the result of many technological steps° that followed each other in rather haphazard manner. New designs had to incorporate basic traditional elements (for example, pedals and steering wheels) so that drivers could transfer their acquired skill to drive new vehicle models.

Driver's mistakes

Vehicle drivers, a highly diverse population, may be the largest group of humans tasked to perform an exceedingly difficult job: driving automobiles. Our current auto technology and traffic conditions require drivers to navigate dangerous vehicles under often dangerous circumstances. In the United States alone, each year about 16,000 drivers die, in most cases either of their own doing or by mistakes made by other drivers.

Driver's education

Drivers have to make swift decisions based on uncertain information: Will the other driver change lanes? Could the road surface be slippery? Drivers have to perform difficult steering, braking, accelerating quickly and accurately; they have to do this with limited vision to the rear and the sides, at night and in fog. It takes a long time of drivers' education to learn the rudiments of those actions, and it takes years of (often hair-raising) experiences to improve them.

Flawless driving required

Driving is a complex task, usually divided into hierarchical levels of control; operational control (such as following a car) is the simplest task, whereas tactical control maneuvers (passing a car) and strategic control (such as trip planning) require higher levels of mastery. Distraction° from the driving task can be visual, manual, and cognitive: visual distractions make drivers look away; manual distractions make drivers to take their hands off the steering wheel; cognitive distractions divert drivers' mental attention away from driving. However, driving requires that vigilant alertness and high-level control skills must be exerted, often for hours. The driver must apply essentially uninterrupted attention to traffic, road, and vehicle; related information can be ambiguous and difficult to interpret. The driver's performance must be nearly flawless because even seemingly slight slips can have serious, even fatal consequences.

Human factors challenges

Vehicle control depends on individuals who can be fatigued°, distracted, and inattentive; who can be overloaded by traffic and road conditions; who may be inexperienced in their youth or disabled by age or anger. If things do go wrong, this may be blamed on human error—but was the driver really at fault or were the circumstances humanly unmanageable? If the traffic conditions are unwieldy, they need to be reformed; if the vehicle is ill designed, it must be improved.

Is this the future? Many traffic conditions have become nearly chaotic: traffic jams during rush hour, mass crashes in fog or on slick roads, gridlock and stop-and-go on overcrowded roads. Here are two outlooks into the near future:

> *Scenario 1. Sarah takes the AA Train to Manhattan:*
>
> Sarah had signaled her autonomous automobile to stop at her front door at 7:45 a.m.—and there it is. She steps in; her AA drives off and then halts at two of her colleagues' doors to let them come in and sit down inside as well. Sarah closes her eyes for a few minutes while her passengers are talking idly, conversing about some private and business issues while the AA drives to the highway. This being rush hour, the lanes contain the regular triple chains of coupled AAs moving toward downtown; Sarah's vehicle accelerates on the entrance track and merges into the nearest column. The smooth and quiet ride takes its regular 20 minutes until Sarah's vehicle weaves out of its AA train and stops at 42nd Street. She has to walk a few steps to her office building because other AAs are at the entrance space; but they all move away quickly together with Sarah's AA. It delivers her colleagues at 44th Street and then parks itself. As programmed, the vehicle will pick all of them up in the afternoon.
>
> *Scenario 2. Niels drives on back roads:*
>
> Niels is a veterinarian. He lives in Northville but has his practice and clinic in Hadelfors. The commute between them takes only a quarter of an hour, which he easily does by letting his vehicle merge into the automated column of AAs on the main road. However, frequently he must drive out into the countryside to treat stricken animals on ranches and grazing grounds, many located on mountain slopes. After heavy rains, the farm paths maybe washed out, and in the winter, snowdrifts can make detours through the fields necessary. Even the newly updated self-driving network cannot handle such on unplanned trips; so Niels must turn the automated program off and, using the old-fashioned manual mode, navigate his vehicle over the rugged terrain.

Early advances toward AA systems

After power brakes and power steering in the second half of the 1900s, antilock brakes and skid and traction control made driving easier. Then, true driver-assists became functional: keeping a proper distance in car following by adaptive cruise control was available in 1999; lane keeping in 2001 together with autobraking to avoid collisions; self-parking in 2014. These features were limited to some high-end car models, but with developing technology, more operational control can be transferred from the driver to the automated systems: self-driving cars, which communicate to avoid each other or are electronically coupled as trains (platoons, convoys, or pulks), were on the verge of becoming feasible in 2015.

Around the year 2000, the path to systems with AAs began to open and the conjured-up scenarios above and similar plots appeared possible in the near future; in 2011, some automation of tactical maneuvers and even rudiments of strategic control were feasible. In 2014, under favorable conditions, fleets of several prototypes of driverless cars negotiated local and long-distance roads. Automated long-distance travel on highways by self-driving trucks seemed imminent. Naturally, there was still a need for much improvement; an almost comical need was to make AAs more assertive because they might simply stop at an intersection if it was uncertain whether another vehicle might have priority.

23.4 New technologies— New ergonomic challenges

Technological progress granted, an array of human factors problems arises. Some of these relate to human performance; others have to do with how we will accept new systems.

The emergency driver

Human performance issues If full automation can be achieved, the former driver becomes a passenger expecting to enjoy effortless, convenient, and safe travel (as in Scenario 1). However, that ideal plot falls apart in case of a failure of the guidance system. Now the passive passenger must instantly morph into an emergency manager and take over vehicle control: steer, brake, avoid, foresee—as in the bad old days of driving. The task of quickly getting hold of the vehicle controls and then properly maneuvering the vehicle is likely to be much more difficult than it was in the preautomation times because the event is unforeseeable and the surprised driver may have lost needed skills during the time of being a passenger.

Driving an advanced vehicle

It appears almost certain that even new hi-tech vehicles will require an old-fashion human driver when an automated guiding system is not available or not capable of mastering a situation, such as going cross-country because of an obstructed road (as in Scenario 2). For human vehicle control (which also includes the emergency driving mentioned earlier), the same human factors design requirements apply that should have been satisfied in earlier conventional automobiles:

- Provide intuitive, unambiguous controls for vehicle direction and speed.
- Detect and react to driver impairment (drowsiness, distraction).
- Install means to preview road conditions and to improve vision in rain and fog and at night.
- Supply assistance for lane keeping; avoid hitting objects.
- Eliminate blind spots.
- Allow comfortable and changeable driving postures.
- Install means to protect humans in case of a crash.
- Select appropriate routing.

New vehicle controllers

No remarkable advances in technology are needed to untie the drivers' feet by eliminating all traditional pedals. Riders of motorcycles and all-terrain vehicles are used to handlebars that combine control of direction and velocity. In airplanes, pilots commonly manipulate attitude and speed by either a control stick (joystick) or a control yoke (a partial wheel). The automobile designer can utilize these experiences and greatly simplify vehicle control by combining the manipulation of both direction and speed: for example, a center column (such as stick or yoke) or controls located at the driver's side(s) could replace the steering wheel; these actuators could control left/right turns as usual and also regulate acceleration/braking by push/pull or tilt actions. The technology to unfreeze the driver and make driving much easier is available and proven—the advent of an excitingly new AA transportation system would provide a psychological opportunity to also introduce brand new vehicle control designs.

Step by step

Go driverless gradually or do it all at once? One possible solution is to improve driver assistance and then create driverless systems incrementally; finally introduce them as they become comprehensive and mature. This approach does cause some human factors concerns; for example, drivers might wrongly assume that their car has advanced features, which it does not have; drivers might get overconfident in the car's ability and make it exceed its limitations; when the vehicle has autonomous capabilities, in an emergency, the human passenger might be unable to take control back, quickly and competently.

Psychologically, a gradual buildup might be easy to accept; economically, the costs of vehicles and of establishing their control system can be kept at bay. It is possible that some conventional manufacturers select a slow gradual approach, whereas some hi-tech companies might leapfrog the competition.

One big step

The other solution is to perfect autonomous abilities; at the same time, bring vehicle controls and interior ergonomically up to date; thoroughly street test them; and then bring AAs to the market all at once. This would require not only a perfect operating system but also buyers who trust engineers and manufacturers. This approach does not involve much learning by the users but necessitates their willingness to make the one big step into the future.

Compromise

An intermediate possibility is to continue offering conventional cars but, simultaneously, select well-mapped areas and supply them with self-driving vehicles and hands-free taxis. Such regions with AA system could grow as needed and feasible to cover more and more terrain.

Summary

In many countries, especially at rush hour in urban regions, the road traffic is nearly chaotic. Traffic conditions often overtax the drivers' abilities; crashes claim many thousands of victims. During the twentieth century, the principal design of vehicles and of roads has not changed significantly, while trucks and cars and motorcycles became faster and more numerous while roads got more congested.

Given the density of road traffic, the central control of individual vehicles appears necessary to ensure their continued and safe flow. Such general guidance system can select the best course in cases of vehicle crowding, road surface problems, obstacles in the way, weather conditions, and the like. Central guidance could prevent inappropriate driver actions during entering and leaving the flow of traffic; it could assure proper distance and speed while staying in a lane, and even provide control of individual vehicles in emergency situations: no more ghost drivers going the wrong direction, no overcompensating or crossing the median. These examples show that such general traffic control could eliminate many, even most, of the current deficiencies relating to human factors.

Obviously, it is a major enterprise with many technical challenges to develop (1) such comprehensive vehicle control systems and (2) fleets of AAs that fit the guidance system. That enterprise also poses new human factors issues: Are drivers and passengers willing to become all passengers—like in trains or taxis or busses or airplanes—in their own vehicles? Will they appreciate not to have drivers' duties and responsibilities but be able to relax, perhaps even enjoy the ride?

While in centrally guided traffic, drivers relinquish the direct control of their vehicles and their travel—but not so when outside automation areas. Here, they manipulate their vehicles almost the old-fashioned way, driving at their self-selected speed and in their individual ways. However, their vehicles are, we hope, ergonomically designed for safe and comfortable operation including, for example, simplifying vehicle manipulation by combined control of both direction and speed; elimination of pedals to allow body posture change; improving vision in fog and rain and at night in all directions; easy travel planning by continual information about traffic and road conditions from the general traffic system; networking among vehicles and by ad hoc communications with other drivers.

The transition from automated vehicle control to individual driving generates particular ergonomics challenges. For example, in an emergency situation (such as the breakdown of the automatic control system), the driver must take over quickly and competently. This means that, pyschologically, the person must be ready to act appropriately; physically, the person has to be in the driver's workplace; physiologically, the person must have the skills to operate the controls. The vehicle must be designed for such unexpected, quick, and skillful actions.

The advent of an excitingly new AA transportation system provides an opportunity to also introduce brand new vehicle control designs.

Notes

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

23.2 Reasons for reengineering road traffic:

In the United States, around 33,000 people died in automobile crashes°: Data retrieved on October 12, 2015 from the website of the National Highway Transportation Administration.

Definitions of human error: Dekker 2014.

Technological steps: Bhise 2011; Nagamachi 2011; Pew and Mayor 2007; Walker, Stanton, and Salmon 2015.

23.3 Better ergonomics:

The pedal arrangement: Wu, Yang, and Yoshitake 2014.

Driver distraction: Victor, Lee, and Regan 2013.

Vehicle control depends on individuals who can be fatigued: Popkin 2015.

23.4 New technologies—New ergonomic challenges:

The surprised emergency driver: Skottke et al. 2014.

CHAPTER TWENTY-FOUR

Making work efficient and pleasant

So far, the text in this book has mostly addressed the physical aspects of “fitting work to the human” by careful human factors engineering, although repeatedly references were made to “fitting the human to work,” such as by personnel selection and training. This last section of the book pulls ergonomic information together to demonstrate how work can be both pleasant, which is of primary interest to the individual, and efficient, especially important to management.

24.1 Using our skills and interests; getting along with others at work

Every one of us is a unique individual, different from everybody else by upbringing, environment, experiences, and personality, all of which make us special. Yet surveys show consistently—in North America, Europe, and Australia/New Zealand and probably everywhere else—that, in general, better job skills and education lead to higher job satisfaction and income. More importantly, features intrinsic to our tasks provide us with basic satisfaction. To do a job well is often reward by itself. Doing what we like to do, exercising our talents, learning new skills and techniques, and applying them, accomplishing tasks make us content, even happy.

Work worthwhile doing

Persons who have a calling° for what they are doing generally feel deeply fulfilled even if their pay is relatively low and their workload rather high. Among the most satisfying jobs are those that make other people get better and feel better; these jobs usually involve caring for others, helping and protecting others, teaching others. If our work leads to improvements in procedures, services, and products, that outcome renders us proud and is by itself recompenses.

Satisfied employees

Seen from the organization's perspective: in part, a company's market value is determined by its hard assets like property and equipment. However, a large part of its value consists of soft attributes: patents, customer base, and especially the firm's human resources. Satisfied and engaged employees are among a company's most valuable assets because they run the business.

Engaged to work

To feel engaged to work requires a good match between a person, her or his interests and aspirations, and the job. The job is defined by

- Its tasks, which include equipment and procedures used
- Its rewards for good performance such as recognition, potential for advancement, and pay
- Its multifaceted working conditions, which include the social relations among people at all levels, often loosely labeled *organizational climate*

Job performance is the product of motivation and ability. As discussed in several chapters of this book, situational factors at work can stymie or enhance performance.

Motivation and job performance

Motivation incites, directs, and maintains our behavior toward goals. Motivation and job performance are intimately related; a person motivated to do well is willing to expend effort to do so. Understanding what motivates people can help us be aware of why they behave on the job as they do and can tell the management how to make people effective and satisfied at work. Several theories try to explain motivation and needs (some of them are outlined in Chapter 13). They fall essentially into two groupings. One focuses on the individual and personal inherent traits; the other places the work environment at the forefront.

Needs-based motivation

Several motivation theories focusing on the individual describe what we need and want. Individuals strive to cover their basic needs first and then work their way up the hierarchy of needs, which has several levels; at its basis are physiological requirements for food and water and shelter, followed by wants for safety and economic and physical security. Higher up are social wishes, for belongingness and esteem including self-confidence, recognition, appreciation, and respect. The highest-order ambitions concern fulfillment of one's talents and potentials; at this level, an individual can perceive full personal success and satisfaction.

Performance and expectance

Expectancy theories assume that an individual's motivation (and resulting satisfaction) depends on the difference between what the person's work environment offers versus what he or she expects. This can be expressed, in its simplest form, as a model that explains motivation as function of two coupled expectations:

- Work will lead to performance, then
- Performance will lead to reward.

Accordingly, the organization should provide rewards for its employees: pay, promotion, formal recognition. (There can be a negative outcome such as getting fired.) The value of the reward differs depending how the individual rates the anticipated reward.

Expected outcomes

The expectancy component is crucial; there must be a connection between how hard one tries and how well one performs. To illustrate, a factory worker on an assembly line may have little incentive to increase her rate of production if the overall speed of the assembly line, and hence her performance, remain unchanged regardless of her efforts. In contrast, a truck driver can deliver more the faster she drives, so she may be motivated to exceed the posted speed limits. The other expected connection is between performance and reward. If the organization does not recognize an employee's effort to augment her performance, then there is little incentive for her to work harder and better; if she experiences recompense, this will most likely make her strive even more.

Proud to work

Surveys of the top U.S. companies provide a summary of the various factors underlying individual job satisfaction and performance. The following comments illustrate why organizations make the list of 100 Best Companies to Work For. Employees say, "This is a positive place. We do good things. We succeed. People are friendly. They feel challenged, respected and valued. And they respond with loyalty." And the company motto, "Treat people the way they want to be treated. Strive for mutual respect and for an atmosphere that makes people proud to work here. Provide good tools and equipment. Offer career opportunities. Say thank you for a job well done."

"Have a life"

Individually, we need to balance our work and our personal life. Only a few people live to work, while most want to have a life outside work. The times of early industrialization are gone when workers labored for 10 or more hours a day, six or seven days a week. Nowadays, the five-day workweek with about eight hours of work a day (less in some industrialized countries) is the norm. Even some high-end management consulting firms, notorious for extraordinarily demanding work schedules that often leave their employees overtaxed, are looking for ways to reduce the workload and let their employees enjoy life outside of their work. Some companies have eliminated weekend work (including business travel) for their employees; they encourage leaving personal phones and computers turned off outside business hours and to take personal days and uninterrupted vacations without being on call.

Bad bosses

Insufficient job performance is often a reason why workers lose their jobs, but bad bosses are not infrequent either. A 2007 survey in the United States° showed that two of five supervisors did not keep their word or failed to give credit when due; one of four bad-mouthed employees or blamed them for mistakes made by the boss. Such managers also produce problems for their company because they generate poor morale, reduce production, and increase employee turnover. Bad managers create severe dissatisfaction among the employees: many who look for another job do not want to leave their company but rather want to get away from their boss.

Taking charge

Good working conditions, including pleasant personal relations at all levels, are important, often more so than small differences in received payment. Abusive relationships between employers and employees were not rare in the past, when the "little people" where dependent on the "big bosses." These medieval conditions have been replaced, almost uniformly, by the understanding that employees at all levels are responsible for making a business prosper or fail, and that they all should pull in the same direction. Yet if for whatever reasons a person feels dissatisfied with the conditions and the treatment at work, there are constructive ways, such as those listed in Table 24.1, to determine the causes of discontent so that the conditions can be improved. Both managers and employees have similar factors to consider, although seen from different points of view, that make their work lives more pleasurable and proficient.

Table 24.1 Taking charge of personal relations at work

This will contribute to making you feel good about your new employment
• When you consider taking up new employment: strive to understand the new organization itself and the "environment" it offers.
• Examine the new company's structure, strategies, policies, conventions and "culture" and make sure they agree with your own personality, your personal style, goals and beliefs.
• Spend some time with your prospective colleagues and supervisors and determine how you feel about them since you will be with them many hours at work.
• Does the new job meet your physical needs, such as sufficient pay and fringe benefits? What about your emotional needs, like recognition and a sense of achievement? How are the work conditions, the management setup, the dress code, and the like—make sure they are appropriate for and pleasing to you.
This will contribute to making you feel good about your work
• Talk with your supervisor/colleagues/subordinates about what should be done, and about how to do it. Propose solutions and listen to proposals.
• Do as well as you can do. Take advantage of any programs available to you, especially if offered by your company, to increase your skills.
• Technology can make your life easier, but make sure it does not keep you chained to work day and night.
What to do when you are miserable at your job
• Talk with your supervisor/colleagues/support staff in a non-confrontational tone about existing problems. It is important that you propose solutions.
• Check your employment contract, the company policies and procedures manual to determine your duties and rights at work.
• Take advantage of any stress-reduction programs your company offers.
• If there is no solution to a problem that bothers you so much that you don't want to work with the organization any more, then look for another position.

Source: Kroemer, A. D., and Kroemer, K. H. E., *Office Ergonomics*, second ed., CRC, Boca Raton, Florida, 2017.

24.2 Setting up our own work, workplace, and work environment

Larger, richer jobs In the early 1900s, Tayloristic principles favored breaking jobs into small task elements that were then standardized. This usually meant that a worker did the same task repeatedly, resulting in extreme specialization and, unfortunately, often acute tedium at high skill. Since the mid-1900s, job enlargement—increasing tasks and task variety—and job enrichment—increasing workers' participation and control—have grown popular. Several motivation and job satisfaction theories try to explain how job design influences behavior. The so-called *job characteristics model*° proposes five core features:

1. Skill variety is the number of different talents and activities that the job requires.
2. Task identity is the specifics of the work that a person does from beginning to end.
3. Task significance is the impact of one's work on other persons, procedures, and products.
4. Autonomy is the degree of independence in planning, controlling, and determining work procedures. This makes the person feel responsible.
5. Feedback is the information about how one's performance is evaluated and perceived.

These five job dimensions provide the jobholder with the experience of meaningful work, the responsibility for work outcomes, and the knowledge of results. These experiences generate high motivation and satisfaction for the employee and, of particular importance to the management, lead to better-quality work and lower absenteeism and turnover.

Suggestions for improvements

When management recognizes and rewards expressions of personal interest in better work, follows up on suggestions, and incorporates proposals for novel work and workplace layout, a spirit of teamwork and cooperation develops that provides motivation and drive to achieve. The design of most workplaces for manual work in production and repair follows well-established traditions, which result from the work procedures employed in the past, the objects to be worked on, the machinery used, and the hand tools needed. In some cases, there is rather little leeway for the individual worker to develop new designs for product, workplace, or work practices. Yet numerous reports and anecdotes show that major enhancements in productivity, safety, and appeal can result from suggestions for improvements made by involved personnel. So smart management encourages workers' suggestions; evidently, collecting and using suggestions in the planning and concept stages is more beneficial than later during production. One of the great success stories is Kansai° engineering.

Work environment

In this book, Chapters 17 through 22 describe work places, tasks, and work procedures that suit the human body and mind.

Special aspects of the environment at work can strongly influence well-being and performance; they prominently concern seeing, hearing, and physical climate, as shown in Chapters 5 through 8.

Vision requires good lighting

The characteristics of human vision discussed in Chapter 5 provide detailed information for designing the environment for proper vision. The most important concept is the provision of suitable workplace lighting that illuminates visual targets as desired. What mostly counts is the luminance of an object—the light reflected or emitted from it—which meets the eye. The acuity of seeing an object is much influenced by strong luminance contrast between the object and its background, including shadows.

Avoid glare; be careful with colors

Another important point is the avoidance of unwanted or excessive glare. Direct glare strikes the eye straight from a light source, such as the sun or a lamp shining into your eyes. Indirect glare is reflected from a surface into your eyes, such as the sun or a lamp mirrored in your computer screen. The use of colors on the visual target, if selected properly, can be helpful; but color vision requires sufficient light, and luminance contrast is usually more important than coloring. Table 24.2 lists recommendations for lighting at work.

Sounds provide important information

Another essential environmental aspect is that of hearing and sounds at work—see Chapter 6. Sounds convey information about the functioning of machinery and of work progress, they provide verbal communications from coworkers and, possibly of vital importance, present warning signals about dangers in the work environment. Furthermore, the sound environment may be hazardous to one's hearing if it produces temporary or permanent damage to our ears. Table 24.3 lists recommendations for the acoustic environment at work.

Suitable climate at work

The third important environmental condition at work concerns the physical climate, determined by temperatures, air movement, and humidity, discussed in some detail in Chapter 8. When we work outside, we have to take the climate as is, and our adjustments are in working habits and clothing; inside, however, a variety of low- and high-tech means are available, listed in Table 24.4, to further well-being and work outcomes.

Table 24.2 Taking charge of the lighting at work

These vision rules will contribute to making you feel good about your work
• General illumination is best at about 500 lx. If there are many dark (light-absorbing) surfaces in the room, illumination may be as high as 1000 lx. If cathode-ray tube (CRT) displays are present, it could be between 200 and 500 lx.
• In rooms with light-emitting displays, illumination of 300 to 750 lx is suitable.
• Prefer indirect lighting, where all light is reflected (at the ceiling or walls of a room, or within the luminaire) before it reaches the work area. This helps to avoid direct and indirect glare.
• Make sure that high-intensity light sources (including windows) are outside a cone-shaped range of 60 degrees around your line of sight. This avoids direct glare.
• Your work area should have dull, matte, non-reflecting surfaces. This avoids indirect glare.
• Shine a task light on your paperwork or another visual target if its seems too dim to you.
• Usually the best place for a visual target at which you look often is • Not more than 1 meter away from your eyes, usually at about arm's length • Straight ahead, neither to the left or right but straight ahead • Below the height of your eyes.
If you are having difficulties seeing objects clearly, or you feel "eye fatigue" or "eye strain" or "dry eyes"
• Have a physician (ophthalmologist or optometrist) check your eyes and advise you about measures that improve and protect your seeing.
What to do if you are not comfortable:
If you feel eye fatigue or eye strain, check and correct, as needed,
• The distance from your eyes to visual targets
• The direction of the line of sight to visual targets
• The luminance contrast between the details of the visual target and the background (such as lines on a source document, letters on the screen, objects on the work bench)
• Any direct glare shining into your eyes, or reflected glare from the display or other mirroring surface.
If a window is in front of you, with the sun or bright daylight shining into your eyes
• Draw a curtain or lower blinds; or turn your workstation so that the window is to your side.
If your white shirt/blouse/sweater or other clothing is mirrored in your computer screen, making it hard to decipher things on the display
• Change into darker clothes.
If you feel fatigue or strain in the neck or the back, check and correct, as needed
• The posture of your neck and back, which may be affected by the following: • The distance from your eyes to visual targets • The direction of the line of sight to visual targets

Source: Kroemer, A. D., and Kroemer, K. H. E., *Office Ergonomics*, second ed., CRC, Boca Raton, Florida, 2017.

Table 24.3 Taking charge of the sound environment at work

These sound rules will contribute to making you feel good about your work
• In the office, the overall sound level it should be between 50 and 65 dB; at all workplaces, it should not exceed 75 dB.
• If your work requires intense concentration, the sound level should not change appreciably or dramatically (except for a warning).
• If the surround sound level exceeds about 75 dB or is otherwise disturbing, your should wear hearing protection devices.
• Many people find background music pleasant, but preferences for the kind of music, its intensity and duration are highly individual. Therefore, music is best presented by individual speakers, such as ear plugs (buds) or caps (muffs), that do not disseminate sound to the environment.
If you are having ringing in your ears or if your hearing is reduced after exposure to loud sounds
• Have a physician (otolaryngologist) check your hearing and advise you about measures that improve and protect your hearing.
If it is too loud for you
• Eliminate the noise at its source:
• Replace noisy equipment or machines with quieter ones.
• Place a noisy piece of equipment outside your room.
• Turn down the sound level of your music.
• Ask your co-workers for quieter behavior.
• Reduce your exposure to noise:
• Encapsulate the source of sound.
• “Soften” hard surfaces reflecting or transmitting the sound with drapes, carpets, acoustic tiles and the like which dampen or absorb sound.
• If all else fails: Move to a different workplace.

Source: Kroemer, A. D., and Kroemer, K. H. E., *Office Ergonomics*, second ed., CRC, Boca Raton, Florida, 2017.

Table 24.4 Taking charge of the climate at work

These climate rules will contribute to making you feel good about your work
• With light physical work, such as in the office, with appropriate clothing, comfortable environment temperature ranges are from the low 20s to about 27°C during the summer; but lower during the winter, between about 18°C and the middle 20s.
• The preferred range of relative humidity is from 30 to 60 percent, best near 40 to 50 percent.
• If the sun shines on you, particularly on warm days, you should be able to get out of the sun or to find shade behind blinds, curtains, screens and the like.
• When you have no control over the climate (like outside), adjust your work intensity, timing and pace (including rest breaks) and your work clothes to achieve sustainable levels of body exertion and temperature.
If you feel too warm
• Lower the room temperature
• Take off a layer of clothing; bare more skin
• Move away from a heat source such as a radiator, a warm wall or window; get out of the sun
• Move closer to a cool surface
• Lower air humidity with a de-humidifier
• Increase the air movement around you (unless it is very hot air)
• Wet your exposed skin; place a cool/moist cloth on your forehead, neck or wrists
• Take a rest break]; do not exercise your body
If you feel too cool
• Increase the room temperature
• Add a layer of closing; cover more skin
• Move closer to a heat source, such as a radiator, a warm wall or window; get into the sunshine
• Move away from a cool surface
• Decrease the air movement around (unless it is nicely warm air)
• Keep your body moving

Source: Kroemer, A. D., and Kroemer, K. H. E., *Office Ergonomics*, second ed., CRC, Boca Raton, Florida, 2017.

Note: Note that these recommendations apply to most conditions in moderate climates, such as northern America and Europe.

I like my work

One of the best statements you can ever make is, “I like my work.” Too often, work is drudgery, an unpleasant way to earn one’s living. However, work can be efficient, easy, successful, satisfying, and even pleasant if it agrees with our interests and suits our skills, when it fits our body and mind—which are the basic aims of ergonomics°.

Summary

Ten ergonomic principles apply throughout:

1. Plan task, equipment, and working conditions for safety, ease, and efficiency. User selection and training cannot substitute for good design.
2. Design for real people, not for statistical phantoms.
3. Design for physical and psychological capabilities of the users.
4. Design to fit the sizes of the users.
5. Strive to accommodate extraordinary people: pregnant women, the elderly, impaired persons, persons with unusual body proportions, children, etc.
6. Design for movements among suitable work postures.
7. Provide clear visual, acoustic, sensory information.
8. Consider that people must be able to perform their tasks over hours, weeks, and years without overexertion or health hazards.
9. Allow people control over their own work.
10. Devise work for comfort and satisfaction, for job enlargement and enrichment, and for efficient efficacy.

Notes and more information

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

24.1 Using our skills and interests; getting along with others at work:

People who have a calling: Smith 2007.

Job performance: Greenberg 2010; Kroemer and Kroemer 2016; Muchinsky and Culberson 2016.

Bad bosses: Harvey et al. 2007.

24.2 Setting up our own work, workplace, and work environment:

Kansai engineering: Nagamachi 2011.

The basic aims of ergonomics: Many books on ergonomics/human (factors) engineering provide guidance and practical advice. These include, published since 2000, the following:

- Bhattacharya and McGlothlin 2012
- Bridger 2014
- Chengular, Rodgers, and Bernard 2003
- Fisk et al. 2009
- Helander 2006
- Karwowski 2006a
- Karwowski, Soares, and Stanton 2011
- Konz and Johnson 2007
- Kroemer 2006c
- Kroemer and Kroemer 2017
- Kroemer, Kroemer, and Kroemer-Elbert 2003
- Lehto and Landry 2014
- Lueder and Rice 2007
- Marras and Karwowski 2006b
- Nagamachi 2011
- Proctor and Van Zandt 2008
- Salvendy 2012
- Vink 2005
- Wickens et al. 2004

The last page

The motto "Fitting the human" points out the two approaches in ergonomics. One is mainly in the domain of industrial psychology: matching individuals with task requirements by personnel selection and training. However, trying to compensate for misguided designs by telling people how to use them properly is a difficult task.

The computer keyboard (Chapter 19) and hand/foot control of road vehicles (Chapter 20) are examples of long-established designs that originally seemed workable but are now inadequate. It is nearly impossible to teach people how to efficiently and safely use equipment that has serious human-engineering deficiencies; consider the clumsy slowness of operating the QWERTY keyboard as computer input and think about the maiming of thousands of people in vehicular mishaps in spite of intensive driver training.

The better ergonomic strategy is to carefully plan all tools and equipment, work tasks and procedures, working hours and shift arrangements, and physical and social conditions. Accommodating the human is the fundamental and most successful approach, the topic of this book: design the overall work system and all its details to fit the human. This makes work safe, efficient, satisfying, and even enjoyable.

Adapted from the March 1986 Ergonomist

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References

Alderfer, C. P. (1969) An empirical test of a new theory of human need. *Organizational Behavior and Human Performance* 4: 2, 142–175.

Ali, H., Li, H., and Lisbon, P. (2015, June) Usability analysis and redesign of infusion pump user interface. *Proceedings of the International Symposium on Human Factors and Ergonomics in Health Care* 4: 129–133.

ANSI/ASHRAE standards, https://www.ashrae.org/resources–publications/bookstore/standards.

ANSI standards: American National Standards Institute, https://www.ansi.org/.

Anderson, A. M., Mirka, G. A., Joines, S. M. B., and Kaber, D. B. (2009) Analysis of alternative keyboards using learning curves. *Human Factors* 51: 35–45.

Armstrong, T. J. (2006) The ACGIH TLV for hand activity work. In Marras, W. S., and Karwowski, K. (eds.), *The Occupational Ergonomics Handbook: Fundamentals and Assessment Tools for Occupational Ergonomics*, second ed., Chapter 41. Boca Raton, FL: CRC.

Arndt, B., and Putz-Anderson, V. (2006) *Cumulative Trauma Disorders*, third ed. Boca Raton, FL: CRC.

Arswell, C. M., and Stephens, E. C. (2001) *Information processing*, pp. 256–259. In Karwowski, W. (ed.), *International Encyclopedia of Ergonomics and Human Factors*. London: Taylor & Francis.

Astrand, P. O., Rodahl, K., Dahl, H. A., and Stromme, S. B. (2004) *Textbook of Work Physiology: Physiological Bases of Exercise*, fourth ed. Champaign, IL: Human Kinetics.

Bailey, R. W. (1996) *Human Performance Engineering*, third ed. Upper Saddle River, NJ: Prentice Hall.

Baker, N. A., Cham, R., Cidboy, E. H., Cook, J., and Redfern, M. S. (2007) Kinematics of the fingers and hands during computer keyboard use. *Clinical Biomechanics* 22: 1, 34–43.

Basbaum, A. I., and Julius, D. (2006) Toward better pain control. *Scientific American* 294: 6, 60–67.

Berger, E. H., Royster, L. H., Royster, J. D., Driscoll, D. P., and Layne, M. (2003) *The Noise Manual*, fifth ed. Fairfax, VA: American Industrial Hygiene Association.

Bernard, T. E. (2002) Thermal stress. In Plog, B. A. (ed.), *Fundamentals of Industrial Hygiene*, fifth ed., Chapter 12. Itasca, IL: National Safety Council.

Bernard, T. E., and Dukes-Dobos, F. N. (2002) *Heat Stress*, second ed. Atlanta, GA: American Industrial Hygiene Association.

Bhattacharya, A., and McGlothlin, J. D. (2012) *Occupational Ergonomics: Theory and Applications*, second ed. Boca Raton, FL: CRC.

Bhise, V. D. (2011) *Ergonomics in the Automotive Design Process*. Boca Raton, FL: CRC.

Bitan, Y., Ramey, S., Philp, G., and Uukkivi, T. (2015, June) Working with paramedics on implementing human factors improvements to their response bags. *Proceedings of the International Symposium on Human Factors and Ergonomics in Health Care* 4: 179–181.

Bjoerkman, T. (1996) The rationalization movement in perspective and some ergonomic implications. *Applied Ergonomics* 27: 111–117.

Black, T. R., Shah, S. M., Busch, A. J., Metcalf, J., and Lim, H. J. (2011) Effect of transfer, lifting, and repositioning injury prevention program on MSD injury among direct care workers. *Journal of Occupational and Environmental Hygiene* 8: 4, 226–235.

Boff, K. R., and Lincoln, J. E. (eds.) (1988) *Engineering Data Compendium: Human Perception and Performance*. Wright-Patterson AFB, OH: Armstrong Aerospace Medical Research Laboratory.

Boff, K. R., Kaufman, L., and Thomas, J. P. (eds.) (1986) *Handbook of Perception and Human Performance*. New York: Wiley.

Booher, H. R. (ed.) (2003) *Handbook of Human Systems Integration*. New York: Wiley.

Borg, G. (2001) Rating scales for perceived physical effort and exertion, pp. 358–541. In Karwowski, W. (ed.), *International Encyclopedia of Ergonomics and Human*. London: Taylor & Francis.

Borg, G. (2005) Scaling experiences during work: Perceived exertion and difficulty, pp. 11-1–11-7. In Stanton, N., Hedge, A., Brookhuis, K., Salas, E., and Hendrick, H. (eds.), *Handbook of Human Factors and Ergonomics Methods*. Boca Raton, FL: CRC.

Boyce, P. R. (2014) *Human Factors in Lighting*, third ed. Boca Raton, FL: CRC.

Bradtmiller, B. (2015) Anthropometry in human systems integration. In Boehm-Davis, D. A., Francis, T. D., and Lee, J. D. (eds.), *APA Handbook of Human Systems Integration*, Chapter 8 (pp. 117–132). Washington, DC: American Psychological Association.

Bridger, R. S. (2014) *Introduction to Ergonomics*, third ed. Boca Raton, FL: CRC.

Brill, S. (2013) Bitter pill. *Time* 181: 8, 16–55.

Carayon, P. (2011) *Handbook of Human Factors and Ergonomics in Healthcare and Patient Safety*, second ed. Boca Raton, FL: CRC.

Carayon, P., and Lim, S. Y. (2006) Psychosocial work factors. In Marras, W. S., and Karwowski, K. (eds.), *The Occupational Ergonomics Handbook*: *Interventions, Controls, and Applications in Occupational Ergonomics*, second ed., Chapter 5. Boca Raton, FL: CRC.

Carroll, A. E. (2015, August 24) No, you do not have to drink 8 glasses of water a day. *New York Times*. Retrieved from http://www.nytimes.com/2015/08/25/upshot/no-you-do-not-have-to-drink-8-glasses-of-water-a-day.html?_r=1.

Casali, J. G., and Gerges, S. N. Y. (2006) Protection and enhancement of hearing in noise. In Williges, R. C. (ed.) *Reviews of Human Factors and Ergonomics*, Volume 2, Chapter 7. Santa Monica, CA: Human Factors and Ergonomics Society.

Casali, J. G., and Robinson, G. S. (2006) Noise in industry. In Marras, W. S., and Karwowski, K. (eds.), *The Occupational Ergonomics Handbook: Fundamentals and Assessment Tools for Occupational Ergonomics*, second ed., Chapter 31. Boca Raton, FL: CRC.

Chaffin, D. B., Andersson, G. B. J., and Martin, B. J. (2006) *Occupational Biomechanics*, fourth ed. New York: Wiley.

Charney, W. (2010) *Handbook of Modern Hospital Safety*, second ed. Boca Raton, FL: CRC.

Chengular, S. N., Rodgers, S. H., and Bernard, T. E. (2003) *Kodak's Ergonomic Design for People at Work*, second ed. New York: Wiley.

Ciriello, V. M. (2001) The effects of box size, vertical distance, and height on lowering tasks. *International Journal of Industrial Ergonomics* 28: 61–67.

Ciriello, V. M. (2007) The effects of container size, frequency, and extended horizontal reach on maximum acceptable weights of lifting for female industrial workers. *Applied Ergonomics* 38: 1, 1–5.

Ciriello, V. M., McGorry, R. W., Martin, S., and Bezverkhny, I. B. (1999) Maximum acceptable forces of dynamic pushing: Comparison of two techniques. *Ergonomics* 42: 1, 32–39.

Colapinto, J. (2015) Lighting the brain. *The New Yorker*, May 18 issue, 74–83.

Colombini, D., Occhipinti, E., Alvarez-Casado, E., and Waters, T. R. (2012) *Manual Lifting*. Boca Raton, FL: CRC.

Corlett, E. N. (2005) The evaluation of industrial seating. In Wilson, J. R., and Corlett, N. (eds.), *Evaluation of Human Work*, third ed., Chapter 27. London: Taylor & Francis.

Costa, G. (2010, December) Shift work and health: Current problems and preventive actions. *Safe Health Work* 1: 2, 112–123.

Cox, T., and Griffiths, A. (2005) The nature and measurement of work-related stress: Theory and practice. In Wilson, J. R., and Corlett, N. (eds.), *Evaluation of Human Work*, third ed., Chapter 19. London: Taylor & Francis.

Czaja, S. J., Zarcadoolas, C., Vaughon, W. L., Lee, C. C., Rockoff, M. L., and Levy, J. (2015) The usability of electronic personal health record systems for an underserved adult population. *Human Factors* 57: 491–506.

Czeisler, C. A., and Gooley, J. J. (2007) Sleep and circadian rhythms in humans. *Cold Spring Harbor Symposia on Quantitative Biology* 72: 579–597.

Daams, B. J. (1993) Static force exertion in postures with different degrees of freedom. *Ergonomics* 36: 397–406.

Daams, B. J. (1994) Human force exertion in user–product interaction: Background for design. Delft, NL: Delft University Press—IOS Press.

Daams, B. J. (2001) Push and pull data, pp. 299–316; torque data, pp. 334–342. In Karwowski, W. (ed.), *International Encyclopedia of Ergonomics and Human*. London: Taylor & Francis.

Dekker, S. (2014) *The Field Guide to Understanding Human Error*. Williston, VT: Ashgate.

Delleman, N. J., Haslegrave, C. M., and Chaffin, D. B. (eds.) (2004) *Working Postures and Movements*. Boca Raton, FL: CRC.

Dempsey, P. G. (1998) A critical review of biomechanical, epidemiological, physiological and psychophysical criteria for designing manual materials handling tasks. *Ergonomics* 41: 73–88.

Dempsey, P. G. (2006) Psychophysical approach to task analysis. In Marras, W. S., and Karwowski, K. (eds.), *The Occupational Ergonomics Handbook: Fundamentals and Assessment Tools for Occupational Ergonomics*, second ed., Chapter 47. Boca Raton, FL: CRC.

Dennerlein, J. T. (2005) Finger flexor tendon forces are a complex function of finger joint motions and fingertip forces. *Journal of Hand Therapy* 18: 2, 120–127.

Dennerlein, J. (2006) The computer keyboard system design. In Marras, W. S., and Karwowski, K. (eds.) *The Occupational Ergonomics Handbook: Interventions, Controls, and Applications in Occupational Ergonomics*, second ed., Chapter 39. Boca Raton, FL: CRC.

Deyo, R. A., and Weinstein, J. N. (2001) Low back pain. *New England Journal of Medicine* 344: 363–370.

Dillon, B. S. (2008) *Reliability, Technology, Human Error, and Quality in Healthcare*. Boca Raton, FL: CRC.

Doidge, N. (2007) *The Brain That Changes Itself*. New York: Penguin.

Driskell, J. E., and Mullen, B. (2005) The efficacy of naps as a fatigue countermeasure: A meta-analytic integration. *Human Factors* 47: 360–377.

Dvorak, A. (1936) Typewriter keyboard. Patent No. 2,040,248. Alexandria, VA, United States Patent Office.

Dvorak, A. (1943) There is a better typewriter keyboard. *The National Business Education Quarterly* 12: 2, 51–58, 66.

Eastman Kodak Company. (1983) *Ergonomic Design for People at Work*. New York: Van Nostrand Reinhold.

Enoka, R. M. (1988) *Neuromechanical Basis of Kinesiology*. Champaign, IL: Human Kinetics.

Ettema, A. M., Zhao, C., Amadio, P. C., O'Byrne, M. M., and An, K. N. (2007) Gliding characteristics of flexor tendon and tenosynovium in carpal tunnel syndrome: A pilot study. *Clinical Anatomy* 20: 3, 292–299.

Fagarasanu, M., and Kumar, S. (2004) Hand strenght. In Kumar, S. (ed.), *Muscle Strength*, Chapter 10. Boca Raton, FL: CRC.

Feathers, D., D'Souza, C., and Paquet, V. (2015) Anthropometry in ergonomic design. In Wilson, J. R., and Shaples, S. (eds.), *Evaluation of Human Work*, fourth ed. Chapter 27, 725–749. Boca Raton, FL: CRC.

Finomore, V. S., Shaw, T. H., Warm, J. S., Matthews, G., and Boles, D. B. (2013) Viewing the workload of vigilance through the lenses of the NASA-TLX and the MRQ. *Human Factors* 55: 1044–1063.

Fisk, A. D., Rogers, W. A., Charness, N., Czaja, S. J., and Sharit, J. (eds.) (2009) *Designing for Older Adults*, second ed. Boca Raton, FL: CRC.

Flier, J. F., and Maratos-Flier, E. (2007) What fuels fat. *Scientific American* 297: 3, 72–81.

Folkard, S., and Monk, T. H. (eds.) (1985) *Hours of Work*. Chichester, UK: Wiley.

Folkard, S., and Tucker, P. (2003) Shift work, safety and productivity. *Occupational Medicine* 53: 95–101.

Folkard, S., Lombardi, D. A., and Tucker, P. T. (2005) Shiftwork, sleepiness and sleep. *Industrial Health* 43: 20–23.

Foster, R., and Kreitzman, L. (2004) Rhythms of life. *The Biological Clocks That Control the Daily Lives of Every Living Thing*. London: Profile.

Fox, J. G. (1983) Industrial music, pp. 221–226. In Oborne, D. J., and Gruneberg, M. M. (eds.), *The Physical Environment at Work*. New York: Wiley.

Freivalds, A. (1999) Ergonomics of hand controls. In Karwowski, K., and Marras, W. S. (eds.), *The Occupational Ergonomics Handbook*, Chapter 27. Boca Raton, FL: CRC.

Freivalds, A. (2006) Upper extremity analysis of the wrist. In Marras, W. S., and Karwowski, K. (eds.), *The Occupational Ergonomics Handbook: Fundamentals and Assessment Tools for Occupational Ergonomics*, second ed., Chapter 45. Boca Raton, FL: CRC.

Freivalds, A. (2011) *Biomechanics of the Upper Limbs: Mechanics, Modeling and Musculoskeletal Injuries*, second ed. Boca Raton, FL: CRC.

Fries, R. C. (2012) *Reliable Design of Medical Devices*. Boca Raton, FL: CRC.

Garg, A., and Marras, W. S. (eds.) (2014) Epidemiological studies of workplace musculoskeletal disorders. *Human Factors (Special issue)* 56: 5–242.

Gavande, A. (2008) The itch. *The New Yorker*, June 30 issue, 58–65.

Gawande, A. (2015) Overkill. *The New Yorker*, May 11 issue, 42–53.

Gibbons, J. D. (1997) *Nonparametric Methods for Quantitative Analysis*, third ed. Columbus, OH: American Sciences.

Goodman, H. J., and Choueka, J. (2005) Biomechanics of the flexor tendons. *Hand Clinics* 21: 2, 129–149.

Gordon, C. C., Blackwell, C. L., Bradtmiller, B., Parham, J. L., Barrientos, P., Paquette, S. P., Corner, B. D. et al. (2014) 2012 Anthropometric Survey of U.S. Army Personnel: Methods and

Summary Statistics. Technical Report NATICK/TR-15/007. Natick, MA: U.S. Army Natick Soldier Research, Development and Engineering Center.

Gordon, C. C., Churchill, T., Clauser, C. E., Bradtmiller, B., McConville, J. T., Tebbetts, I., and Walker, R. A. (1989) 1988 Anthropometric Survey of U.S. Army personnel: Summary Statistics Interim Report. Technical Report NATICK/TR-89-027, Natick, MA: U.S. Army Natick Research, Development and Engineering Center.

Grandjean, E. (1987) *Ergonomics in Computerized Offices*. London: Taylor & Francis.

Greenberg, J. (2010) *Behavior in Organizations: Understanding and Managing the Human Side of Work*, tenth ed. Upper Saddle River, NJ: Prentice-Hall.

Hall, J. E. (ed.) (2015) *Guyton and Hall Textbook of Medical Physiology*, 13th ed. Amsterdam: Elsevier.

Harvey, P., Stoner, J., Hochwarter, W., and Kacmar, C. (2007) Coping with abusive supervision: The neutralizing effects of ingratiation and positive effect on negative employee outcomes. *The Leadership Quarterly* 18: 3, 264–280.

Havenith, G. (2005) Thermal conditions measurement. In Stanton, N., Hedge, A., Brookhuis, K., Salas, E., and Hendrick, H. (eds.), *Handbook of Human Factors and Ergonomics Methods*, Chapter 60. Boca Raton, FL: CRC.

Hedge, A., and James, T. (2012) Ergonomic issues of computer use in a major healthcare system. *Proceedings of the Fourth International Conference on Applied Human Factors and Ergonomics 2012, July 21–25, San Francisco*, 2630–2639.

Heidner, F. (1915) Type-writing machine. Letter's Patent No. 1,138,474. Alexandria, VA: United States Patent Office.

Helander, M. G. (2003) Forget about ergonomics in chair design? Focus on aesthetics and comfort! *Ergonomics* 46: 1306–1319.

Helander, M. G. (2006) *A Guide to Human Factors and Ergonomics*, second ed. Boca Raton, FL: CRC.

Helander, M. G., and Zhang, L. (1997) Field studies of comfort and discomfort in sitting. *Ergonomics* 41: 895–915.

Hendrick, H. W., and Kleiner, B. M. (eds.) (2005) *Macroergonomics: Theory, Methods, and Applications*, second ed. Boca Raton, FL: CRC.

Herzberg, F. (1966) *Work and the Nature of Man*. New York: Thomas.

Herzberg, F. (1968) One more time: How do you motivate employees? Reprinted in the *Harvard Business Review*, September–October 1987 issue, 5–16.

Herzog, W. (2007) Determinants of muscle strength. In Kumar, S. (ed.), *Biomechanics in Ergonomics*, second ed., Chapter 7. Boca Raton, FL: CRC.

Hill, S. G., and Kroemer, K. H. E. (1986) Preferred declination of the line of sight. *Human Factors* 28: 2, 127–134.

Hinkelmann, K., and Kempthorne, O. (1994) *Design and Analysis of Experiments: Vol. 1: Introduction to Experimental Design*. New York: Wiley.

Hinkelmann, K., and Kempthorne, O. (2005) *Design and Analysis of Experiments: Vol. 2: Advanced Experimental Design*. New York: Wiley-Interscience.

Hornberger, S., Knauth, P., Costa, G., and Folkard, S. (eds.) (2000) *Shiftwork in the 21st Century*. Frankfurt, Germany: Lang.

Horne, J. (1988) *Why We Sleep—The Functions of Sleep in Humans and Other Mammals*. Oxford: Oxford University.

Horne, J. A. (2006) *Sleepfaring: A Journey through the Science of Sleep*. Oxford, UK: Oxford University Press.

Houy, D. A. (1983) Range of joint motion in college males, pp. 374–378. In *Proceedings of the Human Factors Society 27th Annual Meeting*. Santa Monica, CA: Human Factors Society.

Howarth, P. A. (2005) Assessment of the visual environment. In Wilson, J. R., and Corlett, N. (eds.), *Evaluation of Human Work*, third ed., Chapter 24. London: Taylor & Francis.

Hsiao, H., Long, D., and Snyder, K. (2002) Anthropometric differences among occupational groups. *Ergonomics* 45: 136–152.

Hughes, R. E., and An, K. N. (2007) Biomechanical models of the hand, wrist, and elbow in ergonomics. In Kumar, S. (ed.), *Biomechanics in Ergonomics*, second ed., Chapter 14. Boca Raton, FL: CRC.

Human Factors and Ergonomics Society 300 Committee (ed.) (2004) *Guidelines for Using Anthropometric Data in Product Design*. Santa Monica, CA: Human Factors and Ergonomics Society.

Imrhan, S. N., Nguyen, M. T., and Nguyen, N. N. (1993) Hand anthropometry of Americans of Vietnamese origin. *International Journal of Industrial Ergonomics* 12: 281–287.

International Labour Office (ed.) (1986) *Introduction to Work Study*, third ed., Chapter 14. Geneva: International Labour Office.

International Labour Office (ed.) (1988) Maximum Weights in Load Lifting and Carrying. Occupational Safety and Health Series #59. Geneva: International Labour Office.

ISO Standards 226-2003. Available from the International Organization for Standardization. Geneva: Switzerland.

ISO 15535:2012 General requirements for establishing anthropometric databases. International Organization for Standardization, Geneva.

ISO 20685:2010 3-D scanning methodologies for internationally compatible anthropometric databases. International Organization for Standardization, Geneva.

ISO 7250-1:2008 Basic human body measurements for technological design—Part 1: Body measurement definitions and landmarks. International Organization for Standardization, Geneva.

Jarrett, A. (ed.) (1973) *The Physiology and Pathology of the Skin*. London: Academic Press.

Juergens, H. W., Aune, I. A., and Pieper, U. (1990) International Data on Anthropometry. Occupational Safety and Health Series #65, 21–42. Geneva: International Labour Office.

Kapandji, I. A. (1988) *The Physiology of the Joints*. Edinburgh: Churchill Livingstone.

Karwowski, W. (ed.) (2006a) *International Encyclopedia of Ergonomics and Human Factors*, second ed. Boca Raton, FL: CRC.

Karwowski, W. (2006b) From past to future. *Human Factors and Ergonomics Society Bulletin* 49: 11, 1–3.

Karwowski, W., Soares, M. M., and Stanton, N. A. (2011) *Handbook of Human Factors and Ergonomics in Consumer Product Design*. Boca Raton, FL: CRC.

Kenny, W. L., Wilmore, J., and Costill, D. (2015) *Physiology of Sport and Exercise*, sixth ed. Champaign, IL: Human Kinetics.

Kincaid, R. D., and Gonzalez, B. K. (1969) Human Factors Design Considerations for Touch-Operated Keyboards. Final Report 12091-FR. St. Paul, MN: Honeywell, Inc.

Klemmer, E. T. (1958) A Ten-Key Typewriter. Research Memorandum RC-65. Yorktown Heights, NY: IBM Research Center.

Klockenberg, E. A. (1926) *Rationalization of the Typewriter and Its Operation* (in German). Berlin: Springer.

Knauth, P. (2006) Workday length and shiftwork issues. In Marras, W. S., and Karwowski, K. (eds.), *The Occupational Ergonomics Handbook: Interventions, Controls, and Applications in Occupational Ergonomics*, second ed., Chapter 29. Boca Raton, FL: CRC.

Knauth, P. (2007a) Extended work periods. *Industrial Health* 45: 125–136.

Knauth, P. (2007b) *Schicht- und Nachtarbeit*, shift work and night work (in German). In Landau, K. (ed.), *Lexikon Arbeitsgestaltung*. Stuttgart: Gentner.

Konz, S., and Johnson, S. (2007) *Work Design: Industrial Ergonomics*, sixth ed. Scottsdale, AR: Holcomb Hataway.

Kroemer, A. D., and Kroemer, K. H. E. (2017) *Office Ergonomics*, second ed. Boca Raton, FL: CRC.

Kroemer, K. H. E. (1965) Ergonomic aspects of control operation (in German). PhD dissertation. Hannover: Technical University Hannover.

Kroemer, K. H. E. (1974) Designing for muscular strength of various populations. AMRL-Technical Report 72-46, Wright-Patterson AFB, OH: Aerospace Medical Research Laboratory.

Kroemer, K. H. E. (1985) Testing individual capability to lift material: Repeatability of a dynamic test compared with static testing. *Journal of Safety Research* 16: 1–7.

Kroemer, K. H. E. (1986) Coupling the hand with the handle. *Human Factors* 28: 3, 337–339.

Kroemer, K. H. E. (1997) *Ergonomic Design of Material Handling Systems*. Boca Raton, FL: CRC.

Kroemer, K. H. E. (1998) Relating muscle strength and its internal transmission to design data, pp. 349–352. In Kumar, S. (ed.), *Advances in Occupational Ergonomics and Safety*. Amsterdam: IOS.

Kroemer, K. H. E. (1999) Assessment of human muscle strength for engineering purposes: Basics and definitions. *Ergonomics* 42: 74–93.

Kroemer, K. H. E. (2001) Keyboards and keying: An annotated bibliography of the literature from 1878 to 1999. *International Journal Universal Access in the Information Society UAIS 1/2*, pp. 99–160. Available at http://www.springerlink.com/index/yp9u5phcqpyg2k4b.pdf.

Kroemer, K. H. E. (2006a) Designing children's furniture and computers for school and home. *Ergonomics in Design* 3: 8–16.

Kroemer, K. H. E. (2006b) Designing for older people. *Ergonomics in Design* 4: 25–31.

Kroemer, K. H. E. (2006c) *"Extra-Ordinary" Ergonomics: How to Accommodate Small and Big persons, the Disabled and Elderly, Expectant Mothers and Children*. Boca Raton, FL: CRC.

Kroemer, K. H. E. (2008) Anthropometry and biomechanics: Anthromechanics. In Kumar, S. (ed.), *Biomechanics in Ergonomics*, second ed., Chapter 2. Boca Raton, FL: CRC.

Kroemer, K. H. E. (2010) 40 Years of human engineering the keyboard. In *Proceedings of the 54th Annual Meeting of the Human Factors and Ergonomics Society*, pp. 1134–1138. Santa Monica, CA: Human Factors and Ergonomics Society.

Kroemer, K. H. E., and Kroemer, A. D. (2001) *Office Ergonomics*. London: Taylor & Francis.

Kroemer, K. H. E., and Kroemer, A. D. (2006) *Office Ergonomics*, Korean ed. Seoul: Kokje Publishing.

Kroemer, K. H. E., and Robinson, D. E. (1971) Horizontal static forces exerted by men standing in common working positions on surfaces of various tractions. AMRL-Technical Report 70-114. Wright-Patterson AFB, OH: Aerospace Medical Research Laboratory.

Kroemer, K. H. E., Kroemer, H. B., and Kroemer-Elbert, K. E. (2003) (amended reprint of the 2001 ed.) *Ergonomics: How to Design for Ease and Efficiency*, second ed. Upper Saddle River, NJ: Prentice Hall/Pearson.

Kroemer, K. H. E., Kroemer, H. J., and Kroemer-Elbert, K. E. (2010) *Engineering Physiology: Bases of Human Factors/Ergonomics*, fourth ed. Heidelberg, Germany: Springer.

Kumar, S. (2001) Theories of musculoskeletal injury causation. *Ergonomics* 44: 1, 17–47.

Kumar, S. (ed.) (2004) *Muscle Strength*. Boca Raton, FL: CRC.

Kumar, S. (ed.) (2007) *Biomechanics in Ergonomics*, second ed. Boca Raton, FL: CRC.

Kumar, S., and Mital, A. (eds.) (1996) *Electromyography in Ergonomics*. London: Taylor & Francis.

Kurowski, A., Buchholz, B., and Punnett, L. (2014) A physical workload index to evaluate a safe resident handling program for nursing home personnel. *Human Factors* 56: 669–683.

Landy, F. J., and Conte, J. M. (2006) *Work in the 21st Century: An Introduction to Industrial and Organizational Psychology*, second ed. Malden, MA: Blackwell.

Langley, L. W. (1988) Ternary chord-type keyboard. Patent No. 4,775,255. Alexandira, VA: United States Patent Office.

Lavender, S. A. (2006) Training lifting techniques. In Marras, W. S., and Karwowski, K. (eds.), *The Occupational Ergonomics Handbook: Interventions, Controls, and Applications in Occupational Ergonomics*, second ed., Chapter 23. Boca Raton, FL: CRC.

Lee, J. C., and Healy, J. C. (2005) Normal sonographic anatomy of the wrist and hand. *Radiographics* 25: 6, 1577–1590.

Lehmann, G. (1953) *Praktische Arbeitsphyiologie*. Stuttgart: Thieme.

Lehmann, G. (1962) *Praktische Arbeitsphyiologie*, second ed., Stuttgart: Thieme.

Lehto, M., and Landry, S. J. (2014) *Introduction to Human Factors and Ergonomics for Engineers*, second ed. Boca Raton, FL: CRC.

Lepore, J. (2009) Not so fast. *The New Yorker* 85: 32, 114–122.

Leyk, D., Kuechmeister, G., and Juergen, H. W. (2006) Combined physiological and anthropometrical databases as ergonomic tools. *Journal of Physiological Anthropology* 25: 6, 363–369.

Li, H., and Ali, H. (2015, June) Human factors considerations in the design of falls prevention technologies for nursing homes: A case study. *Proceedings of the International Symposium on Human Factors and Ergonomics in Health Care* 4: 97–102.

Liberty Mutual Insurance Company (2016) *Manual Materials Handling Guidelines*. Newsletter Winter 2013/14. Available at http://www.libertymutual.com.

Lockhead, G. R., and Klemmer, E. T. (1959) An Evaluation of an Eight-Key Word-Writing Typewriter, Research Report RC-180. Yorktown Heights, NY: IBM Research Center.

Lu, M. L. (2012) *A Practical Guide to the Revised NIOSH Lifting Equation (NLE)*. Cincinnati, OH: National Institute for Occupational Safety and Health.

Lueder, R., and Rice, V. B. (eds.) (2007) *Ergonomics for Children*. Boca Raton, FL: CRC.

Lundervold, A. J. S. (1951) Electromyographic investigations of position and manner of working in typewriting. *Acta Physiologica Scandinavica* 24(Supplement 84): 1–171.

Marklin, R. W., and Simoneau, G. G. (2004) Design features of alternative computer keyboards: A review of experimental data. *Journal of Orthopaedic & Sports Physical Therapy* 34: 638–649.

Marquie, J. C., Tucker, P., Folkard, S., Gentil, C., and Ansiau, D. (2013) Chronic effects of shift work on cognition: Findings from the VISAT longitudinal study. *Occupational and Environmental Medicine* doi: 10.1136/oemed-2013-101993.

Marras, W. S. (2008) *The Working Back: A Systems View*. New York: Wiley.

Marras, W. S., and Karwowski, K. (eds.) (2006a) *The Occupational Ergonomics Handbook: Fundamentals and Assessment Tools for Occupational Ergonomics*, second edition. Boca Raton, FL: CRC.

Marras, W. S., and Karwowski, K. (eds.) (2006b) *The Occupational Ergonomics Handbook: Interventions, Controls, and Applications in Occupational Ergonomics*, second ed. Boca Raton, FL: CRC.

Marras, W. S., and Radwin, R. G. (2006) Biomechanical modeling. In Dickerson, R. S. (ed.), *Reviews of Human Factors and Ergonomics*, Vol. 1, Chapter 1. Santa Monica, CA: Human Factors and Ergonomics Society.

Marras, W. S., McGlothlin, J. D., McIntyre, D. R., Nordin, M., and Kroemer, K. H. E. (1993) *Dynamic Measures of Low Back Performance*. Fairfax, VA: American Industrial Hygiene Association.

Martimo, K. P., Verbeek, J., Karppinen, J., Furlan, A. D., Takala, E. P., Kuijer, P. P. F., Jaihiainen, M., and Viikari-Juntura, E. (2008) Effect of training and lifting equipment for preventing back pain in lifting and handling: Systematic review. *British Medical Journal* 336: 429–431.

Maslow, A. H. (1943) A theory of motivation. *Psychological Review* 50: 370–396.

Maslow, A. H. (1954) *Motivation and Personality* (second ed.: 1970). New York: HarperCollins.

Matthews, G., Reinerman-Jones, L. E., Barber, D. J., and Abich, J. (2015) The psychometrics of mental workload: Multiple measures are sensitive but divergent. *Human Factors* 57: 125–143.

Mauney, J., Furlough, C., and Barnes, J. (2015, June) Developing a better clinical alert system in EHRs. *Proceedings of the International Symposium on Human Factors and Ergonomics in Health Care* 4: 29–36.

McGill, S. M. (2006) Back belts. In Marras, W. S., and Karwowski, K. (eds.), *The Occupational Ergonomics Handbook: Interventions, Controls, and Applications in Occupational Ergonomics*, second ed., Chapter 30. Boca Raton, FL: CRC.

McMillan, G. R. (2001) Brain and muscle signal-based control, pp. 379–381. In Karwowski, W. (ed.), *International Encyclopedia of Ergonomics and Human Factors*. London: Taylor & Francis.

McMillan, G. R., and Calhoun, G. L. (2001) Gesture-based control, pp. 237–239. In Karwowski, W. (ed.), *International Encyclopedia of Ergonomics and Human Factors*. London: Taylor & Francis.

McMin, T. (2013) “A-Weighting”: Is it the metric you think it is? In *Proceedings of Acoustics 2013* (Victor Harbor, November 17–20, 2013). Victor Harbor: Australian Acoustical Society.

McMulkin, M. L., and Kroemer, K. H. E. (1994) Usability of a one-hand ternary chord keyboard. *Applied Ergonomics* 25: 3, 177–181.

Megaw, T. (2005) The definition and measurement of mental workload. In Wilson, J. R., and Corlett, N. (eds.), *Evaluation of Human Work*, third ed., Chapter 18. London: Taylor & Francis.

Merletti, R., Farina, D., and Rainoldi, R. (2004) Myoelectric manifestations of muscle fatigue. In Kumar, S. (ed.), *Muscle Strength*, Chapter 18. Boca Raton, FL: CRC.

Merck Manual of Medical Information (home ed.: 1997). Whitehouse Station, NJ: Merck and Co., Inc.

MIL-Std 759, 1472 (and others): DLA Document Services, Building 4/D, 700 Robbins Avenue, Philadelphia, PA 19111-5094.

Mishan, E. J., and Quah, E. (2007) *Cost-Benefit Analysis*. London: Routledge.

Monk, T. H. (2006) Shiftwork. In Marras, W. S., and Karwowski, K. (eds.), *The Occupational Ergonomics Handbook: Interventions, Controls, and Applications in Occupational Ergonomics*, second ed., Chapter 32. Boca Raton, FL: CRC.

Muchinsky, P. M., and Culberson, S. S. (2016) *Psychology Applied to Work*, 11th ed. Summerfield, NC: Hypergraphic Press.

Nachemson, A., and Elfstroem, G. (1970) Intervertebral dynamic pressure measurements in lumbar discs. *Scandinavian Journal of Rehabilitation Medicine* Supplement 1: 1–40.

Nagamachi, M. (2001) Relationships among job design, macro ergonomics, and productivity. In Hendrick, H. W., and Kleiner, B. M. (eds.), *Macro Ergonomics: Theory, Methods, and Applications*, Chapter 6. Mahwah, NJ: Erlbaum.

Nagamachi, M. (2011) *Kansai Engineering*. Boca Raton, FL: CRC.

NASA (ca. 2015) NASA-STD-3001 Space Flight Human-System Standard Vol. 1 (Crew Health); Vol. 2 (Human Factors, Habitability and Environmental Health); NASA/SP-2010-3407 Human Integration Design Handbook (HIDH). Available at http://www.nasa.gov/centers/johnson/slsd/about/divisions/hefd/standards/index.html.

National Institute for Occupational Safety and Health (NIOSH) (1981) Work practices guide for manual lifting, DHHS (NIOSH) Publication # 81-122. Washington, DC: U.S. Government Printing Office.

National Institute of Occupational Health and Safety (NIOSH) (2015) Work Schedules: Shift Work and Long Hours. DHHS (NIOSH) Publication # 2015-115, August 5, 2015. Washington, DC: U.S. Government Printing Office.

National Research Council (ed.) (1999) *Work-Related Musculoskeletal Disorders: Report, Workshop Summary, and Workshop Papers*. Washington, DC: National Academy.

Nordin, M., and Frankel, V. H. (1989) *Basic Biomechanics of the Musculoskeletal System*. Philadelphia, PA: Lea and Febiger.

Nordin, M., Andersson, G. B. J., and Pope, M. H. (1997) *Musculoskeletal disorders in the Workplace: Principles and Practices*. St. Louis, MO: Mosby.

Noyes, J. (1983a) Chord keyboards. *Applied Ergonomics* 14: 55–59.

Noyes, J. (1983b) The QWERTY keyboard: A review. *International Journal of Man-Machine Studies* 18: 265–281.

Oezkaya, N., Nordin, M., Goldsheyder, D., and Leger, D. (2012) *Fundamentals of Biomechanics*. Heidelberg, Denmark: Springer.

Osler, W. (1892) *The Principles and Practice of Medicine: IX. Professional Spasms; Occupation Neuroses*. New York: Appleton.

Owen, D. (2006) The soundtrack of your life; Muzak in the realm of retail theatre. *The New Yorker*, April 10 issue, 66–71.

Paquette, S., Gordon, C., and Bradtmiller, B. (2009) Anthropometric Survey (ANSUR) II Pilot Study: Methods and Summary Statistics. Technical Report Natick/TR-09/014. Natick, MA: U.S. Army Natick Soldier Research, Development and Engineering Center.

Parsons, H. M. (1974) What happened at Hawthorne? *Science* 18: 922–932.

Parsons, K. C. (2003) *Human Thermal Environments*, second ed. London: Taylor & Francis.

Parsons, K. C. (2005) Ergonomic Assessments of Thermal Environments. In Wilson, J. R., and Corlett, N. (eds.), *Evaluation of Human Work*, third ed., Chapter 23. London: Taylor & Francis.

Parsons, K. C. (2014) *Human Thermal Environments*, third ed. Boca Raton, FL: CRC.

Patterson, E. S., Latkany, P., Brick, D., Gibbons, M. C., Ramaiah, M., and Lowry, S. Z. (2015) Integrating electronic health records into clinical workflow. *Proceedings of the International Symposium on Human Factors and Ergonomics in Health Care* 4: 42–49.

Peebles, L., and Norris, B. (1998) *Adultdata: The Handbook of Adult Anthropometric and Strength Measurements—Data for Design Safety*. DTI/Pub 2917/3k/6/98/NP. London: Department of Trade and Industry.

Peebles, L., and Norris, B. (2000) *Strength Data*. DTI/URN 00/1070. London: Department of Trade and Industry.

Peebles, L., and Norris, B. (2003) Filling "gaps" in strength data for design. *Applied Ergonomics* 34: 73–88.

Pereira, A., Hsieh, C. M., Laroche, C., and Rempel, D. (2014) The effect of keyboard key spacing on typing speed, error, usability, and biomechanics: Part 2: Vertical spacing. *Human Factors* 56: 752–759.

Pereira, A., Wachs, J. P., Park, K., and Rempel, D. (2015) A user-developed 3-D hand gesture set for human–computer interaction. *Human Factors* 57: 607–621.

Permanen, J. (2012) Some reasons to revise the International Standard ISO 226:2003: Acoustics—Normal Equal-Loudness-Level Contours. *Open Journal of Acoustics* 2: 143–149.

Pew, P. W., and Mavor, A. S. (eds.) (2007) *Human-System Integration in the System Development Process*. Washington, DC: The National Academies.

Pheasant, S., and Haslegrave, C. M. (2006) *Anthropometry, Ergonomics and the Design of Work*, third ed. London: Taylor & Francis.

Poore, G. V. (1872) "Writer's cramp": Its pathology and treatment. *Practitioner, August issue*: 341–350.

Poore, G. V. (1887) Clinical lecture on certain conditions of the hand and arm which interfere with the performance of professional acts, especially piano-playing. *The British Medical Journal, February 26 issue*: 441–444.

Popkin, S. M. (ed.) (2015) *Worker Fatigue and Transportation Safety*: *Vol. 10 of Reviews of Human Factors and Ergonomics*. Santa Monica, CA: Human Factors and Ergonomics Society.

Popkin, S. M., Howarth, H. D., and Tepas, D. I. (2006) Ergonomics of work systems, pp. 761–800. In Salvendy, G. (ed.), *Handbook of Human Factors and Ergonomics*, third ed. Hoboken, NJ: Wiley.

Proctor, R. W., and Van Zandt, T. (2008) *Human Factors in Simple and Complex Systems*, second ed. Boca Raton, FL: CRC.

Putz-Anderson, V. (1988) *Cumulative Trauma Disorders: A Manual for Musculoskeletal Diseases of the Upper Limbs*. London: Taylor & Francis.

Ramsey, T., Davis, K. M., Kotowski, S. E., Anderson, V. P., and Waters, T. (2014) Reduction of spinal loads through adjustable interventions at the origin and destination of palletizing tasks. *Human Factors* 56: 1222–1234.

Rea, M. S. (2005) Photometric characterization of the luminous environment. In Stanton, N., Hedge, A., Brookhuis, K., Salas, E., and Hendrick, H. (eds.), *Handbook of Human Factors and Ergonomics Methods*, Chapter 68. Boca Raton, FL: CRC.

Reddy, N. P., and Gupta, V. (2007) Toward direct biocontrol using surface EMG signals: Control of finger and wrist joint models. *Medical Engineering & Physics* 29: 3, 398–403.

Refinetti, R. (2016) *Circadian Physiology*, third ed. Boca Raton, FL: CRC Press.

Remington, R. J., and Rogers, M. (1969) Keyboard Literature Survey, Phase 1: Bibliography, TR 29.0042. Research Triangle Park, NC, BM Systems Development Division.

Rempel, D. (2008) The split keyboard: An ergonomics success story. *Human Factors* 50: 385–392.

Rempel, D., Willms, K., Anshel, J., Jaschinski, W., and Sheedy, J. (2007) The effects of visual display distance on eye accommodation, head posture, and vision and neck symptoms. *Human Factors* 49: 830–838.

Robinson, P. A. (2009) *Writing and Designing Manuals and Warnings*, fourth ed. Boca Raton, FL: CRC.

Rodahl, K. (1989) *The Physiology of Work*. London: Taylor & Francis.

Roebuck, J. A. (1995) *Anthropometric Methods—Designing to Fit the Human Body*. Santa Monica, CA: Human Factors and Ergonomics Society.

Roethlisberger, F. J., and Dickson, W. J. (1943) *Management and the Worker*. Cambridge, MA: Harvard University Press.

Rubio, S., Diaz, E., Martin, J., and Puente, J. M. (2004) Evaluation of subjective mental orkload: A comparison of SWAT, NASA-TLX, and workload profile methods. *Applied Psychology: An International Review* 53: 1, 61–86.

Salvendy, G. (ed.) (2012) *Handbook of Human Factors and Ergonomics*, fourth ed. New York: Wiley.

Saval, N. (2014) *Cubed, A Secret History of the Workplace*. New York: Doubleday.

Selye, H. (1956) *The Stress of Life* (revised ed.: 1978). New York: McGraw-Hill.

Selye, H. (1974) *Stress without Distress*. Philadelphia, PA: Lippincott.

Sheedy, J. (2006) Vision and work. In Marras, W. S., and Karwowski, K. (eds.), *The Occupational Ergonomics Handbook: Interventions, Controls, and Applications in Occupational Ergonomics*, second ed., Chapter 18. Boca Raton, FL: CRC.

Siegel, J. M. (2003) Why we sleep. *Scientific American*, November issue, 92–97.

Skottke, E. M., Debus, G., Wang, L., and Huestegge, L. (2014) Carryover effects of highly automated convoy driving on subsequent manual driving performance. *Human Factors* 56: 1272–1283.

Smith, T. M. (2007) Job satisfaction in America: Trends and sociodemographic correlates. Available at http://www-news.uchicago.edu/releases/07/pdf/070827.jobs.pdf.

Snook, S. H. (2000) Back risk factors: An overview. In Violante, F., Armstrong, T., and Kilbom, A. (eds.), *Occupational Ergonomics: Work-Related Musculoskeletal Disorders of the Upper Limb and Back*, Chapter 11. London: Taylor & Francis.

Snook, S. H. (2005) Psychophysical tables: Lifting, lowering, pushing, pulling, and carrying. In Stanton, N., Hedge, A., Brookhuis, K., Salas, E., and Hendrick, H., (eds.), *Handbook of Human Factors and Ergonomics Methods*, Chapter 13. Boca Raton, FL: CRC.

Snook, S. H., and Ciriello, V. M. (1991) The design of manual handling tasks: Revised tables of maximum acceptable weights and forces. *Ergonomics* 34: 9, 1197–1213.

Sommerich, C. M., and Marras, W. S. (2004) Electromyography and muscle force. In Kumar, S. (ed.), *Muscle Strength*. Chapter 17. Boca Raton, FL: CRC.

Sprent, P. (2000) *Applied Nonparametric Statistical Methods*. Boca Raton, FL: Chapman and Hall/CRC.

Staff, K. R. (1983) A comparison of range of joint mobility in college females and males. Unpublished Master's Thesis. College Station, TX: Texas A&M University.

Stanton, N., Hedge, A., Brookhuis, K., Salas, E., and Hendrick, H. (eds.) (2005) *Handbook of Human Factors and Ergonomics Methods.* Boca Raton, FL: CRC.

Strokina, A. N., and Pakhomova, B. A. (1999) Anthropo-ergonomic atlas. Moscow, Russia: Moscow State University Publishing House.

Strong, E. P. (1956) *A Comparative Experiment and Simplified Keyboard Retraining and Standard Keyboard Supplementary Training*. Washington, DC: General Services Administration.

Strokina, A. N., and Pakhomova, B. A. (1999) *Anthropo-ergonomic Atlas*. Moscow, Russia: Moscow State University Publishing House.

Swink, J. R. (1966) Intersensory comparisons of reaction time using an electro-pulse tactile stimulus. *Human Factors* 8: 143–145.

Tamhane, A. C. (2009) *Statistical Analysis of Designed Experiments: Theory and Applications*. Hoboken, NJ: Wiley.

Taylor, F. (1911) *The Principles of Scientific Management*. New York: Norton.

Toomingas, A., Mathijssen, S. E., and Tornquist, E. W. (2011) *Occupational Physiology*. Boca Raton, FL: CRC.

Ugbolue, U. C., Hsu, W. H., Goitz, R. J., and Li, Z. M. (2005) Tendon and nerve displacement at the wrist during finger movements *Clinical Biomechanics* 20: 1, 50–56.

University of Nottingham (2002) *Strength Data for Design Safety: Phase 2*. DTI URN 01/1433. London: Department of Trade and Industry.

Useem, J. (2015) Are bosses necessary? *The Atlantic*, October issue, 28–32.

Vercruyssen, M., and Hendrick, H. L. (2011) *Behavioral Research and Analysis*, fourth ed., Boca Raton, FL: CRC.

Victor, T. W., Lee, J., and Regan, M. A. (2013) *Driver Distraction and Inattention*. Abingdon, UK: Ashgate.

Vink, P. (2005) *Comfort and Design: Principles and Good Practice*. Boca Raton, FL. CRC.

Violante, F., Armstrong, T., and Kilbom, A. (eds.) (2000) *Occupational Ergonomics: Work-Related Musculoskeletal Disorders of the Upper Limb and Back*. London: Taylor & Francis.

Walji, A. H. (2007) Functional anatomy of the upper limb (extremity). In Kumar, S. (ed.), *Biomechanics in Ergonomics*, second ed., Chapter 8. Boca Raton, FL: CRC.

Walker, G., Stanton, N. A., and Salmon, P. (2015) *Human Factors in Automotive Engineering and Technology*. Abingdon: Ashgate.

Wang, M. J. J., Wang, E. M. Y., and Lin, Y. C. (2002) *Anthropometric Data Book of the Chinese People in Taiwan.* Hsinchu, Taiwan: The Ergonomics Society of Taiwan.

Wargo, M. J. (1967) Human operator response speed, frequency and flexibility: A review and analysis. *Human Factors* 9: 221–238.

Waters, T. R. (2006) Revised NIOSH lifting equation. In Marras, W. S., and Karwowski, K. (eds.), *The Occupational Ergonomics Handbook: Interventions, Controls, and Applications in Occupational Ergonomics*, second ed., Chapter 46. Boca Raton, FL: CRC.

Waters, T. R. (2010) Introduction to ergonomics for healthcare workers. *Rehabilitation Nursing* 35: 5, 185–91.

Waters, T. R., and Putz-Anderson, V. (1999) Revised NIOSH lifting equation. In Marras, W. S., and Karwowski, K. (eds.), *The Occupational Ergonomics Handbook: Interventions, Controls, and Applications in Occupational Ergonomics*, second ed., Chapter 57. Boca Raton, FL: CRC.

Waterson, P. (2014) *Patient Safety Culture*. Abingdon, UK: Ashgate.

Weinger, M. B., Wiklund, M. E., and Gardner-Bonneau, D. J. (2010) *Handbook of Human Factors in Medical Device Design*. Boca Raton, FL: CRC.

Whitcome, K. K., Shapiro, L. J., and Lieberman, D. E. (2007, December 12) How women bend over backwards for baby. *Nature*, doi: 10.1038/news.2007.374.

Wickens, C. D., Lee, J., Liu, Y., and Gordon-Becker, S. (2004) *An Introduction to Human Factors Engineering*, second ed. Upper Saddle River, NJ: Prentice-Hall/Pearson Education.

Williges, R. C. (2007) *CADRE: Computer-Aided Design Reference for Experiments*. Electronic Book CD-ROM-07-01. Blacksburg, VA: Virginia Polytechnic Institute and State University.

Wilmore, J. H., Costill, D., and Kenney, W. L. (2008) *Physiology of Sport and Exercise*, fourth ed. Champaign, IL: Human Kinetics.

Wilson, J. R., and Corlett, N. (eds.) (2005) *Evaluation of Human Work*, third ed. London: Taylor & Francis.

Wilson, J. R., and Sharples, S. (eds.) (2015) *Evaluation of Human Work*, fourth ed. Boca Raton, FL: CRC.

Winter, D. A. (2009) *Biomechanics and Motor Control of Human Movement*, fourth ed. New York: Wiley.

Wright, W. C. (1993) *Diseases of Workers* (Translation of Bernardino Ramazzini's *1713 De Morbis Articum*). Thunder Bay, ON: OH&S.

Wu, G., Siegler, S., Allard, P., Kirtley, C., Leardini, A., Rosenbaum, D., Whittle, M. et al. (2002) ISB recommendation on definitions of joint coordinate system of various joints for the reporting of human joint motion: Part I. Ankle, hip, and spine. *Journal of Biomechanics* 35: 543–555.

Wu, J., Yang, J., and Yoshitake, M. (2014) Pedal errors among younger and older individuals during different pedal operating conditions. *Human Factors* 56: 621–630.

Youle, A. (2005) The thermal environment. In Gardiner, K., and Harrington, J. M. (eds.), *Occupational Hygiene*, third ed. Oxford, UK: Blackwell.

Zhang, X., and Chaffin, D. B. (2006) Digital human modeling for computer-aided design. In Karwowski, W., and Marras, W. S. (eds.), *Intervention, Controls, and Applications in Occupational Ergonomics*. Chapter 10. Boca Raton, FL: CRC.

Zhao, C., Ettema, A. M., Osamura, N., Berglund, L. J., An, K. N., and Amadio, P. C. (2007) Gliding characteristics between flexor tendons and surrounding tissues in the carpal tunnel: A biomechanical cadaver study. *Journal of Orthopaedic Research* 25: 2, 185–190.

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