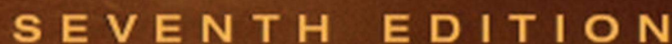


WORK DESIGN

OCCUPATIONAL ERGONOMICS

Stephan KONZ
Steven JOHNSON

SEVENTH EDITION

WORK DESIGN

OCCUPATIONAL ERGONOMICS

Stephan KONZ

KANSAS STATE UNIVERSITY, EMERITUS

Steven JOHNSON

UNIVERSITY OF ARKANSAS

CRC Press
Taylor & Francis Group
Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

Library of Congress Cataloging-in-Publication Data

Konz, Stephan.
Work design : occupational ergonomics / Stephan Konz, Steven Johnson.
p. cm.
Includes bibliographical references and index.
ISBN 978-1-890871-79-6
1. Human engineering. 2. Work design. I. Johnson, Steven. II. Title.
TA166.K69 2008
620.8—dc22
2007033109

First published 2008 by Holcomb Hathaway Publishers

Published 2016 by CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

© 2008 by Taylor & Francis
CRC Press is an imprint of Taylor & Francis Group, an Informa business

No claim to original U.S. Government works

Printed on acid-free paper

International Standard Book Number-13: 978-1-890871-79-6 (Paperback)

This book contains information obtained from authentic and highly regarded sources. Reasonable efforts have been made to publish reliable data and information, but the author and publisher cannot assume responsibility for the validity of all materials or the consequences of their use. The authors and publishers have attempted to trace the copyright holders of all material reproduced in this publication and apologize to copyright holders if permission to publish in this form has not been obtained. If any copyright material has not been acknowledged please write and let us know so we may rectify in any future reprint.

Except as permitted under U.S. Copyright Law, no part of this book may be reprinted, reproduced, transmitted, or utilized in any form by any electronic, mechanical, or other means, now known or hereafter invented, including photocopying, microfilming, and recording, or in any information storage or retrieval system, without written permission from the publishers.

For permission to photocopy or use material electronically from this work, please access www.copyright.com (http://www.copyright.com/) or contact the Copyright Clearance Center, Inc. (CCC), 222 Rosewood Drive, Danvers, MA 01923, 978-750-8400. CCC is a not-for-profit organization that provides licenses and registration for a variety of users. For organizations that have been granted a photocopy license by the CCC, a separate system of payment has been arranged.

Trademark Notice: Product or corporate names may be trademarks or registered trademarks, and are used only for identification and explanation without intent to infringe.

Visit the Taylor & Francis Web site at
http://www.taylorandfrancis.com

and the CRC Press Web site at
http://www.crcpress.com

CONTENTS

List of Text Boxes *vii*
Preface *ix*

PART I

INTRODUCTION TO WORK DESIGN

1 TECHNOLOGICAL SOCIETY 1

Technological Society 2
Work Smart, Not Hard 7
Efficiency of a Job or an Operation 10
Review Questions 16

2 ANATOMY, BIOMECHANICS, WORK PHYSIOLOGY, AND ANTHROPOMETRY 17

Musculoskeletal Anatomy 18
Biomechanics of Muscular Movement 26
Cardiovascular Anatomy 30
Metabolism 32
Response to Exercise 34
Cardiovascular Limits 38
Responses to Mental Work 41
Fit the Job to the Person 41
Population Values 42
Statistical Calculations 48
Review Questions 50

PART II

THE DESIGN PROCESS

3 CRITERIA 51

Organizations 52
Employees 52
Work Design Criteria 56
Review Questions 58

4 ENGINEERING DESIGN 59

Scientific Method 60
Engineering Design 60
Cost Allocation 64
Return on Investment 65
Cost Analysis 67
Review Questions 71

5 SEARCH FOR SOLUTIONS 73

Unstructured Search 74
Structured Search: Systematic 75
Structured Search: SEARCH 77
Review Questions 86

6 OPERATIONS ANALYSIS 87

Location of One Item 88
Systematic Layout of Multiple Items 90
Important Items First (Pareto) 93
Flow Diagrams and Process Charts 94
Multi-Activity Charts 96
Fish Diagrams 98
Decision Structure Tables 100
Subjective Opinions 101
Evolutionary Operation of Processes (EVOP) 104
Project Scheduling 106
Review Questions 109

7 OCCURRENCE SAMPLING 111

Problem 112
Required Number of Observations 113
Representative Sample 116
Data Gathering 119

Data Analysis 120
Applications of Occurrence Sampling 124
Review Questions 126

PART III

ERGONOMIC GUIDELINES

8 MACRO ERGONOMICS 127

Plan the Work, Then Work the Plan 128
Reward Results 128
Optimize System Availability 130
Minimize Idle Capacity 133
Use Filler Jobs or Filler People 135
Communicate Information 138
Review Questions 138

9 ORGANIZATION OF WORKSTATIONS 139

Use Specialization Even Though It Sacrifices Versatility 140
Consider Group Technology 141
Consider Both Non-Progressive and Progressive Assembly 143
Balance Flow Lines 145
Minimize Material Handling Cost 147
Decouple Tasks 149
Make Several Identical Items at the Same Time 163
Combine Operations and Functions 165
Vary Environmental Stimulation Inversely with Task Stimulation 166
Review Questions 168

10 OFFICE ERGONOMICS 169

How Office Layout Differs from Factory Layout 170
Types of Office Arrangements 170
Furniture 176
Security 176
Special Areas 178
Review Questions 182

11 WORSTATION DESIGN 183

Avoid Static Loads and Fixed Work Postures 184
Reduce Musculoskeletal Disorders 191
Set the Work Height at 50 mm Below the Elbow 192
Furnish Every Employee with an Adjustable Chair 197
Use the Feet as Well as the Hands 203
Use Gravity; Don't Oppose It 204
Conserve Momentum 205
Use Two-Hand Motions Rather Than One-Hand Motions 206
Use Parallel Motions for Eye Control of Two-Hand Motions 208
Use Rowing Motions for Two-Hand Motions 208
Pivot Motions About the Elbow 209
Use the Preferred Hand 210
Keep Arm Motions in the Normal Work Area 210
Let the Small Person Reach; Let the Large Person Fit 212
Review Questions 214

12 MUSCULOSKELETAL DISORDERS 215

General Comments 216
Hand/Wrist 226
Shoulder/Neck/Elbow 229
Back 236
Leg 240
Review Questions 240

13 MANUAL HANDLING 241

Background 242
Pushing and Pulling 242
Holding 247
Carrying 249
Lifting 251
Guidelines for Manual Handling 260
Review Questions 269

14 HANDTOOLS 271

Use Special-Purpose Tools 272
Design Tools to Be Used by Either Hand 273
Power with Motors More Than with Muscles 275
Use the Proper Grip 277
Make the Grip the Proper Thickness, Shape, and Length 281
Make the Grip Surface Smooth, Compressible, and Nonconductive 285
Consider the Angles of the Forearm, Grip, and Tool 286

Use the Appropriate Muscle Group 289
Review Questions 292

15 CONTROLS 293

Select the Proper Type of Control 294
Select the Proper Control Characteristics 296
Prevent Unintended Activation 300
Prevent Incorrect Identification 303
Make Accomplishments Equal Intentions 305
Properly Locate and Arrange the Controls 306
Review Questions 308

16 DISPLAYS 309

Select Legible Characters 310
Arrange Characters and Symbols 312
Decide Among Menus, Tables, Formulas, Graphs, Symbolic Messages, and Maps 316
Project Your Message 323
Select the Instrument Display 324
Locate/Arrange the Display 327
Review Questions 329

17 ERROR REDUCTION 331

Introduction 332
Error Analysis Techniques 333
Error Reduction Guidelines 336
Review Questions 350

18 SAFETY 351

Introduction 352
Reduction of Unsafe Conditions 354
Unsafe Acts 359
Medical Management 362
Review Questions 362

19 TEMPORAL ERGONOMICS 365

Fatigue 366
Shiftwork 376
Guidelines 383
Review Questions 386

PART IV
WORK ENVIRONMENTS

20 VISION AND ILLUMINATION 387

The Eye and Light 388
Reduction of Visual Problems 396
General Lighting 404
Special Lighting 406
Review Questions 411

21 HEARING AND NOISE 413

The Ear 414
Noise 417
Effects of Noise 421
Noise Reduction 426
Review Questions 435

22 CLIMATE 437

Comfort 438
Heat Stress 441
Cold Stress 449
Air Volume and Quality 452
Review Questions 454

23 CHEMICAL ENVIRONMENT 455

Poisons 456
Poison Routes 457
Poison Targets 459
Poison Elimination 461
Threshold Limit Values 462
Controls 464
Review Questions 468

PART V
WORK MEASUREMENT

24 DETERMINING TIME/JOB 469

Why Determine Time/Job? 470
Establishing Time Standards 471
Allowances 476

Learning 481
Documenting, Using, and Maintaining Standards 486
Review Questions 486

25 **TIME STUDY** 487

Overview 488
Preparation 488
Timing 489
Rating 495
Review Questions 499

26 **PREDETERMINED TIME SYSTEMS** 501

History and Development 502
Methods-Time Measurement 502
MOST Work Measurement System 512
MODAPTS 514
Comments on Predetermined Time Systems 514
Review Questions 516

27 **STANDARD DATA** 517

Reasons for Standard Data 518
Standard Data Structure 519
Curve Fitting 521
Review Questions 526

PART VI

IMPLEMENTING THE DESIGN

28 **JOB INSTRUCTION/TRAINING** 527

Problem 528
Medium and the Message 530
Training (Memorization) 534
Job Aids 537
Review Questions 540

29 **MANAGING AN ERGONOMICS PROGRAM** 541

History of Ergonomics Programs 542
Organizational Functions Involved in an Ergonomics Program 543
Program Elements 545
Review Questions 555

30 **MANAGING CHANGE** 557

Challenge of Change 558
Process of Change 558
Quality Circles 562
Proposing Change 567
Goal of Job Evaluation 571
Job Description 572
Arranging Jobs in Order 574
Review Questions 577

References 579
Index 603

LIST OF TEXT BOXES

1.1 The Rise of Ergonomics 6
1.2 Waste Minimization 14

2.1 Biomechanics of Walking, Running, and Stepping 26
2.2 Electromyography (EMG) 29
2.3 Cardiac Output 31
2.4 Blood Pressure 31
2.5 Percent Fat 33
2.6 Metabolic Cost of Walking/Running/Carrying 35
2.7 Oxygen Uptake and Pulmonary Ventilation 38
2.8 The Divine Proportion, 1.618 45
2.9 Principle of Similitude 46
2.10 Age of Workforce 48

3.1 Americans with Disabilities Act (ADA) 53
3.2 Productivity Versus Stress Reduction 57

4.1 Releasing a Part for Manufacturing 61
4.2 Benchmarking 63
4.3 Justifying Ergonomics 65

7.1 SAS Program for Occurrence Sampling 121
7.2 Steps to Make an Occurrence Sample 125

8.1 Reduce Waiting 132
8.2 Maintenance Access 132

9.1 Just-in-Time 150
9.2 Breaks for Lines 153
9.3 Break/Rest Area Design to Improve Socialization 167

10.1 Supercenter Management Office 172
10.2 Local Insurance Office 173
10.3 Surgeon's Office 174
10.4 Call Centers 175
10.5 Territoriality and Personal Space 177

11.1 Office VDT Workstations 193
11.2 Supermarket Checkout Workstations 195
11.3 Information Content of Motions 207

12.1 Hazard Zone Jobs 221
12.2 Reducing Ergonomics Risks 223
12.3 Video Recording Jobs 224
12.4 Assumptions for Work-Related CTS 227
12.5 Rapid Upper Limb Assessment (RULA) 230

14.1 Handtool Selection 272
14.2 Gloves 276
14.3 Hand–Arm Vibration 277
14.4 Shovels, Hoes, and Rakes 278

17.1 Signal Detection Theory (SDT) 334
17.2 Crimes 336
17.3 Usability Studies 336
17.4 Making Decisions/Actions Public 337
17.5 Inspection 344
17.6 Inspection Workstation 346
17.7 Inspector: Police or Partner? 346
17.8 Medical Errors 347
17.9 Error Message Guidelines 349

18.1 Safety/Ergonomics Organizations 352
18.2 Health and Safety Committee 354
18.3 Electrical Safety 356

18.4 Fault Trees 360
18.5 Warnings 361
18.6 Risk 362
18.7 Workers' Compensation 363

19.1 Muscle Fatigue 368
19.2 Caffeine 375
19.3 Shiftwork Criteria 378
19.4 Recovery/Work Ratio 384
19.5 Biologic Half-Life 386

20.1 Task-Specific Glasses 394
20.2 Windows 398
20.3 Reading 403

22.1 Homeostasis 445
22.2 Odor Perception 453
22.3 Static Electricity 453

23.1 Electrical and Magnetic Fields 456
23.2 Ultraviolet Radiation 460
23.3 Exposure/Recovery for Chemicals 463
23.4 Clean Rooms 465

24.1 Consequences of Not Making Standard 471
24.2 Incentive Applications 474
24.3 Financial Incentives for Nonincentive Employees 475

25.1 Statistical Formula for Number of Observations 492

27.1 Order Picking in Dry-Grocery Warehouses 522
27.2 SAS Curve Fitting 525

28.1 Memory 535
28.2 Information Repositories 537

29.1 Program Elements 545

30.1 Communication Skills 570

We in the 21st century are in danger of being overwhelmed with information. Hundreds of television channels are available 24/7. Thousands of new books are published each year, in addition to hundreds of technical and professional journals. And of course there is the Internet, with its amazing world of information and powerful search engines.

The seventh edition of this book strives to concisely organize selected knowledge about the area of work design—the design of jobs in their physical and social environments. The text is designed for undergraduate engineering students, but it includes over 900 references from professional and technical journals and books for those who would like to dig deeper. Discussions also include relevant websites for further exploration.

Work Design is well suited for a presentation that "branches" rather than the standard linear mode of presentation, if that is more appropriate to your course(s). That is, each chapter is self-contained so chapters can be read in any sequence. Within a chapter, students can "detour" to topics given in boxes (see a complete list of text boxes on p. vii). Multiple navigation aids direct readers toward their goals. In addition to an extensive index, the opening page of each chapter includes (1) the relation of the chapter to other chapters in that part, (2) a chapter overview, (3) a list of sections within the chapter, and (4) a list of the chapter's key concepts, each accompanied by the chapter section number in which it appears. Key concepts appear in boldface in the text discussion. Each chapter ends with review questions. Answers to the questions can of course be found in the chapter discussion, and for review purposes, the answers are also included as part of the ERGO program, which is described in more detail below.

Work Design: Occupational Ergonomics is divided into six parts: (I) Introduction to Work Design (consisting of 2 chapters), (II) The Design Process (5 chapters), (III) Ergonomic Guidelines (12 chapters), (IV) Work Environments (4 chapters), (V) Work Measurement (4 chapters), and (VI) Implementing the Design (3 chapters).

Part I discusses the technology and economics of our society and introduces the key concept "work smart, not hard." It also begins our discussion of the human body in relation to work design. Part II, The Design Process, offers a variety of techniques to use when designing jobs. Part III, Guidelines, is the ergonomic heart of the book. It offers specific guidelines on job design, including macro ergonomics; office design and work station design; reducing cumulative trauma; design and use of handtools, controls, and displays; error reduction; safety; and temporal ergonomics. Part IV, Environments, analyzes the visual, auditory, thermal, and chemical environments. Part V, Measurement, gives the why and how to determine time/job. Finally, Part VI covers implemen- tation, describing how to turn ideas into accomplished procedures.

Features of the Seventh Edition include:

- A new chapter, Office Ergonomics, because over 50 percent of employees in the United States work in offices.
- Website addresses related to ergonomics and job design, to help readers access and use the vast amounts of information available on the Web.
- Extensive updates.
- Numerous examples of the economic benefits of ergonomics interventions.
- For purposes of further review and application of material, please download a version of the ERGO software, which offers easy access to more than 100 ergonomics tools. Readers may download the program. ERGO includes nine divisions:Forms (16 programs), Anthropometry (14 programs), Environment (16), Lift/Move (13), Work Physiology (8), Statistics/Math (10), Time (6), and Units (18). The ninth division consists of quiz questions, with answers, for each chapter. The programs can be solved with either metric or U.S. units.

ACKNOWLEDGMENTS

We wish to thank the following individuals, who offered feedback regarding the book or its software and thus helped to make *Work Design* a better book: Thomas J. Albin, University of St. Thomas; James W. Barany, Purdue University; Regina Barker, Practical Ergonomics; William Brown, West Virginia University at Parkersburg; Paul J. Componation, The University of Alabama in Huntsville; Kimberly Dunn, Oregon State University; Steven E. Guffey of West Virginia University; Carter J. Kerk, South Dakota School of Mines; D. L. Kimbler, Clemson University; Paul McCright, University of South Florida; James D. McGlothlin, Purdue University; Thomas W. Merritt, University of Alabama; William C. Moor, Arizona State University; Susan Murray, University of Missouri–Rolla; P. E. Patterson, Iowa State University; Jerry P. Purswell, Colorado State University–Pueblo; Marc Resnick, Florida International University; Diane Schaub, University of Florida; David Smith, Georgian College; JoDell K. Steuver, Purdue University Southeast Indiana; John N. Taylor, Florida State University; Edward Williams, University of Michigan–Dearborn; and Jeffrey Wolstad, Oregon State University.

1 TECHNOLOGICAL SOCIETY

Overview

The developments that make entire nations (rather than just a few individuals) rich are the pivotal developments of history. These developments have occurred both in the larger social structure and within the area of economic development (standard of living).

The foundations of technological society are the following historical developments: specialization of labor; energy from machines; standardization and interchangeable parts; use of machines; mass production and mass consumption; the assembly line; computers and computer networks. More recently, international trade has become an integral part of our modern culture.

CHAPTER TOPICS

1 Technological Society

2 Work Smart, Not Hard

3 Efficiency of a Job or an Operation

Key Concepts

accurate machine tools (1.4)
assembly line (1.4)
components of productivity (2.2)
continuous improvement (1.4)
dynamo (1.4)
electric motor (1.4)
electronics (1.4)
ergonomics (Box 1.1)
extra work content (3.2)
factory system (1.4)
incentive wages (1.4)
integrated software (1.4)
interchangeable parts (1.4)
internal combustion engine (1.4)
machine computation (1.4)
mass consumption (1.4)
motion study (1.4)
personnel selection (1.4)
prime movers (1.4)
scientific study of work (1.4)
Taylorism (1.4)
technological society (1.1)
telephone (1.4)
work smart, not hard (2)

1 TECHNOLOGICAL SOCIETY

1.1 Key concepts. Technological society has as its foundation seven key concepts:

1. specialization of labor
2. energy from machines
3. standardization and interchangeable parts
4. use of machines
5. mass production and mass consumption
6. the assembly line
7. computers and computer networks

The first six of these concepts, though historical, are as relevant today as in the past. As discussed below in Section 1.4, which introduces some of the individuals key to the discovery of these concepts and tools, the development of energy from machines, standardization of and interchangeable parts, the assembly line, and so forth, led to our modern **technological society** and thus to mass production and mass consumption. With the advent of computers, computer networks, and the Internet, we have entered a new technological age, one in which communication and trade are extending beyond national borders.

1.2 Improved living standards. The following qualities are both the genesis of and the result of a country's technological development: increased knowledge, diffusion of knowledge, political stability (and freedom from war within one's borders), capital, an orientation toward development, and a large customer base. Literacy and education are essential for technological development; in addition, a country must want to be developed and capital (deferred consumption) must be available for investment. Today, a developed country has as its customer base the entire world—international trade is now possible.

1.3 International trade. Worldwide trade (globalization) is the result of improved information and communication networks, improved transportation, and growth of multinational firms.

As a result of improved transportation, Asian products now routinely arrive in the United States within 24 hours of Asian departure. In 2001, sales outside the U.S. for General Motors were 23%; for IBM, 59%. For Honda, 75% of its sales were outside Japan. International shipping companies such as FedEx and UPS have allowed multinational firms to deal not only with firms in other countries but with branches of their own firm in other countries. (In 2005, FedEx and UPS both served over 200 countries; Fed Ex had 670 aircraft and 45,000 ground vehicles while UPS had 577 planes and 98,000 ground vehicles.)

This country's increase in international trade has been driven by low wages in other countries (often 10% or less of U.S. wages), which has created a demand for work performed outside of our borders. As a result, if a product has a high labor content (either because of high production volume or a high labor cost/unit), *it will not be made in the United States.* (Military products and perishable products, such as food, can be an exception.) To produce a high labor cost item in the U.S., it must have its labor cost reduced through mechanization/automation.

1.4 Individual contributors to modern society.

The reasonable man adapts to the world. The unreasonable man tries to adapt the world to himself. Therefore all progress comes from unreasonable men.

G. B. SHAW

The following list gives a brief view of some of the movers and shakers who contributed to the world's industrial and technological development.

James Watt: The steam engine. Before James Watt there were four basic sources of power **(prime movers):** human, animal, wind, and water. Watt's steam engine permitted the power source to be located anywhere and to be of unlimited magnitude. It permitted implementation of the **factory system** (where machines are concentrated in one central location), cheap and fast transportation (steam-powered ships and trains), and urbanization as people moved from rural communities to a new life of working and living in the factory and city.

Henry Maudslay: Accurate machine tools. The concept of interchangeable parts is based on the premise of each part being alike (from accurate machine tools); in practice, each part will not be alike unless the machines that make the parts are accurate. In 1807, Henry Maudslay had 43 machines at Portsmouth make wooden pulleys for the British navy; each machine did one step. This was an early example of the specialized factory. Maudslay is also famous due to his improvement of the mother tool of the industrial age, the lathe.

Eli Whitney: Interchangeable parts. Eli Whitney was born in 1765 and as a 14-year-old manufactured nails to remedy shortages caused by the Revolutionary War. He graduated from Yale at age 27 and planned to study law. While pursuing a job as a tutor in the South, he visited a southern plantation and within two weeks had invented the cotton gin. For his next project, he turned to the federal government. In 1798 he signed a contract for 10,000 muskets for $13.40 apiece (normal price was $9.40), all to be delivered in 2 years. The key concept was that of interchangeable

parts. Although Whitney emphasized interchangeable parts and in 1801 demonstrated a musket on which he could fit any of several locks, technically he did not achieve his objective. Nonetheless, he receives credit for "the American system of manufacture."

Michael Faraday and Joseph Henry: The dynamo, the source of electricity; the motor, a new prime mover. Michael Faraday, one of a blacksmith's 10 children, did not attend school. Self-taught, in 1823, he liquefied gases under pressure; in 1825 he discovered benzene; and in 1831 he had his greatest discovery, the **dynamo** and the **electric motor.** When Queen Victoria heard of the invention of the dynamo, she asked "What good is it?" Faraday replied, "Madam, someday you will tax it!" The electric motor has three major advantages over the steam engine: It can be made any size (especially smaller); it can be started and stopped quickly; and it can be powered at a distance by use of wires. Somewhat surprisingly, motors were not applied until about 1880, but then their growth was rapid.

In 1829, Joseph Henry made a vastly improved electromagnet that lifted 750 lbs; in 1835 he invented the electrical relay (in effect, the telegraph).

Samuel Colt: Assembly line. Sam Colt designed a repeating pistol: "the six shooter," "Colt's Patent Pacifier," "The Difference." He opened a factory in Paterson, New Jersey, in 1835 that used the assembly line for production.

The first workman would receive two or three . . . important parts and would affix them together and pass them on to the next who would add a part and pass the growing article to another who would do the same . . . until the complete arm is put together.

The National Bureau of Standards reports that the conveyor belt for assembly was not used until 1908.

Nikolaus Otto: The internal combustion engine, a new prime mover. Reuleaux wrote in 1875 of the need for a small engine due to a high capital cost of steam engines: "How to make power independent of capital? . . . Engineers must provide small engines with low running costs. . . . These little engines are the true power units of the people." In steam engines, combustion takes place outside the engine; in 1860 Jean Lenoir built the first engine in which the combustion was internal. It was powered with illuminating gas and had a very poor efficiency, but it was a start. Then, in 1862, Nikolaus Otto (with his partner Eugen Langen) began work on internal combustion engines. In 1876 (100 years after the steam engine) he produced the silent Otto, the first 4-cycle engine. Advantages of the internal combustion engine over the steam engine were low capital cost, quick starts, and high power/weight. The advantage over the electric motor was the elimination of the tether—the wire. The age of the automobile and the airplane began.

Thomas Edison: Electric illumination. Thomas Edison represents the classic tale of the self-made man: the poor boy who, without schooling or influence, made his way to fame and fortune by intelligence and hard work. With 1,093 patents to his name, he was the most productive inventor in the history of the United States. Early inventions of an improved telegraph and the stock market ticker permitted Edison (age 29) to found Menlo Park (an "invention factory," the first industrial research laboratory in the world—in itself one of Edison's many inventions) in 1876. He hoped to produce a new invention every 10 days! In fact, during one 4-year stretch before he became involved in finance, he obtained 300 patents, or one every 5 days.

In 1876 he improved the **telephone** and made it practical; in 1877 he invented the phonograph; in 1878 he announced he would tackle the problem of producing light by electricity. Edison, who scorned theory, used the research method since then known as the Edison method—a trial of many possible alternatives. In 1879, he produced the first practical light bulb. To apply the concept of electric illumination, he had to invent a host of auxiliary inventions—devices for sealing the bulbs, screw-in sockets, light switches, electric meters, safety devices—and then founded the first electric utility, Consolidated Edison, which opened in 1882. He also founded what became General Electric. Consolidated Edison began the concept of the electrical utility. At first, electrical power was sold only for lights. But in the 1890s, electricity was used for streetcars. Steam power hung on in manufacturing, and not until 1919 did over half of manufacturing power come from electric motors.

Alexander Graham Bell: Telephone. In 1874 Bell began thinking of a "speaking telegraph." This required a "sound-shaped" current. One possibility was a diaphragm armature vibrated by the voice that would induce such a current in another electromagnet. Then, in 1875, he plucked free from its electromagnet a receiver reed. Beyond a partition, another reed twanged and began vibrating. Bell recognized the implication that the motion of one reed had generated an effective current by induction. By 1876 he had a patent. Among his other contributions were crusades to teach speech to the deaf, the first iron lung, and the original work on tetrahedral frames (later developed into geodesic domes by Fuller).

Herman Hollerith: Machine computation. After receiving a degree in mining engineering in 1880, Herman Hollerith worked on statistics for the census office. Marking tallies with dip-pen and ink was just too slow. He needed a method of machine computation to automate the process. At first he tried edge-marked cards.

Then he tried holes in paper tape. But the tape had to be wound and unwound to find the information!

At this time train robbers were posing as train passengers, and the government asked conductors to keep track of those aboard; to do so, they punched the ticket in specific places to indicate specific body characteristics—brown hair, blue eyes, medium weight—a punch-photograph. Herman adopted the idea into the Hollerith card, the size of an 1890 dollar bill so it could fit existing file drawers. He developed a keyboard punching machine, rented his machines, and astounded the world with the speed of his census machine. From these beginnings, the computer industry was born.

Frederick Taylor: Scientific study of work. Frederick Taylor asked the question: "What is the best way to do this job?" He did not accept opinions; he wanted facts—evidence. The questioning scientific approach (hypothesis, experiment, evaluation of data to prove or disprove the hypothesis) is well known today. It was known then and applied to chemistry and physics but not to the design of everyday jobs. This is Taylor's primary contribution—application of the principles of science to improving jobs (the scientific study of work). For example, Taylor conducted studies to determine the best-size shovel for specific tasks, greatly improving productivity.

Taylor instituted another concept that was quite radical for that day. He did not believe that all the benefits from increased productivity should be retained by the organization; the worker also should benefit. Therefore, he specified a standard tonnage to be shoveled for each type of material. The worker was trained in the proper work method, given the proper tools, and put to work. When he achieved standard, he received a 60% bonus above the day wage rate. If he could not achieve standard even after training, he was put on a different job. The concepts of pay-by-results **(incentive wages)** and **personnel selection** (select the best people for each job) are commonplace today; they were radical innovations then.

After these methods were applied to the yard at Bethlehem, the same amount of work formerly done by 400–600 men was done with 140 men; material handling cost for the company (including the cost of the study, toolroom, and bonuses) was reduced from $.08/ton to $.04. Employee wages, of course, were 60% higher. Taylor's scientific management is a good example that technology includes techniques as well as devices. Taylorism emphasizes the three S's: standardization, specialization, and simplification—basically, management of time.

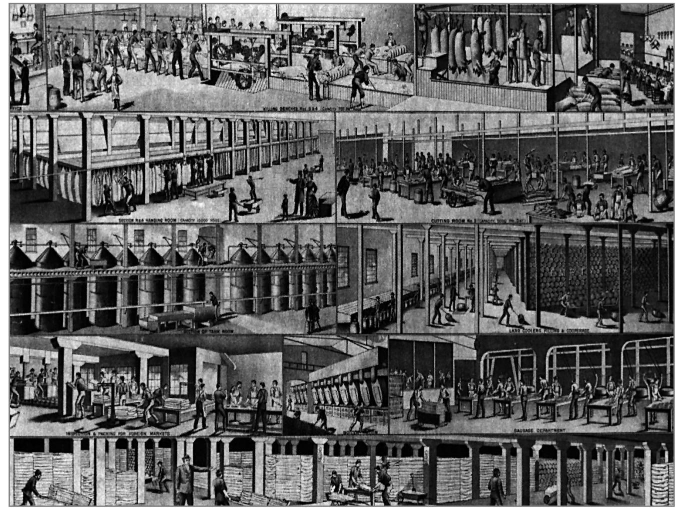
The concept that the "one best way" to do a job is determined by experts (engineers) and the worker's duty is just to follow instructions is called **Taylorism.** It resulted in dramatic improvements in productivity and the standard of living in many cultures for approximately 100 years. Instead of the static world of "one best way," however, we now have the dynamic world of **"continuous improvement"** (both the product and the process to produce the product change continuously). Continuous improvement requires more participation of the workers in job design. The educational level of the workforce, however, has risen over time (see Table 30.3), so "intelligence" now is distributed throughout the workforce, not just located in supervisors and staff. Chapter 30 provides more discussion on worker participation.

Henry Ford: High pay for workers, low-cost auto, mass consumption. Henry Ford is incorrectly credited with the auto assembly line. The specialization of labor, combined with use of conveyors, had been used earlier in slaughterhouses (a "disassembly" line) (see Figure 1.1). The auto, however, was the product in the public eye. Ransom Olds applied the assembly-line concept to building Oldsmobiles in 1899, 10 years before Ford installed an assembly line. By 1904, Oldsmobile production had reached 5,000/yr. Ford, however, dominated auto production. In 1924 Model Ts accounted for one-half of the world's motor vehicles. Ford's assembly line cut throughput time/car from 13 hours to 1. Formerly one man took 20 minutes to assemble a magneto by himself; using a subassembly line with 29 operators, time was cut to 13 man-minutes/unit.

High pay for workers and a low-cost auto were implemented with Ford's decision in 1914 to pay his workers $5 for an 8-hour day when they had been getting $2.50 for a 9-hour day. In addition, he set up a $30,000,000 profit-sharing fund. How could he double wages while reducing costs? Through productivity. (High wages without accompanying productivity mean either losses or inflation.) The concept of **mass consumption** is the key to our society. When Ford's employees received low wages, they were not able to purchase cars (see Table 1.1). As long as cars were priced so that only a few people could afford them, the total output of cars was small. And, looking at the problem as a businessman, Ford saw that even though his profit/car was satisfactory, his total profit was limited due to the small number of cars he could sell because of their high price.

To maximize his total profits, Ford set up his assembly line, made a standardized product ("any color you want as long as it's black") at high volume (and thus low cost), and paid his workers well (permitted by the high volume, which was permitted by the high sales, which were permitted by the high wages and low costs, which were permitted by the high volume, which was permitted by the high sales, which were permitted . . .). The natural result was that Henry Ford became the richest man in the world.

FIGURE 1.1



Assembly lines did not begin with the automobile, as is proven by the lithograph "Interior View of a Modern First Class Pork Packing & Canning Establishment of the United States of America" (Courtesy of the Chicago Historical Society), published in 1880. Titles under the respective pictures are: The Office; Killing Benches Nos. 3 & 4 (capacity 700 pr. hour); Fire Department (at dinner); Section No. 4 Hanging Room (capacity 10,000 hogs); Cutting Room No. 3 (capacity 5,000 pr. day); Section of Tank Room; Lard Coolers, Filling & Cooperage; Inspection & Packing for Foreign Markets; Boiler Room; Sausage Department; Curing Room No. 4 Temperature 38 Fah. Year to Year; Polishing; Canning Department Filling by Machinery, Meat Untouched by Hand, Soldering; Labelling. A question might be why it took so long to apply assembly-line technology to other industries.

The main effect of the mass consumption of automobiles may really be less important than the side effect of personal mobility obtained as a result of the automobile. In the United States it has increased our radius of daily travel from the limits of the streetcar to approximately 50 to 100 miles; this in turn has changed population distributions in both cities and small towns. Although at one time factories were located in the center of cities in order to obtain employees (who walked to work or took streetcars), since 1940 virtually no factories have been built in the center of cities in the United States. Trade and distribution jobs began moving out of the city center in the 1950s. The population of many American cities now resembles a doughnut with a relatively empty center and a population living in the suburbs. It is difficult to determine in advance the main effects of developments; it is exceedingly difficult to anticipate the side effects and interactions occurring after a time lag.

Frank and Lillian Gilbreth: Motion study. Frank Gilbreth's business was construction. A key construction job was laying brick. Frank, who had learned the bricklayer's trade as a teenager, applied his analytical skills to the study of bricklaying. He did this by studying the job in great detail—motion study. As a result of his studies and methods, the number of motions/brick was reduced from 18 to 4.5. In a test of the new method, bricklayers laid 350 bricks/hour while the previous record for this type of construction had been 120 bricks/hour. The reason Gilbreth's results attracted such attention was the task studied—bricklaying. Men had laid brick since antiquity. If there was any skill in which no more change could be anticipated, it seemed that bricklaying, with its 3,000 years of experience, certainly would be it. Yet one man, by systematic study, had made a 300% improvement over the experience of 3,000 years! A powerful example. When Frank died, his wife,

TABLE 1.1

Prices of Fords vs. wages/hour.

YEAR	TYPE OF MODEL T	PRICE ($)	WAGE/HOUR OF UNSKILLED LABOR IN FORD FACTORY	NORMAL HOURS/ DAY	HOURS OF WORK REQUIRED TO BUY CAR
1908	Roadster	825	.19	10	4,340
1913	Runabout	500	.26	10	1,923
1918	Runabout	434	.50	8	870
1923	Runabout	265	.75–.85	8	331

Courtesy of Ford Archives.

Lillian, continued his work on motion study. The many small elements of jobs have been named therbligs—Gilbreth spelled backward (almost). See Box 1.1 about the rise of ergonomics.

Lee de Forest: Three-electrode tube (triode). The telegraph was a great boon to speedier communication, but it required a wire connecting the sender and receiver. Marconi developed the wireless telegraph, the sending of dots and dashes without intervening wires. Edison, who had been a telegrapher himself, had discovered the Edison effect: electrons flowed across a gap between two electrodes inside a vacuum tube. Fleming developed the concept into a device—the two-electrode tube or rectifier. In 1906, de Forest added the third electrode (the grid). A varying weak signal on the grid could be converted into a varying strong signal between the cathode and anode. Signals could now be continuous (rather than just discrete) and could be amplified. In 1912, he added the concept of a feedback circuit. Radio and the age of **electronics** began.

Armstrong receives credit for inventing FM radio in 1934. By analogy to waves of water, electronic noise affects wave height (amplitude) more than the spacing between waves (frequency); Armstrong developed frequency modulated (FM) radio vs. the amplitude modulation (AM) radio.

Microsoft/Apple: Integrated software. The previous vignettes described individual contributors. Today, however, most technical advancements are beyond individuals, requiring corporate research, development, and funding. A contributor becomes leader of a team, perhaps not even the technical leader but a managerial leader. Teams of individuals were essential in developing the contemporary microprocessor. The microprocessor of 2005 was 100,000 times faster than its 1950s counterpart, and, when inflation is considered, cost 1,000 times less. Although we sometimes focus on the improvement of the computer itself (the "hardware"), just as important are the operating system and programs (the "software"). Initial computers were large, stand-alone computers with one input and one output station, and they were run by specialists. Gradually computers evolved into small, desktop models (and now laptops, BlackBerries, and so forth) run, for the most part, by non-experts. Microsoft Corporation and Apple Computers, along with countless others, developed a great variety of software packages (word processing, spreadsheets, presentation programs, databases, and so on). In addition to performing the designated tasks, these programs needed to be easy to use, compatible with one another, and eventually, be transferable via the Internet. As these firms and others continue to develop new programs, computer use continues to advance efficiency and flexibility worldwide.

The Rise of Ergonomics — BOX 1.1

Taylor's and Gilbreth's successors were active in the management division of the American Society of Mechanical Engineers and the Society for Advancement of Management. The first Ph.D. in industrial engineering in the United States was given to Ralph Barnes by Cornell University in 1933. Barnes' book *Motion and Time Study,* first published in 1936, had its seventh edition 44 years later in 1980. The American Institute of Industrial Engineers was founded in 1948; it is now the International Institute of Industrial Engineers.

During World War II, research was conducted to maximize human performance in military applications. In 1949 the Ergonomics Research Society (now Ergonomics Society) was founded in the United Kingdom.

Murrell developed the name **ergonomics** from the Greek *erg* (work) and *nomos* (laws, study of). Over the years, this focus on "work" has expanded to cover all aspects of the human-machine interaction, not just the industrial workplace.

The International Ergonomics Association (IEA), the umbrella society of the various national societies, was founded in 1959. The IEA website (www.iea.cc) lists each of the national societies, together with its website, postal address, phone, fax, and email addresses. People interested in ergonomics may be members of societies affiliated with their specialties. For example, in the United States there are people interested in traffic ergonomics who belong to the Society of Automotive Engineers (www.sae.org); those in agricultural ergonomics who belong to the Agricultural and Biological Engineers (www.asabe.org); people in safety who belong to the National Safety Council (www.nsc.org); and so forth.

During the 1960s, industrial ergonomics was the province of Ph.D. scientists. During the 1970s, it was taught to M.S. students and even a few B.S. students in Industrial Engineering. During the 1980s, ergonomics became "mainstream" for B.S. industrial engineering students. During the 1990s, it became more and more a technology (not just a science), being extensively taught to people without university degrees, through short courses and continuing education. This continues today, along with extensive computerization of many aspects of the field.

2 WORK SMART, NOT HARD

The rich nation is the exception; techniques that make not only individuals but entire nations rich are the pivots of history. Our standard of living, which can be measured in leisure, health care, or weapons, as well as consumer goods, depends on productivity. Productivity comes from efficient technology (combination of scientific, engineering, and managerial techniques) applied to land, materials, machines, and labor. The key to productivity is to **WORK SMART, not to WORK HARD.** The ergonomics guidelines in this book will show you how to work smart.

2.1 Benefits of productivity. Figure 1.2 gives the output/work-hour from 1890 to 2002. Table 1.2 gives a concise view of the changes in standard of living relevant to our discussion of ergonomics in the United States since 1930. What do you predict for 2030? Hint: If productivity increases 2% per year, the standard of living doubles in 35 years. Table 1.3 shows the differences among countries regarding numbers of hours worked per year per employed person. Note how some countries take the benefits of productivity in the form of leisure rather than in goods and services. Some countries, such as the Netherlands, have a large number of part-time workers (working fewer than 30 hours per week).

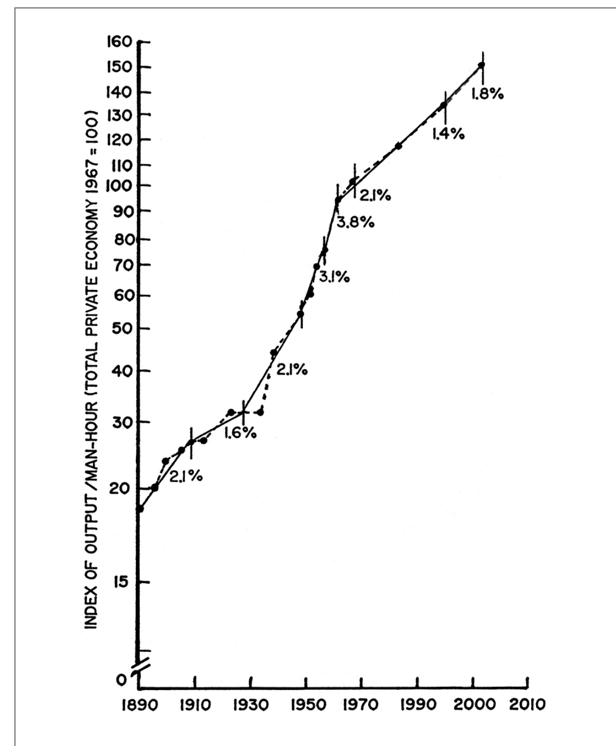
The long-term trend is to have fewer and fewer individuals work full-time as they age. The proportion of men aged 60–64 still in the workforce is 50% in the United States, about 35% in Germany, and less than 20% in France and the Netherlands. Retirement, a concept that barely existed in 1900, now begins in the developed world at an age so early that in 2000 men spent about 36 years in employment and 36 years not in employment. However, with increased health and longevity and decreased physical requirements of work, many older people want to work part-time. Thus, designers should consider that some workers may be over 70.

Although working hours/year have declined over the years, in recent years they may have started going up in the United States, especially for professional and managerial employees. Individuals in the United States tend to prefer more income to more leisure and the system now seems to reward employers for employing fewer people for longer hours rather than more people for shorter hours.

Of the over 50% of the U. S. workforce now in office jobs, a substantial number telecommute. In the United States in 2000, an estimated 24 million telecommuted regularly or occasionally (Voigt, 2001). Technology (e.g., computers, pagers, cell phones, voice-mail, instant messaging) has put us in a sea of work with no boundaries between work time and personal time. Using these devices, people work not only at the office and at home but also in cars, airports, hotels, and so forth. There were 160 million mobile phones in the United States in 2003, up from 34 million in 1995.

FIGURE 1.2

Output/work hour in U.S., 1890–2002. For the years 1000 to 1820, real annual per capita growth in the West and Japan averaged .13%. Since then it's been 1.67%, which compounded over 200 years gives a population 20 times better off (Fox, 2002). For the ten years from 1995 to 2004, productivity increased 2.5% per year.



2.2 Components of productivity. Productivity is the ratio between input and output. One definition of output gives four essentials **(components of productivity):** labor, materials, energy, and information. The special character of a technical society is that the materials, energy, and information replace labor. There are four classic factors: land, materials, machines, and labor. (Sometimes materials and machines are called capital.) Overriding these four factors is a fifth factor—technology (the combination of scientific, engineering, and managerial techniques).

Improved productivity from *land* might involve using better seed to grow 10% more corn/acre or better trees, which will mature in 20 years instead of 25. Fertilizer or insecticides may increase crop yield. Output/unit of land increases. (For industrialized coun-

TABLE 1.2

A concise view of the change in the standard of living of the average person in the United States since 1930. The changes are due to improved productivity.

INDEX	1930	1970	2000
Population	123,000,000	213,000,000	273,000,000
Housing	Frame houses. 67% of dwellings single family. Multi-story of brick with steel frame. 3.8 population/dwelling unit (median).	Frame houses. Apartments, condominiums. 63% own their own home. 3.1 population per dwelling unit; 5.0 rooms/dwelling unit.	67% own their own home; 5.3 rooms/dwelling unit.
House furnishings & equipment	Factory-made furniture. *Urban* *Rural* Electricity: 96% 31% Indoor toilet: 92 11 Running water: 92 18 Mech. refrigerator: 56 15 Central heat: 58 10 6,000,000 pianos	*% of dwelling units* Flush toilet + H & C water + bath or shower: 94% Running water: 98 Telephone: 94 TV: 99 Air conditioning: 45 Home freezer: 32	*Per 100 households* TV: 99% Microwave: 83 AC: 71 Phone line: 66 Computer: 62 Dishwasher: 50 Cell phone: 44
Food and drink	Regional and world supply. Mech. refrig. in transport and home. 54 cans of food/yr/capita. 141 lbs red meat/yr/capita.	Regional and world supply. Fresh at all seasons, frozen, freeze dried, convenience goods. 101 cans of food/yr/capita. 129 lbs red meat/yr/capita (49 fowl, 11 fish). Food cost = 16% of disposable income.	116 lbs red meat/yr/capita (49 fowl, 15 fish). 10.6% of personal income for food.
Clothing	Factory-made for men and women. Rayon and silk plus cotton and wool.	Factory-made for all. Synthetic fabrics. Fabric treatments (permapress, soil and water resistant).	
Health	Life expectancy at birth = 60. 6,150 hospitals; .009 beds/capita. 125 doctors/100,000 pop.	Life expectancy at birth = 71. 7,100 hospitals; .0075 beds/capita. 174 doctors, 57 dentists, 353 nurses/100,000 pop. 36% of pop. have major medical insurance.	286 doctors, 55 dentists, 828 nurses/100,000 pop. Medicaid. Health spending = 12.9% of GDP. Life expectancy at birth = 74.6 (males).
Transportation	227 pieces of mail/yr/capita. 200,000 miles of RR track. 53% of families own a car (1937). Some commercial air transport.	409 pieces of mail/yr/capita. .6 telephones/capita. 204,000 miles of RR track. 3,700,000 mi. of highway. 83% of families own 1 or more cars (.47 cars & .1 truck/capita). 150,000,000 air passengers/yr. Man on moon.	3,900,000 mi. of highway. 614,000,000 air passengers/year.
Work and leisure	40 h/wk or less for 50% of wage earners. Begin work at 16-18. Retire without pay before death; some vacations. Unions 15% of workers; 30% white collar (1940). 90,000,000/wk movie attendance. Radio. 6000 golf courses. Baseball and football pro sports.	56% of people over 16 hold at least one job. 40/h/wk or less average for entire workforce. Retire at age 65 (Social Security and company benefits). 6 or more paid holidays a year for 97% of workforce; 15 days paid vacation after 15 years for 93%. Unions 23% of workers; 50% white collar. Newspaper circulation = .29/day/capita. 6600 radio, 707 TV stations; 1463 symphony orchestras, 713 opera companies, 763 museums, 11,000 golf courses. 100% of homes have TV. 3.7 visits/yr/capita to federal parks or recreation areas.	Unions 9% for private employers; 37% for government. Internet; cable and satellite TV; cell phones; photocopiers/scanners, CDs, DVDs and DVRs; express mail, faxes, bar codes, personal video cameras; digital cameras.

TABLE 1.2

Continued.

INDEX	1930	1970	2000
Education	Education (including secondary and college) government responsibility. Free education for 12 grades. Median school completed by pop. over 25 = 8.0 yr. 96% literacy. School expense = 3.1% of GNP. 6,200 public libraries.	Median school completed by population over 25 = 12.2 years. Literacy = 99%. School expense = 8.0% of GNP. 7109 public libraries.	9,800 public libraries. Education spending = 5.0% of GDP.
Government	New York City government expense/yr/capita = $189 (1935). Taxes = 10% of GNP. Government (all levels) workers = 9.7% of all workers.	Federal $729, state and local $731 expense/yr/capita (nationwide). NYC government expense/yr/capita = $1,207. Taxes = 31% of GNP. Public responsibility for unemployment and recreation. Government (all levels) workers = 19.3% of all workers (1975).	Federal government 21% of GDP.

TABLE 1.3

Working hours per employed person. The average annual hours worked per employed person has declined from 1994 to 2005 as countries take some gains from productivity in more leisure rather than more goods/services. In some countries (such as the Netherlands), there are a large number of part-time workers.

COUNTRY	1995	2005
New Zealand	1842	1810
Australia	1872	1811
United States	1849	1804
Italy	1876	1790
Spain	1815	1769
Japan	1884	1775
Canada	1775	1737
Portugal	1799	1685
Britain	1739	1672
Sweden	1626	1587
Belgium	1542	1531
France	1651	1535
Germany	1529	1435
Netherlands	1344	1367
Norway	1414	1360

Source: Organization for Economic Cooperation and Development, Dept. of Labor.

tries, the farm population has shrunk to less than 5% of the population due to the high productivity of farmers.)

Improved productivity from *materials* might be the use of a collector container to catch the drips from barrels of viscous chemicals so that 99.7% of a container's contents are used instead of 98.5%, or the use of a noncorrosive material to extend the life of a bridge or truck. Insulation reduces the need for fuel oil. Output/unit of material increases. Shields on the top of semi-trailer cabs reduce the coefficient of drag and thus save energy. (Other examples of drag reduction are air bubbles and winglets on airplane wing tips and the below-the-water bulb in the front of tankers.)

Improved productivity from *machines* might be scheduling a truck to haul materials both going and coming rather than returning empty, or using a ceramic cutting tool in a lathe to enable a higher speed, or using e-mail rather than regular mail. (Increasingly, machines are used to process information, not just materials in the "information economy.") A machine's physical life might be 36,000 h. Use of 1 shift (1,800 h/yr) would allow the machine to be used 20 years. Two shifts (3,600 h/yr) improve machine utilization and decrease the risk of obsolescence. (Because the problems of shift work are social rather than physiological, shift work may not be utilized if public transport or recreation or shopping is closed during part of the day.) Output/unit of machine time increases.

Improved productivity from *labor* might be improvement in the work methods of a nurse to permit attending to more patients, or a simplified form so a clerk could calculate more vouchers/h. The use of a fixture to hold parts can permit assembly with two hands instead of one. Output/unit of time increases.

Although the examples assume the same input with an increase in output, productivity also can improve by decreasing input for the same output, by increasing output faster than input, or by decreasing input more than output. Productivity should be recorded in nonmonetary units so comparisons are not distorted by inflation. Example indices are vouchers/week from the accounts

payable office, number of student credit hours/teacher, and area cleaned/day by the janitors.

Productivity is a mixture of the factors of land, materials, machines, and labor. Later-developing nations have an advantage in that they can selectively accept ideas from an ever-larger store of global knowledge. This knowledge is not just physical hardware but also social knowledge (e.g., quality circles, interlibrary loans, double-entry bookkeeping, agricultural extension agents). The popular press often writes as if only reduction in labor costs is meaningful and ignores improved productivity for the other factors. Historically, the developed countries have substituted cheap energy and materials for labor. As the developed countries have become "information societies," the per capita use of materials has decreased. In the United States labor costs now dominate, while in the less-developed countries a shortage of foreign exchange or surplus of labor makes material cost or machine cost dominant.

2.3 Uses of productivity. The standard of living/capita is the product of working smart and working hard; typically it is defined numerically by:

$$GDP = HGDP\ (H)$$

where GDP = Gross domestic product/capita

$HGDP$ = Hourly gross domestic product/capita

H = Hours worked/year/capita (ages 15–64)

Some values for HGDP in 1997 (Doyle, 2000) (where U. S. = 100) are: Belgium 107, France 103, Germany 88, England 83, Canada 81, and Japan 68.

H depends on (1) the labor force participation rate and (2) the average hours worked by each person per year. The labor force participation rate depends on the age when people enter the workforce, the age when people leave the workforce, and the unemployment rate. In 2002, the workforce participation rate in the United States was 78% for males and 66% for females; in Germany it was 71% for males and 59% for females; and in France it was 68% for males and 54% for females. Table 1.3 also indicates that Americans work more hours per year. The average hours worked/year depends upon full- versus part-time work, vacation and holiday time, and overtime.

It seems that the higher standard of living of Americans when compared to much of the rest of the world is a result not only of higher productivity but also of having a higher participation rate, working more hours/year, and retiring later. The official retirement age in most countries is 65 (although actual retirement ages tend to be lower in the U.S. and other countries). However, in the United States, the official retirement age is gradually increasing from 65 to 67; thus, the actual retirement age probably will increase.

Assume a worker enters the labor force at 18 and retires at 63—giving 45 years of work. Assume that work on 5 days/week times 52 weeks gives 260 days/year; reduce this number by 10 days vacation and 10 holidays to get 240 working days/year. Assume an 8-h/day minus two breaks of 15 min to get a 7.5-h/day. Then, $45 \times 240 \times 7.5 = 81{,}000$ h/lifetime.

The approximation of 81,000 h is affected by absenteeism, strikes, illness, unemployment (voluntary or involuntary), overtime, second jobs, more or less schooling, and early or late retirement. The 81,000 h must support not only the worker's needs for food, furniture, and frivolity but also support the children, aged, blind, and other nonproducers (either directly or through taxes). In this book we will discuss "how to increase the size of the cake" rather than "how to cut the cake"—that is, how to multiply, not how to divide.

The output from the 81,000 h can be increased by working efficiently (work smart) or by working with more effort (work hard). Work smart is the desirable alternative because (1) there is more potential for improvement through reducing the excess work than through making the worker work harder, and (2) people don't like to work hard and therefore resist efforts to make them do so.

3 EFFICIENCY OF A JOB OR AN OPERATION

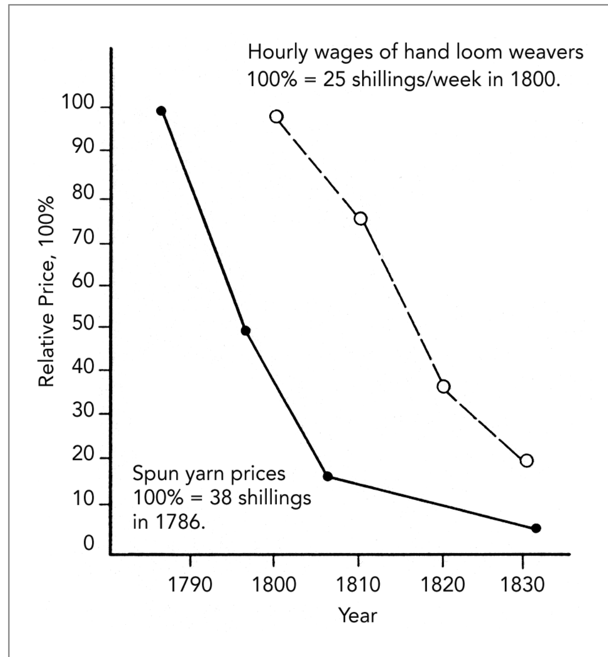
How can expensive American labor compete with low-cost labor from Asia? By substituting capital (i.e., machinery) for labor. Figure 1.3 shows that this technique has been known for several centuries. In 1970, the manufacturing wage/h ($3.36) and the price of a barrel of oil ($3.18/barrel) were almost equal. Although there certainly are fluctuations in the ratio of a barrel of oil to manufacturing labor, the long-run tendency will be to increase the relative cost of oil and, thus, oil-based energy costs. Therefore, energy from other sources (such as coal) and conservation should become relatively more important.

Some countries have a great surplus of labor, and thus the relative price of labor is low. In some countries foreign exchange is limited, which may cause energy or materials to be relatively expensive. Capital may be relatively expensive or cheap in various countries depending on the country. Capital has been relatively cheap in Japan, so Japan has tended to substitute capital for labor more rapidly than other countries. In addition, some industries are labor-intensive, some skill-intensive, and some knowledge-intensive. Thus engineers in different countries and organizations will have different objectives.

3.1 Who gets benefits? Any program to raise productivity by reducing time/unit must consider the

FIGURE 1.3

Substitution of capital (i.e., machinery) for labor can make wages noncompetitive. Cheyney (1908) showed how the introduction of machinery to spin yarn made it noneconomic to spin by hand. The introduction of mechanical weaving had a similar effect on the wages of hand loom weavers.



workers' fears (1) that they will work themselves out of a job and (2) that employers will receive all the benefits of the higher productivity. Policies to ensure adequate employment and satisfactory distribution of the benefits of the productivity are not merely desirable parts of productivity programs—they are the foundation. (The good of the whole conceals the cost to the few.)

Reducing time/unit has costs: (1) erosion of individual skills and experience, (2) the need for some workers to change their jobs and perhaps their place of residence, and (3) the inability of some individuals to make the changes required. Thus workers, individually and collectively, must have the costs of improved productivity not fall too heavily on any one person. In the United States, employers attempt to use normal turnover and expansion of sales to cushion layoffs; severance pay and unemployment pay are backup systems.

People also differ on who should receive the benefits of higher productivity: the workers through higher wages, the society through lower prices, or the person who risks the capital through greater profits. Wars have been fought over this issue. When political rhetoric is brushed aside, the answer is that benefits must be split among the three. Naturally there is always discussion on the amount of the split. Samuel Gompers expressed labor's opinion concisely when asked what labor wanted: "More." Table 1.4 demonstrates how productivity relates to cost of living.

TABLE 1.4

"Low cost of living" is made possible by changes in productivity (Cox, 1998), decreasing the cost to the consumer and increasing the wage. The product also has quality and performance improvements, so the table understates the benefits of productivity.

YEAR	PRODUCT	AVERAGE LABOR H NEEDED TO BUY		
		Early cost ($)	1970 cost ($)	1997 cost($)
1908	Automobile	4,696	1,397	1,385
1915	Refrigerator	3,162	112	68
1915	Long-distance call	90	.4	.03
1917	Movie ticket	.48	.47	.32
1919	Air travel (1000 mi)	221	18	11
1919	Chicken, 3-lb fryer	2.6	.4	.2
1947	Microwave oven	2,467	176	15
1954	Color TV	562	174	23
1971	Soft contact lenses	95	n/a	4
1972	VCR	365	n/a	15
1984	Cellular phone	456	n/a	9
1984	Computing (1,000,000 instructions/second)	57	n/a	.4

Source: Reprinted with permission of the Federal Reserve Bank of Dallas and *The Wall Street Journal.* © 1998 Dow Jones & Company, Inc. All rights reserved.

3.2 Extra work content. **Extra work content** is defined as work that is not essential. Extra work content can be due to the basic concept of the customer and the service to the customer. Consider a restaurant. The standard restaurant gives: (1) the customer a selection from a wide variety of food items, (2) service of individual portions, (3) a specified amount of food for a specified price, (4) personal service to the customer, and (5) service within a limited portion of the 168 h of the week. What are some alternative strategies?

A popular strategy is to minimize the labor cost of the server. One possibility is automation—a vending machine. Another strategy is to minimize the menu selection—fast food. The strategy of self-service has two options with no table service: a cafeteria (limited portion of food) and buffet (unlimited portion of food).

The following discussions and examples emphasize manufacturing, although the extra work concept can be applied to retailing, health services, transportation, and so forth. For simplicity, productivity is assumed to depend only on the time required for the person or the machine.

3.3 Poor product design. Five types of poor product design are as follows.

Improper design. Design for easy maintenance. Design a product to use weldments instead of castings (although in some cases, castings are better). Coat steel used in corrosive atmospheres. If truckloads are weight-limited, use aluminum instead of steel on the trucks so they can carry more payload. Reduce the cost of shipping also by using stackable containers and thereby utilizing the cube. Use semitrailers that open from the side as well as the rear. Fasteners for access covers/panels should be captive (so they don't get lost), minimum type and number (to minimize the number of tools required), and robust (using coarse threads and large heads to avoid stripping). Yokogawa Electric used die casting of a plastic recorder cover instead of an assembly of 31 pieces; cost of materials was reduced 90%, and assembly time was reduced 96%.

One firm had an "ergonomic" problem of cumulative trauma when making flywheels; part of the solution was to improve flywheel forging specifications and thereby reduce flywheel weight by 2 lbs. (This example points out that reducing "ergonomic" problems often leads to reduced material and labor expenses.) As another example, Milton Bradley had a problem of "excessive wrist movements" (Marcotte and Kessler, 1997). The solution, coordinated with Packaging Engineering, resulted in a packaging change that not only reduced wrist movements 50% but also achieved a cost savings of more than $1,000,000, and the company decided not to discontinue the product!

Helander and Willen (1999) say design to minimize assembly time requires (1) perception, (2) decision making, and (3) manipulation. For perception, organize parts by different shapes, sizes, or colors. For decision making, see item 2 in Table 1.5. For manipulation, see items 1, 3, 4, and 5 in Table 1.5 as well as Figure 1.5.

Nonstandardization. Use standard materials, not special materials. Use standard parts, not special parts. For example, can a standard washer, bracket, screw, or bolt be used instead of a special? Lack of standardization splits the production volume between the parts, increases paperwork, and makes supply of spare parts more expensive and difficult.

A key factor in cost of assembly is the number of components that have to be assembled. A popular strategy is to reduce the number of components. Can a nut and washer set be replaced by a single integrated part? GM had 80–90 parts/bumper in its 1980s cars; current cars have bumpers with fewer than 20 parts. Ford has cut the number of types of car horns from 30 to 3, the number of types of batteries from 40 to 14, and the number of types of steering wheels from 50 to 11. The company also expects to save 7% on trunk carpeting by installing a single material and color in all Ford vehicles. It saved $1.50 on the Taurus by using a part from a Lincoln to reinforce the seats.

Incorrect quality standards. The quality specified can be too low or too high. An example of low quality might be a plastic part instead of a metal part, or a container that allows the product to be damaged. An example of too-high quality is using precision threads when standard threads are sufficient. In overdesign ("goldplating"), each engineer designs for the "worst case" rather than "real world." It is nice to have good quality, but not everyone can afford a Mercedes.

Material wastage. A stamping pattern might be fitted poorly on the strip of a coil-fed press (see Figure 1.4). An office form might use a large sheet of paper when a small piece would do. For faxes, cover sheets usually can be omitted; if they are used, they do not have to be 8.5 x 11 inches. (See Box 1.2.)

Many firms now are designing for "product end of life" to minimize the problems of recycling. As examples, don't use bleached cartons for packaging; make the plastics in a product a single-resin type; make plastic parts with integral finishes (eliminates painting as well as easing end-of-life processing); and use resins and paints that do not have polybrominated biphenyls (PBBs), polybrominated biphenyl ethers (PBBEs), lead, cadmium, or mercury metal.

Energy wastage. Two examples of energy wastage are use of a standard electric motor instead of a high-efficiency motor and use of an incandescent bulb

TABLE 1.5

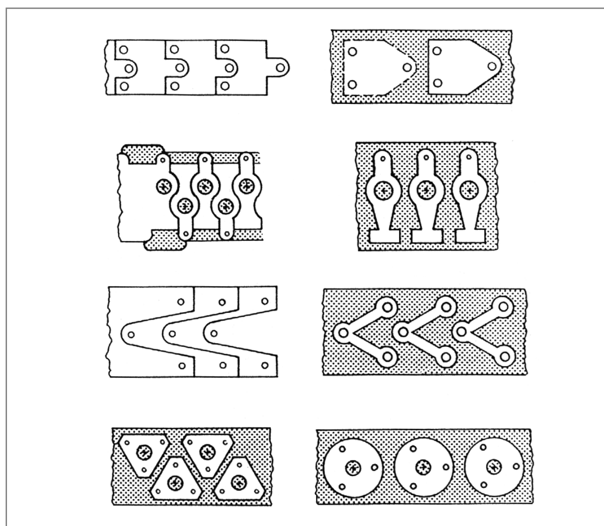
Design for manufacturability (DFM) guidelines for assembly. Note that DFM aids both manual and robotic assembly.

GUIDELINE	COMMENTS
1. Use a base part as the product and fixture	■ Insert fasteners from one direction (above or in front) to minimize wrist deviations and simplify tool use. ■ Have the product have a flat bottom and simple shape, permitting ease of transport. This allows use of roller and wheel conveyors without parts carriers and minimizes weight lifted.
2. Eliminate or minimize different types or sizes of fasteners	■ Combine parts if: —no relative motion between the parts —parts are made of the same material ■ Eliminate fasteners. For example, use "snap and insert" assembly. ■ Minimize number, types, and sizes of screws; this means fewer bins, handtools, errors, and spare parts. ■ Don't use separate washers. Use components in which the washer is part of the screw.
3. Facilitate handling of parts	■ Use parts that are easy to grip. ■ Avoid flexible parts (wires, cables, belts), as they are difficult to handle. ■ Avoid parts that nest or tangle. Consider coiled springs with closed (not open) ends. ■ Avoid weak or fragile parts that bend, chip, or crack.
4. Facilitate orientation of parts	■ Use symmetrical parts. ■ For nonsymmetrical parts, provide orientation aids (shape such as lugs or notches, color). ■ Consider parts feeders (magazines, vibratory bowl feeders).
5. Facilitate assembly	■ Use self-locating parts (chamfers, notches, guides, tapers) (see Figure 1.4). Reduce tolerances in part mating. For example, can a slotted hole replace a circular hole? ■ Use torx screws to eliminate the push force to keep the drive bit in; avoid cross-recess drivers (Phillips screws); avoid drill point screws (push force can be >40 lbs).

Source: M. Helander, ***A Guide to the Ergonomics of Manufacturing.*** Chapter 17. © Copyright 1995 by Taylor & Francis. Reprinted by permission.

FIGURE 1.4

Layout of items within a strip to reduce waste. Two good strategies are changing nonfunctional perimeter shape and reversing the item.



instead of a compact fluorescent bulb. A truck or car may have an engine with poor fuel economy; a semitrailer may not have a shield on the cab top to streamline air flow. A PC may not power down (have a sleep or hibernate mode) when not in use. Many devices are always "on"; buy those with low wattage standby modes. Energy may also be wasted because of poor usage patterns. For example, turn off the lights when no one is in the room; turn off conveyor motors during lunch breaks.

3.4 Poor methods. The following are examples of poor methods:

Poor macro method. For example, a person might play "telephone tag" instead of using voice-mail, a fax, or e-mail. Further examples are data being entered by hand instead of by scanner and bar code; a factory not being organized for "lean production" and, therefore, having many uncorrected problems; a machine cutting one item at a time instead of 60 at a time; and a product being sent by rail when using a truck would be better (or vice versa).

Waste Minimization

BOX 1.2

Three ways to minimize waste involve the product, the supplies, and the packaging.

Product. Minimize product waste by changing product materials and reducing manufacturing waste.

Changing product materials. Reduce use of chemicals for cleaning through mechanical agitation (air or water jets, brushes, ultrasonics). Kill insects with bug zappers instead of insecticides. Make wastes nonhazardous (e.g., use inks without cadmium).

Reducing manufacturing waste. As examples of saving trees: Photocopy on both sides of a sheet of paper, replace letters and envelopes with electronic communication (e-mail, faxes), file correspondence electronically rather than with photocopies, and reuse envelopes for internal correspondence. A plant found that it was throwing away several pounds of varnish per drum because it was not allowing the drum to drain long enough.

Supplies. Consider solvents, coolants and lubricants, metal finishing, and painting and coating.

Solvents. Reduce "dirt" and thereby use fewer solvents for cleaning (e.g., use less lubricant on dies, and use electrostatic painting). If the item is cleaned before the contaminant has had time to harden, less solvent is needed (just think of dishes being washed in a dishwasher).

Coolants and lubricants. Extend the life of coolants and lubricants by reducing contamination (e.g., using a biocide to kill bacteria in the coolant) and removing contaminants, thereby permitting reuse of coolant (e.g., use of settling tanks or centrifuges).

Metal finishing. Some examples are reducing impurities entering the plating solution (drag in) and loss of solution from the tank (drag out). Some drag-out approaches are increasing drip time to allow liquid to drain from the part; minimizing pockets, cavities, and depressions that can bail from a tank; decreasing solution viscosity (e.g., increase solution temperature); and decreasing surface tension (add wetting agents).

Painting and coating. Avoid conventional spray painting, which deposits only 40% of the paint on the product; use electrostatic or powder coating.

Packaging. Consider reduction, reuse, and recycling/disposal.

Reduction. Minimize the weight (volume) of the package in relation to the product. Can the box hold 10 units instead of 5? Or can the product be shrunk (e.g., concentrate the product and the customer adds water)? Can more cartons be placed on a pallet (additional layer or larger pallet)?

Reuse. One example is reusable pallets. Another is returned containers (it helps if they can nest when being returned).

Recycling/disposal. Design packaging to be recycled. For example, minimize corrugated paper stapled to wood or glued to foam (staples and foam prevent reuse of cardboard). Eliminate ink containing hazardous materials (any hazardous material, regardless of its percent of the total, makes the entire container of material hazardous).

Poor micro method. For example, a waitress might have to enter orders on a form with handwriting instead of circling preprinted information, or the wrong type or size of screwdriver, pliers, or other tool may be used.

Assembly time depends not only on how the parts of a product are designed, but also on how the parts are stored and presented to the operator, and how the parts are moved to the point of assembly. See Table 1.6 and Figure 1.5.

Poor arrangement. Examples are machines arranged in a job-shop layout when a flow-line arrangement is better (or vice versa), supplies located in a crib when storage at the machine is better (or vice versa), or a bin at a workstation that is not conveniently located. Ground maintenance depends on location of trash containers. Disney found people reluctant to carry trash more than 28 paces (about 60 ft) and so places containers accordingly.

Poor equipment use. The equipment may not be used properly if the worker is not properly trained. Training should include not only the main person assigned to the task but all people who do the task as well. The thrust has been to multiskilled workers so they can do all tasks (cross-training).

3.5 Poor management. Examples of poor management include the following:

Too many product models. Are your customers really more interested in increased selection or in lower price? Sales groups are always pushing for a wide variety of models to fulfill the needs of any possible customer. Unfortunately, this tends to fragment the market and results in very low volumes for each product and, thus, high cost/unit. If many different models must be produced for marketing reasons, insist that nonstyle components such as screws, washers, motors, brackets, clips, and so forth be

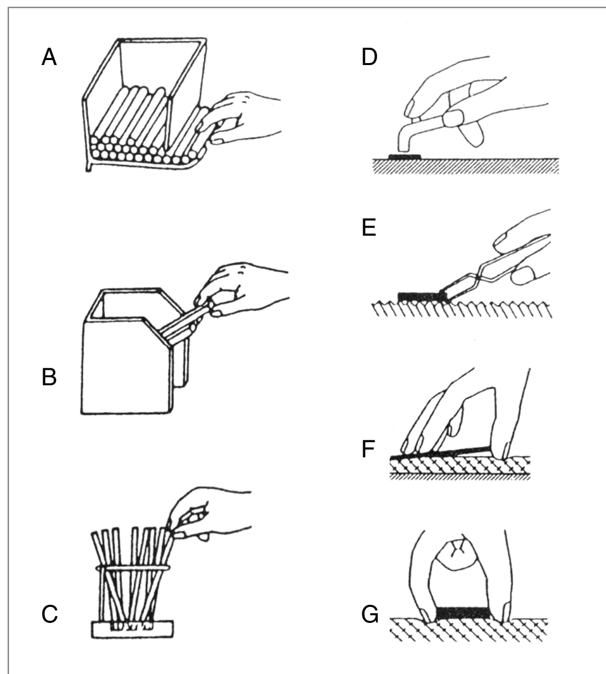
TABLE 1.6

"Best case" vs. less efficient alternatives, using MTM-1 classifications (Helander and Willen, 1999). See Ch. 26 for information on MTM.

MOTION	BEST CASE	LESS EFFICIENT	% TIME SAVING OF BEST CASE
Reach	To fixed location (case A)	To variable location (case B)	30
		To small or jumbled objects (case C)	40
Grasp: pickup	Easily grasped (1A)	Object on flat surface (1B)	75
		Small object (1C2)	400
Grasp: select	Large jumbled objects (4A)	Object smaller than 1 x 1 x 1 inch (4B, 4C)	50
Move	Against a stop or to other hand (A)	To exact location without a stop or barrier (C)	15
Position: symmetrical	Symmetrical (S)	Semi-symmetrical, 45° turn typical (SS)	20
		Non-symmetrical, 75° turn typical (NS)	30
Position: depth of insertion	No depth	4-inch insertion	100
Position: pressure to fit	Gravity, no pressure (1)	Light pressure (2)	210
		Heavy pressure (3)	500
Disengage 2 parts: class of fit	Loose	Tight	500
Disengage: ease of handling	Easy	Difficult	40

FIGURE 1.5

Gripping aids for assembly. (A) Self-feeding container. (B) Container with inclined opening. (C) A ring holder with smaller bottom diameter. (D) Use of vacuum gripper. (E) Tweezers or tongs used against a rippled table surface. (F and G) Gripping against a soft surface (Luczak, 1993).



standardized so they, at least, can have reasonable production quantities and ease of spare parts supply.

Poorly designed product. The product may not be designed to withstand the stresses of normal use. The customer will be unhappy and will tend to refuse to buy more products from that organization, thereby killing the organization in the long run. Rework, repair, and warranty expenses will be high.

Poor production scheduling. Poor scheduling can increase setup time, cause missed customer shipment dates, and require overtime and layoffs. A unit train hauling coal shows how scheduling a shipment all at once instead of in small amounts can improve transportation efficiency.

Poor maintenance. Equipment breakdowns annoy everyone. In addition to loss of production, product quality may suffer.

Poor safety and health. Safety pays. In addition to the moral responsibility of organizations to have safe working conditions, safety can be justified just from the economic benefits. (See Chapters 4 and 18.)

3.6 Poor workers. Not all the excessive work is the fault of management. Some is caused by workers. Workers can fail to start on time, quit early, and stretch breaktimes; they can be absent and thus cause extra work for their coworkers; they can waste time

web browsing and emailing. They can cause poor quality—although most quality problems result from poor product design, poor tools, poor procedures—in short, from poor management. In most operations or jobs, the effect of workers in causing extra work is relatively minor compared to the extra work caused by poor design, work methods, or management.

Obtaining better productivity (the benefits to be shared among the workers, the society, and the providers of capital) is a shared responsibility. The importance of better productivity and the means to achieve it, safely and efficiently, will be the subjects of the remainder of this book.

Review Questions

1. What was the greatest technological development of the last 1,000 years, in your opinion? Some possible candidates: moveable type, gunpowder, railroads, electric motors, the internal combustion engine, television, computers.
2. How are accurate machine tools and interchangeable parts related?
3. Prime movers are essential to an industrial society. Why was the steam engine important? Why was the electric motor important? Why was the internal combustion engine important?
4. Ergonomics is based on what two words?
5. Briefly discuss the change in hours of work over the last century. What do you predict the typical hours of work/yr will be when you are 40? Give assumptions.
6. Give the two reasons why it is more important to work smart than to work hard.
7. Discuss how standard of living is a function of productivity, workforce participation, and hours worked per lifetime.

2 ANATOMY, BIOMECHANICS, WORK PHYSIOLOGY, AND ANTHROPOMETRY

Overview

Anatomy is given for three body subassemblies: the spine, the upper extremity, and the foot. Joints, tendons, muscles, and nerves are briefly described as is biomechanics. Then the cardiovascular system is described as well as metabolism and recommended exercise limits. Mental work is described briefly. Finally, anthropometry values are given with design emphasis on minimizing the number of people excluded.

CHAPTER TOPICS

1 Musculoskeletal Anatomy
2 Biomechanics of Muscular Movement
3 Cardiovascular Anatomy
4 Metabolism
5 Response to Exercise
6 Cardiovascular Limits
7 Responses to Mental Work
8 Fit the Job to the Person
9 Population Values
10 Statistical Calculations

Key Concepts

aerobic vs anaerobic (5.1)
age effects (6.3.2)
anthropometry (8.1)
artery–vein differential (5.3)
blood pressure (3.1)
bursa (1.4.2)
cardiovascular system (3)
carpal tunnel (1.3)
cartilage (1.4.2)
circulation, pulmonary/ systemic (3.1)
DuBois surface area (9.3.3)
edema (3.1.1)
electromyogram (EMG) (2.2.3)
ergonomics (8.1)
exclude few (8.3)
exercise, response to (5)
gender effects (6.3.1)
heart rate, cost of work (5.1)
heart rate, measurement (5.1)
heat acclimatization (3.1.2)
isoinertial (2.2.3)
isometric (2.2.3)
isotonic (2.2.3)
isovelocity (2.2.3)
joints (1.4)
kyphosis (1.1)
levers, skeletomuscular (2.1)
ligaments (1.1)
lordosis (1.1)
maximum voluntary contraction (MVC) (2.2)
mental load (7)
metabolism, activity (4.2)
metabolism, basal (4.1)
metabolism, digestion (4.3)
muscles (1.6)
nerves (1.7)
oxygen debt (5.5)
oxygen uptake, maximum ($\dot{V}O_2$) (6.1)
personal space (9.3.5)
population percentile (8.3)
proportion of capacity (6.2)
rating of perceived exertion (RPE) (5.1)
scoliosis (1.1)
selection vs job modification (8.2)
similitude, principle of (9.1)
stroke volume (5.2)
surface area/volume (9.1)
tendons (1.5)
venous pooling (3.1.1)

1 MUSCULOSKELETAL ANATOMY

Anatomy (*anatomia,* Greek, to cut up) describes the build of the human body. (Physiology deals with the functions of the living body, including the physical and chemical processes.) Skeleto-muscular anatomy is divided into the ergonomically important "subassemblies" of the spine, the upper extremity, and the lower extremity; then, the "components" of joints, tendons, muscles, and nerves.

1.1 Spine. Figure 2.1 shows the spine. The spine is divided into the cervical, thoracic, lumbar, and sacrum regions. The sacrum is linked to the ilium (top part of the pelvis) with a joint on each side—the sacroiliac joints. The low back, Lumbar 4 and Lumbar 5 (abbreviated L4 and L5) is the problem area. Note how these discs angle downward instead of being horizontal. The weight of the torso therefore tends to push these discs forward. The disc pressure is 50–100% higher when sitting than standing, especially when sitting with a slumped back. Reduce that pressure by using chairs with armrests (the armrests support some of the torso weight).

The spine is concave backward in the cervical and lumbar region; it is concave forward in the thoracic region. **Lordosis** is an increase in lumbar curvature—a swayback posture, with the stomach protruding. **Kyphosis** is an increase in thoracic curvature—a hunchback posture, with the shoulders rolling forward and the person slouching. **Scoliosis** is a bending of the spine to the side (i.e., from a front view).

Due to cumulative compressive loading on the discs, body stature shrinks about 1.1% during the day. However, sleep restores the shrinkage. Krag et al. (1990) found the change was relatively rapid; 26% of the 8-h loss occurred in the first hour upright and 41% of the 4-h recovery occurred in the first hour recumbent.

Figures 2.2 and 2.3 show how the vertebrae and discs are held together with **ligaments.** There are many "low-back" problems due to the narrow width of the rear ligament in the low back. Figure 2.4 shows how the discs separate the bony segments; Figure 2.5 shows a detail of a disc. Note the ringlike structure of the disc, which gives great strength. In the young adult, the discs are so strong that when violence is applied to the vertebral column (e.g., parachutist whose chute didn't open), the bones usually give way rather than the discs.

FIGURE 2.1

The spine is divided into cervical, thoracic, lumbar, and sacrum areas.

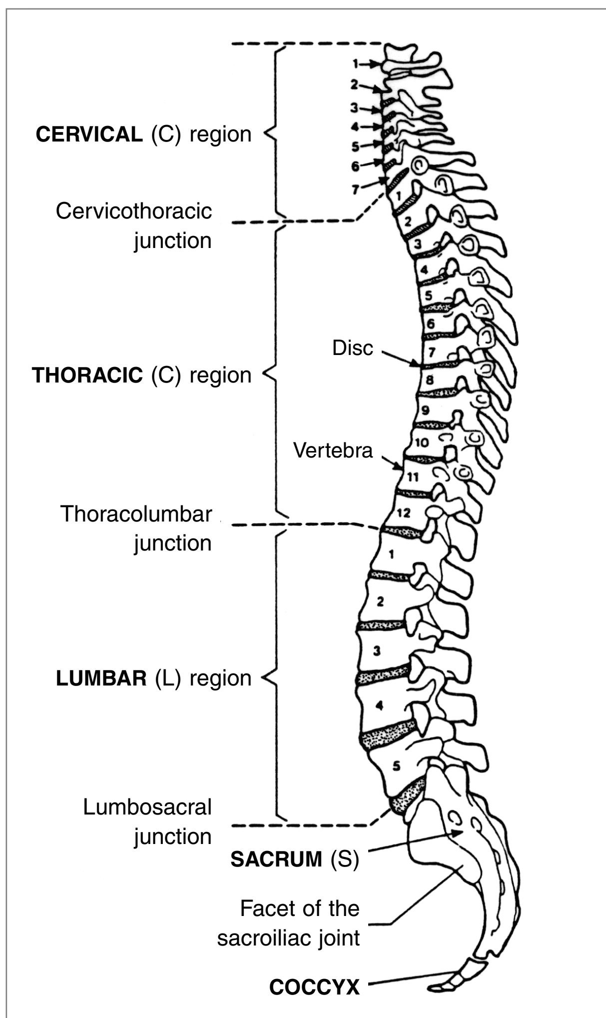
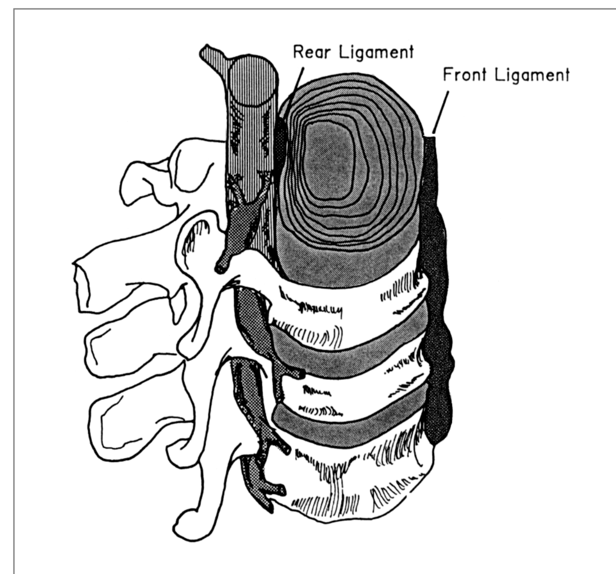


FIGURE 2.2

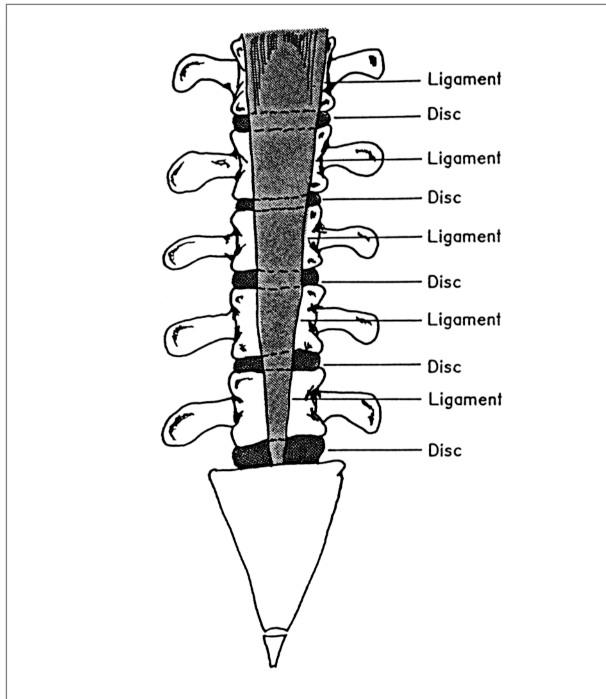
Two ligaments hold the vertebrae together.



Source: L. Ring, *Facts on Backs.* Copyright © 1981 by Institute Press, Loganville, GA. Reprinted with permission of L. Ring.

FIGURE 2.3

The rear ligament narrows as it descends. In the lumbar region, the ligament width is only half its original width, exposing unprotected discs on either side.



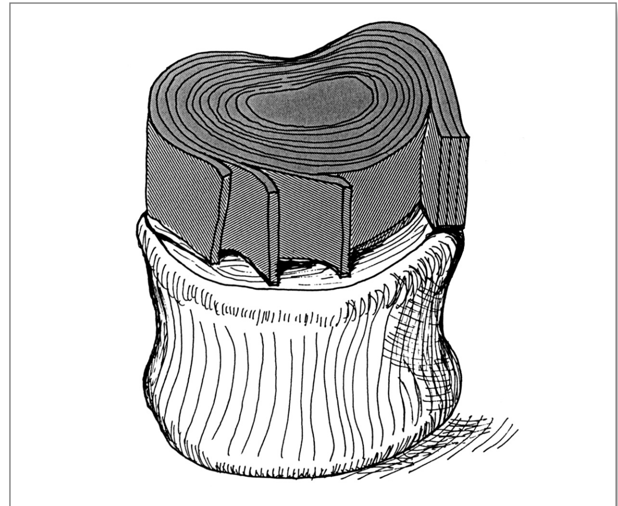
Source: L. Ring, *Facts on Backs.* Copyright © 1981 by Institute Press, Loganville, GA. Reprinted with permission of L. Ring.

Discs fail because they wear out. "Normal daily activities ultimately exact their toll in the form of microscopic stretching, tearing, and raveling of the casing fibers. The increments of microdamage become cumulative until, finally, the casing is no longer capable of containing the packing material. Usually, slow leaks of the fluid of the gel occur from time to time and the disc begins to narrow and gradually go flat. Less commonly, the weakened casing may bulge [see Figure 2.7] or a sudden blowout may occur" (Rowe, 1985, p. 140).

The two load-bearing structures (the facets, excluding the synovial membrane, and the intervertebral discs) do not have nociceptors, the peripheral pain nerves. *Thus, one can injure them without experiencing pain* (Garg, 1992); low-back pain may be the culmination of a series of point-in-time painless injuries. Disc problems are shown in Figure 2.6 (side view) and 2.7 (top view)—emphasizing the pinching of the nerve.

FIGURE 2.5

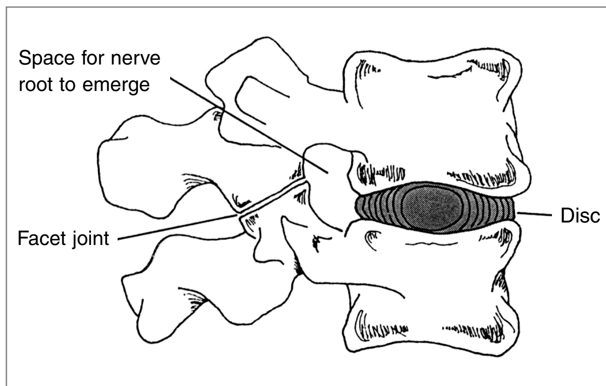
Discs have a ringlike structure surrounding a sac of fluid.



Source: L. Ring, *Facts on Backs.* Copyright © 1981 by Institute Press, Loganville, GA. Reprinted with permission of L. Ring.

FIGURE 2.4

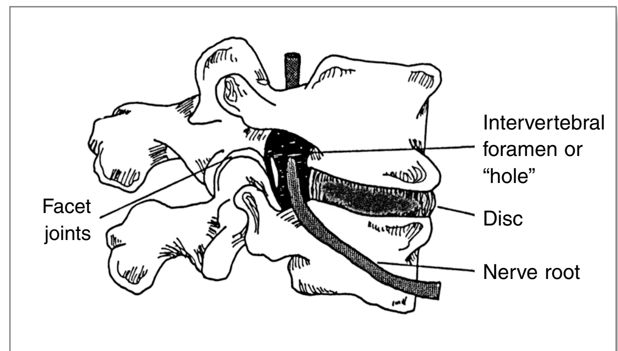
Discs separate bony facets.



Source: L. Ring, *Facts on Backs.* Copyright © 1981 by Institute Press, Loganville, GA. Reprinted with permission of L. Ring.

FIGURE 2.6

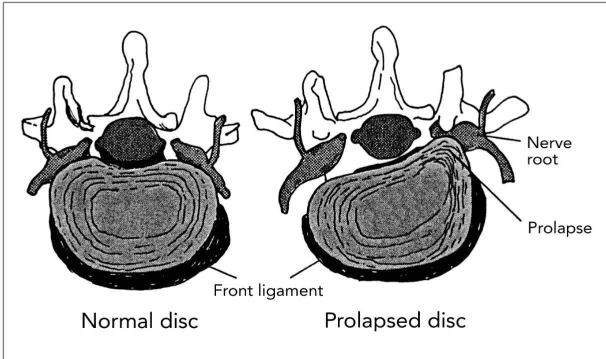
Disc degeneration reduces the space available for the nerve to emerge, possibly causing pinching of the nerve.



Source: L. Ring, *Facts on Backs.* Copyright © 1981 by Institute Press, Loganville, GA. Reprinted with permission of L. Ring.

FIGURE 2.7

Normal disc (left) and prolapsed (herniated, ruptured) disc (right). A prolapsed disc (incorrectly called a "slipped disc") pinches the nerve.



Source: L. Ring, *Facts on Backs.* Copyright © 1981 by Institute Press, Loganville, GA. Reprinted with permission of L. Ring.

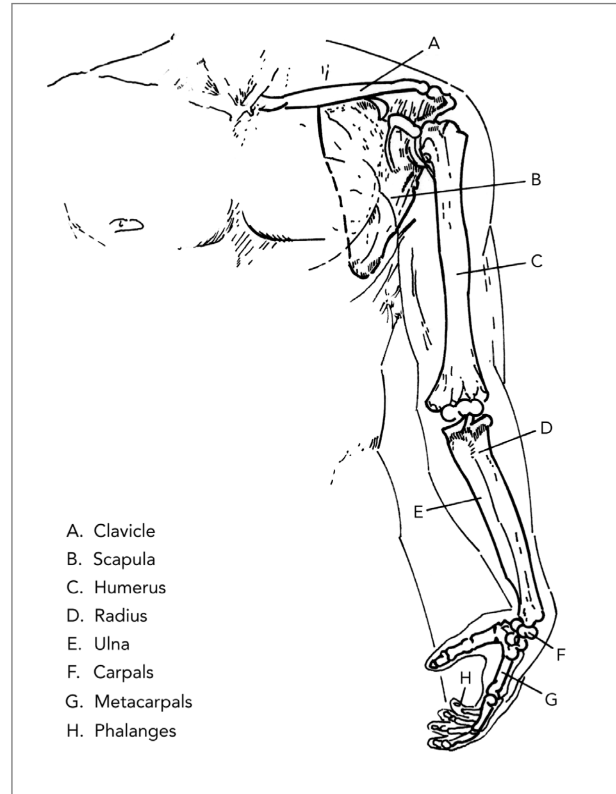
Although the back is complex, mathematical models of the spine have been developed. Three-dimensional models have been developed that predict lumbar compression as well as shear and torsional forces during various activities.

1.2 Upper extremity. This section is divided into shoulder, arm, and hand.

1.2.1 Shoulder. Figure 2.8 shows an overview of the bones of the upper extremity. Figure 2.9 shows some detail of the shoulder. The clavicle and scapula form the shoulder itself. The shoulder, designed for mobility

FIGURE 2.8

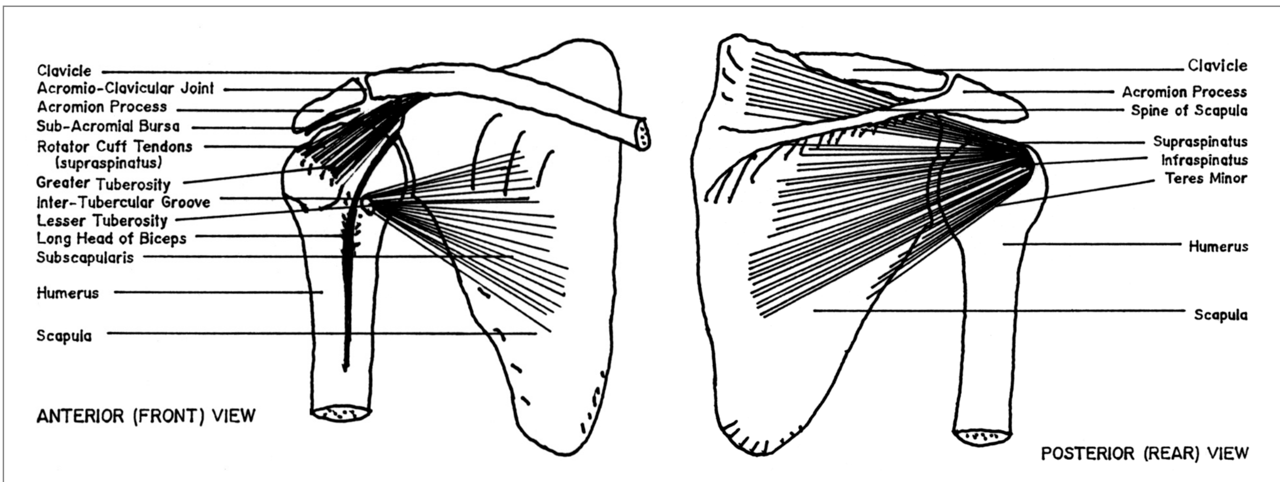
Bones of the upper extremity. The clavicle and scapula form the shoulder. The humerus is the single bone in the upper arm. The radius and ulna are the two bones in the forearm. The metacarpals and phalanges form the hand.



Source: V. Putz-Anderson, (ed.). *Cumulative Trauma Disorders.* Copyright © 1988 by Taylor and Francis, London. Reprinted with permission.

FIGURE 2.9

Right views of the shoulder (Rowe, 1985).



Copyright © 1985 by Perinton Press.

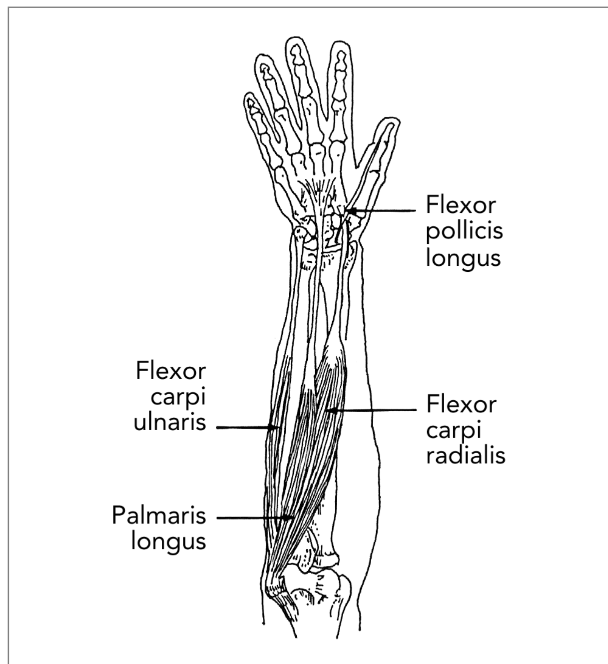
instead of stability, is stabilized almost exclusively by tendons instead of the mechanical fit of opposing bones or snug ligaments. The round end of the upper arm bone (humerus) fits into a shallow groove in the scapula (like a golf ball rests on a tee). Only about 1/3 of the ball surface engages the socket. In the more-stable hip socket, over 1/2 of the ball surface is engaged.

The rotator cuff is the cojoined sheet of three tendons (supraspinatus, infraspinatus, and teres minor); it is surrounded by connective tissue (the shoulder capsule). Some shoulder problems include: tendinitis (rotator cuff tendons inflamed or damaged), bursitis (inflammation of the bursa between the tendons and the shoulder bone), tendon or muscle tear, and frozen shoulder (adhesive capsulitis—inflammation of the shoulder capsule).

1.2.2 Arm. The upper arm has a single bone—the humerus, followed by the lower arm's two bones—radius and ulna. Figures 2.10 and 2.11 show palm views of the arm muscles. Figures 2.12 and 2.13 show back-of-the-hand views of the muscles. Table 2.1 lists the functions of forearm muscles.

FIGURE 2.10

Flexing the wrist (right palm view) is done by the three flexor muscles. There are 19 muscles to control the fingers and thumb. The 10 entirely within the hand are called intrinsic muscles; the 9 in the forearm (with tendon attachments to the thumb or fingers) are called extrinsic muscles.



Source (Figures 2.10–2.13): From Kathryn Luttgens, Helga Deutsch, and Nancy Hamilton, *Kinesiology: Scientific Basis of Human Motion,* 8th ed. Copyright © 1992 Wm. C. Brown Communications, Dubuque, IA. Used by permission of The McGraw-Hill Companies.

FIGURE 2.11

Extending the wrist (back of right hand, anterior view) is done by combinations of muscles. Radial flexion of the wrist (abduction) is produced by the flexor carpi radialis (Fig. 2.10), flexor carpi radialis longus (Fig. 2.13), and the abductor pollicis longus of the thumb.

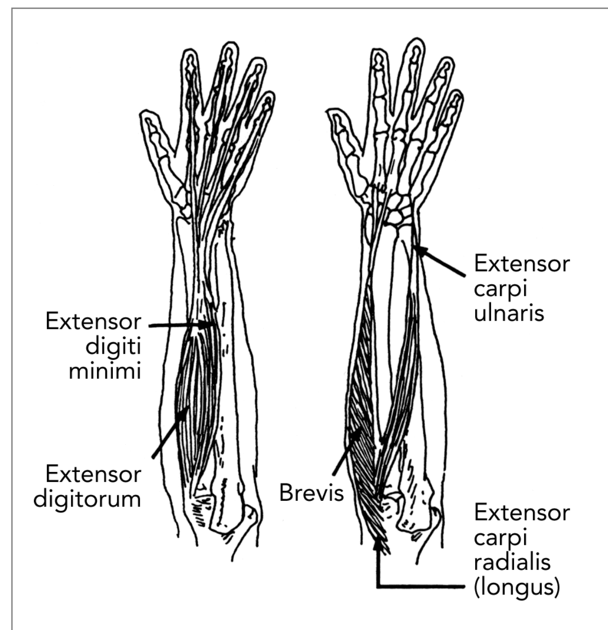


FIGURE 2.12

Closing (flexing) the fingers (right palm view) is done with muscles in the forearm; see Table 2.1. The closing muscles have over twice the strength of the opening (extensor) muscles.

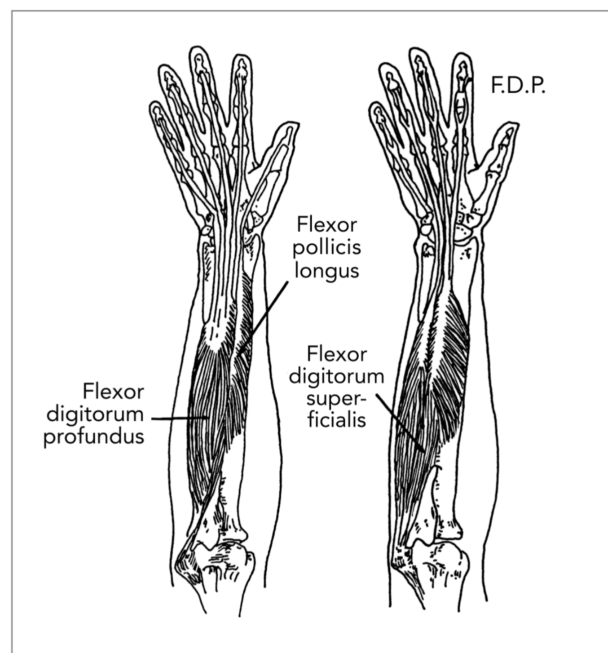


FIGURE 2.13

Opening (extending) the fingers (back of right hand, anterior view) is done with two sets of muscles; see Table 2.1. Ulnar flexion (adduction) of the wrist is produced by the extensor carpi ulnaris, extensor carpi radialis longus, and extensor carpi radialis brevis.

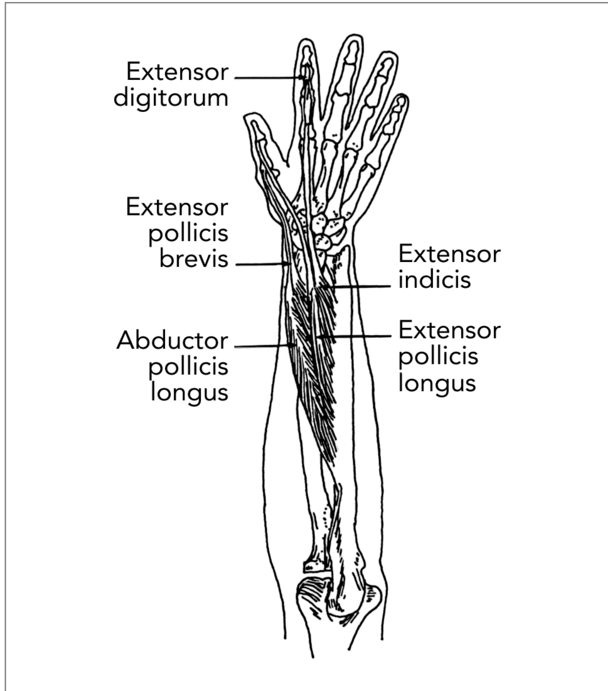


TABLE 2.1

Functions of forearm muscle.

WRIST	DIGITS
Rotate the radius on the ulna: ■ pronator teres ■ pronator quadratus ■ supinator	Flex the digits: ■ flexor digitorum superficialis ■ flexor digitorum profundus ■ flexor pollicis longus
Flex the hand: ■ flexor carpi radialis ■ flexor carpi ulnaris ■ palmaris longus	Extend the digits (except thumb): ■ extensor digitorum ■ extensor indicis ■ extensor digiti minimi
Extend the hand: ■ extensor carpi radialis longus ■ extensor carpi radialis brevis ■ extensor carpi ulnaris	Extend the thumb: ■ adductor pollicis longus ■ extensor pollicis brevis ■ extensor pollicis longus

1.2.3 Hand. The bones of the wrist are followed by the bones of the hand and fingers. Figure 2.14 shows a cross-section of the wrist. Figure 2.15 shows the parts of the fingers.

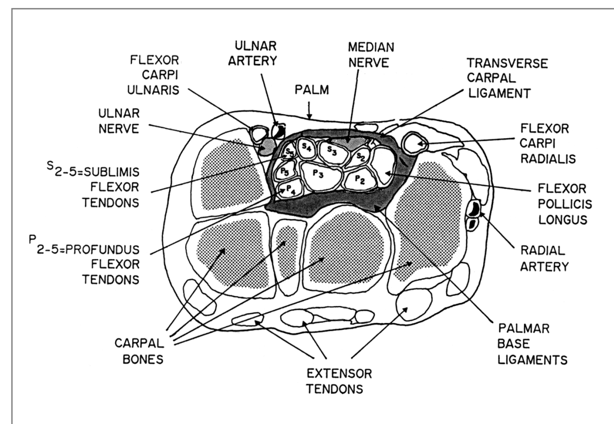
1.3 Lower extremity. From an ergonomics viewpoint, the bones of the hip, upper leg (femur), knee, and lower leg (tibia and fibula) present relatively few problems. Problems are in the ankle and in the foot. However, Figure 2.16 shows that unequal leg lengths can present back pain problems.

The mean distance between the inside of the two feet, when standing, is about 100 mm; between foot centerlines, it is about 200 mm; and between the outside edges, it is about 300 mm (Rys and Konz, 1994). The mean height for males is 1750 mm; thus, there is a base of only 200–300 mm for a structure of 1750 mm. (The base can be increased if the person stands with one foot forward; one foot forward also reduces twisting stress if the turn is to the side opposite the forward foot.)

This structure has two supports (legs) up to the waist and then one support (the spine). Thus, there is sway—especially front to back. When standing, the center of gravity passes from the ear opening forward of the spine (even L4–L5) so the body normally has a forward-bending moment, counteracted by ligament and back muscle forces and soleus muscles of the calf. At eleva-

FIGURE 2.14

Carpal tunnel is shown with a section of the right wrist (looking toward the fingers). The carpal tunnel (dark boundary) contains: (1) the median nerve (which fills in the available space below the transverse carpal ligament), (2) flexor digitorum superficialis (four tendons), and (3) flexor digitorium profundus (four tendons) and flexor pollicis longus.



Source: S. Tanaka and J. McGlothlin, "A Conceptual Quantitative Model for Prevention of Work-Related Carpal Tunnel Syndrome (CTS)," *Int. J. of Industrial Ergonomics,* Vol. 11, pp. 181–93. Copyright © 1993 by Elsevier Science, Amsterdam, Netherlands. Reprinted with permission.

tion (>4 m eye height), sway increases in both lateral and front–back directions (Hsiao and Simeonov, 2001).

"Quiet" standing actually is a dynamic event as the weight shifts incessantly from side to side. Satzler et al. (1993) recorded foot movements for 120 min of standing; people moved one foot approximately every 90 s.

FIGURE 2.15

Parts of the fingers. The five fingers are the thumb, index, middle, ring, and little. The thumb has a metacarpal and a proximal and distal phalanx. However, the other fingers have a metacarpal plus three phalanx (proximal, middle, and distal).

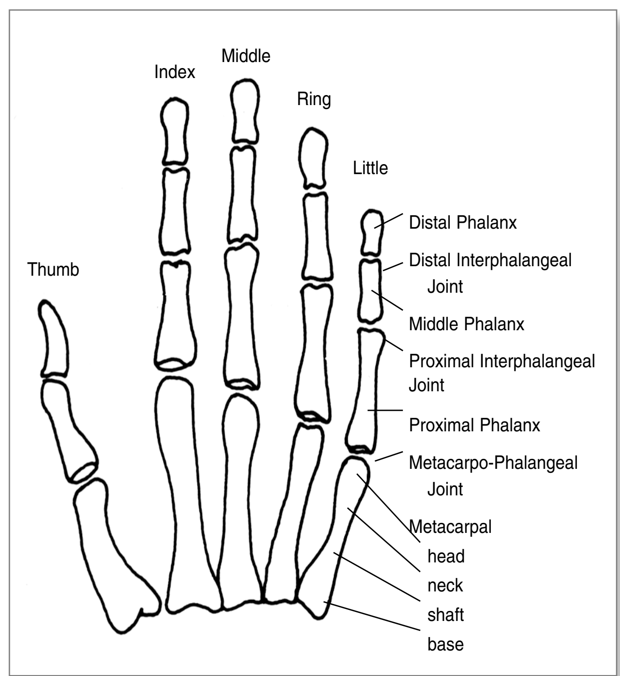
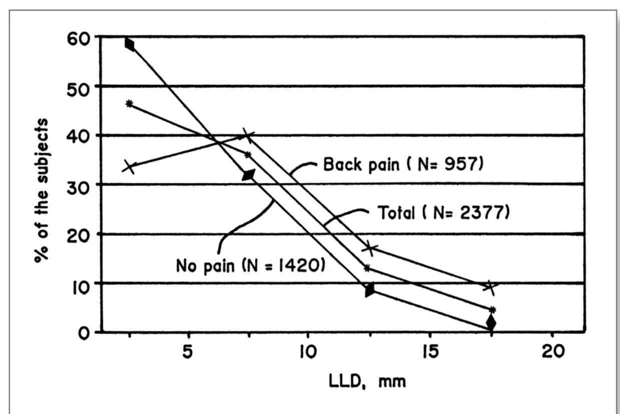


FIGURE 2.16

Leg-length discrepancy affects back pain.



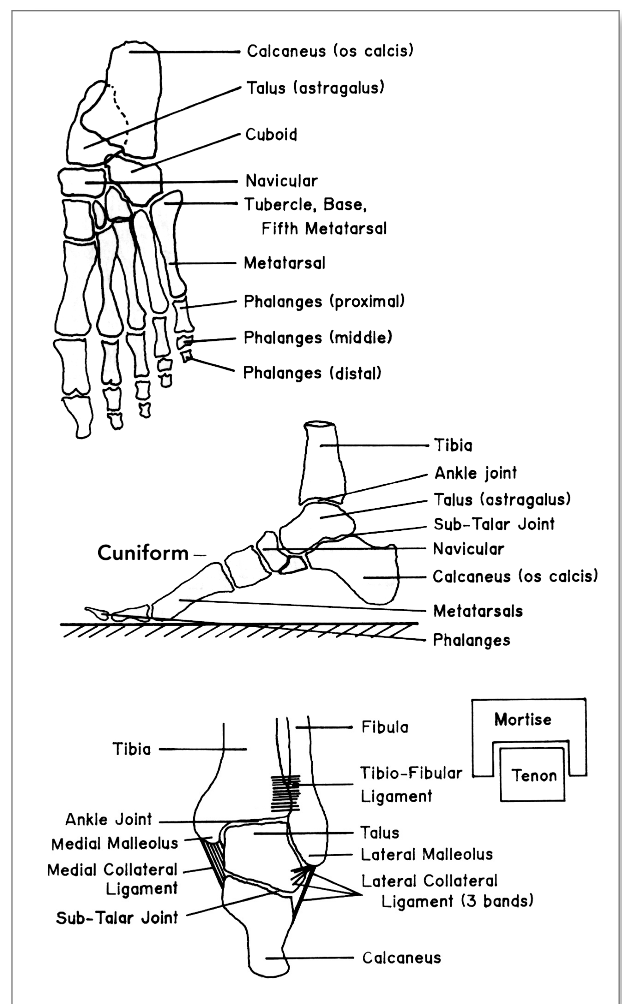
Source: Contreras, Rys, & Konz, 1993.

Figure 2.17 shows the ankle and foot. The foot is connected to the ankle with a mortise-and-tenon joint. The vertical leg of the mortise is short on the lateral side (outside); in addition, the ligaments holding the bottom of the fibula (lateral malleolus) to the talus and calcaneus are relatively weak. In contrast, the vertical leg of the inside (medial) mortise is longer and the ligaments holding the bottom of the tibia (medial malleolus) to the talus are relatively strong.

Inward rotation (inversion) of the foot tends to pull the ligaments from the bone. With proper treatment, healing usually is complete in 3 weeks. The danger is that the injured person may not seek medical advice—even with a complete tear of the ligaments (connecting either the malleolus and the talus or the tibia and the fibula). Then, surgical repair and rigid fixation in a cast is needed for 2–3 months.

FIGURE 2.17

Bones of the ankle and foot. The right foot is viewed from below (top left) and the outside (middle); the left ankle (bottom) is viewed from the front.



External rotation (eversion) of the foot tends to break one of the malleoli bones (vertical part of the mortise). The person tends to recognize this serious injury and go to a physician.

Approximately 80% of all foot fractures involve the toes. Almost all could be prevented by safety shoes, as the fractures lie within the area protected by the metal toe cap.

The toes (foot fingers) are divided into *metatarsals* and three *phalanges* (except for the big toe, which has only two phalanges). In supporting the body, the *calcaneus* (heel) supports 50% of the weight; the first and second metatarsals 25%; and the third, fourth, and fifth metatarsals 25%. In between are two arches: (1) the medial arch (the calcaneus; the talus; the navicular; the cuneiform bones; and the first, second, and third metatarsals), and (2) the lateral arch (the calcaneus, the talus, the cuboid, and the fourth and fifth metatarsals). The plantar fascia is a fibrous tissue that forms the arch underneath your foot from the heel to the toes. If it weakens, the fascia can cause pain to either the heel end or the toe end.

Under the heel (calcaneus) is an important shock absorber, the heel pad (about 1.8 cm thick). The bottom of the calcaneus is spherical but has two small "mountains"; the pad reduces the pressure on these mountains, and thus on the ankle, knee, and back.

1.4 Joints. **Joints** are formed by two or more bones that are connected by thick tissues. The bone ends are covered with cartilage to prevent bone-to-bone contact. Most joints are enclosed by a capsule, lined with the tissue synovium. Synovium produces a lubricant fluid. Arthritis is a disease that causes joint inflammation.

1.4.1 Types of joints. Joint design can emphasize mobility (e.g., shoulder) or stability (e.g., ankle). The body has four types of joints: ball-and-socket, hinge, pivot, and fixed.

Ball-and-socket joints (e.g., hips, shoulders) have a large round end of a long bone that fits into the hollow part of another bone. This permits swinging and rotating movements.

Hinge joints (e.g., knee) are like a door hinge. The elbow has a hinge joint between the upper arm bone (the humerus) and the ulna (in the forearm).

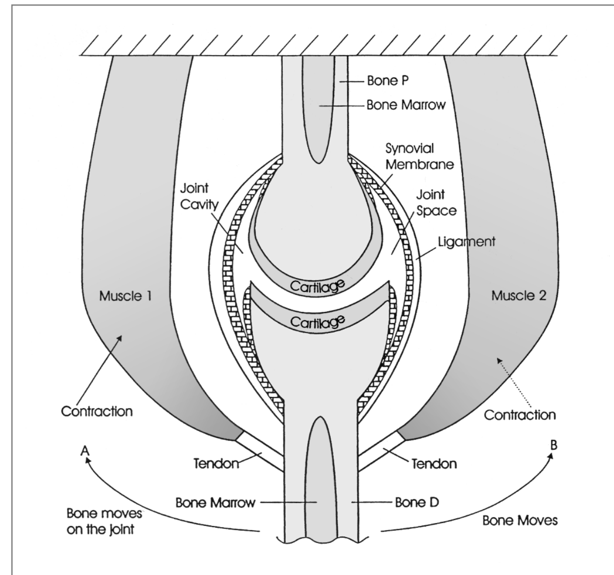
Pivot joints (e.g., elbow) allow rotation. The elbow has a pivot joint of the smaller bone in your forearm (the radius, on the thumb side) and the larger forearm bone (the ulna); it allows you to place your palm up or down.

Fixed joints (e.g., skull) don't move, except to absorb shock. Figure 2.18 gives a schematic joint.

1.4.2 Cartilage and ligaments. **Cartilage** (Kumar, 2001) is a tough and pliant material; it has two major components: (1) collagen fibers are arranged in wide

FIGURE 2.18

Schematic joint.



Source: Kumar, 2001. Reprinted with permission of the author.

arches with their domes directed outward and (2) the intervening space is densely packed with a protein-carbohydrate complex (proteoglycan). Pads of cartilage line the terminal ends of bones at their articulating ends with other bones.

Joint capsules are sheets of collagen fibers surrounding the entire joint from all sides. The collagen fibers are laid in a bed of proteoglycan that binds the fibers together—much like concrete and metal rods or wire mesh.

Synovial fluid is present in the capsules of all articulated joints; it acts as a dynamic lubricant. Its velocity is shear-rate dependent. In slow motions, it maintains a high viscosity, however, in rapid motions, its viscosity drops instantly to allow appropriately thinned lubrication.

Where ligaments are subject to friction, a lubricating device called a **bursa** (a small, flat, fluid-filled sac lined with synovial membrane—the body has about 200 of them) shields the structure from rubbing against the bone. An inflamed bursa is called *bursitis.*

Both ligaments and tendons are made from the same protein—collagen. Ligaments are a flat sheet with a small number of collagen fibers in different directions. Ligaments are well supplied with blood vessels and nerve fibers. Tendons, however, are a "rope" with densely packed collagen fibers running in one direction. They are less vascular. Ligaments provide joint support and stability. They accommodate the normal range of joint motion.

A sprain is a tearing of ligament or muscle—within itself or from the bone.

1.5 Tendons. **Tendons,** which transmit force from muscles to bones, have a very high modulus of elasticity (close to mild steel!) and very high tensile strength (45 to 125 N/m^2). See Figure 2.19. Synovial sheaths, containing a lubricant called synovial fluid, often (but not always) surround the tough, ropelike tendon. A tendon in a sheath is like a wire in a soda straw. A *strain* is the tearing apart of tendon fibers (akin to fraying a rope). *Tendinitis* (also called tendonitis) is the inflammation of the tendon. *Tenosynovitis* (also called tendosynovitis, tendovaginitis, and peritendinitis) results when the sheath produces excessive synovial fluid, making the sheath swollen and painful. Tendons have virtually no blood supply, and thus, they heal very slowly. An inflammatory reaction may begin in the damaged tendon area. The inflamed tissue carries with it a blood supply for tendon repair, but it also has a nerve supply that can cause severe pain.

If the tendon sheath constricts (stenosis), it is called *stenosing tenosynovitis.* The most common example is DeQuervain's disease, affecting the long abductor and short extensor tendons on the side of the wrist and base of the thumb. The person is unable to "bridge a wide span" (spread thumb and index finger apart) and may have difficulties with a combination firm grip and forearm roll (wringing motion).

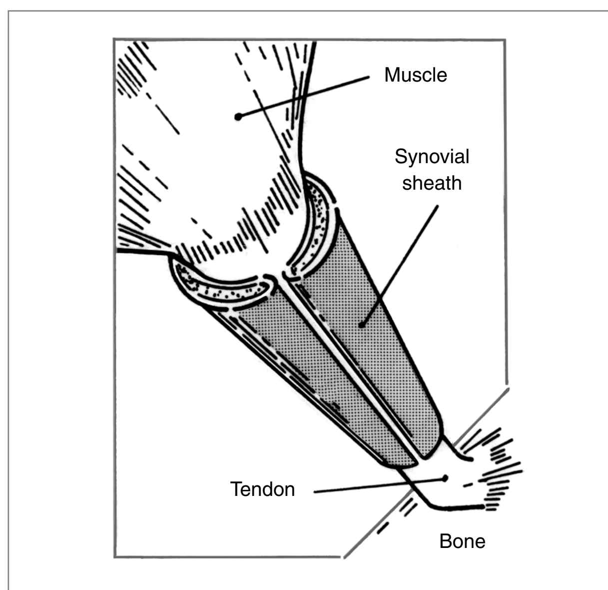
If a tendon becomes locked in a swollen sheath, the movement will be snappy or jerky. In a finger, this is called *trigger finger.* This often occurs with extended use of sharp-edged tools. A sheath that swells with fluid may form a ganglionic cyst (a bump).

The unsheathed tendons in the elbow can get tendinitis. The humerus bone of the upper arm splits into two condyles at the elbow; the epicondyle is the outside protrusion on each condyle. Medial epicondylitis (golfer's elbow) is on the inside (medial side) of the elbow; it often occurs when the forearm is rotated when the wrist is bent. Lateral epicondylitis (pitcher's elbow, bowler's elbow, tennis elbow) is on the outside (lateral side) of the elbow; it often occurs when the arm is used for impact or jerky throwing motions.

Tendons and many ligaments have a reversible range of deformation of 4–6% (Kumar, 2001). Deformation beyond this, even upon full recovery, shows residual deformation. At 8–10%, rupture occurs. Occasionally, a single load causes failure but, more commonly, repetitive exertions and inadequate time for recovery reduce the cross-sectional area of the stressed connective tissues, thereby increasing the stress concentration. This lowering of the tissue's stress tolerance increases the chance of injury. Prolonged static load results in creep, making the tissues vulnerable in a similar manner.

FIGURE 2.19

Tendons connect muscles to bones.



Source: V. Putz-Anderson (ed.). *Cumulative Trauma Disorders.* Copyright © 1988 by Taylor and Francis, London. Reprinted with permission.

1.6 Muscles. There are three types of **muscles** in the body: (1) cardiac muscle (found in the heart), (2) smooth muscle (internal organs and walls of blood vessels), and (3) skeletal muscles (attached to bones). We will discuss skeletal muscles.

Skeletal muscle is striated because it is the interlacing of two types of filaments: thick filaments (long proteins with molecular heads, called myosin) and thin filaments (globular proteins, called actin). Muscles are composed of white fibers (for strength and speed) and red fibers (for endurance). You can train to emphasize speed/strength or endurance.

The muscle origin is the proximal end (pointing toward the body center); the muscle insertion is the distal end (moving with the moving body segment). The muscle motor units are controlled by neurons. Fine control (e.g., eyeball rotation) may have only 7 motor units/neuron, while gross control may have 1,000 motor units/neuron.

Muscles usually are attached to bones in a paired arrangement. The action (agonist, protagonist) muscles perform the main movement of the body segment; the opposer (antagonist) muscles act as the controller. For example, the agonist muscle initially contracts to provide rotation about a joint; a short time later, the antagonist muscle slows or stops the motion.

Arteries furnish nutrients, oxygen, and hormones to the muscles; veins remove the waste products. The exchange takes place in the capillaries.

1.7 Nerves. Nerves are divided into the central nervous system (brain and spinal cord) and the peripheral nervous system. Peripheral **nerves** supply the communication within the body. Motor nerves bring messages (efferent signals) from the brain to the muscles. Sensory nerves bring messages (afferent signals) from the body (e.g., muscles, pain transducers, pressure transducers) to the brain. Autonomic nerves control various functions, such as sweat production.

In addition to the nervous system (electrical, instantaneous, point-to-point), communication occurs with the hormonal system (chemical, slow and prolonged, to entire body).

2 BIOMECHANICS OF MUSCULAR MOVEMENT

Box 2.1 describes the biomechanics of leg movement. See Section 5.4 of Chapter 13 for a brief discussion of biomechanical software. This section is divided into lever systems; force capability; and gender, age, and training effects.

Biomechanics of Walking, Running, and Stepping — BOX 2.1

Walking

When walking, the activity of one leg has a shorter swing phase (when the foot is being passed forward) and a longer support (stepping, contact) phase (when the foot is on the ground). The support phase starts at heel strike and ends at toe-off; it has an early passive section and a later active (propulsion) section.

At heel strike, the forward-moving heel hits the ground (causing deceleration). Continued forward motion of the body results in the forefoot contacting the ground, and propulsion (acceleration) begins. The heel rises and the foot is pushed backward under the body. This tendency is resisted by friction under the sole; the body is propelled forward. The foot is everted, increasing forefoot contact on the inner side, until only the skin around the big toe is in ground contact. Finally, the contact ceases and the cycle repeats.

Because the swing phase is shorter than the support phase, heel strike of the opposite limb occurs during the propulsion part of the support phase. At heel strike, horizontal velocity decreases from about 450 cm/s to 20 cm/s; heel angle to the floor changes from about 20° prior to heel contact to 0° at 100 ms after contact (Redfern and Rhoades, 1996). During a slip, instead of stopping, the heel continues to move and the leading foot moves out in front of the body.

Running

Walking changes to running, for normal size adults, at about 2.5 m/s (6 miles/h), since it uses less energy (for the same speed).

Running differs from walking in that both feet are off the ground for part of the stride. In addition, the heel strike should be renamed the "foot strike," since the initial contact probably will be forward of the heel. After foot strike (usually on the outside edge of the foot), the foot rolls inward and flattens out (pronation). Then the foot rolls through the ball and rotates outward (supination).

Peak force is about 3 (body weight) at about .1 s after contact. For running, the average contact duration is .29 s. In contrast, it is .48 s for walking (Scanton and McMaster, 1976).

Stepping

Descending stairs demands a gait quite different from ascent (Templer, 1992).

For descent, the leading foot swings forward over the nosing edge and stops its forward motion when it is directly over the tread below; the toe is pointed downward. Meanwhile, the heel of the rear foot begins to rise, starting a controlled fall downward toward the tread. The heel of the forward foot then is lowered and the weight is transferred to the forward foot. The rear foot then begins to swing forward.

We tend to hold our center of gravity as far back as possible by leaning backward. Problems are overstepping the nosing with the forward foot, catching the toe of the forward foot, and snagging the heel of the rear foot on the nosing as it swings past. Falls tend to be down the stairs.

For ascent, the leading foot has a toe-off, swing, and first contact with the upper step. The foot is approximately horizontal. The ball of the foot is well forward of the tread; the heel may or may not be on the tread. The rear foot then rises on tiptoes, pushing down and back. The rear leg then begins the swing phase. The primary problem is catching the toe, foot, or heel of either foot on the stair nosing. Another problem is the rear foot slipping when it pushes backward. Falls tend to be upward.

See Box 2.6 for the energy costs of walking, running, and carrying.

(Konz, 1999)

2.1 Lever systems. Muscles and bones are arranged into three types of **skeletomuscular levers.**

2.1.1 First-class levers. As shown in Figure 2.20, the fulcrum is between the two loads, which is good for fine positional control. Common examples outside the body are the seesaw, scissors, and platform balance.

2.1.2 Second-class levers. As shown in Figure 2.21, the fulcrum is at one end. The force is exerted through a longer moment arm than the resistance so the force has a mechanical advantage over the resistance. Common examples outside the body are wheelbarrows and refrigerator doors.

2.1.3 Third-class levers. As shown in Figure 2.22, the fulcrum is at one end. However, the force is exerted through a shorter moment arm than the resistance so the resistance has a mechanical advantage over the force. Thus, there is a higher internal force in the body than external force outside the body. Most levers in the limbs are third-class levers. A example outside the body is a forceps.

Assume the muscle is inserted .025 m from the fulcrum and the weight is .30 m from the fulcrum. If the weight is 2 kg, then the weight's external torque is .3 (2) = .6 kg-m; the internal force is .6/.025 = 24 kg.

FIGURE 2.20

First-class levers. The fulcrum is between the two loads. An anatomical example is the head moving up and down. A sports example is an oar in a rowboat.

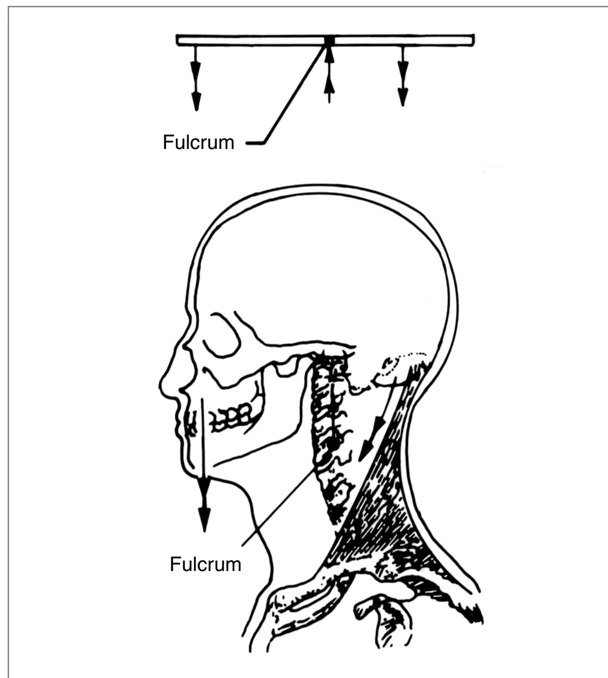


FIGURE 2.21

Second-class levers. The fulcrum is at one end; the force has a mechanical advantage over the resistance. An anatomical example is the ankle joint when walking. A sports example is a pole in a pole vault, when the pole is bent downward just before the athlete springs off the ground.

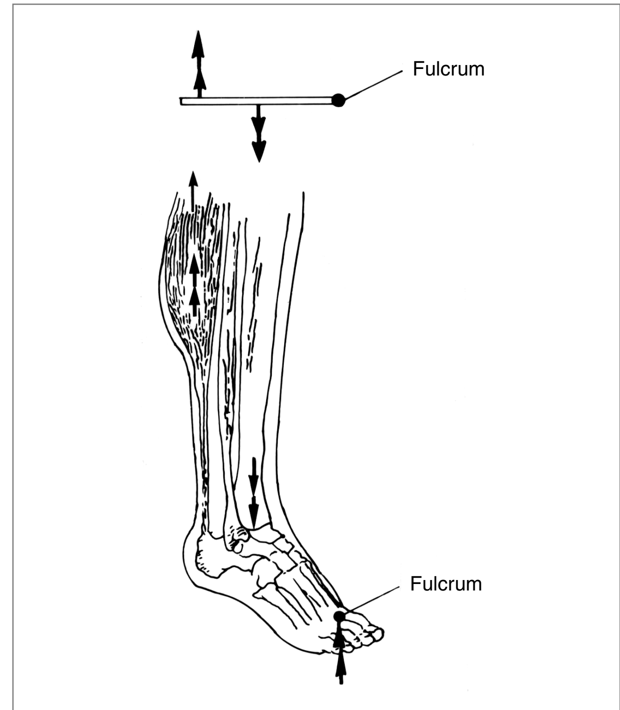
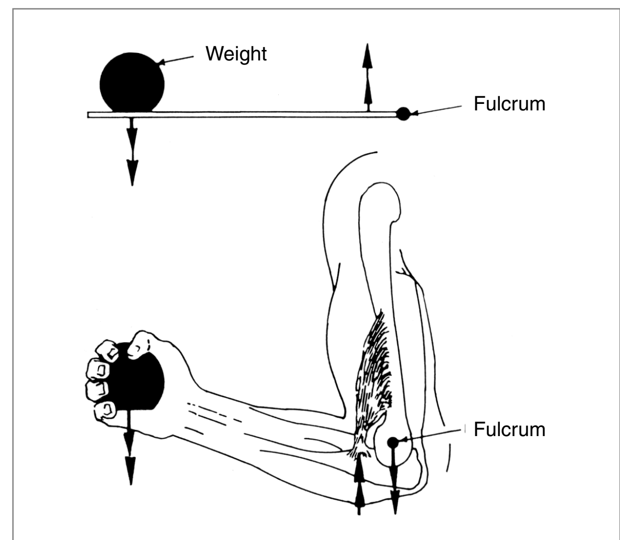


FIGURE 2.22

Third-class levers. The fulcrum is at one end; the resistance has a mechanical advantage over the force. An anatomical example is holding a weight in the hand. A sports example is movement of the arm when throwing.



Note that the internal moment arm (the .025 m in the example) becomes smaller as the forearm is raised or lowered from a 90° angle, thus increasing the internal force. (The internal moment arm is quite low when the upper and lower arms are aligned—as in a long reach.) In addition, as the length of the muscle changes from the 90° value, the resulting tension drops.

In reality, there is an additional weight involved. Assume the forearm plus hand weight is 2.3% of body weight; assume its center of gravity is .15 m from the fulcrum. Then, a 70-kg person would have an additional torque of .023 (70) (.15) = .24 kg-m to overcome.

The above static analysis ignores the effect of accelerations, momentum, and friction, but it shows that good design minimizes these moments by using lighter tools and loads and reducing reach distances.

2.2 Force capability. See Kroemer (2006) for a more detailed discussion of strength. Force capability is divided into posture factors and individual factors.

2.2.1 Posture factors. Table 2.2 and Figure 2.23 show the effect, for seated males, of elbow angle and movement direction. Warwick et al. (1980) reported that their subjects could push (using both hands) with a force of 29.8 kg (100%), pull back with a force of 17.3 (58%), push right with 15.9 (53%), and push left with 17.0 (57%). They could lift up with 39.4 (132%) and push down with 34.7 (116%). Haselgrave et al. (1987), studying maintenance postures, defined pushing horizontally while standing as 100%; most forces while lying supine or working overhead while standing ranged from 35% to 45%, although some angles and positions had values of 140% to 240%.

Ferguson and Mason (1988) studied force capability using wrenches. They told designers: (1) at fastener heights below .5 m above the floor, don't require downward movement of the wrench; (2) at heights above .5 m above the floor, don't have horizontal movement of the wrench unless the workers can brace themselves; and (3) at heights above 1 m, move the wrench up or down but not horizontally. Jorgensen et al. (1989) recommended that, when cutting meat with knives, cuts be made pulling toward the body and the knife edge should be down, not up.

Haselgrave et al. (1997a) reported foot placement can have large effects on exertable force. Haselgrave et al. (1997b) reported that exertions are stronger when kneeling on one knee than when kneeling on two knees.

FIGURE 2.23

Arm muscle strength versus angle. Table 2.2 shows how strength varies greatly with elbow angle.

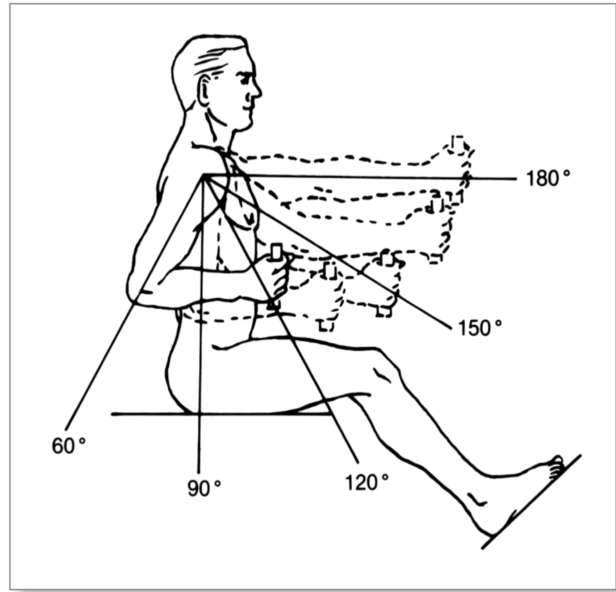


TABLE 2.2

Variables in arm strength. Forces (kg) exertable on a vertical handgrip with the right arm at various elbow angles (Damon et al., 1966, citing Hunsicker, 1955). Arm strength depends upon the angle, the direction, the arm, and the individual. See Figure 2.23. N = 55 college males. The mean coefficient of variation was 42%.

	ELBOW ANGLE, DEGREES					
Movement	60	90	120	150	180	Left arm, % of Right
Pull	28.6	40.0	47.3	55.5	54.5	.94
Push	41.8	39.1	46.8	55.9	62.7	.92
Move right	19.1	16.8	15.5	15.0	15.5	1.30
Move left	23.6	22.7	24.1	24.5	22.7	.60
Up	22.3	25.5	27.3	25.5	19.5	.92
Down	23.2	24.1	26.4	21.4	18.6	.88

Electromyography (EMG) — BOX 2.2

For heavy work, measure heart rate. But for lighter work, specific muscles may be of interest, so consider using an electromyogram (EMG), in which electrodes are taped on the skin above the specific muscles of interest. An EMG can provide information about:

- whether the muscle was in use (on/off)
- a relative activity level
- force generation (under special conditions)
- muscle fatigue

Fatigue is estimated by the decrease in frequency. Kim and Jung (1998) reported that mean power frequency was superior to median frequency at 30% to 75% of MVC. Fatigue also can be quantified by the slope of frequency versus time. However, Kumar (1997) reported that different muscles had different median frequencies, and, for the same muscle, frequency differed between males and females, and between holding upright and stooping.

2.2.2 Individual factors. Strength varies greatly with individuals. Note the 42% coefficient of variation in Table 2.2. That is, for a standardized lab experiment using college males, the standard deviation was 42% of the mean. Thus, to include 2 sigma in each direction (i.e., 95% of the people), the range would be +84% of the mean to –84% of the mean! Industrial workers doing real work probably would vary even more. See Section 2.3 for the effects of gender, age, and training.

Strength also varies greatly with time exerted. See Figures 19.1 and 19.2. **Maximum voluntary contraction (MVC),** the maximum sustained force of a muscle, declines exponentially with time. The asymptote at which a force can be held indefinitely is about 10% of MVC.

2.2.3 Strength measurement. Testing types are isometric, isoinertial, and isovelocity. If the muscle length does not move (there is a balance between muscle torque and external torque), the test is **isometric.** If there is a constant mass being moved, it is **isoinertial.** If movement is constant, it is **isovelocity. Isotonic** (concentric) contractions have a constant internal force of the muscle, but the muscle shortens.

Isovelocity testing is recommended due to its greater predictive ability as well as greater safety for the person being tested. Also see Kroemer et al. (2001).

Muscle activity can be evaluated with an **electromyogram** (see Box 2.2).

2.3 Gender, age, and training effects. Three individual variables are gender, age, and training.

2.3.1 Gender. The average female has less muscular strength than the average male, although individual females may be stronger than individual males. The most simple approximation is that females have 2/3 the strength of males. However, there are differences by muscle groups. Laubach (1976) reported 56% for upper body strength, 72% for lower extremity strength, 64% for trunk strength, and 69% for dynamic strength. The differences are primarily due to the smaller size (shorter lever arms) and muscle masses of women rather than gender itself. Franson and Winkel (1991) reported that 35% of the gender differences in hand strength are due to hand size differences.

Females have less muscle mass than males but also lighter arms. Hence, rhythmic work performed by the arms (such as most bench work) may result in a higher risk of musculoskeletal disorders because females are working at a higher percent of their capacity.

2.3.2 Age. Figure 2.24 shows the effect of age on muscle strength for males and females. Figures 2.28 and 2.29 show more age effects. Speed of movement decreases with age; older people slow down most on more difficult movements. Roozbahar et al. (1979) give grip strength as:

$$GS = 608 - 2.94\,AGE$$

where

GS = Grip strength of dominant hand, N
AGE = Age, years

Rhodes (1983), in a review of the relation between age and job performance, indicated that approximately 1/3 of the studies report that job performance increases with age, 1/3 say it remains the same, and 1/3 say it decreases. See also Waldman and Avolio (1986).

2.3.3 Training. There are three main types of exercise: endurance (aerobic), strength, and flexibility. Endurance (walking, stair climbing) is for cardiovascular fitness. Strengthening improves the strength of specific muscles. Flexibility improves the range of motion. Flexibility exercises also are useful for warm up (increasing blood flow to muscles) and

FIGURE 2.24

Isometric strength of arms and legs. Strength varies with gender, with limb, and with age (Asmussen and Heeboll-Nielsen, 1962). Male strength at age 20–22 is set as 100%.

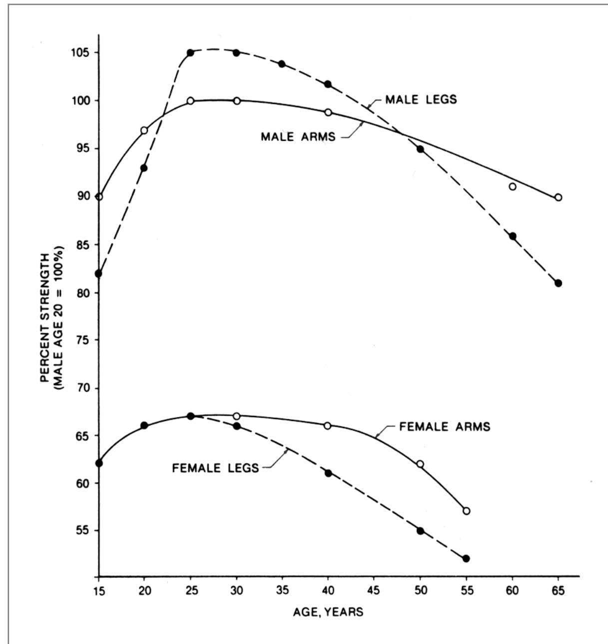
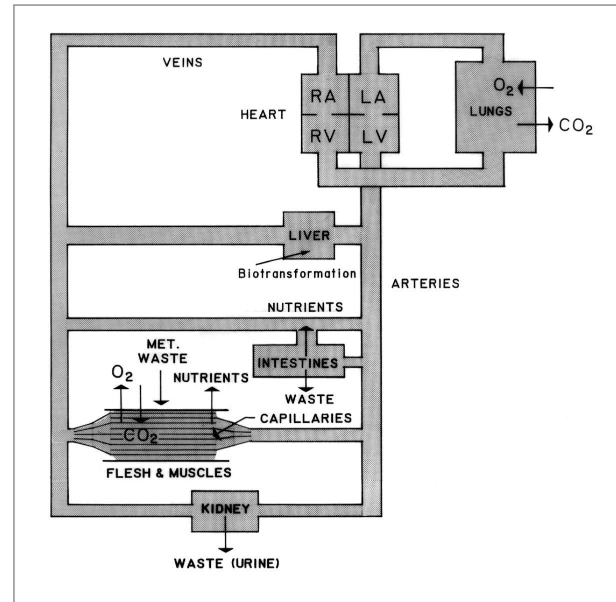


FIGURE 2.25

Engineer's view of the cardiovascular system.



cool down (returning muscles to normal from their contracted state). For industrial jobs, training should consider all three.

A short, intensive training program can substantially improve strength and endurance. To improve strength, the training load should be >50% of the person's initial dynamic strength. Strength increases faster and to a greater extent for males; thus, training may increase gender differences.

A challenge is the "weekend warrior," who is mostly sedentary during the week and then exercises violently on weekends with muscles not up to the strain.

3 CARDIOVASCULAR ANATOMY

Work physiology deals primarily with the response of the **cardiovascular system** to exercise. Thus, we will begin with an introduction to the anatomy of the cardiovascular system. (For skeleto-muscular anatomy, see the beginning of this chapter.) The discussion will cover the overall system and then local systems.

3.1 Overall system. Figure 2.25 shows an "engineer's view" of the cardiovascular system.

Pulmonary circulation starts at the right atrium (*little room,* Latin) and goes through a valve to the right ventricle (the pump itself). Systole is the contraction of the heart muscle; it ends with blood ejection from the heart (aortic valve opens). Diastole is the relaxation of the heart (aortic valve closes). At 75 beats/min, systole takes about .3 s and diastole about .5 s. At 150 beats/min, both take about .2 s; thus, an increase in heart rate takes place primarily by decreasing diastole. When the blood returns from the lungs (with more oxygen and less carbon dioxide), it enters the **systemic circulation.**

After passing through the left atrium and ventricle, the blood primarily enters the aorta (which has a "candy cane" shape and a "garden hose" thickness and diameter). It runs between the spine and the torso organs until just below the bellybutton, where it branches to supply the two legs. The blood enters smaller arteries, goes through the arteries, goes through the capillaries, and then returns in the veins. The circulating blood has not only transferred gases and compounds (including enzymes and hormones) around the body; it has also transferred heat. It also stores gases and compounds.

Blood volume is divided into plasma (55%, mostly water) and solids (45%). The solids are primarily red cells, white cells, and platelets. Hematocrit is the percent of red cell volume in the total blood volume.

Box 2.3 describes cardiac output and Box 2.4 describes blood pressure.

3.1.1 Legs. Three venous systems drain the lower limbs: (1) a deep central system drains the muscles, (2) a superficial system drains the foot and skin

Cardiac Output BOX 2.3

Cardiac output is the output of the left ventricle:

$$CO = HR\ (SV)$$

where

CO = Cardiac output, liters/min
HR = Heart rate, beats/min
SV = Stroke volume, liters/beat

Cardiac output, for a resting young man, is about 5 liters/min. Maximum, for a normally sedentary young man, is about 25 and, for a world-class athlete, is about 35.

Cardiac output can be predicted from formulas.

Basal cardiac output is (Guyton, 1961):

$$COBASL = CI\ (DBSA)$$

where

$COBASL$ = Basal cardiac output, liters/min
CI = Cardiac index, liters/(min - m^2)
= $4.29 - .029\ AGE + .003\ AGE^2$
($5 < AGE < 70$)
AGE = Age, years
$DBSA$ = DuBois surface area, m^2

Activity cardiac output is (Astrand and Rohdahl, 1986):

$$COACT = CLMW\ (TOTMET)$$

where

$COACT$ = Activity cardiac output, liters/min
$CLMW$ = Conversion from liters of blood to watts
= .166 for $TOTMET$ <700 W
= .114 for $TOTMET$ >700 W

Activity cardiac output increases (up to 18 times basal flow) primarily in the muscles.

Skin cardiac output (Stolwijk, 1970) is .4 liters/min for basal conditions. For tasks with $TOTMET$ <.2 $\dot{V}O_2$max, any increase in skin blood flow comes from $COBASL + COACT$ rather than an increase in CO—that is, a redistribution of blood flow rather than an increase (Rowell, 1974).

However, with vasodilation, skin cardiac output can reach 1.6 liters/min. This vasodilation circulation bypasses the muscles as the blood flows from the small arteries (arterioles) to the small veins (venules) through bypasses (arteriovenous anastomoses). This high-resistance flow increases heart rate.

However, if people are accustomed to heat **(heat acclimatization),** they have an enhanced ability to sweat (losing heat by evaporation). Thus, they do not have to lose heat by vasodilation and the blood does not use the high-resistance paths. Acclimatized people have lower heart rates in heat stress than do unacclimatized people.

Blood Pressure BOX 2.4

Blood pressure (the pressure blood puts on the blood vessel walls) commonly is measured with a sphygmomanometer. The cuff is applied to the upper arm and while it is being tightened, one listens to the sound of the blood flowing in the artery below the cuff. After the cuff is tight, there is no sound because no blood is flowing in the artery. As the cuff is loosened, blood begins to flow turbulently and a noise is heard. This first sound indicates systolic (maximum) blood pressure. As the cuff is loosened further, the turbulence decreases until the flow becomes laminar and the sound disappears, indicating diastolic blood pressure, the minimum or base pressure exerted by the blood on the artery walls.

Pulse pressure = Systolic pressure – diastolic pressure

Blood pressure can be estimated (Roozbahar et al., 1979) as:

$$SBP = 101.3 + .68\ AGE$$
$$DBP = 63.7 + .36\ AGE$$

where

SBP = Systolic blood pressure, mm Hg
DBP = Diastolic blood pressure, mm Hg
AGE = Age, years

Life insurance studies indicate that blood pressures below 110/70 are optimal for a long life span. Resting diastolic pressure below 90 is satisfactory, from 90–100 is suspicious, and above 100 is poor. In 2003, the National Heart, Lung, and Blood Institute lowered the recommended blood pressure to 120/80. Reduce blood pressure by avoiding overweight, avoiding saturated and total fat, minimizing salt, being physically active, moderating use of alcohol, and avoiding smoking.

of the leg, and (3) a perforating system connects the deep and superficial systems.

The veins store the body's blood. If the legs don't move, the blood from the heart tends to go down to the legs and stay there **(venous pooling).** This causes more work for the heart, as, for a constant supply of blood, when blood/beat is lower, then there must be more beats. Venous pooling causes swelling of the legs **(edema)** and varicose veins.

Venous pressure in the ankle of sedentary people is approximately equal to the hydrostatic pressure from the right auricle. Pollack and Wood (1949) gave a mean ankle venous pressure of 56 mm Hg for sitting and 87 for standing. Nodeland et al. (1983) gave 48 for sitting and 80 for standing. Pollack and Wood reported that walking about 10 steps drops ankle venous pressure to about 23 mm Hg; Nodeland et al. (1983) reported 21.

A fall occurs because the calf muscles contract while taking the next step before venous filling is complete. Thus, additional blood is pumped out of the leg, causing a further drop in pressure when the calf muscles relax. The drop stabilizes in about 10 steps when the incoming flow to the veins from the capillaries equals the flow out of the leg.

Thus, walking can compensate partially for standing posture. For example, Nodeland et al. (1983) reported that standing benchwork (i.e., with occasional steps around the area) had ankle pressure approximately equal to sitting at a desk (48 mm Hg).

Walking aids blood circulation through the "milking action" of the leg muscles; this reduces the work of the heart. Active standing (walking 2–4 min every 15 min) results in less discomfort than standing without walking (Konz et al., 1988). Also see Table 2.3.

3.1.2 Thermal regulation. During heat stress, the body may heat acclimatize. In brief, because acclimatized people sweat more, there is less need for peripheral blood flow, and thus, less work by the heart. See Box 2.3 and Chapter 22 for more on the physiology of thermal regulation and techniques to overcome its challenges.

4 METABOLISM

The cardiovascular system primarily responds to changes in metabolism. In some cases, heart response is affected by emotions and by heat stress. In industry, metabolism usually is determined from tables and formulas; see below and the ERGO program. In a laboratory, metabolism can be determined from oxygen consumption (indirect calorimetry), which gives the total of basal, activity, and digestion metabolism.

Table 2.4 gives some of the possible units and their conversions. The standard power unit is watts, abbreviated *W.* The energy content of food is given in kcal (commonly spoken of as Calories rather than the technically correct kilocalories). Table 2.5 gives metabolic rate as a function of exertion level.

Metabolic rate is divided into three parts: basal, activity, and digestion.

4.1 Basal metabolism. **Basal metabolism** maintains body temperature, body functions, and blood circulation.

$$BSLMET = BSMET\,(WT)$$

where

$BSLMET$ = Basal metabolic rate, W

$BSMET$ = 1.28 W/kg for males
1.16 W/kg for females

WT = Body weight, kg

BSMET is lower for females because females tend to have a higher percentage of fat than males. Fat has a limited metabolism.

ERGO has a more complex formula that considers a person's age (from 5 to 70). Children have a higher basal metabolic rate/kg because they have a higher surface area/volume (thus, requiring more heat to maintain body temperature) and because growth takes energy. Resting metabolic rate also is given in METs where 1 MET = 3.5 ml of oxygen/kg of body weight.

TABLE 2.3

Cardiovascular effects of sitting and standing for 16 adults between 18 and 51 with mean age of 30 (Ward et al., 1966).

CRITERION	STAND (A LITTLE WALKING)	SIT	SIT/STAND %
Cardiac output, L/min	5.1	6.4	125
Stroke volume, mL/beat	54.5	78.3	144
Mean arterial pressure, torr	107.0	87.9	82
Heart rate, beats/min	97.2	84.9	87
Total peripheral resistance, dynes/cm^2-s.	1820.0	1207.0	66

TABLE 2.4

Energy conversions.

MULTIPLY UNITS BY 1	TO EQUAL UNITS	MULTIPLY UNITS BY 1	TO EQUAL UNITS
Joule	1.0 Nm		
Joule	.000239 kcal		
Watt	1.0 J/s		
Watt	85885 kcal/h	kcal/h	1.163 W
Watt	3.413 BTU/h	BTU/h	.293 W
Watt	.00134 HP	HP	746.0 W
Watt	.116 (kg-m)/min	(kg-m)/min	.1635 W
Watt/sq m	.01718 mets	met	58.2 W/sq m
Watt/sq m	10.764 W/sq ft	W/sq ft	.0929 W/sq m
Kcal	3.968 BTU	BTU	.252 kcal
		BTU	776.65 ft-lb

TABLE 2.5

Metabolism as a function of exertion. Moderate (for a 70 kg male) includes playing the piano, carpentry, walking 3 km/h, and dancing the waltz. ILO 8996 (1990) considers very light work to be $<100\ W/m^2$, light work to be 100 to 165, and moderate to heavy to be ≥ 165.

EXERTION LEVEL	TOTAL METABOLISM RATE WATTS	KCAL/H
Light	Up to 230	Up to 189
Moderate	230 to 350	189 to 300
Heavy	Over 350	Over 300

4.2 Activity metabolism. **Activity metabolism** provides the energy for activities. See Table 2.6 for some examples. Working in a contorted posture (kneeling, bent over) increases metabolic rate (Freivalds and Bise, 1991). Box 2.6 gives the metabolic cost for walking/running/carrying. For lifting, Garg et al. (1978) give the equation:

$$LFTMET = .0109\ BWLB + F\ (LOADF)$$

where

$LFTMET$ = Lifting metabolism, kcal/min
$BWLB$ = Body weight, lb
F = Frequency of lifts, lifts/min
$LOADF$ = Load factor
= $LFBW\ (BWLB) + LF\ (W) + GENF\ (W)$
$LFBW$ = Lift factor: body weight = .0002 for arm lift, .0012 for stoop, .0019 for squat
LF = Lift factor: load = .0103 for arm lift, .0052 for stoop, .0081 for squat

Percent Fat — BOX 2.5

Percent fat can be determined by (1) underwater weighing (most accurate, but requires special facilities) or (2) by using formulas. (The formulas are provided in ERGO.)

Fat indices

A number of body mass indices combine weight (W, kg) and height (H, m)—but with large errors. Two examples are Quetelet's index (W/H^2) and the ponderal index ($W^{.33}/H$). A Quetelet's index from 19 to 25 is "healthy," from 25 to 29 is "moderately overweight," and above 29 is "severely overweight."

Fat distributions

Fat distributed around the waist (apple shape) increases the risk of heart attack, stroke, diabetes, breast cancer, high blood cholesterol, and high blood pressure; weight around the hips and thighs (pear shape) is not as bad. Using a flexible tape, measure your waist at its narrowest point. Then, measure your hips around the fullest part of the buttocks. An acceptable waist/hip ratio for men is <1.0; for women, <.80.

The amount of fat increases with age. Garn and Harper (1955) reported that although lean body weight changes little from age 20 to 60, fat increases from 16% of body weight at ages 20–30 to 22% of body weight at ages 50–60. If you are overweight, 20–35% of the excess weight is lean tissue used to support the fat. This lean tissue increases your basal metabolic rate.

About 3% of body weight is "essential" fat (cell membranes, nerve tissue, tissue in and around various organs). Women have sex-specific fat (primarily breasts and hips) of 9–12%. Thus, anything over 3% for men and 15% for women is storage fat.

The body has two types of lipoproteins—low density cholesterol (LDL) (considered "bad") and high density cholesterol (HDL) (considered "good"). LDL ferries cholesterol throughout the body, where it performs functions such as repairing cell membranes and aiding hormone production. HDL then escorts excess cholesterol back to the liver for disposal. But if there is too much LDL relative to HDL, then fatty deposits (plaques) build up in the arteries.

TABLE 2.6

Activity cost for various activities. For total energy cost, add the basal metabolism and, if appropriate, the cost of digestion. See Box 2.6 for equations for walking, carrying, and running.

W/KG	ACTIVITY
.4	Crocheting, eating, reading aloud, sitting quietly, writing
.6	Playing cards, standing relaxed
.7	Paring potatoes, standing office work, standing at attention, violin playing
.8	Dressing and undressing, knitting a sweater
.9	Singing in a loud voice
1.0	Driving a car
1.2	Dishwashing
1.4	Washing floors
1.5	Cello playing, light laundry
1.6	Riding a walking horse, sweeping floor with broom
1.7	Golfing, organ playing, painting furniture with brush
1.9	Sweeping with hand (push) carpet sweeper
2.7	Doing heavy carpentry
3.0	Cleaning windows
3.1	Cleaning with upright vacuum cleaner
3.5	Dancing the waltz
4.1	Ice skating
4.5	Weeding a garden
5.0	Horseback riding (trot)
5.1	Playing ping pong
5.8	Dancing rhumba, playing tennis
6.6	Sawing wood (handsaw)
7.9	Playing football
8.9	Fencing

$GENF$ = Gender factor = –.0017 G for arm lift, .0028 G for stoop, and .0023 G for squat
G = Gender (female = 0; male = 1)
W = Object weight, lb

In industrial applications, estimate metabolism from tables or formulas as in ERGO. But remember that most work is not continuous as people take microbreaks. Estimate the time of each activity from a video.

The body burns additional Calories after the exercise stops so exercise benefits weight loss more than you might calculate.

4.3 Digestion metabolism. **Digestion metabolism** (also called specific dynamic action) accounts for transformation of food within the body. We burn:

4 kcal/g of carbohydrate
9 kcal/g of fat
4.3 kcal/g of protein

For reference, there are 7 kcal/g for alcohol. Alcohol is a problem as it decreases lipid (fat) oxidation about 33% (Suter et al., 1992). For the typical carbohydrate/fat/protein mixture of the U. S. diet and disregarding time following the meal:

$$DIGMET = .1\,(BSLMET + ACTMET)$$

4.4 Calories required. Metabolism is related to calories and body weight.

Assume a 70 kg male spent 24 h in bed without eating. Then, basal metabolism would be (70)(1.28) = 89.6 W. To convert this rate to an amount/hour, multiply by .86. Then, for a 24 h period, this 70 kg male would require 89.6 W (.86 kcal/W-h)(24 h) = 1849 kcal (1000 calories = 1 kcal = 1 Cal).

Hopefully, he will move during the day! Assume activity metabolism is .7 W/kg for 16 waking hours. Then, .7 (70) (.86) (16) = 674 kcal would be needed, or a total of 2523 kcal. Assuming 10% for digestion of food, this means he could eat 1.1 (2,523) = 2,773 kcal/day without gaining or losing weight.

If you eat more or less than your equilibrium amount, you will gain or lose weight. There are 3,500 kcal/lb, 7,700 kcal/kg. If you eat 20 kcal less per day (or increase exercise by 20 kcal/day), you will lose 7,300 kcal/year or 2.1 pounds/year or 21 lbs in 10 years. Small changes in eating or exercise can have large cumulative effects!

As a side note, Klieber (1961) determined the following formula for a variety of animals (dove, rat, pigeon, hen, dog, sheep, human, cow, and steer):

$$DAYMET = 70\,WT^{3/4}$$

where

$DAYMET$ = Metabolism during a day, kcal
WT = Weight, kg

The exponent could have been predicted to be 2/3 since surface area increases by a power of 2 and volume increases by a power of 3. Peters (1989) says the difference is due to the differing shape of animals as the size increases.

5 RESPONSE TO EXERCISE

The cardiovascular system has five **responses to exercise:** (1) heart rate, (2) stroke volume, (3) artery–vein differential, (4) blood distribution, and (5) going into debt.

Metabolic Cost of Walking/Running/Carrying

BOX 2.6

Box 2.1 discusses the biomechanics of walking, running, and stepping.

Pace

For many time studies, the concept of a normal pace is walking 3 mph (4.84 km/h; 1.39 m/s). The speed that minimizes energy expenditure is 2.2 mph (3.6 km/h) (Bunc et al., 2000).

The pace of Methods-Time-Measurement (MTM) is 3.57 miles/h (1.64 m/s) at a stride of 34 inches (.86 m)—.000015 h/stride. It is based on studies of 125 people walking a variety of paces (Maynard et al., 1948). MTM uses .000015 h/stride for climbing stairs. For carrying a load of up to 16 kg, MTM uses .000015 h/stride, but .76 m strides. For walking through obstructed areas, MTM uses .000017 h/stride and .86 m strides.

The length of stride *(L)* divided by stature height *(h)* varies linearly with velocity; $L/h = .67$ at $v = .8$ m/s and $L/h = .9$ at 1.7 m/s (Alexander, 1984). Thus, for the same velocity, a short person takes more steps. *L* decreases as floor slipperiness and weight carried increase (Myung and Smith, 1997).

Walking: Metabolic cost

Pandolf et al. (1976) gave the metabolic cost (total) of walking without a load as:

$$WLKMET = C\,(2.7 + 3.2\,(v - .7)^{1.65})$$

where

$WLKMET$ = Walking metabolism (total), W/kg of body weight

C = Terrain coefficient
= 1.0 for blacktop road, treadmill
= 1.1 for dirt road
= 1.2 for light brush
= 1.3 for hard-packed snow; $C = 1.3 + .082$ (foot depression, cm)
= 1.5 for heavy brush
= 1.8 for swamp
= 2.1 for sand

v = velocity, m/s (for $v > .7$ m/s [2.5 km/h, 1.56 miles/h])

Walking stooped requires more energy: 12% more for a 10% stoop (90% of stature height), 51% more for a 20% stoop, and 91% more for a 30% stoop (Morrisey et al., 1981).

A person walking on a treadmill swings the arms and legs, so the effective air movement is not zero but about .9 m/s (Nishi and Gagge, 1970).

Running: Metabolic cost

The cost of running (Van der Walt and Wyndham, 1973) is:

$$RUNMET = -142/WT + 11 + .04\,V^2$$

where

$RUNMET$ = Running metabolism (total), W/kg

V = Velocity, km/h

WT = Weight, kg

Carrying/standing: Metabolic cost

The metabolic cost of carrying (walking with a load) depends on the load location. Soule and Goldman (1980) reported that loads on the head used 1.2 times the energy of carrying a kg of your own body weight; in the hands, loads required 1.4 to 1.9 times as much; on the feet, loads required 4.2 to 6.3 times as much.

As a general guide for carrying, minimize the load's moment arm—both in the frontal and transverse axes. See also Section 4, Chapter 13.

Pandolf et al. (1977), for carrying very slowly or standing, give:

$$WLKMETT = 1.5\,WT + 2\,(WT + WTL)\,(WTL/WT)^2 + C\,(WT + WTL)\,(1.5\,v^2 + .35\,vG)$$

where

$WLKMETT$ = Metabolic rate (total) for walking slowly, W

WT = Body weight, kg

WTL = Weight of a load on the shoulders, kg

v = velocity of walking, m/s ($v < 1$ m/s)

C = Terrain coefficient (see above)

G = Grade, %

The first term (1.5 *WT*) is the metabolic cost of standing without a load (1.5 W/kg). The second term is the cost of bearing a load while standing. Walking on the level is $C\,(WT + WTL)\,(1.5\,v^2)$. The cost of walking up a grade is $C\,(WT + WTL)\,(.35\,vG)$.

5.1 Heart rate. For light and medium workloads (see Table 2.7), heart rate is a good predictor of metabolic rate. Three exceptions are:

1. *Emotions.* Emotions increase heart rate. The effect is relatively larger when the metabolic rate is low.
2. *Vasodilation.* In heat stress, unacclimatized people vasodilate, while acclimatized people sweat more and thus need less vasodilation and fewer heart beats.
3. *Heavy exercise.* In heavy exercise, other cardiovascular responses such as stroke volume and artery–vein differential may reduce the need for some of the increase in heart rate.

There are four ways of **measuring heart rate:**

1. *Light* can be used by shining it on an artery in the earlobe. A photocell on the far side of the earlobe sees the light during "ebb tide" between beats. Another model works by reflecting light on the finger. Both the earlobe and the finger techniques are sensitive to body movement, so they work best with a stationary person.
2. *Sound* through a stethoscope is used by physicians.
3. *Palpation* is the detection, with the fingers, of the surge of blood that follows each beat. Common locations are the arteries in the wrist and neck. Count the number of beats during 10 or 15 s and multiply by 6 or 4. In working situations, this is done after the work stops—that is, you measure recovery pulse.
4. *Electronics* is the most common and only practical technique for a nonstationary person. The recording unit is about the size of a pack of cigarettes and is belt-mounted. The output can be sent immediately or stored for later analysis.

Heart rate can be estimated by asking a person for his/her **rating of perceived exertion (RPE).** The scale is a column of numbers from 6 to 20. The person votes his/her perceived exertion as a number, using accompanying words for guidance; the heart rate is estimated by multiplying the rating by 10. For example, the words accompanying level 9 are "Very light" and the word with 11 is "Light." If the person identifies his/her exertion as "Light," the heart rate would be estimated as 10(11) = 110 beats/min. The concept has been validated by many experimenters for many tasks. Ljunggren (1986) reported it is not even necessary to have the individual's own perceived exertion—the exertion can be estimated by an observer.

TABLE 2.7

Oxygen uptake and heart rate as a function of exertion.

EXERTION LEVEL	OXYGEN UPTAKE, L/MIN	HEART RATE, BEATS/MIN
Light	<.5	<90
Moderate	0.5–0.99	90–110
Heavy	1.0–1.49	110–130
Very heavy	1.5–2.00	130–150
Extremely heavy	>2.0	150–170

Maximum heart rate can be estimated by:

$$HRMAX = 220 - AGE$$

where

$HRMAX$ = Maximum heart rate, beats/min
AGE = Age, years

The standard deviation of the prediction is 10 beats/min. Thus, an average person age 20 would have a maximum heart rate of 200 beats/min, with 95% of that age having from 180 to 220 beats/min. Maximum heart rate is relatively unaffected by physical fitness. (When exercising for physical fitness, initially exercise at 60–70% of *HRMAX.* An experienced exerciser can use 75–85% of *HRMAX.*)

A predictor equation of heart rate for light and medium workloads (Andrews, 1969) is:

$$INCHR = K + .12\ INCMET$$

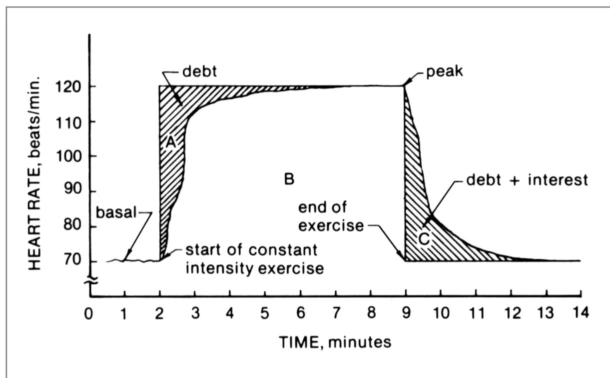
where

$INCHR$ = Increase in heart rate, beats/min
K = Constant
= 2.3 for arm work (cranking)
= –11.5 for leg work (walking) or arm and leg work (The 13.8 difference in the coefficient for the legs is due to venous pooling in the legs.)
$INCMET$ = Increase in metabolism, W

Figure 2.26 shows how the heart rate (primarily determined by aerobic oxygen supply) responds to constant-intensity exercise. At the start of exercise, the **aerobic response** (and therefore heart rate) lags. (**Aerobic** refers to reactions using oxygen from the lungs.) The resulting deficit (Figure 2.26, area A) is replaced by anaerobic oxygen. **Anaerobic** (without oxygen) reactions use oxygen stored as compounds in the blood. The anaerobic supply is composed of alactate (energy equivalent of 1.9 L of oxygen) and lactate (equivalent of 3.1 L). During recovery (Figure 2.26, area C), the anaerobic oxygen used from the blood is replaced; however, the replacement process itself uses oxygen ("interest"), so area C is larger than area A. Area C, the excess post-exercise oxygen consumption, is also known as "after-burn." Typically it amounts to 10–15% of the calories consumed during exercise. Thus, during exercise you burn a few more

FIGURE 2.26

Heart rate response to exercise.



calories than shown in the direct metabolic measurements. For task cost, use areas B + C.

The **heart rate cost of work** can be determined three ways. The simplest is to subtract an individual's basal heart rate from the peak. For example, Joe's peak of 110 and basal of 70 give a task cost for him of 40 beats/min. This assumes that the peak represents the work heart rate—that is, that the top of the curve in Figure 2.26 is flat.

Determining the basal is more complex than it might seem. People subconsciously increase their heart rate just before exercise. Measure basal 5 to 10 min before beginning the exercise.

A second way is to determine area B under the curve in Figure 2.26. However, this assumes that the heart rate instantaneously accelerates and decelerates at the start and stop of work. Thus, use a third method, totaling areas B + C (Chen and Lee, 1998).

5.2 Stroke volume. The heart also can adjust oxygen supply to the body through changing **stroke volume,** the amount of blood pumped by the left ventricle.

$SV = STROVB + .000\,050\,(TOTMET - 200)$
$TOTMET \leq 500$

where

SV = Stroke volume, liters/beat

$STROVB$ = Basal stroke volume, liters/beat (females = .9 male)

= $SI\,(DBSA)/1{,}000$

where

SI = Stroke index, ML(beat-m^2)

= $53.45 + .194\,AGE$

AGE = Age, years

$DBSA$ = DuBois surface area, m^2

= $.007\,184\,HT^{.725}\,WT^{.425}$

HT = Height, cm

WT = Weight, kg

$TOTMET$ = Total metabolism, W. For $TOTMET$ over 500 W, add $.000\,025\,(TOTMET - 500)$ to the SV equation.

Stroke volume also depends on body posture, exercise, and physical fitness. For sitting and standing, stroke volume of .08 liters/beat is typical but, for lying down, the value may be .12. Exercise with the legs improves venous return; stroke volume may increase. Arm exercise permits venous pooling in the legs, so stroke volume changes little.

Physical fitness affects maximum stroke volume. Maximum SV = .135 for excellent cardiovascular fitness, .120 for good, .100 for fair, .090 for poor, and .085 for very poor. See Table 2.8 for maximum oxygen uptake values for these fitness levels. Stroke volume peaks at about 40% of maximum oxygen consumption.

5.3 Artery–vein differential. A third method of adjusting oxygen supply to the body is **artery–vein differential.**

$OXUPTK = CO\,(AVDIF)$

where

$OXUPTK$ = Oxygen uptake, $\dot{V}O_2$ at standard temperature (0°C) and pressure (760 torr) dry (STPD), liters of oxygen/min. See Box 2.7.

CO = Cardiac output, liters of blood/min

$AVDIF$ = Arterial-venous oxygen differential, liters of oxygen/liter of blood

While resting, the arterial oxygen content is 19 mL/100 mL of blood, while the venous oxygen content is 15 mL/100 mL. That is, for every 100 mL of blood passing through the muscles, the muscles get 4 mL of oxygen. In an emergency (e.g., fleeing from a tiger), the veins drop to 6 mL and the *AVDIF* becomes 13 mL. The coronary blood supply, even under nor-

TABLE 2.8

Maximum oxygen consumption $\dot{V}O_2$max, mL/(kg-min) for U. S. males with various ages and degrees of cardiovascular fitness.

Cardiovascular Fitness	AGE, YEARS Under 30	30–39	40–49	50+
Very poor	<25.0	<25.0	<25.0	—
Poor	25.0–33.7	25.0–30.1	25.0–26.4	25.0
Fair	33.8–42.5	30.2–39.1	26.5–35.4	25.0–33.7
Good	42.6–51.5	39.2–48.0	35.5–45.5	33.8–43.0
Excellent	51.6+	48.1+	45.1+	43.1+

Source: The New Aerobics by Kenneth H. Cooper. Copyright © 1970 by Kenneth H. Cooper. Used by permission of Bantam Books, a division of Random House, Inc.

Oxygen Uptake and Pulmonary Ventilation — BOX 2.7

In some circumstances, the response of an individual may be measured.

TOTMET = 60 *ENERGY (OXUPTK)*

where

TOTAL = Total metabolism, W

ENERGY = Energy equivalent of 1 liter of oxygen, W-h/liter

Energy depends on the respiratory quotient (RQ), which in turn depends on the proportion of fat versus carbohydrate metabolized during the exercise.

= 5.36 for RQ = .83 (rest)

= 5.66 for RQ = .86 (exercise up to 60% of maximum rate)

= 6.40 for RQ = 1.00 (100% of maximum oxygen uptake)

OXUPTK = Oxygen uptake, $\dot{V}O_2$, liters of oxygen/min

Pulmonary ventilation is:

PULVNT = *(LAPLOX) (OXUPTK)*

where

PULVNT = Pulmonary ventilation, liters of air/min

LAPLOX = Liters of air/liter of oxygen

= 20–25 at rest and for work less than 1.5 L/min

= 30–35 during maximal work

See the ERGO program for calculations.

mal circumstances, has an *AVDIF* of 17. Therefore, more oxygen for the heart must come from more blood, not an increase in the *AVDIF.*

5.4 Blood distribution. Redistribution is the fourth way of getting more blood to a muscle. During exercise, capillary density increases from a resting 200/mm^2 to 600. Muscle blood flow can increase from 2 mL/100 mL of tissue to 14 mL. Blood stored in the lungs can change from 500 mL to 1500. As exercise increases, the kidneys and intestines have less blood since it has been sent to the skin and muscles. If food is present in the stomach, cramps may result.

5.5 Debt. If "underdeposited" for aerobic oxygen, the body goes into oxygen debt. The muscles then draw upon the anaerobic oxygen stored in the blood **(oxygen debt).** However, the anaerobic supply is limited and it must be repaid—with "interest." See Figure 2.26.

6 CARDIOVASCULAR LIMITS

There are two questions: (1) What is an individual's work capacity? and (2) What proportion of the capacity should be used?

6.1 Capacity. An individual's cardiovascular capacity is determined from **maximum oxygen uptake,** $\dot{V}O_2$max, mL/kg-min. $\dot{V}O_2$max is a product of cardiac output and A–V differential. Table 2.8 shows five fitness categories for U. S. males. Females typically have $\dot{V}O_2$max 15–30% below that of males so their critical values would be about 75% of males'. A male under age 30 in fair shape would have a value of 33 mL/kg-min. But a female under age 30 with a value of 33 would compare with 33/.75 = 44 and be in good shape.

How is $\dot{V}O_2$max determined? Four possibilities are given. The most accurate test (requires trained staff and equipment) is to do a maximal test on a treadmill or bicycle ergonometer. The person exercises until exhaustion.

A submaximal test is the step test. There are two 5-min sessions of stepping up and down on a 40-cm step with 15 cycles/min for the first test and 25 cycles/min for the second test. The heart pulse is measured from 30 to 60 s after work stops, from 90 to 120 s, and from 150 to 180 s.

The last two tests use the distance a person can walk/run in a time period. The first is:

$\dot{V}O_2max$ = –10.3 + 35.3 *DIST*

where

$\dot{V}O_2max$ = Maximum oxygen uptake, mL/kg-min

DIST = Distance run in 720 s, miles

Bunc (1994) recommends standardizing the distance at 2 km and recording the time:

$\dot{V}O_2max$ = 85.7 – 251.3 *T* (for males)

= 61.9 – 124.2 *T* (for females)

where

T = Time to run 2 km, h

Testing an individual's capability for screening purposes has become controversial in the United States due to discrimination laws.

6.2 Proportion of capacity. For an individual, what **proportion of capacity** is reasonable for work?

The general concept is to avoid anaerobic metabolism. Jorgensen (1985) recommends 50% for trained workers and 33% for untrained. If the task is primarily upper body work, the maximum should be about 30% less.

Mital et al. (1993) give lifting guidelines of 21–23% of uphill treadmill aerobic capacity or 28–29% of bicycle aerobic capacity. Note that lifting has static as well as dynamic components.

For shorter or longer periods, see Figure 2.27. Kodak recommends 33% for an 8-h shift, 30.5% for a 10-h shift, and 28% for a 12-h shift (Kodak, 1986; their Figures 11.1 and 14.1). Mital et al. (1993) reduce their 28–29% for bicycle capacity for 8 h to 23–24% for 12 h. Mital et al. (1994) reported that workers in an air-cargo firm's package handling section, hired for only a 2-h shift, worked at 43–50% of their maximum capacity.

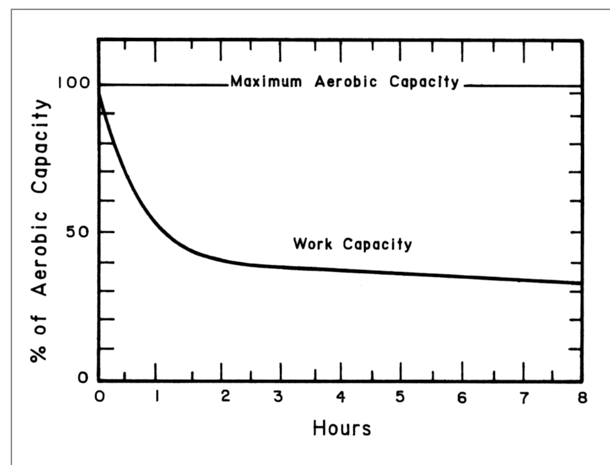
Assuming you wish to exclude only a small percentage of the population, the above criteria are about 350 W, 5 kcal/min, and 100–120 heartbeats/min. Wisner (1989) states, "It is more or less universally admitted that heartbeat rates should not exceed 110 beats/min during the working day. During more intensive work periods, 130 beats/min should not be exceeded." Kroemer and Grandjean (1997) give, for extended periods of work, a maximum of 35 beats/min over resting level.

The fact that people can work hard does not mean they should. High-metabolic rate jobs are prime candidates for mechanization. After all, although scientists may be interested in physiology, engineers should be interested in productivity.

Reduce cardiovascular stress with both engineering and administrative solutions.

FIGURE 2.27

Aerobic work capacity declines with working time.



The primary engineering solution is to use a motor. For material handling, consider the use of forklifts, hoists, and powered conveyors. Workers should slide rather than lift objects (horizontal transfer rather than vertical transfer); lower objects instead of lifting them; use wheeled transfer (carts and dollies) instead of carrying loads; and use powered handtools. Balancers and manipulators can reduce static load. See Chapter 13.

Two administrative solutions are job rotation and part-time work. With job rotation, people periodically shift jobs during the day. With part-time work, the job is split among several people, each of whom works part of a shift. For example, Joe works for 4 h in the morning and Pete for 4 h in the afternoon. Or hire a large number of people so the entire task is done in part of a shift. For example, package handling for delivery services often is done in 2–3 h.

When setting work standards, industrial engineers usually add fatigue allowances. See Chapter 24.

6.3 Gender, age, and training effects.

6.3.1 Gender. Physical work has **gender effects** on performance. The average female has a $\dot{V}O_2$max 15–30% lower than that of males because of a higher percent of body fat and a lower hemoglobin level. Since fat tissue has little blood, blood volume for an adult male averages 75 mL/kg and 65 for a female (it is 60 for a child). For the same age and body weight, females have lung volumes about 10% lower than males. Females also have lower hemoglobin content than males (13.9 vs 15.3), lower hematocrit (42 vs 47), and lower arterial oxygen content (16.7 mL/100 mL vs 19.2). Therefore, for submaximal work (oxygen uptake of $<$1.5 L/min), females need 9 liters of cardiac output to transport 1 liter of oxygen, while males require only 8.

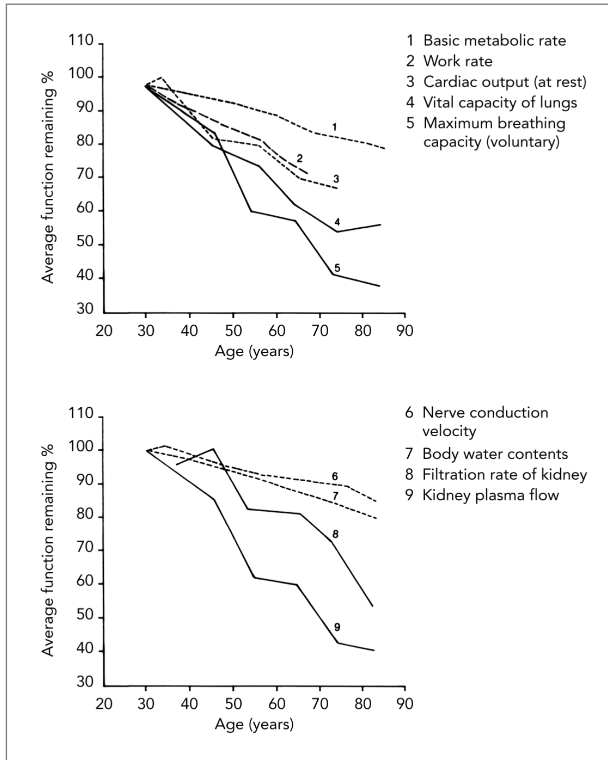
Although these figures help explain the difference in athletic performance, in industrial work, cardiovascular differences between average males and females should have little importance since most industrial tasks should not be designed to require maximum cardiovascular output.

6.3.2 Age. The body's physical performance peaks sometime around ages 25–30. After that, it is all "downhill" **(age effects).** See Figures 2.28 and 2.29.

For the specific index of $\dot{V}O_2$max, Dehn and Bruce (1972) reported, from three studies by others, declines of 1.04, .94, and .93 mL/kg-min/year; in their own study, the decline was 1.32 for habitually inactive males and .65 for active males. Astrand et al. (1973) reported declines for Swedish physical education instructors, over a 21-year period, of .64 for males and .44 for females. Illmarinen (1992) says that the decline in $\dot{V}O_2$max after ages 20–25 is 1–2%/year, but there are large individual variations.

FIGURE 2.28

Age effect on 9 physiological variables (Shock, 1962). Originally, we have surplus capacity but, as age increases, capacity eventually declines below requirements. (If you wish to calculate your life expectancy, select "Health Profile" at healthcentral.com.)



Bunc (1994) reports for European subjects:

$$\text{Male } \dot{V}O_2max = 57.7 - .404\ AGE \quad \text{Std. dev.} = 8.8 \text{ mL}$$
$$\text{Female } \dot{V}O_2max = 46.6 - .344\ AGE \quad \text{Std. dev.} = 6.4 \text{ mL}$$

where

$\dot{V}O_2max$ = Mean maximum oxygen uptake, mL/kg-min

AGE = Age, years

Schacherer et al. (1992) used the variables of gender, age, and fat to predict treadmill $\dot{V}O_2$max:

$$\text{Male } \dot{V}O_2max = 66.734 - .315\ AGE - .678\ PFAT$$
$$\text{Female } \dot{V}O_2max = 58.094 - .356\ AGE - .494\ PFAT$$

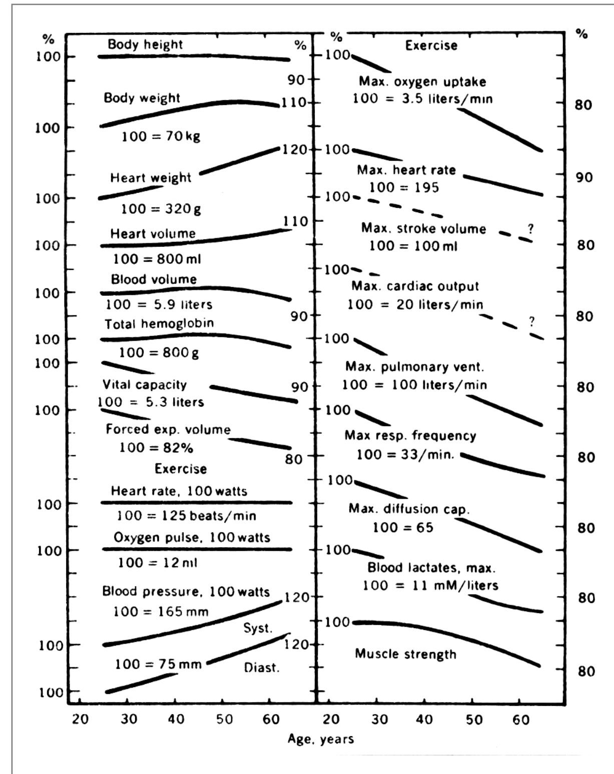
where

$PFAT$ = Body fat, percent

Jackson et al. (1992) emphasize that most of the decline is due to physical activity level and percent body fat, not aging. The aging effect was just .27 mL/kg-min/year.

FIGURE 2.29

Age effect on 21 physiological variables (Astrand and Rodahl, 1986). Heart rate, oxygen pulse, and blood pressure are reported for a total metabolism of 100 W.



$$\text{Male } \dot{V}O_2max = 47.9 - .27\ AGE + 3.41\ SRPA - .20\ PFAT - .09\ (SRPA)(PFAT)$$

where

$SRPA$ = Self-report of physical activity

What does this decline in oxygen uptake mean for jobs? In summary, cardiovascular capacity to perform light to moderate physically exhausting work is not grossly age-dependent up to age 65, although capacity for hard, exhausting work is strongly age-dependent, with maximum capacity between ages 20 and 25.

Intelligence has two aspects: fluid intelligence (understanding new, complex relationships; it begins declining around age 20) and crystallized intelligence (breadth and depth of knowledge; it continues to increase with age) (Mitzner et al., 2006).

6.3.3 Training. Fitness has dimensions of cardiovascular endurance, muscle strength, and flexibility. Specific training techniques are more appropriately found in books on kinesiology or athletics. However, two statements can be made: (1) For training the cardiovascular system for cardiac output, train with large-muscle groups and (2) for training the strength

of specific muscles, train the specific muscles. Some exercises strengthen weak muscles (work hardening, work conditioning), and other exercises stretch tight muscles and ligaments. If the work loads the muscles dynamically, relax and stretch them. If the work loads the muscles statically, the exercise should move them. Training variables include duration (repetitions) and intensity (weight, resistance).

7 RESPONSES TO MENTAL WORK

Kalsbeek (1968) proposed a heart rate variability (sinus arrhythmia) as an index of **mental load** (the load on the brain). Low variability went with high load. Sharit and Salvendy (1982) recommended the use of a "high pass filter" (the mean square successive difference) as it reduced the effect of the respiratory rate. Atsumi et al. (1993) systematically investigated the high pass filter idea. They determined it was best to use a sample of three successive beats:

$$RRV3 = \text{Sum}\,(RRI_i - RRI_m)^2/3$$

where

$RRV3$ = R to R variability of 3 beats, $(\text{ms})^2$

RRI_i = Individual R to R interval, ms

RRI_m = Mean R to R interval for 3 successive beats, ms

Table 2.9 gives an example calculation. The *RRV3* is calculated on successive triads of heartbeats, adding a new value and dropping the oldest value. The rate of change of a person is:

$$CRRV3 = (WRRV3 - RRRV3)/RRRV3$$

where

$CRRV3$ = Change in *RRV3,* proportion

$WRRV3$ = *RRV3* during work, $(\text{ms})^2$

$RRRV3$ = *RRV3* during rest, $(\text{ms})^2$

TABLE 2.9

Example calculation of RRV3.

HEART RATE, BEATS/MIN	RRI, MS	DEVIATION, MS	DEVIATION SQUARED $(\text{MS})^2$
91	659	–8	64
90	667	0	0
89	674	7	49
Mean	667		37.7

Atsumi, who worked for Toyota, used *RRV3* to evaluate the stress caused by operating various vehicle controls and displays during driving. Also see Yokoyama and Kamiya (2004).

8 FIT THE JOB TO THE PERSON

8.1 Variability. **Anthropometry,** from the Greek *anthropos* (man) and *metrein* (to measure), explains how people vary. **Ergonomics** also comes from the Greek: *erg* (work) and *nomos* (study of). A more formal definition of ergonomics is "a body of knowledge about human abilities, human limitations, and other human characteristics that are relevant to design."

This section will quantify human variability—put it into numbers. As Lord Kelvin said, "When you can measure what you are speaking about and express it in numbers, you know something about it; but when you cannot express it in numbers, your knowledge is of a meager and unsatisfactory kind."

People vary in many dimensions, for example, initiative, needs, dexterity, intelligence, visual acuity, imagination, determination, upper back strength, age, and leg length.

8.2 Selection versus job modification. Assume a heavy box is to be moved from point A to point B. Realizing that people vary, there are two basic strategies.

One alternative is to use **selection.** That is, from the population of workers, select a strong person. This alternative can be labeled *fit the person to the job.* The other alternative is **job modification** so that almost everyone can do it. This alternative can be labeled *fit the job to the person* or, more personally, *fitting the job to you.* In general, follow the second alternative, as the key to our improved living standard has been to challenge the environment and make the environment adjust to people rather than people adjust to the environment.

Given the decision to modify the job, one question is how much modification is necessary. That is, how much weight can employees lift? Or in other jobs, how far can they reach? How much space do they need?

8.3 Exclude as few as possible. Sometimes you need to design for a "special population." Kroemer (2005) explains how to design for "extraordinary populations"—extraordinary because of pregnancy, age (both children and the frail elderly), or sensory and motor impairments. For example, Morrissey (1998) gives recommendations for pregnant workers. (Pregnant women are like the canary in a mine. Whatever is affecting them also affects the workforce as a whole. They are the most vulnerable.) Design to **exclude few** so that as many people as possible can do

the job. Not only does this minimize the number of people excluded but also this design strategy tends to make the job easier—benefiting everyone, not just the person who might have been excluded.

The percent of people to exclude depends on the tradeoff between the seriousness of exclusion versus the cost of inclusion. The more serious the exclusion, the smaller the percent that are excluded. For example, if a button is outside the normal reach distance but the operator can reach it by stretching, it is not good but it may still be allowed. However, if a control requires more strength to operate than the operator can exert, that is not allowable.

The cost of including a larger percent of the population may be negligible or it may be high. In most applications a taller door (so people don't hit their heads) adds little expense; however, if the door is in a warship and weakens the structure, the cost may be high. In a fighter airplane, a taller, heavier pilot requires a larger cockpit, which increases the cross-section, which may incur severe performance penalties. Thus, most military organizations have a height restriction on fighter pilots.

Or consider the weight of a tote pan to be used in a factory. If the weight is so low that a very high percentage of the population can move it easily, more tote pans/day must be moved. That is, 50 pans each weighing 10 kg are moved instead of 40 pans each weighing 12.5 kg. The engineer will have to balance the benefits of less weight/pan versus more pans to move.

An excluded **population percentile** can be the upper, lower, or both upper and lower portions of the population. For example, a door might exclude the tallest .1% of the population. For manual dexterity, a test might exclude those with the least dexterity. For a factory job, a firm might exclude those who score low on an intelligence test (who can't learn how to do the job) *and* those who score high (who may become bored and quit).

Note that if the design is for the mean (50th percentile) instead of, for example, the 1st or 99th percentile, many are eliminated. This is most obvious for reach distances. For example, if a pedal is designed so the average person can barely reach it, 50% can't reach it. Because of the relatively low coefficient of variation of human dimensions (about 5%), however, accommodating more people doesn't require much change in physical dimensions.

8.4 Design recommendations. While this chapter focuses on dimensions of the human body, later chapters and the ERGO program give design data.

9 POPULATION VALUES

9.1 Dimensions. Figures 2.30, 2.31, and ERGO give technical descriptions for body postures. Designers should not design using their personal

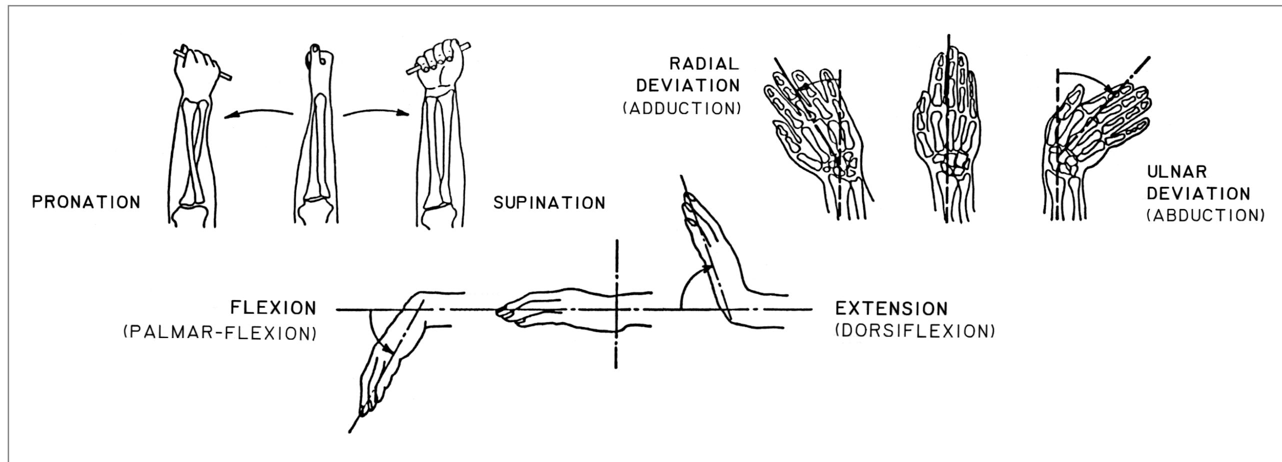
FIGURE 2.30

Terminology for body position descriptions.

PLANES	DESCRIPTION
Sagittal:	Divides body into left and right
■ Medial (Y):	Close to center
■ Lateral (+Y or –Y):	Away from medial on left (+Y) or right (–Y)
Coronal:	Divides body into front and back
■ Anterior (+X):	Front or ventral side
■ Posterior (–X):	Back or dorsal side
Transverse:	Divides body into top and bottom
■ Superior (+Z):	Closer to head
■ Inferior (–Z):	Closer to feet
LIMBS	
Proximal:	Closer to torso
Distal:	Farther from torso
WRIST/HAND MOTIONS	
Flexion (bend hand down; palm toward front of wrist) versus **extension** (bend hand up; palm toward back of wrist)	
Radial deviation (bend horizontal hand toward thumb) versus **ulnar deviation** (bend horizontal hand toward little finger)	
Pronation (rotation toward palm down) versus **supination** (rotation toward palm up)	

FIGURE 2.31

Terminology for hand movements and positions. Radial/ulnar deviation (radial toward the thumb, ulnar toward the little finger) and flexion/extension (flexion toward the palm, extension toward the back of the hand) occur in the wrist joint. Pronation/supination is a function of the radius rotating around the ulna in the forearm. Pronation is "thumbs down"; supination is "thumbs up."



dimensions or capabilities. Only slightly better is designing using the dimensions/capabilities of the people in the designer's department; although using a variety of people gives some variability, mean and variability of fellow engineers is unlikely to be the mean and variability of users. Thus, the first step is to define the user population. The focus of this book is on the individual at work. See Kroemer et al. (2001) for a detailed discussion of children and of seniors. Pheasant (1996) has tables for infants and children of various ages as well as tables for adults from England and other countries.

Chaffin and Faraway (2000), in a study of vehicles, showed that movement of the shoulder and torso can have great effects on reach distances; the following data do not consider shoulder and torso movements.

Table 2.10 gives some useful physical dimensions of the nude U. S. adult civilian population (Kroemer et al., 1994). The data were gathered in 1988 using U. S. Army personnel (Gordon et al., 1989).

Marras and Kim's (1993) data on Midwestern U. S. industrial workers (384 males, 124 females) showed that the army data were a good representation of the industrial workforce except for weight and abdominal dimensions. Mean male weight was 182.3 lbs (versus 173.0 for the army); mean female weight was 139.2 lbs (versus 136.7). For adjustment of nude data, they recommend:

- Shoe height adds 1 in. (2.5 cm) for males and .6 in. (1.5 cm) for females.
- Clothing increases torso breadths by .3 in. (.8 cm).
- Clothing increases torso circumferences by .6 in. (1.5 cm).
- Shoes add 2.0 lb (.9 kg) of weight.
- Clothing (except shoes) adds 1.0 lb (.45 kg) of weight.

Annis and McConville (1996) add, for normal industrial clothing, 4.7 cm for stature, 1.9 cm for sitting height, and 3.4 cm for knee height. Add 6.5 cm for chest depth, 13.0 cm for forearm-forearm breadth, and 14.3 for hip breadth, sitting. Add 3.4 cm for foot length and 1.1 cm for foot breadth.

Females tend to be smaller than males. But, if you compare the 50th percentile male versus female in Table 2.10, the ratio is not constant for various dimensions; for sitting hip breadth, females are larger than males.

Military populations tend to be selected (young, healthy, fit), and so are biased estimators of the civilian population. Americans are clearly, on average, taller than Japanese and Chinese. That is, design for an American population may not be appropriate for a non-American population. However, the U. S. population certainly is not homogeneous. In addition to the male–female difference, there are ethnic differences (people of Swedish descent are taller than those of Mexican descent), racial differences (African Americans are taller than Asians; African Americans of a given stature have longer limbs than white Americans), occupational differences (farmers are stronger than bookkeepers), and so forth. Protective workers (e.g., firefighters, police, and guards) are taller and heavier than the general population (Hsiao et al., 2002). Naturally, adults differ from children. In addition, older (e.g., over 50) people tend to be weaker than those age 30; after

TABLE 2.10

Body dimensions (cm) of nude U. S. adult civilians. Average height in the U. S. has been reasonably stable since the 1960s.

	PERCENTILES							
	5th		50th		95th		Standard Deviation	
	Fem.	Male	Fem.	Male	Fem.	Male	Fem.	Male
HEIGHTS (Above Floor)								
Stature (height)	152.78	164.69	162.94	175.58	173.73	186.65	6.36	6.68
Eye height	141.52	152.82	151.61	163.39	162.13	174.29	6.25	6.57
Shoulder (acromial) height	124.09	134.16	133.36	144.25	143.20	154.56	5.79	6.20
Elbow height	92.63	99.52	99.79	107.25	107.40	115.28	4.48	4.81
Wrist height	72.79	77.79	79.03	84.65	85.51	91.52	3.86	4.15
Crotch height	70.02	76.44	77.14	83.72	84.58	91.64	4.41	4.62
HEIGHTS (Above Seat)								
Height (sitting)	79.53	85.45	85.20	91.39	91.02	97.16	2.49	3.56
Eye height (sitting)	68.46	73.50	73.87	79.20	79.43	84.80	3.32	3.42
Shoulder (acromial) height (sitting)	50.91	54.85	55.55	59.78	60.36	64.63	2.86	2.96
Elbow height (sitting)	17.57	18.41	22.05	23.06	26.44	27.37	2.68	2.72
Thigh height (sitting)	14.04	14.86	15.89	16.82	18.02	18.99	1.21	1.26
Knee height (sitting)	47.40	51.44	51.54	55.88	56.02	60.57	2.63	2.79
Popliteal height (sitting)*	35.13	39.46	38.94	43.41	42.94	47.63	2.37	2.49
DEPTHS								
Forward (thumbtip) reach	67.67	73.92	73.46	80.08	79.67	86.70	3.64	3.92
Buttock-knee distance (sitting)	54.21	56.90	58.89	61.64	63.98	66.74	2.96	2.99
Buttock-popliteal distance (sitting)**	44.00	45.81	48.17	50.04	52.77	54.55	2.66	2.66
Elbow-fingertip distance	40.62	44.79	44.29	48.40	48.25	52.42	2.34	2.33
Chest depth	20.86	20.96	23.94	24.32	27.78	28.04	2.11	2.15
BREADTHS								
Forearm-forearm breadth	41.47	47.74	46.85	54.61	52.84	62.06	3.47	4.36
Hip breadth (sitting)	34.25	32.87	38.45	36.68	43.22	41.16	2.72	2.52
HEAD DIMENSIONS								
Head circumference	52.25	54.27	54.62	56.77	57.05	59.35	1.46	1.54
Head breadth	13.66	14.31	14.44	15.17	15.27	16.08	0.49	0.54
Interpupillary breadth	5.66	5.88	6.23	6.47	6.85	7.10	0.36	0.37
FOOT DIMENSIONS								
Foot length	22.44	24.88	24.44	26.97	26.46	29.20	1.22	1.31
Foot breadth	8.16	9.23	8.97	10.06	9.78	10.95	0.49	0.53
Lateral malleolus height	5.23	5.84	6.06	6.71	6.97	7.64	0.53	0.55
HAND DIMENSIONS								
Circumference, metacarpal	17.25	19.85	18.62	21.38	20.03	23.03	0.85	0.97
Hand length	16.50	17.87	18.05	19.38	19.69	21.06	0.97	0.98
Hand breadth, metacarpal	7.34	8.36	7.94	9.04	8.56	9.76	0.38	0.42
Thumb breadth, interphalangeal	1.86	2.19	2.07	2.41	2.29	2.65	0.13	0.14
WEIGHT (kg)	39.2	57.7	62.01	78.49	84.8	99.3	13.8	12.6

**Underside of the thigh.*
***Rear of the calf.*

From *Ergonomics* by K. Kroemer et al., © 2001 by Prentice Hall. Reprinted with permission.

30, people even begin to shrink in height (due to changes in spinal disc thickness). In addition, clothing will increase many of the dimensions, especially with winter outdoor clothing.

The ERGO program includes tables for many countries giving 19 anthropometric dimensions. Data are available in metric or English units, depending on which units you select (left corner of toolbar). If you want the key ergo dimensions of *your* workers, measure their elbow height (standing or sitting, depending on their job).

A large part of the variation in human stature is in the length of the legs; the torso is relatively constant in height. There is a desire to predict various body dimensions from a person's height. Unfortunately, most body dimensions have coefficients of determination versus height of less than 50%—that is, the statistical relationship is poor. However, approximations sometimes may be useful. Annis and McConville (1996) give, for the ratio of the dimension to stature height, 128% for maximum overhead reach, 122% for fist height for overhead reach, 74% for kneeling height, and 64% for squatting height.

Note that because a person is tall does not mean that the person has high intelligence. A short person does not necessarily have low manual dexterity. That is, because a person is average in one characteristic does not mean the person is average in another characteristic—even if all the characteristics are dimensions. For example, a person who is at the 50th percentile in height may be 40% in reach distance and 75% in weight.

If only male anthropometric data for a population are available, the female dimensions can be estimated as 93% of the corresponding male dimensions; males and females differ primarily in leg length rather than torso or arm length (van Schoor and Konz, 1996; Annis, 1996). See Box 2.8 for a description of the "divine proportion."

Between species, however, there is a general relationship between size and shape—the **principle of similitude.** See Box 2.9 for the principle of similitude.

9.2 Strengths. On average, females have 63% of the isometric strength of males, but the ratio depends on part of the body (60% for the arms, 64% for the trunk, and 72% for the legs). For equal lean body weights, females average 90% of male strengths (Annis, 1996). The 63% value means that women are far more exposed to risk of injury when muscular work is required.

Strengths for a specific muscle group vary greatly. Expect the coefficient of variation (standard deviation/mean) to be 50% or more. Strengths are greatly affected by the limb (arm versus leg), by direction exerted, and, for arms, by whether it is the preferred hand. The average difference in muscular strength between symmetrical muscle groups is 5%–11%.

Table 2.2 gives arm strengths. Tables 14.1 and 14.8 give handgrip strengths, and Table 14.2 gives finger strengths. Figures 15.2 and 15.11 give leg strengths. Figure 2.24 shows the effect of age.

To summarize: (1) The leg is approximately 3 times stronger than the arm. (2) Direction is very important, with arm force at the nonoptimum angles being 50%–80% of the force at the optimum angle. (3) The nonpreferred arm averages 60%–150% of the strength of the preferred arm, depending on the angle and direction. (4) There seems to be no appreciable difference between the strength of the left and right legs.

9.3 Other characteristics.

9.3.1 Weight and center of mass. See Table 2.11. Kaleps et al. (1984) give mass distribution properties of the head.

9.3.2 Manual dexterity. In general, for "simple" tasks (such as manual handling), the range of performance from the least qualified to the most qualified is small (say 2); for the entire population the range might be 4 or 5. For complex tasks (such as computer programming), the performance range of those qualified for the job would be much larger (say 50).

9.3.3 Surface area. Body surface area from the DuBois formulas (based on 5 subjects) is:

$$DBSA = .007\,184\,(HT)^{.725}\,(WT)^{.425}$$

where

$DBSA$ = **DuBois surface area,** m^2

The Divine Proportion, 1.618 BOX **2.8**

One plus the quotients of adjacent terms of the Fibonacci sequence (1, 1, 2, 3, 5, 8, 13, 21, 34…) approach 1.618. For example, 21/34 = .6176 + 1 = 1.6176. This "divine proportion" (also called the golden section) occurs many times in nature. In human adults, it is the ratio of total stature/the belly button to floor, the ratio of hip to floor/knee to floor, and shoulder to fingertips/elbow to fingertips. It also is the ratio of each spiral's diameter in a nautilus and the ratio of spiral's diameter in heads of sunflower seeds. It is the ratio of line segments in a 5 pointed star and the number of female bees in a hive/number of male bees.

Principle of Similitude

BOX 2.9

The basic concept of the principle of similitude is that, due to the ratio of **surface area/volume,** for every volume, there is an optimum shape (Haldane, 1928).

- For a cylinder's (tube, pipe) ratio of surface area/volume (ignoring ends):
  $2\,(pi)\,rL/(pi)\,r^2\,L = 2/r = 4/d$ (1)
- For a sphere's ratio:
  $4\,(pi)\,r^2 \,/\, (4/3)(pi)\,r^3 = 3/r = 6/d$ (2)
- For a cube's ratio:
  $6L^2/L^3 = 6/L$ (3)

To minimize surface area/volume, use a sphere. Within a cylinder, sphere, or cube, smaller diameters have more area in proportion to volume. Greater areas maximize exchange with the "environment."

What if you scale a specific shape up or down? Consider a man 2 m tall. If you made him a giant of 20 m, then his weight would increase by 10 (for height) × 10 (for width) × 10 (for thickness) = 1000. However, his leg bone cross-section increases only by 10 × 10 = 100, so with every step, the stress on the leg is 10 times what it would be in a normal-size human. So, when he runs, his leg breaks! If trees increase in size, their limit is approximately 100 m, due to the stress of the wind on their increased surface area.

Consider the giant grasshoppers often found in grade D movies. Grasshoppers breathe through their skin. Giant grasshoppers would increase oxygen intake by the square and mass by the cube and so would die of oxygen starvation. Klieber's Rule, for a variety of animals, is that metabolic rate = k (body weight)$^{3/4}$. The exponent is 3/4, not 2/3, as larger animals have different shapes than smaller animals.

People living in cold climates tend to be "spherical," which minimizes their surface area-to-volume ratio. However, in the tropics you want to be more like a radiator than a boiler, so long arms and legs are good. Elephants increase their surface area through "fins"—commonly known as ears. Gloves (i.e., separate fingers) lose more heat than mittens, due to their greater surface area/volume. The surface area/volume of the hand as a whole is 1.1, but individual fingers have a surface area/volume of around 2.0 (Mignano and Konz, 1994).

From a biomechanics viewpoint, big people not only have larger muscles (increasing by the cube) but also a longer moment arm (length of arm or leg), and so they can exert much more force or torque than small people.

For buildings occupied by people, the sphere is not generally used, even though it minimizes surface area in relation to volume. But the sphere is popular for storage of liquids and gases because it minimizes material cost and energy exchange with the environment. A popular compromise is a cylinder (e.g., for storage of pressurized gas). A dome minimizes material use for volume enclosed and strongly resists external pressure (although weaker for internal pressure); thus, it finds applications in military bunkers and igloos.

The cube is an efficient enclosure for cartons and boxes.

The shape used for industrial buildings is the square or rectangle with a wall height of about 15 feet (low bay) or about 30 feet (high bay). For heating and ventilating ducts, for the same air flow, round ducts have less perimeter than rectangular ducts; this results in less friction (i.e., smaller fans and thus lower energy costs) and heat transfer to the environment.

See Hanna and Konz (2004) for a more extensive discussion of surface area/volume and of perimeter/area.

HT = Height, cm
WT = Weight, kg

Mitchell et al. (1971) recommend a corrected formula (based on an improved measurement technique and 16 subjects):

$$SA = .208 + .945\,DBSA \text{ or}$$
$$= .208 + .006\,789\,(HT)^{.725}\,(WT)^{.425}$$

where

SA = surface area, m^2
$DBSA$ = DuBois surface area, m^2

The total body area can be apportioned into two arms and hands = 18.1% (hands 5.1% and arms 13.0%), the two legs and feet = 35.9% (legs 29.8%, feet 6.1%), the trunk = 37.5%, and head and neck = 8.5%. Some people remember the division by the "rule of 9s": head and neck = 9%, each hand–arm = 9%, each leg–foot = 18%, and trunk = 36%. Mignano and Konz (1994) reported one clenched fist is 1.6% of body surface area, one hand open with fingers joined is 2.7%, and one hand open with fingers spread is 3.1%.

9.3.4 Age. Box 2.10 discusses the effect of age.

9.3.5 Personal space. The space around an individual, called **personal space,** has four zones:

- Intimate (0–18 inches)

TABLE 2.11

Weight and center of mass for various body segments in adult males (Clauser et al., 1969).

BODY SEGMENT	WEIGHT OF SEGMENT/ TOTAL BODY WEIGHT		STANDARD ERROR	LOCATION OF CENTER OF MASS AS RATIO OF SEGMENT SIZE
Head		7.28	.16	.46 (top of head/ht of head) .40 (back of head/head length)
Trunk		50.70	.57	.38 (suprastern/trunk length)
Hand	0.65		.02	.18 (meta 3/styl-meta 3 length) .56 (med aspect/hand breadth)
Forearm	1.61		.04	.39 (radiale/rad-styl length) .49 (ant aspect/ap at cm)
Forearm + hand	2.27		.06	.63 (radiale/rad styl length) .52 (ant aspect/ap at cm)
Upper arm	2.63		.06	.51 (acrom/acrom-rad length) .51 (ant aspect/ap at cm)
Total arm	4.90		.09	.41 (acromion/arm length)
Both arms and hands		9.80		
Foot	1.47		.03	.45 (heel/foot length) .54 (sole/sphyrion height)
Calf	4.35		.10	.37 (tibiale/calf length) .42 (ant aspect/ap at cm)
Calf + foot	5.82		.12	.47 (tibiale/tibiale height) .33 (ant aspect/ap at cm)
Thigh	10.27		.23	.37 (trochanterion/thigh length) .53 (ant aspect/ap at cm)
Total leg	16.10		.26	.38 (troc/trochanteric height) .63 (ant aspect/ap at cm)
Both legs and feet		32.20 99.98		

An improved estimate can be made for some segments using the following equations where X is total body weight, kg:

SEGMENT	EQUATION	STANDARD ERROR
Trunk	$.551\,X - 2.837$	1.33
Head and trunk	$.580\,X + .009$	1.36
Total arm	$.047\,X + .132$	.23
Upper arm	$.030\,X - .238$	.14
Thigh	$.120\,X - 1.123$	.54
Foot	$.009\,X + .369$	.06

- Personal (18–48 inches)
- Social (4–12 ft)
- Public (>12 ft)

The exact boundaries vary with nationalities, gender (females are comfortable with smaller zones), and how well you know the other person. A related concept is territoriality (from animals who mark out their territory); personal space is a temporary rather than long-term occupancy of space. Thus, the amount of space required for groups of individuals depends not only on the physical size of the individuals but, perhaps more important, on their personal space and territory.

9.3.6 Aisles/corridors and doors. Aisle width depends upon whether the aisle is for people only or for people plus vehicles (Hanna and Konz, 2004). For one-way traffic and people only, 3 ft is a minimum. Use 6 ft if there is a door opening *into* the aisle from one side; use 8 ft if doors open into the aisle from both sides. For two-way traffic, double the dimensions. If doors open *from* the aisle into individual

Age of Workforce — BOX 2.10

Life expectancy (and the number of older people) has been going up for 300 years. But the decline in the number of young people is something new. The replacement birth rate is 2.1/woman (the extra .1 allows for deaths before child bearing). In 2000, it was 1.3 in both Japan and Germany; rates are similar in most of Europe. The U. S. rate is 2.1.

Thus, the workers will have to come from immigration and/or people working longer. Working longer could be more hours/year or more years/lifetime. Both seem to be occurring. The more hours/year is occurring especially in the managerial and professional workforce. The more years/lifetime, contrasted with the desire of some to retire "early," has resulted in a blurring of the traditional retirement age of 65. Some people retire before 65 and some work into their 70s—especially in part-time work. Thus, ergonomists will have to consider older workers in their job designs.

offices, use 6 ft. Aisles for people only (such as in offices) need not be straight; aisles for vehicles plus people should be straight.

Corridors are aisles with walls. Because people can step outside of aisles to avoid oncoming traffic, aisles can be narrower than corridors. Shoulder width is the key factor. See Table 2.12.

TABLE 2.12

Recommended corridor widths (inches) for people-only traffic.

NUMBER OF PEOPLE	SITUATION	MINIMUM	BETTER
1	Avoid touching equipment or hitting switches	20	24
2	Passing one person standing with back to wall	30	36
3	All three walking abreast in same direction	60	72

For doors, see Table 2.13. See Hanna and Konz (2004) for more on aisles and doors.

9.4 Anthropometric sources. For anthropometric techniques, see Kroemer et al. (1994) and Roebuck (1995). For data, see Gordon et al. (1989) and the ERGO program.

10 STATISTICAL CALCULATIONS

10.1 Normal distribution. Probably the most useful single descriptor is the population mean. Although many anthropometric characteristics are not precisely fitted by a normal distribution, the normal distribution will give answers that are close enough, and so the normal distribution is used. Assuming the normal distribution allows us further to state that the mean is equivalent to the 50th percentile. The normal distribution has the further useful characteristic of being symmetrical.

TABLE 2.13

Considerations in door design.

1. DOOR'S PURPOSE (e.g., security, fire, noise, climate control, insects)	2. CONDITIONS/USERS	3. SOLUTIONS
■ Door for people or vehicles or both? ■ One-way or two-way passage? Panic bar OK? ■ Will door be locked? How will door/lock be actuated/opened? ■ Will door slide or be hinged? If hinged and not locked, push plate may suffice. ■ How often will door be used (e.g., per 24 h)? ■ Are esthetics an issue?	■ Will the door be used by adults, children, aged? Design force for 1% female adult? ■ Will people in wheelchairs use the door? ■ What will be the posture of door user (e.g., seated, standing, holding objects)? ■ Will users wear gloves? ■ What is the lighting on the door? ■ Is the door indoors or outdoors?	■ Eliminate door. ■ Use a motorized door. Consider various triggers. ■ For manual opening, a lever is a better choice than a knob: a. Can be opened by small children (little force). b. Can be opened by elbow. A "return curve" on lever will reduce snagging.

The absolute variability of a population is given by the standard deviation, abbreviated S.D. The relative variability of a population is given by the coefficient of variation, which is the standard deviation/mean. For example, in Table 2.10 the mean height of females is 162.94 cm and the standard deviation is 6.36 cm. The coefficient of variation is 6.36/162.94 = 3.9%.

See Figure 2.32 for how to sketch the normal distribution of a characteristic. Table 16.6 is a table of the normal distribution. The coefficient of variation (COV) of "bony" dimensions, such as stature, is on the order of 3.5% to 5%. Then ± 2 sigma of the data for height is within ± 8% of the mean (Kreifeldt and Nah, 1996).

Assume you wish to calculate your percentile height. See Figure 2.32. If you are male and have a height of 170 cm, then you are 175.58 minus 170.0 = 5.58 cm below the mean. Next you will have to convert from cm to standard units. The conversion factor is 1 standard deviation = 6.68 cm, so you are 5.58/6.68 = .84 standard units below average in height. From a table of the normal distribution, this is the 20th percentile. That is, 20% of the population is shorter than you and 80% of the population is taller than you.

Assume you wish to calculate the 99th percentile of the male population (that is, you are going to exclude the largest 1% of the population). Then, from a normal table, 99% is 2.33 standard deviations above the mean. Converting from standard units to cm makes the distance above the mean equal to 2.33 (6.68) = 15.6 cm. Adding this to 175.58 gives 191.2 cm. If you wish to calculate the 1st percentile, subtract 15.6 from 175.58 to get 159.98 cm.

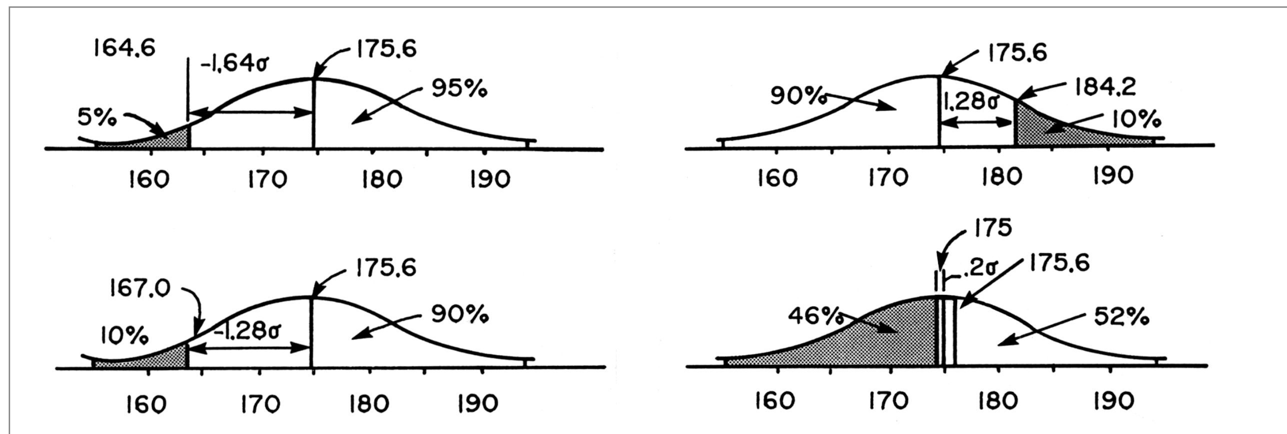
10.2 Designing for a population/person.

Assume you wish to design a workstation, a handtool, gloves, or whatever. There are a number of steps.

10.2.1 Population or person? Are you going to design for Joe Velasquez, who works the second shift, or for all the people presently on the second shift, or all the people on all shifts, or all people who might

FIGURE 2.32

Normal distribution of male stature height. From Table 2.10, the mean is 176.6 cm with std. deviation = 6.7 cm. Using the normal curve (discussed numerically in Table 16.6):



(1) Put the mean at 175.6.
(2) Draw the curve concave downward between the mean and ±1 standard deviation; that is, 175.6 – 6.7 = 168.9 and 175.6 + 6.7 = 182.3. These are the inflection points of the curve.
(3) Draw the curve upward outside this range.
(4) Have the curve approach the axis at the mean ±3 standard deviations; that is, at 175.6 + 20.1 = 155.5 and 175.6 + 20.1 = 195.7.

For the vertical scale, if the height of the mean is 1.0, then the height of the curve at ±1 standard deviation = .58, at ±2 standard deviations = .12 and at ±3 standard deviations = .01.

The 5th percentile height is 175.6 – 1.64 (6.7) = 164.6. The 10th percentile height is 175.6 – 1.28 (6.7) = 167.0. The 90th percentile height is 175.6 + 1.28 (6.7) = 182.2.

If you wish to determine what percentile is below 175 cm, this is 175 – 175.6 = –0.6 cm/6.7 cm/S. D. = .09 S. D. below the mean. From a table of the normal distribution, 46% of the U. S. male population is below 175 cm.

ever work at your facility, or all people who might work for your company anywhere in the world? Note that even if you design specifically for Joe, Joe may put on weight and no longer fit your design.

If you design for a population, which population will you use? What percentiles will you include (see Section 14 in Chapter 11)? Computerized databases (such as with ERGO) give data for different populations. There are many computer programs now available to show the designer the consequences (e.g., vision, reach, access) of various decisions. Some programs are COMBIMAN, CREW CHIEF, and JACK. Cardboard mock-ups are another alternative.

Designing for a specific individual usually is done through equipment adjustability. Conveyor height can be adjusted by turning screws on the conveyor legs. Chairs can be adjusted in height.

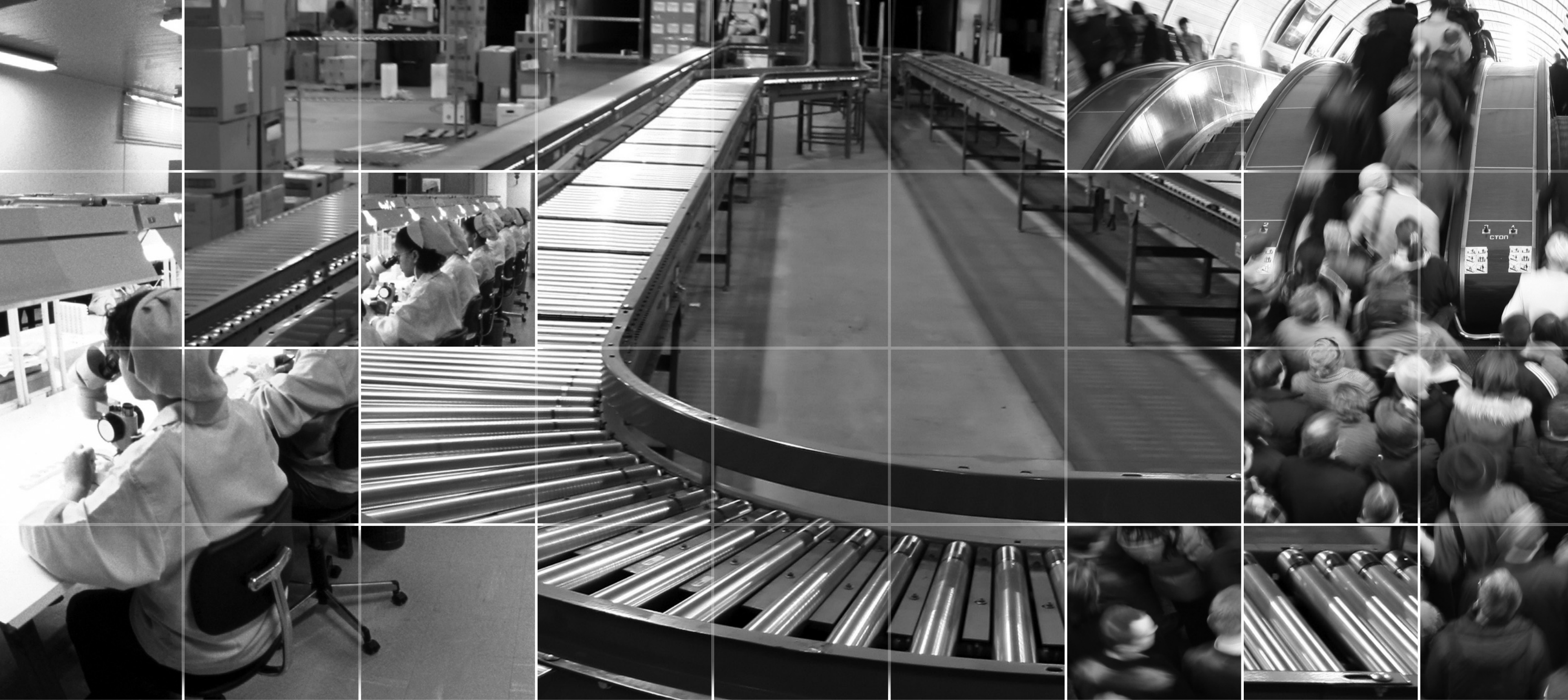
The adjustment may not be continuous; there may be discrete sizes. For example, clothing often comes in a variety of sizes. Sometimes the device sizes may adjust automatically (clothing in which "one size fits all"); one-size-fits-all tends to yield lower manufacturing and inventory costs but relatively poor fit. Although salespeople emphasize "ease of adjustment," it may not be important if the adjustment is made rarely.

10.2.2 Sizes. The number of sizes needed varies with several factors. *First,* how much does the population vary along the relevant dimension? For example, for shoes, feet may vary in length from 21 cm (1st percentile) to 29 cm (99th percentile). *Second,* how well can a specific size fit part of the population? Sizes near the mean will fit better; sizes at the extreme will fit less well. Also, how much mismatch is acceptable at a given size? For example, a foot 25 cm long might be fitted only by a shoe from 25 to 26 cm in length. If a greater mismatch is accepted, fewer sizes are needed. *Third,* how many dimensions are relevant? For shoes, width should be considered as well as length. The effect of additional dimensions depends upon the correlation between dimensions. That is, in cases where more than one dimension is relevant (such as clothing design, cockpit design), it is important to realize that a person who is 90% in one dimension (such as shoulder height) is unlikely to be 90% in another dimension (such as hip breadth); that is, the correlation is not 1.0. Hudson et al. (1998) comment on a technique (principal components analysis) to use in such cases.

In many cases, sizes and adjustability interact. Adjustability reduces the number of sizes needed; sizes reduce the needed adjustment range.

Review Questions

1. Where in the body do you have each of the following types of joints: ball and socket, hinge, pivot, and fixed?
2. What is a bursa?
3. Why is a prolapsed disc bad?
4. Sketch a 1st-, 2nd-, and 3rd-class lever for the human body.
5. Briefly describe how an electromyogram is obtained.
6. Sketch a schematic of the cardiovascular system, showing pulmonary and systemic circulation. Identify input and output of the following to the blood: oxygen, carbon dioxide, nutrients, and metabolic wastes.
7. Oxygen supply to a muscle is adjusted in what five ways?
8. List four ways by which heart rate can be measured.
9. Define cardiac output using a formula.
10. What is A–V differential?
11. Discuss the effect of age on the ability to do work.
12. What can you use as an index of mental load?
13. Briefly describe how HDL and LDL cholesterol work.
14. If you design a footpedal for the distance an average person can reach, what percent of the population will not be able to reach the pedal?
15. Contrast the two opposing strategies of selection and job design.
16. Discuss what percentage of the employees you would exclude from a manual material handling job.
17. If King Kong (the giant gorilla) had really lived, why would he have had to be hollow?
18. Design a tote pan that 95% of the employees can lift. Assume the mean for what a person can lift is 20 kg and 1 standard deviation is 5 kg.
19. Select another person in your class. How would you design that person's office workstation so the person's elbow is even with the bottom of the keys? Would your design change if the workstation were used on two shifts?
20. How is the Fibonacci value of 1.618 calculated?



3 CRITERIA

Overview

Work design requires a tradeoff of multiple criteria. The criteria are vague, and no explicit tradeoff equations are available. Six design criteria are given.

CHAPTER TOPICS

1 Organizations
2 Employees
3 Work Design Criteria

Key Concepts

Americans with Disabilities Act (ADA) (1.2)
criteria of job design (3.2)
enlargement/enrichment (2.3.3)
foundations of job design (3.1)
goals (1.1)
knowledge-based pay (2.3.3)
limits (restraints) (1.2)
machines as slaves (3.2)
needs, Maslow's hierarchy (2.2)

1 ORGANIZATIONS

1.1 Goals. Organization **goals** include survival and growth, among others. *Survival* is the first rule of any organism, whether bacterium, insect, human, corporation, or state. Carrying the analogy further, the organism must have sufficient nutrition. To an organization, money is the food. A surplus of income over outgo (called profits in capitalist countries and net favorable balance in socialist countries) is necessary in the long run. In the short run, a "diet" will not kill the patient, if the diet is not too severe or prolonged. Normally, organizations set prices at a level that more than covers costs. If the price charged is higher than the market can bear or than the government permits, either costs must be reduced or starvation begins. One exception is transfusions of public funds; this, in effect, has the taxpayer (a nonuser of the goods or services) pay some of the cost of the goods or services.

Growth is the second rule of an organism. Biological organisms, however, mature, stop growth, and die. Social organisms, such as auto manufacturers, universities, hospitals, and governments, are composed of "replaceable parts" and attempt to grow, grow, grow. Isn't a university with 15,000 students better than one with 7,000? Isn't a firm with 20,000 employees better than one with 10,000? Isn't a hospital with 500 employees better than one with 250? Isn't a bureau with 1,000 employees better than one with 500?

Although some may not believe that bigger is better, more employees do give more power, prestige, status, and income to higher managers of an organization than do smaller numbers. Since the higher managers set the organization's goals, their rewards are what count. Thus, number of employees is an important managerial criterion. Although this is not even admitted to exist as a criterion, it is a rare manager who would not prefer to supervise 2,000 rather than 1,000.

In the United States, a publicly proclaimed goal is a larger net income; profits of $1,000,000 are considered better than profits of $200,000. A more sophisticated criterion is net income/assets; return on investment of 10% is better than return of 5%. See Table 4.5 for returns on investment of some firms.

1.2 Limits. There are often **limits** (external **restraints**) imposed by society (usually governments and unions; see Box 3.1) but sometimes by public opinion or religious/moral values. The public influences and changes decisions through laws concerning pollution, safety, or other issues. These restraints can be quite different in developed and developing countries; they can be quite different in Judeo-Christian, Moslem, and Buddhist countries; and they can be quite different in capitalist and socialist countries.

Regulations (and enforcement) can be quite different concerning threshold limit values for toxic compounds. Environmental regulations can vary greatly, as do wage and employment regulations.

Japan provides an example of a religious/moral limit. Many of the major firms (although not the small firms) still have a "lifetime" employment policy. Since labor is considered a fixed cost, there is tremendous pressure to continue producing product no matter what the price at which it can be sold. For example, as long as a car can be sold for a price exceeding the cost of purchased components, it will be cheaper to make it than not to make it. Finding a local market may be a problem, so the Japanese export. Thus, prices in Japan often are considerably higher for products made in Japan than for the same product exported to other countries. Maintaining employment is a higher priority than profits to Japanese firms.

2 EMPLOYEES

The organizational goals are affected by the goals of the employees. These goals are divided into physiological and psychological–social.

2.1 Physiological. Employees naturally want to work with the least stress.

2.2 Psychological–social. The adaptation of **Maslow's hierarchy of needs** in Figure 3.1 gives perspective to this concept. Maslow proposed a hierarchy of individual needs. **Physical needs,** at the lowest level, concern basics such as the need for food, shelter, and health. Once these physical needs have been satisfied, the second level of needs, **security (safety) needs,** becomes important. In job terms, security needs might be having seniority on a job or having a supervisor who doesn't threaten you. The third level, **social needs,** becomes important after the second level is satisfied. Work examples of social needs are having a job with status, a job you enjoy, a job with friendly coworkers, or working in a physical location in which you can talk with fellow workers while working.

The fourth level, **ego (esteem) needs,** concerns challenge and achievement. Does the job challenge you? Do you have a feeling of contribution, or are you "just a number"? The fifth level, **self-actualization,** concerns personal fulfillment and realization of potential. For example, is the organization "serving humanity," or are you merely making common items such as soap, autos, or chairs? Satisfying the fifth level may call for a "missionary" type of endeavor such as ecology, religion, or its secular equivalent, politics. Some find it in teaching, music, or running their own businesses.