Physics of the Human Body

BIOLOGICAL AND MEDICAL PHYSICS, BIOMEDICAL ENGINEERING

The fields of biological and medical physics and biomedical engineering are broad, multidisciplinary and dynamic. They lie at the crossroads of frontier research in physics, biology, chemistry, and medicine. The Biological and Medical Physics, Biomedical Engineering Series is intended to be comprehensive, covering a broad range of topics important to the study of the physical, chemical and biological sciences. Its goal is to provide scientists and engineers with textbooks, monographs, and reference works to address the growing need for information.

Books in the series emphasize established and emergent areas of science including molecular, membrane, and mathematical biophysics; photosynthetic energy harvesting and conversion; information processing; physical principles of genetics; sensory communications; automata networks, neural networks, and cellular automata. Equally important will be coverage of applied aspects of biological and medical physics and biomedical engineering such as molecular electronic components and devices, biosensors, medicine, imaging, physical principles of renewable energy production, advanced prostheses, and environmental control and engineering.

Editor-in-Chief:

Elias Greenbaum, Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA

Editorial Board:

Masuo Aizawa, Department of Bioengineering, Tokyo Institute of Technology, Yokohama, Japan

Olaf S. Andersen, Department of Physiology, Biophysics and Molecular Medicine, Cornell University, New York, USA

Robert H. Austin, Department of Physics, Princeton University, Princeton, New Jersey, USA

James Barber, Department of Biochemistry, Imperial College of Science, Technology and Medicine, London, England

Howard C. Berg, Department of Molecular and Cellular Biology, Harvard University, Cambridge, Massachusetts, USA

Victor Bloomfield, Department of Biochemistry, University of Minnesota, St. Paul, Minnesota, USA

Robert Callender, Department of Biochemistry, Albert Einstein College of Medicine, Bronx, New York, USA

Britton Chance, University of Pennsylvania Department of Biochemistry/Biophysics Philadelphia, USA

Steven Chu, Lawrence Berkeley National Laboratory, Berkeley, California, USA

Louis J. DeFelice, Department of Pharmacology, Vanderbilt University, Nashville, Tennessee, USA

Johann Deisenhofer, Howard Hughes Medical Institute, The University of Texas, Dallas, Texas, USA

George Feher, Department of Physics, University of California, San Diego, La Jolla, California, USA

Hans Frauenfelder, Los Alamos National Laboratory, Los Alamos, New Mexico, USA

Ivar Giaever, Rensselaer Polytechnic Institute, Troy, NewYork, USA

Sol M. Gruner, Cornell University, Ithaca, New York, USA

Judith Herzfeld, Department of Chemistry, Brandeis University, Waltham, Massachusetts, USA

Mark S. Humayun, Doheny Eye Institute, Los Angeles, California, USA

Pierre Joliot, Institute de Biologie Physico-Chimique, Fondation Edmond de Rothschild, Paris, France

Lajos Keszthelyi, Institute of Biophysics, Hungarian Academy of Sciences, Szeged, Hungary

Robert S. Knox, Department of Physics and Astronomy, University of Rochester, Rochester, New York, USA

Aaron Lewis, Department of Applied Physics, Hebrew University, Jerusalem, Israel

Stuart M. Lindsay, Department of Physics and Astronomy, Arizona State University, Tempe, Arizona, USA

David Mauzerall, Rockefeller University, New York, New York, USA

Eugenie V. Mielczarek, Department of Physics and Astronomy, George Mason University, Fairfax, Virginia, USA

Markolf Niemz, Medical Faculty Mannheim, University of Heidelberg, Mannheim, Germany

V. Adrian Parsegian, Physical Science Laboratory, National Institutes of Health, Bethesda, Maryland, USA

Linda S. Powers, University of Arizona, Tucson, Arizona, USA

Earl W. Prohofsky, Department of Physics, Purdue University, West Lafayette, Indiana, USA

Andrew Rubin, Department of Biophysics, Moscow State University, Moscow, Russia

Michael Seibert, National Renewable Energy Laboratory, Golden, Colorado, USA

David Thomas, Department of Biochemistry, University of Minnesota Medical School, Minneapolis, Minnesota, USA

More information about this series at http://www.springer.com/series/3740

Irving P. Herman

Physics of the Human Body

Second Edition

Springer

Irving P. Herman
Department of Applied Physics
and Applied Mathematics
Columbia University
New York, NY
USA

ISSN 1618-7210 ISSN 2197-5647 (electronic)
Biological and Medical Physics, Biomedical Engineering
ISBN 978-3-319-23930-9 ISBN 978-3-319-23932-3 (eBook)
DOI 10.1007/978-3-319-23932-3

Library of Congress Control Number: 2015951417

Springer Cham Heidelberg New York Dordrecht London
© Springer International Publishing Switzerland 2006, 2016
This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.
The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.
The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, express or implied, with respect to the material contained herein or for any errors or omissions that may have been made.

Printed on acid-free paper

Springer International Publishing AG Switzerland is part of Springer Science+Business Media (www.springer.com)

This book is dedicated to Daniel, Jonathan, and Janet, to Sandy Koufax, and to the life of Ron McNair

Preface to the Second Edition

Near the end of one of the most famous speeches in American history, Abraham Lincoln made reference to "government of the people, by the people, for the people" [5]. In a similar vein, a text about physics and the human body could cover "physics of the body, by the body, and for the body," but perhaps that would be too broad. Our main focus in this second edition is still the physics of the body, namely the physics of physiology, and the text is again largely organized by topics in physiology. There is still a strong emphasis on modeling physiology. As noted in the excellent book by Rideout [7], general modeling in physiology includes that of momentum (such as blood flow), mass (oxygen, carbon dioxide, and so on in the blood), energy (heat flow), and information (signals in nerves, hormones in the bloodstream) [7]. Models coupling multiple systems are also important. (After all, we are all strongly coupled multiple physiological systems, which are, of course, ultimately determined by physics.) We will still confine ourselves to the more physical and less chemical aspects of physiology modeling; chemical modeling is addressed well elsewhere [1, 2, 3, 4, 6, 7]. Within our focus of "physics of the body," we have enhanced the discussion of the physics of disease, aging, motion, and the structure and function of muscles, and now explore how balance, metabolism, and the circulatory system change during pregnancy and birth. The physics of the cross-cutting lifecycle events of pregnancy, injuries, diseases and disorders, aging, and dying transcend the topics of any single chapter. They are now overviewed in the new Appendix F; this appendix also describes how to locate discussions of these topics within the main text.

"Physics by the body" includes the physics of common locomotion and that during athletic events and collisions. These topics were addressed in several parts of the first edition, including many problems. They are now discussed in more detail in both the text and the problems. In particular, the physics of motion, kinesiology, and balance [8] are more directly discussed by the analysis of multisegment modeling and the expanded treatment of the physics of sports. A discussion of human performance of ordinary tasks and at the extremes of athletic competition also transcends the topics of any single chapter and couples many

of them, especially those addressing statics, motion, metabolism, breathing, and blood circulation. To help unify the discussion of athletics, Appendix G has been added to link relevant topics in these chapters and to unify references to different sports activities.

"Physics for the body" includes the physics of measurement analysis and diagnosis and the physics of treatment, much of which is called medical physics. The first edition had some discussion of measurements and diagnosis and essentially none concerning treatment. The presentation of measurement analysis included several methods and a bit about measurement results. A broad overview of this topic is now presented in the new Appendix H, which includes a locator describing where physics analysis of the body is described in the text and problems. Aside from the new brief discussion in Appendix H, treatment is still not addressed in this edition.

This text can still be adapted for use in either lower- or upper-level undergraduate courses, as well as for some low-level graduate courses. It can serve the needs of a primary text for an entire course or as a secondary source, such as through the use of individual chapters. Appendices F, G, and H unite the cross-cutting themes presented in several chapters, and can be used to guide discussion of these topics.

This edition includes numerous additional problems that address the material in the text and explore it in much more detail. Many additional solutions are now provided at the end of the book. The author strongly recommends that you at least peruse the content of the related problems at the end of the chapter when you read any section of the text (even if you do not plan on solving them) because many essential approaches and ideas are covered only in the problems.

Several excellent texts on related topics were cited in the previous edition. In particular, we note again several of the outstanding books describing mathematical models of physiology [1, 2, 3, 4, 6, 7], which are for the most part at a level more advanced than that of this text. Also, of more general interest is the recent "The Story of the Human Body" by Daniel E. Lieberman, which discusses the evolution of the human body and includes extraordinary insights into the structure and function of the bodies of modern-day humans.

The author is indebted to Julio Fernandez, Glenn Fleisig, Joel Gersten, Daniel Herman, Jonathan Herman, Ronald Koder, Jeffrey Kysar, David Lerner, Kristin Myers, Herman Pontzer, and Alejandro Tello, and many others for their comments, suggestions, and insights as he prepared this second edition, to the numerous students, including Sarah Beck, who found errors in the first edition, and to those who helped in preparing the first edition. He would also like to thank the Columbia University Library system for speedy retrieval of reference books and articles (and for letting the author renew books many, many times).

New York, NY Irving P. Herman
July 2015

References

1. E. Carson, C. Cobelli, *Modelling Methodology for Physiology and Medicine* (Academic, San Diego, 2001)
2. J.L. Hargrove, *Dynamic Modeling in the Health Sciences* (Springer, Berlin, 1998)
3. F.C. Hoppensteadt, C.S. Peskin, *Modeling and Simulation in Medicine and the Life Sciences*, 2nd edn. (Springer, Berlin, 2002) (First Edition from 1992 was called *Mathematics in Medicine and the Life Sciences*)
4. J. Keener, J. Sneyd (eds.), *Mathematical Physiology II: Systems Physiology*, 2nd edn. (Springer, Berlin, 2009)
5. A. Lincoln, *Lincoln: Speeches and Writings:* 1859–1865 (Library of America, New York, 2012)
6. J.T. Ottesen, M.S. Olufsen, J.K. Larsen (eds.), *Applied Mathematical Models in Human Physiology* (SIAM, Philadelphia, 2004)
7. V.C. Rideout, *Mathematical and Computer Modeling of Physiological Systems* (Prentice-Hall, Englewood Cliffs, 1991)
8. N. Hamilton, W. Weimar, K. Luttgens, *Kinesiology: Scientific Basis of Human Motion*, 12th edn. (McGraw-Hill, New York 2012)

Preface to the First Edition

Physics explains everything from the beginning to the end of any complete description of the human body. Such a comprehensive discussion should begin with the basic structure of matter, as explained by quantum mechanics—the physics at small dimensions, and end with the mechanics of human motion, the energetics of metabolism, the fluid dynamics of blood flow through vessels, the mechanisms for speaking and hearing, and the optical imaging system we call the eye. All of required combinations of atoms to form the complex molecules and organs of organisms that live and reproduce can be explained by quantum mechanics; however, such explanations can get pretty complex. The fields of chemistry and biology have been developed, in part, to explain the gap between the extremes—the microphysics and macrophysics of organisms such as the human body.

This book focuses mostly on the macrophysics end of the human body. We will assume that atoms form molecules that form cells that form organs. We want to understand the physics of human organs and of humans themselves. We will apply and somewhat extend freshman-level physics to see how the body works. In addition to applying physical concepts to the body, we will try to understand the body from a viewpoint that is more numerical than is often adopted in biological and medical presentations.

One way to characterize this text is by saying what it is and what it is not. It is certainly about the physics of the human body. It is not about human anatomy, although we will need to use some basic anatomical concepts. It is not about human physiology, although it can be called a book about the physics of physiology. It is not a monograph in biomedical engineering per se, although about half of this volume concerns biomechanics, one important area in biomedical engineering. Medical physics is more closely related to health physics, the use of ionizing radiation, imaging, and instrumentation than to the macrophysics of the body. Biophysics concerns how physics can be used to study biology and focuses much more on the molecular basis and the cellular basis than will we (see Appendix E). One could say that the physics of the human body is synonymous with understanding the human machine.

Our goal is to understand physical issues concerning the human body, in part by solving problems to further this understanding. The focus is not at all on learning and memorizing medical terminology. Still some very basic concepts in anatomy and physiology will be introduced and used. Several of the many excellent general anatomy and physiology texts are cited at the end of the chapter [11, 16, 21, 22, 23, 24, 25, 26, 27, 29].

One theme that runs throughout this text is developing and then using simple and subsequently more refined models of the macrophysics of the human body [7, 13, 15]. Physicists tend to model concepts in as simple terms as possible at first. For example, to zero order a physicist would model a cow as a sphere. (This is sometimes used as part of a joke.) We will get a bit more complex here, but not much more. Another theme is to address issues in human biology quantitatively that are often addressed only qualitatively. The call for more quantitative thinking in physiology by Burton in *Physiology by Numbers* [5] is much appreciated by the author. In addition, we will present real physiological data and tie them with quantitative analysis and modeling.

If there is an applied force, energy, fluid flow, a light ray, an electric current, or an electric or magnetic field associated with the body, we will call it physics and we will analyze it. We will tend to avoid topics that delve into more chemistry and biology issues, but will briefly address physical chemistry issues involving concentration gradients and such, as they relate to fluid exchange in capillaries and conduction in nerves. Although we emphasize the physics of the body over the instrumentation used to make physical measurements on the body and probe body function, such instrumentation is addressed as needed.

Our intent is to use basic physics and not to teach it, particularly from scratch. Many chapters include a brief review of the physics principles needed in that chapter and subsequent chapters. Some topics are developed a bit further, and some even a bit further—and these are identified as advanced topics. More detailed overviews are given for topics seldom covered in detail during a two-semester physics course, such as fluids (Chap. 7), acoustics (Chap. 10), and optics (Chap. 11) and for areas used in several contexts, such as harmonic motion (Chap. 3). Some differential and integral calculus is used. (Partial differentiation is used sparingly, and mostly in sections labeled as advanced topics.) A brief review of the solutions to the simple differential equations used here is presented in Appendix C to help students with a limited background in calculus.

We will start with a comparison of medical- and physics-type terminology in Chap. 1. The first chapter also includes a discussion of the "standard" human and introduces the concept of scaling relations. We can group the topics in subsequent 11 chapters into four areas in human body physics. (1) In Chaps. 2–5, the mechanics of the static body (Chap. 2) and the body in motion (Chap. 3) are analyzed and are then linked to the mechanical properties of the materials of the body (Chap. 4) and the body's motors: muscles (Chap. 5); these topics can be characterized as *Locomotion on Land*. (2) The second topic, *Energetics of the Body Metabolism*, is discussed in Chap. 6 and is needed to understand the discussions of body locomotion and function that precede and follow it. (3) Chapters 7–9 cover the *Locomotion of Humans in Fluids (other than on land) and the Motion of Fluids in*

Humans. Chapter 7 overviews the physics of fluids and addresses locomotion in water (swimming) and in air—above ground (at least, the prospect for human flying). Chapters 8 and 9 respectively cover the fluidics of blood (cardiovascular system) and air (respiratory system) in the body. (4) Chapter 10 explores the acoustics of sound waves in speaking and hearing. The optics of eyes and vision are investigated in Chap. 11. Basic electrical properties of the body are developed in Chap. 12, along with a brief description of the magnetic properties of the body. So these three chapters respectively address sound, electromagnetic, and electrical waves, which we can collectively call *Waves and Signals*. (The electromagnetic nature of light waves is not discussed in Chap. 11.)

Chapter 13 examines how the body automatically uses the basic engineering principle of feedback and control in regulating all aspects of function. The physics of sensation of three of the five senses are described: hearing, seeing, and touch—the last briefly in Chap. 2. Some connection is made between the physics of sensation, biochemistry of sensation, and perception (psychophysics) in Chap. 1. The sense of taste and smell are purely chemical, with little basis in physics (other than the chemistry of the molecular interactions in each being clear applications of physics), and are not covered—except for a brief discussion of the electrical properties of the taste and smell sensory neurons in Chap. 12. The emphasis throughout is on how physics can explain the functioning of the body under normal and unusual circumstances. We will concern ourselves with the human body with its common body coverings: footwear to minimize stress during movement (Chap. 4), clothes to regulate heat loss (Chap. 6), and corrective lenses to improve vision (Chap. 11).

The chapters are set more to address specific areas in physics rather than specific parts or systems in the body. It is difficult to construct chapters with clean divisions because different areas of physics are needed to understand many components of the body. For example, to understand the physics of the heart, you need to address its role in circulation (Chap. 8), the action of muscles (Chap. 5, which is more focused on skeletal muscle than the fairly similar cardiac muscle), and the electrical signals generated by the heart (Chap. 12).

This text concludes with five appendices. Appendix A overviews symbols and units, and references tables of units presented in the chapters. Appendix B lists the figures and tables that describe the main features of human anatomical and anthropometric information, which are used throughout this text. The types of differential equations used in the text are reviewed in Appendix C. These same differential equations are used throughout the text in mechanical, fluid flow, and electrical models; the connections between these models are made in Appendix D. Appendix E attempts to define the field of biophysics, and connects the contents of this text with this field.

This text has been developed from the author's lecture notes developed for the course *Physics of the Human Body*, which is a "professional-level" restricted elective course he developed taken mostly by first- and second-year undergraduates in the Columbia University Fu Foundation School of Engineering and Applied Science. This course was designed so it could be taken by all first-year students in

their second term (in conjunction with second-term physics and calculus). The author usually covers Chaps. 1–10 in some detail and Chaps. 11–13 in less detail in a full semester.

Courses at different levels, including mid-level and upper-level undergraduate courses, can be taught by purposely including or excluding more detailed and advanced topics in the text and problems. Depending of the level of desired depth, material in about half to all the chapters can be covered in one term.

This text can also be used as a companion volume in introductory physics courses, and assist premedical undergraduates in learning and reviewing physics. It can also serve as a text in introductory biomedical engineering or medical materials courses. Medical students interested in a more quantitative approach to physiology and those doing medical research may also appreciate the approaches adopted here.

Many problems are presented at the end of each chapter, ranging from simple to more advanced problems (the latter are denoted as such). Several problems have multiple parts, and only a few of these parts can be assigned. Answers to selected problems are given after the appendices.

Usually SI (MKS, m-kg-s) units are used; when more convenient, other metric units, including CGS (cm-g-s) units and mixed metric units are used. English FPS (ft-lb-s) units are sometimes purposely used to make a connection to the real world (at least in countries such as the USA and the UK). For example, it would be strange to hear a baseball announcer say, "This pitcher is really throwing some heat. The radar gun clocked his last pitch at 43.8 m/s (or 158 km/h)," as opposed to 98 mph. It would be stranger to hear a football (i.e., American football) announcer say, "They have first (down) and 9.144 to go," meaning 9.144 m instead of 10 yd. Similarly, it would be strange to discuss the physics of the body in these sports, such as in throwing a baseball, in any but the usual units. Angles are given in radians, except when using degrees gives a more physical picture.

Several excellent texts cover material that overlaps topics covered here, each with a different focus. They are magnificent resources in their own right. *Physics of the Body* by Cameron, Skofronick, and Grant [6] spans most of the topics in this book and provides excellent physical insight. It is at a level of physics that is lower than that used here and derives and presents fewer of the equations necessary for a more rigorous treatment, but it provides a very good basic background in human physiology for nonexperts. In a way, the emphasis of *The Human Machine* by Alexander [2] coincides with ours, but, again, the explanations are more qualitative. The mode of physical thinking it presents is impressive. *Physics with Examples from Medicine and Biology* by Benedek and Villars [3] is a series of three comprehensive introductory physics texts in which excellent examples and problems have been chosen concerning the physics of the body. The authors have taken several fairly complex topics and have made them utterly understandable. Many other first-year general physics texts commonly used nowadays have several examples and chapter problems dealing with the body. *Intermediate Physics for Medicine and Biology* by Hobbie [14] is a more advanced text that emphasizes both physics and physical chemistry. *Medical Physics and Biomedical Engineering* by Brown et al. [4] is a bit more advanced and focuses also on classic areas in medical

physics, such as radioactivity and instrumentation. Many of the illustrative problems concerning human biology and related topics have been collected in the beautiful books: *Biomedical Applications of Introductory Physics* by Tuszynski and Dixon [28], *Physics in Biology and Medicine* by Davidovits [9], *Biophysics Problems: A Textbook with Answers* by Maróti, Berkes, and Tölgyesi [17], *Physics for the Biological Sciences: A Topical Approach to Biophysical Concepts* by Hallett, Stinson, and Speight [12], and *Topics in Classical Biophysics* by Metcalf [18]. Many of the issues in exercise physiology, such as the metabolism during sporting activities, are described in elementary terms in *Fox's Physiological Basis for Exercise and Sport* by Foss and Keteyian [10] and *Physiology of Sport and Exercise* by Wilmore and Costill [30]. *Basic Biomechanics of the Musculoskeletal System*, edited by Nordin and Frankel [20] is a comprehensive and clear overview of the biomechanics of structures, joints, and motion. The applications of physics at a more molecular and cellular level, more in the classical domain of biophysics, are described in *Biophysics: An Introduction*, by Cotterill [8] and *Biological Physics: Energy, Information* by Nelson [19]. The more general application of physics to animals is addressed in the exciting and very comprehensive book *Zoological Physics: Quantitative Models, Body Design, Actions and Physical Limitations in Animals* by Ahlborn [1]. All of these texts are highly recommended for more details. They, along with the anatomy and physiology texts cited earlier, have contributed to the preparation of this text.

The author thanks the many people who have made valuable comments contributing to this book, including Marlene Arbo, Gerard Ateshian, Sarbajit Benerjee, Alex Breskin, Bill Burdick, Yi-Ting Chiang, Kevin Costa, Ted Ducas, Yossi Goffer, Daniel Herman, Jonathan Herman, Steven Heymsfield, Jeffrey Holmes, Mark Langill, Barclay Morrison III, Elizabeth Olson, Thomas Pedersen, Harry Radousky, Paul Sajda, Michael Sheetz, and Samuel Sia. He would also like to thank the Columbia University Library system.

This author began writing this text when he was a Lady Davis Scholar on sabbatical at Hebrew University in Jerusalem as a guest of Uri Banin, and he gratefully acknowledges this support.

New York, NY Irving P. Herman
November 2006

References

1. B.K. Ahlborn: *Zoological Physics: Quantitative Models, Body Design, Actions and Physical Limitations in Animals* (Springer, Berlin Heidelberg New York 2004)
2. R. McNeill Alexander: *The Human Machine* (Columbia University Press, New York 1992)
3. G.B. Benedek, F.M.H. Villars: *Physics with Illustrative Examples from Medicine and Biology*, Three volumes, 2nd edn (AIP/Springer, New York/Berlin Heidelberg New York 2000)
4. B.H. Brown, R.H. Smallwood, D.C. Barber, P.V. Lawford, D.R. Hose: *Medical Physics and Biomedical Engineering* (Institute of Physics, Philadelphia 1999)

5. R.F. Burton: *Physiology by Numbers: An Encouragement to Quantitative Thinking* (Cambridge University Press, Cambridge 1994)
6. J.R. Cameron, J.G Skofronick, R. Grant: *Physics of the Body*, 2nd edn (Medical Physics, Madison, WI 1999)
7. E. Carson, C. Cobelli: *Modelling Methodology for Physiology and Medicine* (Academic, San Diego 2001)
8. R.M.J. Cotterill: *Biophysics: An Introduction* (Wiley, New York 2002)
9. P. Davidovits: *Physics in Biology and Medicine*, 2nd edn (Elsevier/Academic, San Diego 2001)
10. M.L. Foss, S.J. Keteyian: *Fox's Physiological Basis for Exercise and Sport*, 6th edn (McGraw-Hill, Boston 1998)
11. A.C. Guyton, J.E. Hall: *Human Physiology and Mechanisms of Disease*, 6th edn (Saunders, Philadelphia 1997)
12. F.R. Hallett, R.H. Stinson, P.A. Speight: *Physics for the Biological Sciences: A Topical Approach to Biophysical Concepts* (Methuen/Chapman & Hall, Toronto 1982)
13. J.L. Hargrove: *Dynamic Modeling in the Health Sciences* (Springer, Berlin Heidelberg New York 1998)
14. R.K. Hobbie: *Intermediate Physics for Medicine and Biology*, 3rd edn (AIP, New York 1997)
15. F.C. Hoppensteadt, C.S. Peskin: *Modeling and Simulation in Medicine and the Life Sciences*, 2nd edn (Springer, Berlin Heidelberg New York 2002) (First Edition from 1992 was called *Mathematics in Medicine and the Life Sciences*)
16. E.N. Marieb: *Human Anatomy & Physiology*, 5th edn (Benjamin Cummings, San Francisco 2001)
17. P. Maróti, L. Berkes, F. Tölgyesi: *Biophysics Problems: A Textbook with Answers* (Akadémiai, Budapest 1998)
18. H.J. Metcalf: *Topics in Classical Biophysics* (Prentice-Hall, Englewood Cliffs, NJ 1980)
19. P. Nelson: *Biological Physics: Energy, Information, Life* (Freeman, New York 2003)
20. M. Nordin, V.H. Frankel (eds.): *Basic Biomechanics of the Musculoskeletal System*, 3rd edn (Lippincott Williams & Wilkins, Philadelphia 2001)
21. P.E. Pack: *Anatomy and Physiology* (Cliff Notes, Lincoln, NE 1997)
22. H.D. Patton, A.F. Fuchs, B. Hille, A.M. Scher, R. Steiner (eds.): *Textbook of Physiology*, 21st edn (Saunders, Philadelphia 1989)
23. R.R. Seeley, T.D. Stephens, P. Tate: *Anatomy & Physiology*, 6th edn (McGraw-Hill, Boston 2003)
24. L. Sherwood: *Human Physiology: From Cells to Systems*, 5th edn (Thomson Brooks/Cole, Belmont, CA 2004)
25. D. Shier, J. Butler, R. Lewis, *Hole's Human Anatomy and Physiology*, 9th edn (McGraw-Hill, Boston 2002)
26. A. Stalheim-Smith, G.K. Fitch: *Understanding Human Anatomy and Physiology* (West, St. Paul, MN 1993)
27. G.J. Tortora, S.R. Grabowski: *Principles of Anatomy and Physiology*, 10th edn (Wiley, New York 2003)
28. J.A. Tuszynski, J.M. Dixon: *Biomedical Applications of Introductory Physics* (Wiley, New York 2002)
29. J.B. West (ed.): *Best and Taylor's Physiological Basis of Medical Practice*, 12th edn (Williams & Wilkins, Baltimore 1991)
30. J.H. Wilmore, D.L. Costill: *Physiology of Sport and Exercise*, 3rd edn (Human Kinetics, Champaign, IL 2004)

Contents

1 Terminology, the Standard Human, and Scaling 1
1.1 Anatomical Terminology 2
1.2 Motion in the Human Machine 5
1.3 The Standard Human 16
1.4 Scaling Relationships 23
1.4.1 Allometric Rules 24
1.4.2 Scaling in the Senses 26
1.5 Summary 27
Problems 27
References 37

2 Statics of the Body 39
2.1 Review of Forces, Torques, and Equilibrium 39
2.2 Statics: Motion in One Plane and Levers 42
2.3 Statics in the Body 46
2.3.1 The Lower Arm 46
2.3.2 Hip Problems 52
2.3.3 Statics of Other Synovial Joints 61
2.3.4 Lower Back Problems 69
2.3.5 Three-Force Rule 78
2.3.6 Multisegment Modeling 79
2.4 The Sense of Touch 81
2.5 Diversion into the Units of Force and Pressure 82
2.5.1 Force 82
2.5.2 Pressure 83
2.6 Summary 84
Problems 85
References 93

3 Motion 95
3.1 Kinematics and Musculature 98
3.2 Standing 105

3.2.1 Stability . . . 105
3.2.2 Forces on the Feet . . . 109
3.3 Walking . . . 109
3.3.1 Kinematics . . . 110
3.3.2 Muscular Action . . . 112
3.3.3 Friction . . . 113
3.3.4 Energetics . . . 118
3.3.5 Review of Harmonic Motion, Pendulums, and Moments of Inertia . . . 121
3.3.6 Ballistic (or Pendulum) Model of Walking . . . 126
3.3.7 Inverted Pendulum Model . . . 129
3.4 Running . . . 130
3.4.1 Kinematics . . . 130
3.4.2 Muscular Action . . . 132
3.4.3 Energetics . . . 133
3.4.4 Bouncing Ball/Pogo Stick Model . . . 139
3.5 Jumping . . . 140
3.5.1 Vertical Jump . . . 141
3.5.2 Pole Vault . . . 145
3.5.3 High Jump and Long Jump . . . 147
3.6 Throwing a Ball . . . 150
3.6.1 Comparing Throwing Motions . . . 163
3.6.2 Power Generated During a Throw . . . 164
3.7 Batting and Swinging Motions . . . 165
3.8 Other Types of Motion . . . 167
3.9 Multisegment Modeling (Advanced Topic) . . . 170
3.10 Collisions of the Human Body . . . 173
3.10.1 Kinematics of a Collision . . . 173
3.10.2 Consequences of Collisions . . . 175
3.10.3 Contact Sports . . . 182
3.10.4 Hitting Balls . . . 187
3.10.5 Running . . . 191
3.10.6 Jumping . . . 193
3.10.7 Chewing Food . . . 193
3.11 Sustained Acceleration . . . 194
3.12 Flight of the Ball . . . 195
3.12.1 The Effect of Air Drag on Moving Balls and Humans . . . 196
3.12.2 The Flight of a Spinning Ball . . . 202
3.12.3 Bouncing, Rolling and Hitting Balls, including those with Spin . . . 204
3.13 Summary . . . 210
Problems . . . 210
References . . . 240

4 Mechanical Properties of the Body 247
4.1 Material Components of the Body 250
4.1.1 Bone 251
4.1.2 Ligaments and Tendons 253
4.1.3 Cartilage 254
4.2 Elastic Properties 255
4.2.1 Basic Stress–Strain Relationships 255
4.2.2 Other Stress–Strain Relations 258
4.2.3 Bone Shortening 259
4.2.4 Energy Storage in Elastic Media 260
4.3 Time-Independent Deviations in Hookean Materials 263
4.3.1 Non-Hookean Materials 272
4.4 Static Equilibrium of Deformable Bodies (Advanced Topic) 274
4.4.1 Bending of a Beam (or Bone) 279
4.5 Time-Dependent Deviations from Elastic Behavior: Viscoelasticity 283
4.5.1 Perfect Spring 287
4.5.2 Perfect Dashpot 287
4.5.3 Simple Viscoelastic Models 289
4.6 Viscoelasticity in Bone 297
4.7 Bone Fractures 299
4.7.1 Modes of Sudden Breaking of Bones 300
4.7.2 Stress Fractures (Advanced Topic) 307
4.8 Common Sports Injuries 311
4.9 Avoiding Fractures and Other Injuries: Materials for Helmets 314
4.10 Mechanical Properties of Food 317
4.11 Summary 319
Problems 319
References 326

5 Muscles 331
5.1 Skeletal Muscles in the Body 332
5.1.1 Types of Muscle Activity 335
5.2 The Structure of Muscles 336
5.3 Activating Muscles: Macroscopic View 341
5.3.1 Mechanical Model of the Active State of Muscles 344
5.4 Passive Muscles 350
5.5 Active/Tetanized Muscles: Microscopic View 351
5.5.1 Total Muscle Tension 352
5.5.2 Everyday Proof of the Limited Range of Useful Muscle Length 353
5.6 Hill Force–Velocity Curve 355
5.7 The Combined Muscle-Tendon System 362

5.8 The Sliding Filament Model: Nanoscopic View . . . 363
5.8.1 Statistical Model of the Hill Force–Velocity Curve (Advanced Topic) . . . 368
5.9 Titin . . . 370
5.10 Coordination of Muscles . . . 371
5.11 Muscle Strength and Evolution . . . 374
5.11.1 Increasing Strength with Training . . . 374
5.11.2 Muscle Evolution with Age . . . 376
5.11.3 Muscle Fatigue . . . 377
5.12 Summary . . . 378
Problems . . . 378
References . . . 388

6 Metabolism: Energy, Heat, Work, and Power of the Body . . . 393
6.1 Conservation of Energy and Heat Flow . . . 394
6.2 Energy Content of Body Fuel . . . 396
6.2.1 Metabolizable Energy . . . 400
6.2.2 Energy Storage . . . 402
6.3 Energy Storage Molecules . . . 405
6.3.1 How ATP Is Produced and Used as an Energy Source . . . 405
6.3.2 How ATP Is Actually Used by the Body . . . 407
6.4 Metabolic Rates . . . 415
6.4.1 Basal Metabolic Rate . . . 415
6.4.2 Metabolic Rates During Common Activities . . . 421
6.4.3 Weight Gain and Loss . . . 438
6.5 Loss of Body Heat . . . 442
6.5.1 Modes of Heat Loss . . . 444
6.6 Body Temperature . . . 459
6.7 Summary . . . 466
Problems . . . 467
References . . . 485

7 Fluid Pressure, Fluid Flow in the Body, and Motion in Fluids . . . 491
7.1 Characteristic Pressures in the Body . . . 492
7.1.1 Definition and Units . . . 492
7.1.2 Measuring Pressure . . . 492
7.2 Basic Physics of Pressure and Flow of Fluids . . . 494
7.2.1 Law of Laplace . . . 495
7.2.2 Fluids in Motion . . . 497
7.2.3 Equation of Continuity . . . 498
7.2.4 Bernoulli's Equation . . . 499
7.2.5 Interactions Among the Flow Parameters . . . 500
7.2.6 Resistance in Flow: Viscous Flow and Poiseuille's Law . . . 501

7.2.7 Compliance in Flow . . . 509
7.2.8 Inertance in Flow . . . 511
7.2.9 Flow Under Special Conditions . . . 512
7.2.10 Flow of Objects in Fluids: Drag and Lift . . . 513
7.3 Diffusion (Advanced Topic) . . . 515
7.4 Pressure and Flow in the Body . . . 518
7.5 Motion of Humans in Fluids . . . 519
7.5.1 Swimming . . . 520
7.5.2 Human Flight . . . 523
7.6 Summary . . . 524
Problems . . . 525
References . . . 530

8 Cardiovascular System . . . 533
8.1 Overview of the Circulatory System and Cardiac Cycle . . . 533
8.1.1 Circulation . . . 533
8.1.2 Cardiac Cycle . . . 541
8.1.3 Valves . . . 544
8.2 Physics of the Circulation System . . . 546
8.2.1 Properties of Blood . . . 546
8.2.2 Blood Pressure and Flow in Vessels . . . 547
8.2.3 Capillaries and Osmotic Pressure . . . 561
8.2.4 Blood Flow Rates and Speeds . . . 564
8.2.5 Consequences of Clogged Arteries . . . 572
8.2.6 Work Done by the Heart and the Metabolic Needs of the Heart . . . 576
8.3 Strokes and Aneurysms . . . 577
8.3.1 Hemorrhagic Strokes . . . 578
8.3.2 Ischemic Strokes . . . 587
8.4 Modeling the Circulatory System and the Heart . . . 588
8.4.1 Model of the Heart . . . 588
8.4.2 Model of the Overall Flow in the Circulatory System . . . 592
8.4.3 The Arterial Pulse . . . 596
8.4.4 Windkessel Model . . . 600
8.4.5 Modeling the Malfunctioning Heart . . . 601
8.5 Summary . . . 605
Problems . . . 605
References . . . 618

9 Lungs and Breathing . . . 623
9.1 Structure of the Lungs . . . 624
9.2 The Physics of the Alveoli . . . 628
9.3 Physics of Breathing . . . 632
9.4 Volume of the Lungs . . . 635

9.5 Breathing Under Usual and Unusual Conditions 637
9.5.1 Flow of Air During Breathing 637
9.5.2 Mechanical Model of Breathing and Model Parameters 640
9.5.3 Inspiration/Expiration Cycle 640
9.5.4 Breathing with a Diseased Lung 641
9.5.5 Breathing at Higher Elevations and Under Other Unusual Conditions 644
9.6 Work Needed to Breathe 646
9.7 Summary 647
Problems 648
References 654

10 Sound, Speech, and Hearing 657
10.1 The Physics of Sound Waves 658
10.1.1 The Speed and Properties of Sound Waves 659
10.1.2 Intensity of Sound Waves 661
10.1.3 What Happens When Sound Travels from One Medium to Another? 667
10.1.4 Resonant Cavities 670
10.2 Speech Production 673
10.2.1 Types of Sounds 673
10.2.2 Systems in Speech Production 677
10.2.3 Parameters of the Human Voice 691
10.2.4 The Energetics of Speaking 692
10.3 Hearing 693
10.3.1 Auditory Sensitivity 694
10.3.2 Connections to Hearing Perception 712
10.4 Other Vibrations in the Body 716
10.4.1 Cardiac and Other Sources of Sounds 716
10.5 Summary 719
Problems 719
References 728

11 Light, Eyes and Vision 731
11.1 Structure of the Eye 731
11.2 Focusing and Imaging with Lenses 738
11.2.1 Image Formation 738
11.2.2 Scientific Basis for Imaging 741
11.2.3 Combinations of Lenses or Refractive Surfaces 745
11.3 Imaging and Detection by the Eye 753
11.3.1 Transmission of Light in the Eye 753
11.3.2 The Eye as a Compound Lens 755
11.3.3 Accommodation 761

11.3.4 Field of View and Binocular Vision 763
11.3.5 Adjustments of Light Levels 763
11.3.6 Limitations to Visual Acuity. 765
11.3.7 Imperfect Human Vision 775
11.3.8 Correction of Vision by Eyeglasses, Contact Lenses, and Other Means 780
11.4 Types of Vision Impairment 790
11.5 Connections to Visual Perception 791
11.6 Vision in Other Animals 798
11.7 Summary 802
Problems 802
References 815

12 Electrical and Magnetic Properties 819
12.1 Review of Electrical Properties 820
12.2 Electrical Properties of Body Tissues 824
12.2.1 Electrical Conduction Through Blood and Tissues. . . . 824
12.3 Nerve Conduction 825
12.3.1 Cell Membranes and Ion Distributions. 827
12.3.2 Types of Cell Membrane Excitations. 836
12.3.3 Model of Electrical Conduction Along an Axon 838
12.4 Ion Channels, Hair Cells, Balance, Taste, and Smell 849
12.5 Electrical Properties of the Heart 851
12.6 Electrical Signals in the Brain 859
12.7 Effects of Electric Shock 861
12.8 Magnetic Properties 862
12.8.1 Magnetic Field from an Axon. 863
12.8.2 Magnetic Sense 864
12.9 Electromagnetic Waves 864
12.10 Summary 864
Problems 865
References 870

13 Feedback and Control 873
13.1 Basics of Feedback and Control 874
13.1.1 Control Theory (Advanced Topic). 876
13.2 Regulation of the Body 878
13.2.1 Regulation of Temperature. 878
13.2.2 Control of Blood Pressure 884
13.2.3 Regulation During Exercise 885
13.2.4 Regulation of the Pupil Size. 885
13.3 Summary 887
Problems 887
References 888

Appendix A: Symbols and Units 889

Appendix B: Locator of Major Anatomical and Anthropometric Information 895

Appendix C: Differential Equations 897

Appendix D: Similar Model Systems 905

Appendix E: Biophysics of the Human Body 911

Appendix F: Physics of Life Cycles: Pregnancy, Injuries, Diseases and Disorders, Aging, and Dying 913

Appendix G: Physics of Sports 917

Appendix H: Physics for the Body: Measurements, Imaging, and Treatment 921

Solutions to Selected Problems 927

Index 941