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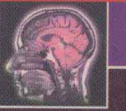
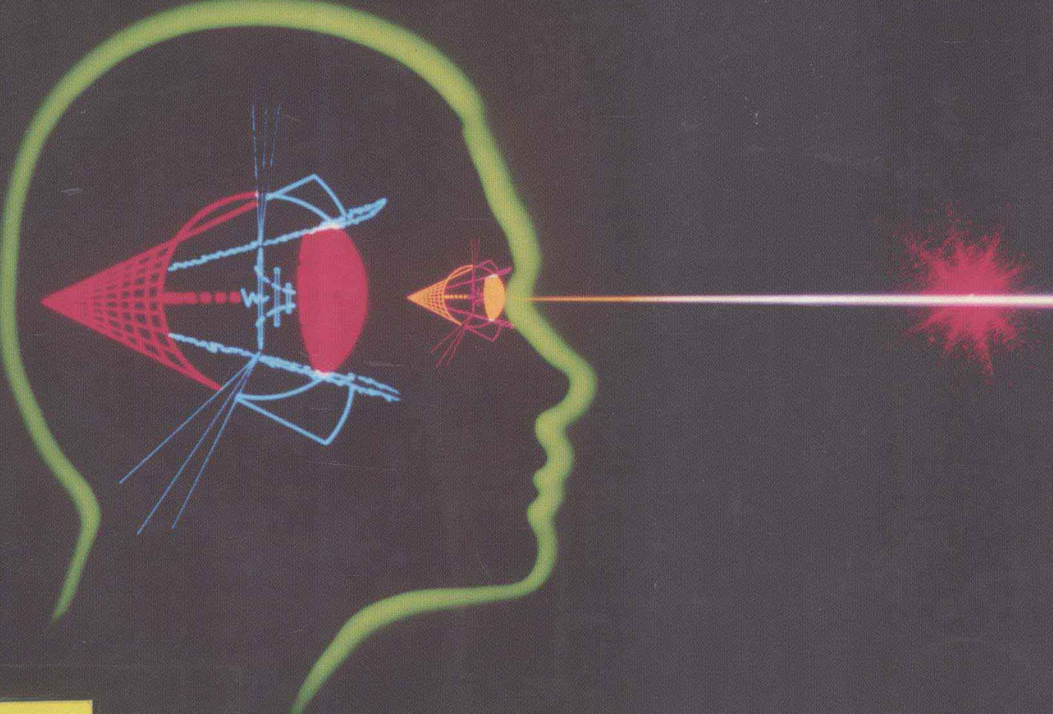


Physics in Biology and Medicine

SECOND EDITION



Paul Davidovits

Second Edition

Physics in Biology and Medicine

Paul Davidovits

Department of Chemistry
Boston College
Chestnut Hill, Massachusetts

HARCOURT ACADEMIC PRESS

A Harcourt Science and Technology Company

San Diego San Francisco New York Boston London Sydney Tokyo

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Cover Design	G. B. D. Smith
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Preproduction	Supplinc
Composition	Archetype Publishing, Inc.
Printer	Bertelsmann Industry Services, Inc.

Front cover photograph: Diagram of human eyesight © 2000 PhotoDisc, Inc.
Series logo: Image © 2000 PhotoDisc, Inc.

This book is printed on acid-free paper. ∞

Academic Press
A Harcourt Science and Technology Company
525 B Street, Suite 1900, San Diego, California 92101-4495, U.S.A.
http://www.academicpress.com

Academic Press
A Harcourt Science and Technology Company
Harcourt Place, 32 Jamestown Road, London NW1 7BY, UK
http://www.academicpress.com

Harcourt/Academic Press
A Harcourt Science and Technology Company
200 Wheeler Road, Burlington, Massachusetts 01803
http://www.harcourt-ap.com

Library of Congress Catalog Card Number: 00-107669

International Standard Book Number: 0-12-204840-7

PRINTED IN THE UNITED STATES OF AMERICA
00 01 02 03 04 05 BS 9 8 7 6 5 4 3 2 1

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Preface

Until the mid 1800s it was not clear to what extent the laws of physics and chemistry, which were formulated from the observed behavior of inanimate matter, could be applied to living matter. It was certainly evident that on the large scale the laws were applicable. Animals are clearly subject to the same laws of motion as inanimate objects. The question of applicability arose on a more basic level. Living organisms are very complex. Even a virus, which is one of the simplest biological organisms, consists of millions of interacting atoms. A cell, which is the basic building block of tissue, contains on the average 10^{14} atoms. Living organisms exhibit properties not found in inanimate objects. They grow, reproduce, and decay. These phenomena are so different from the predictable properties of inanimate matter that many scientists in the early 19th century believed that different laws governed the structure and organization of molecules in living matter. Even the physical origin of organic molecules was in question. These molecules tend to be larger and more complex than molecules obtained from inorganic sources. It was thought that the large molecules found in living matter could be produced only by living organisms through a "vital force" that could not be explained by the existing laws of physics. This concept was disproved in 1828 when Friedrich Wöhler synthesized an organic substance, urea, from inorganic chemicals. Soon thereafter many other organic molecules were synthesized without the intervention of biological organisms. Today most scientists believe that there is no special vital force residing in organic substances. Living organisms are governed by the laws of physics on all levels.

Much of the biological research during the past hundred years has been directed toward understanding living systems in terms of basic physical laws. This effort has yielded some significant successes. The atomic structure of many complex biological molecules has now been determined, and the role of these molecules within living systems has been described. It is now possible to explain the functioning of cells and many of their interactions with each other. Yet the work is far from complete. Even when the structure of a complex molecule is known, it is not possible at present to predict its function from its atomic structure. The mechanisms of cell nourishment, growth, reproduction, and communication are still understood only qualitatively. Many of the basic questions in biology remain unanswered. However, biological research has so far not revealed any areas where physical laws do not apply. The amazing properties of life seem to be achieved by the enormously complex organization in living systems.

The aim of this book is to relate some of the concepts in physics to living systems. In general, the text follows topics found in basic college physics texts. The discussion is organized into the following areas: solid mechanics, fluid mechanics, thermodynamics, sound, electricity, optics, and atomic and nuclear physics.

Each chapter contains a brief review of the background physics, but most of the text is devoted to the applications of physics to biology and medicine. No previous knowledge of biology is assumed. The biological systems to be discussed are described in as much detail as is necessary for the physical analysis. Whenever possible, the analysis is quantitative, requiring only basic algebra and trigonometry.

Many biological systems can be analyzed quantitatively. A few examples will illustrate the approach. Under the topic of mechanics we calculate the forces exerted by muscles. We examine the maximum impact a body can sustain without injury. We calculate the height to which a person can jump, and we discuss the effect of an animal's size on the speed at which it can run. In our study of fluids we examine quantitatively the circulation of blood in the body. The theory of fluids allows us also to calculate the role of diffusion in the functioning of cells and the effect of surface tension on the growth of plants in soil. Using the principles of electricity, we analyze quantitatively the conduction of impulses along the nervous system. Each section contains problems that explore and expand some of the concepts.

There are, of course, severe limits on the quantitative application of physics to biological systems. These limitations are discussed.

Many of the advances in the life sciences have been greatly aided by the application of the techniques of physics and engineering to the study of living systems. Some of these techniques are examined in the appropriate sections of the book.

This new edition has been updated and includes a discussion of information theory and descriptions of CT scan and MRI imaging, two techniques that were not available at the writing of the first edition.

A word about units. Most physics and chemistry textbooks now use the MKS International System of units (SI). In practice, however, a variety of units continue to be in use. For example, in the SI system, pressure is expressed in units of pascals (kg/m^2). Both in common use and in the scientific literature one often finds pressure also expressed in units of $dynes/cm^2$, Torr (mm Hg), psi, and atm. In this book I have used mostly SI units. However, other units have also been used when common usage so dictated. In those cases conversion factors have been provided either within the text or in a compilation at the end of Appendix A.

In the first edition of this book I expressed my thanks to W. Chameides, M. D. Egger, L. K. Stark, and J. Taplitz for their help and encouragement. In the writing of this second edition I want to thank Professors R. K. Hobbie and David Cinabro for their careful reading of the manuscript and helpful suggestions. I also appreciate the encouragement and competent direction of J. Hayhurst, S. Stevens, N. Donaghy, and J. Dinsmore at Harcourt/Academic Press.

Paul Davidovits
Chestnut Hill, Massachusetts

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Chapter 1

Static Forces

Mechanics is the branch of physics concerned with the effect of forces on the motion of bodies. It was the first branch of physics that was applied successfully to living systems, primarily to understanding the principles governing the movement of animals. Our present concepts of mechanics were formulated by Isaac Newton, whose major work on mechanics, *Principia Mathematica*, was published in 1687. The study of mechanics, however, began much earlier. It can be traced to the Greek philosophers of the fourth century B.C. The early Greeks, who were interested in both science and athletics, were also the first to apply physical principles to animal movements. Aristotle wrote, "The animal that moves makes its change of position by pressing against that which is beneath it. . . . Runners run faster if they swing their arms for in extension of the arms there is a kind of leaning upon the hands and the wrist." Although some of the concepts proposed by the Greek philosophers were wrong, their search for general principles in nature marked the beginning of scientific thought.

After the decline of ancient Greece, the pursuit of all scientific work entered a period of lull that lasted until the Renaissance brought about a resurgence in many activities including science. During this period of revival, Leonardo da Vinci (1452–1519) made detailed observations of animal motions and muscle functions. Since da Vinci, hundreds of people have contributed to our understanding of animal motion in terms of mechanical principles. Their studies have been aided by improved analytic techniques and the development of instruments such as the photographic camera and electronic timers. Today the study of human motion is part of the disciplines of kinesiology, which studies human motion primarily as applied to athletic activities, and biomechanics, a broader area that is concerned not only with muscle movement but also with the physical behavior of bones and organs such as the lungs and the heart. The development of prosthetic devices such as artificial limbs and mechanical hearts is an active area of biomechanical research.

Mechanics, like every other subject in science, starts with a certain number of basic concepts and then supplies the rules by which they are interrelated. Appendix A summarizes the basic concepts in mechanics, providing a review rather than a thorough treatment of the subject. We will now begin our discussion of mechanics by examining static forces that act on the human body. We will first discuss stability and equilibrium of the human body, and then we will calculate the forces exerted by the skeletal muscles on various parts of the body.

1.1 Equilibrium and Stability

The Earth exerts an attractive force on the mass of an object; in fact, every small element of mass in the object is attracted by the Earth. The sum of these forces is the total weight of the body. This weight can be considered a force acting through a single point called the center of mass or center of gravity. As pointed out in Appendix A, a body is in static equilibrium if the vectorial sum of both the forces and the torques acting on the body is zero. If a body is unsupported, the force of gravity accelerates it, and the body is not in equilibrium. In order that a body be in stable equilibrium, it must be properly supported.

The position of the center of mass with respect to the base of support determines whether the body is stable or not. A body is in stable equilibrium under the action of gravity if its center of mass is directly over its base of support (Fig. 1.1). Under this condition, the reaction force at the base of support cancels the force of gravity and the torque produced by it. If the center of mass is outside the base, the torque produced by the weight tends to topple the body (Fig. 1.1c).

The wider the base on which the body rests, the more stable it is; that is, the more difficult it is to topple it. If the wide-based body in Fig. 1.1a is displaced as shown in Fig. 1.2a, the torque produced by its weight tends to restore it to its original position (F_r shown is the reaction force exerted by the surface on the body). The same amount of angular displacement of a narrow-based body results in a torque that will topple it (Fig. 1.2b). Similar considerations show that a body is more stable if its center of gravity is closer to its base.

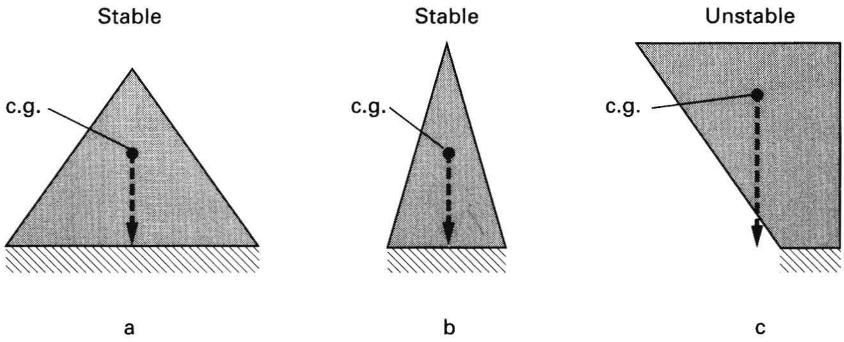

FIGURE 1.1 ▶ Stability of bodies.

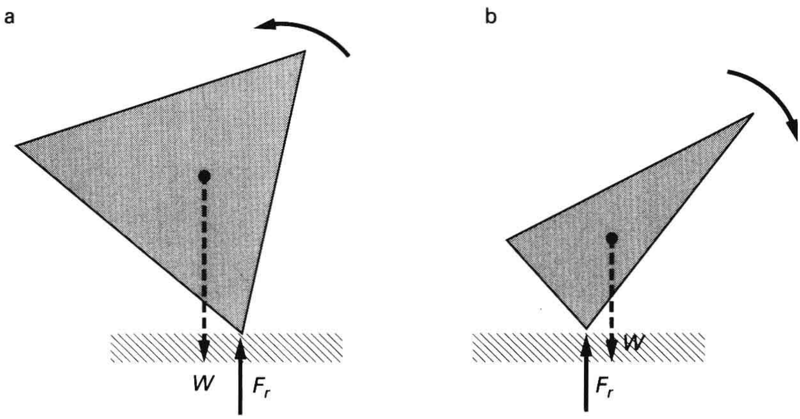

FIGURE 1.2 ▶ (a) Torque produced by the weight will restore the body to its original position. (b) Torque produced by the weight will topple the body.

1.2 Equilibrium Considerations for the Human Body

The center of gravity (c.g.) of an erect person with arms at the side is at approximately 56% of the person's height measured from the soles of the feet (Fig. 1.3). The center of gravity shifts as the person moves and bends. The act of balancing requires maintenance of the center of gravity above the feet. A person falls when his center of gravity is displaced beyond the position of the feet.

When carrying an uneven load, the body tends to compensate by bending and extending the limbs so as to shift the center of gravity back over the feet. For example, when a person carries a weight in one arm, the other arm swings away from the body and the torso bends away from the load (Fig. 1.4). This tendency of the body to compensate for uneven weight distribution often