Y. C. Fung

Biomechanics

Mechanical Properties of Living Tissues

Y. C. Fung

Biomechanics

Mechanical Properties of Living Tissues

Y. C. Fung

Professor of Applied Mathematics
and Engineering Sciences/Bioengineering
University of California, San Diego
La Jolla, CA 92093
USA

Library of Congress Cataloging in Publication Data

Fung, Yuan-cheng, 1919–
Biomechanics.

Bibliography: p.
Includes index.
1. Tissues. 2. Biomechanics. 3. Rheology
(Biology) I. Title. [DNLM: 1. Biomechanics. QT34 F981b]
QP88.F87 599.01'852 80-16532

With 244 illustrations.

Printed in the United States of America.

9 8 7 6 5 4 3 2 1

ISBN 0-387-90472-7 Springer-Verlag New York
ISBN 3-540-90472-7 Springer-Verlag Berlin Heidelberg

Preface

The motivation for writing a series of books on biomechanics is to bring this rapidly developing subject to students of bioengineering, physiology, and mechanics. In the last decade biomechanics has become a recognized discipline offered in virtually all universities. Yet there is no adequate textbook for instruction; neither is there a treatise with sufficiently broad coverage. A few books bearing the title of biomechanics are too elementary, others are too specialized. I have long felt a need for a set of books that will inform students of the physiological and medical applications of biomechanics, and at the same time develop their training in mechanics. We cannot assume that all students come to biomechanics already fully trained in fluid and solid mechanics; their knowledge in these subjects has to be developed as the course proceeds. The scheme adopted in the present series is as follows. First, some basic training in mechanics, to a level about equivalent to the first seven chapters of the author's *A First Course in Continuum Mechanics* (Prentice-Hall, Inc. 1977), is assumed. We then present some essential parts of biomechanics from the point of view of bioengineering, physiology, and medical applications. In the meantime, mechanics is developed through a sequence of problems and examples. The main text reads like physiology, while the exercises are planned like a mechanics textbook. The instructor may fill a dual role: teaching an essential branch of life science, and gradually developing the student's knowledge in mechanics.

The present volume is the first in a series. In this book the mechanical properties of biological materials are discussed. This will be followed by a forthcoming volume devoted to the mechanics of circulation and respiration.

Yet biomechanics at the level of current research cannot be bound by elementary mathematics. To develop the subject fully, advanced methods in continuum mechanics would have to be used. These more advanced topics, perhaps accessible only to students with suitable training in fluid and solid mechanics, are presented in a third volume, *Advanced Biomechanics*.

To strike a balance between biological and physical topics in a single course is not easy. Biology contains a great deal of descriptive material, whereas mechanics aims at quantitative analysis. The need to unify these topics sometimes renders the text nonuniform in style, stressing a mathematical detail here and describing an anatomy there. This nonuniformity is more pronounced at the beginning, when the necessary background material has to be introduced.

A special word needs to be said about the exercises. Students of mechanics thrive on exercises. We must constantly try to formulate and solve problems. Only through such practice can we make biomechanics a living subject. I do not wish to present this book as a collection of solved problems. I wish to present it as a way of thinking about problems. I wish to illustrate the use of mechanics as a simple, quantitative tool. For this reason many problems for solution are proposed in the text; some are used as a vehicle to inform the readers of some published results, others are intended to lead the reader to new paths of investigation. I followed this philosophy even at the very beginning by presenting some problems and solutions in the Introductory Chapter 1. I think colleagues who use this as a textbook would appreciate this, because then they can assign some problems to the students after the first lecture.

With our limited objective, this book does not claim to be a compendium or handbook of current information on the selected topics, nor a review of literature. For those purposes a much larger volume will be needed. In this volume we develop only a few topics that seem related and important. A comprehensive bibliography is not provided; the list of references is limited to items quoted in the text. Though the author can be accused of quoting papers and people familiar to him, he apologizes for this personal limitation and hopes that he can be forgiven because it is only natural that an author should talk more about his own views than the views of others. I have tried, however, never to forget mentioning the existence of other points of view.

Biomechanics is a young subject. Our understanding of the subject is yet imperfect. Many needed pieces of information have not yet been obtained; many potentially important applications have not yet been made. There are many weaknesses in our present position. For example, the soft tissue mechanics developed in Chapter 7, based on the concept of quasilinear viscoelasticity and pseudo-elasticity, may someday be replaced by constitutive equations that are fully nonlinear but not too complex. The blood vessel mechanics developed in Chapter 8 is based on a two-dimensional average. Our discussion of the muscle mechanics in Chapter 9–11 points out the deficiency in our present knowledge on this subject. An alternative to Hill's model is presented. I was hoping that by the time this book went to print the experimental work to validate the alternative model would have been completed; but this was not the case; and the fading memory approach remained just an idea. In Chapter 12 we discussed the constitutive equations for growth or resorption of tissues under stress. This is a subject of universal importance in the study of every living tissue; but only on bone do we have some quantitative information on this topic. It is safe to predict that the study of the constitutive equations for growth or resorption will be a great theme for biomechanics in the future. These equations have immediate applications to the art of surgery, orthopedics, orthodontics, orthoptics, body building, and athletic training. Basically they distinguish biomechanics from all other branches of mechanics. It is for the purpose of conveying this sense of growth and change that we devoted long passages on blood circulation in the bone in Chapter 12. All this means that I expect rapid progress in our subject in the future.

I wish to express my thanks to many authors and publishers who permitted me to quote their publications and reproduce their figures and data in this book. I wish to mention especially Professors Sidney Sobin, Evan Evans, Harry Goldsmith, Jen-shih Lee, Wally Frasher, Richard Skalak, Andrew Somlyo, Salvatore Sutera, Andrus Viidik, Joel Price, Savio Woo, and Benjamin Zweifach who supplied original photographs for reproduction.

This book grew out of my lecture notes used at the University of California, San Diego over the past ten years. To the students of these classes I am grateful for discussions. Much of the results presented here are the work of my colleagues, friends, and former students. Professors Sidney Sobin, Benjamin Zweifach, Marcos Intaglietta, Arnost and Kitty Fronek, Wally Frasher, Paul Johnson, and Savio Woo provided the initial and continued collaboration with me on this subject. Drs. Jen-shi Lee, Pin Tong, Frank Yin, John Pinto, Evan Evans, Yoram Lanir, Hyland Chen, Michael Yen, Donald Vawter, Geert Schmid-Schoenbein, Peter Chen, Larry Malcom, Joel Price, Nadine Sidrick, Paul Sobin, Winston Tsang, and Paul Zupkas contributed much of the material presented here. The contribution of Paul Patitucci to the numerical handling of data must be especially acknowledged. Dr. Yuji Matsuzaki contributed much to my understanding of flow separation and stability. Professor Zhuong Feng-Yuan read the proofs and made many useful suggestions. Eugene Mead kept the laboratory going. Rose Cataldi and Virginia Stephens typed the manuscript. To all of them I am thankful.

Finally, I wish to thank the editorial and production staffs of Springer-Verlag for their care and cooperation in producing this book.

La Jolla, California Yuan-Cheng Fung

Contents

Chapter 1
Introduction: A Sketch of the History and Scope of the Field 1

1.1 What Is Biomechanics? 1
1.2 Historical Background 1
1.3 What's in a Name? 6
1.4 Mechanics in Physiology 7
1.5 What Contributions Has Biomechanics Made to Health Science? 10
1.6 Our Method of Approach 12
References 21

Chapter 2
The Meaning of the Constitutive Equation 22

2.1 Introduction 22
2.2 Stress 22
2.3 Strain 26
2.4 Strain Rate 31
2.5 Constitutive Equations 32
2.6 The Nonviscous Fluid 33
2.7 The Newtonian Viscous Fluid 33
2.8 The Hookean Elastic Solid 35
2.9 The Effect of Temperature 37
2.10 Materials with More Complex Mechanical Behavior 38
2.11 Viscoelasticity 41
2.12 Response of a Viscoelastic Body to Harmonic Excitation 47
2.13 Use of Viscoelastic Models 50
2.14 Methods of Testing 56
References 61

Chapter 3
The Flow Properties of Blood 62

3.1 Blood Rheology: An Outline 62
3.2 The Constitutive Equation 68
3.3 Laminar Flow of Blood in a Tube 72
3.4 Speculation on Why Blood Viscosity Is the Way It Is 80
3.5 Fluid-Mechanical Interaction of Red Blood Cells with a Solid Wall 89
3.6 Coagulation 91
3.7 Medical Applications of Blood Rheology 93
References 98

Chapter 4
Red Blood Cells and Their Deformability 101

4.1 Introduction 101
4.2 Human Red Cell Dimensions and Shape 104
4.3 The Extreme-Value Distribution 108
4.4 The Deformability of Red Blood Cells (RBC) 112
4.5 Theoretical Considerations of the Elasticity of Red Cells 114
4.6 Cell Membrane Experiments 122
4.7 Elasticity of the Red Cell Membrane 132
4.8 The Red Cell Membrane Model 135
References 136

Chapter 5
The Rheology of Blood in Microvessels 139

5.1 Introduction 139
5.2 Apparent Viscosity and Relative Viscosity 139
5.3 Effect of Size of the Blood Vessel on the Apparent Viscosity of Blood: The Fahraeus-Lindqvist Effect 146
5.4 The Distribution of Suspended Particles in Fairly Narrow Rigid Tubes 149
5.5 The Motion of Red Cells in Tightly Fitting Tubes 150
5.6 Inversion of the Fahraeus-Lindqvist Effect in Very Narrow Tubes 156
5.7 Hematocrit in Very Narrow Tubes 159
5.8 Theoretical Investigations 167
References 172

Chapter 6
Bio-viscoelastic Fluids 174

6.1 Introduction 174
6.2 Methods of Testing and Data Presentation 177
6.3 Protoplasm 181
6.4 Mucus from the Respiratory Tract 182
6.5 Saliva 186

6.6 Cervical Mucus and Semen 187
6.7 Synovial Fluid 188
References 194

Chapter 7
Bio-viscoelastic Solids 196

7.1 Introduction 196
7.2 Some Elastic Materials 197
7.3 Collagen 203
7.4 Thermodynamics of Elastic Deformation 214
7.5 Behavior of Tissues Under Uniaxial Loading 219
7.6 Quasi-linear Viscoelasticity of Soft Tissues 226
7.7 Incremental Laws. The Concept of Pseudo-elasticity 238
7.8 Biaxial Loading Experiments on Soft Tissues 242
7.9 Description of Three-Dimensional Stress and Strain States 245
7.10 The Constitutive Equation of Skin 248
7.11 Generalized Viscoelastic Relations 253
7.12 The Complementary Energy Function: Inversion of the Stress-Strain Relationship 253
References 257

Chapter 8
Mechanical Properties of Blood Vessels 261

8.1 Introduction 261
8.2 Correlation of the Mechanical Properties of a Vessel with the Content and Structure of Its Material Composition 262
8.3 The Behavior of Arteries Under Uniaxial Loading 267
8.4 Stresses in Arteries Under Biaxial Loading 276
8.5 Mathematical Representation of the Pseudoelastic Stress-Strain Relationship 277
8.6 Dynamic Testing: Wave Propagation 282
8.7 Arterioles 284
8.8 Capillary Blood Vessels 286
8.9 Veins 290
8.10 Long Term Response to Stress 295
References 298

Chapter 9
Skeletal Muscle 302

9.1 Introduction 302
9.2 The Functional Arrangement of Muscles 303
9.3 The Structure of Skeletal Muscle 305
9.4 The Sliding Element Theory of Muscle Action 308

9.5 Single Twitch and Wave Summation 308
9.6 Contraction of Skeletal Muscle Bundles 309
9.7 Hill's Equation for Tetanized Muscle 310
9.8 Hill's Three-Element Model 316
9.9 Other Approaches 324
References 327

Chapter 10
Heart Muscle 329

10.1 Introduction: The Difference Between Myocardial and Skeletal Muscle Cells 329
10.2 Properties of Unstimulated Heart Muscle 333
10.3 The Behavior of Active Myocardium 342
10.4 Active Muscle at Shorter Length with Negligible Resting Tension 343
10.5 Stimulated Papillary Muscle at Lengths at Which Resting Tension Is Significant 350
10.6 Heart Muscle Mechanics and Whole Heart Behavior 351
References 353

Chapter 11
Smooth Muscles 355

11.1 Types of Smooth Muscles 355
11.2 The Contractile Machinery 358
11.3 Rhythmic Contraction of Smooth Muscle 360
11.4 The Property of a Resting Smooth Muscle: Ureter 365
11.5 Resting Smooth Muscle: Taenia Coli 371
References 381

Chapter 12
Bone and Cartilage 383

12.1 Mechanical Properties of Bone 383
12.2 Bone as a Living Organ 389
12.3 Functional Adaptation of Bone 392
12.4 Blood Circulation in Bone 397
12.5 Cartilage 400
12.6 Viscoelastic Properties of Articular Cartilage 401
12.7 The Lubrication Quality of Articular Cartilage Surfaces 406
References 413

Author Index 417

Subject Index 425

CHAPTER 1

Introduction: A Sketch of the History and Scope of the Field

1.1 What Is Biomechanics?

Biomechanics is mechanics applied to biology. The word "mechanics" was used by Galileo as a subtitle to his book *Two New Sciences* (1638) to describe force, motion, and strength of materials. Through the years its meaning has been extended to cover the study of the motions of all kinds of particles and continua, including quanta, atoms, molecules, gases, liquids, solids, structures, stars, and galaxies. In a generalized sense it is applied to the analysis of any dynamic system. Thus thermodynamics, heat and mass transfer, cybernetics, computing methods, etc., are considered proper provinces of mechanics. The biological world is part of the physical world around us and naturally is an object of inquiry in mechanics.

Biomechanics seeks to understand the mechanics of living systems. It is an ancient subject and covers a very wide territory. In this book we concentrate on physiological and medical applications, which constitute the majority of recent work in this field. The motivation for research in this area comes from the realization that physiology can no more be understood without biomechanics than an airplane can without aerodynamics. For an airplane, mechanics enables us to design its structure and predict its performance. For an organ, biomechanics helps us to understand its normal function, predict changes due to alterations, and propose methods of artificial intervention. Thus diagnosis, surgery, and prosthesis are closely associated with biomechanics.

1.2 Historical Background

To explain what our field is like, it is useful to consider its historical background. Since science and scientists have always been concerned with the world of living things, it is natural that biomechanics has roots which reach back to the dawn of civilization. Of the ancient philosophers, Aristotle (384–322 B.C.) was an eloquent speaker for the connection between "physics"—which for him was a general description of the universe—and the study of living things. His writings cover the whole area of knowledge, and as a whole were deeply influenced by his biological studies. We quote the following translation by Singer in *A Short History of Scientific Ideas to 1900* (1959, p. 40) from Aristotle's great work *On the Parts of Animals*:

> Of things constituted by nature, some are ungenerated, imperishable, eternal; others subject to generation and decay. The former are excellent beyond compare and divine, but less accessible to knowledge. The evidence that might throw light on them, and on the problems which we long to solve respecting them, is furnished but scantily by our senses. On the other hand, we know much of the perishable plants and animals among which we dwell. We may collect information concerning all their various kinds, if we but take the pains.
>
> Yet each department has its own peculiar charm. The excellence of celestial things causes our scanty conceptions of them to yield more pleasure than all our knowledge of the world in which we live; just as a mere glimpse of those we love is more to us than the grandest vista. On the other side we may set the certitude and completeness of our knowledge of earthly things. Their nearness and their affinity to us may well balance the loftier interest of things of heaven, that are the objects of high philosophy.
>
> But of a truth every realm of nature is marvellous. It is told that strangers, visiting Heracleitus and finding him by the kitchen fire, hesitated to enter. "Come in, come in," he cried, "the gods are here too." So should we venture on the study of every kind of creature without horror, for each and all will reveal something that is natural and therefore beautiful. [Somewhat paraphrased.]

We may not agree with him as to which subject is easier to study, but we must agree that the physical world and the biological world are equally beautiful. However, the modern development of mechanics received its impetus mainly from engineering, and to most engineers today biomechanics sounds like a new subject. But if we look at the following slate of names of those who contributed significantly to biomechanics, we have to admit that this field has been alive all along.

Galileo Galilei (1564–1642)
William Harvey (1578–1658)
René Descartes (1596–1650)
Giovanni Alfonso Borelli (1608–1679)
Robert Boyle (1627–1691)
Robert Hooke (1635–1703)
Leonhard Euler (1707–1783)
Thomas Young (1773–1829)
Jean Poiseuille (1799–1869)
Herrmann von Helmholtz (1821–1894)

Adolf Fick (1829–1901)
Diederik Johannes Korteweg (1848–1941)
Horace Lamb (1849–1934)
Otto Frank (1865–1944)
Balthasar van der Pol (1889–1959)

A brief account of the contributions of these people may be of interest. William Harvey, of course, is credited with the discovery of blood circulation. He made this discovery in 1615. Having no microscope, he never saw the capillary blood vessels. This should make us appreciate his conviction in logical reasoning even more deeply today because, without the capability of seeing the passage from the arteries to the veins, the discovery of circulation must be regarded as "theoretical." The actual discovery of capillaries was made by Marcello Malpigi (1628–1694) in 1661, 45 years after Harvey made the capillaries a logical necessity.

A contemporary of William Harvey was Galileo. You remember that Galileo was a student of medicine before he became famous as a physicist. He discovered the constancy of the period of a pendulum, and used the pendulum to measure the pulse rate of people, expressing the results quantitatively in terms of the length of a pendulum synchronous with the beat. He invented the thermoscope, and was also the first one to design a microscope in the modern sense in 1609, although rudimentary microscopes were first made by J. Janssen and his son Zacharias in 1590.

Young Galileo's fame was so great and his lectures at Padua so popular that his influence on biomechanics went far beyond his personal contributions mentioned above. According to Singer (*History*, p. 237), William Harvey should be regarded as a disciple of Galileo, though he himself might not be aware of it. Harvey studied at Padua (1598–1601) while Galileo was active there. By 1615 he had attained to a conception of the circulation of the blood. He published his demonstration in 1628. The essential part of his demonstration is the result not of mere observation but of the application of Galileo's principle of measurement. He showed first that the blood can only leave the ventricle of the heart in one direction. Then he measured the capacity of the heart, and found it to be two ounces.* The heart beats 72 times a minute, so that in one hour it throws into the system $2 \times 72 \times 60$ ounces $= 8640$ ounces $= 540$ pounds! Where can all this blood come from? Where can it all go? He concludes that the existence of circulation is a necessary condition for the function of the heart.

Another colleague of Galileo, Santorio Santorio (1561–1636), a professor of medicine at Padua, used Galileo's method of measurement and philosophy to compare the weight of the human body at different times and in different circumstances. He found that the body loses weight by mere exposure, a process which he assigned to "insensible perspiration." His experiments laid

* We know today that the resting cardiac output is very close to one total blood volume per minute in nearly all mammals.

the foundation of the modern study of "metabolism." (See Singer, *History*, p. 236.)

The physical discoveries of Galileo and the demonstrations of Santorio and of Harvey gave a great impetus to the attempt to explain vital processes in terms of mechanics. Galileo showed that mathematics was the essential key to science, without which nature could not be properly understood. This outlook inspired Descartes, a great mathematician, to work on physiology. In a work published posthumously (1662 and 1664), he proposed a physiological theory upon mechanical grounds. According to Singer, this work is the first important modern book devoted to the subject of physiology. Descartes did not have any extensive practical knowledge of physiology. On theoretical grounds he set forth a very complicated model of animal structure, including the function of nerves. Subsequent investigations failed to confirm many of his findings. These errors of fact caused the loss of confidence in Descartes' approach—a lesson that should be kept in mind by all theoreticians.

Other attempts a little less ambitious than Descartes's were more successful. Giovanni Alfonso Borelli (1608–1679) was an eminent Italian mathematician and astronomer, and a friend of Galileo and Malpighi. His *On Motion of Animals* (*De Motu Animalium*) (1680) is the classic of what is variously called the "iatrophysical" or "iatromathematical" school ιατρός, Gr., physician). He was successful in clarifying muscular movement and body dynamics. He treated the flight of birds and the swimming of fish, as well as the movements of the heart and of the intestines.

Robert Boyle studied the lung and discussed the function of air in water with respect to fish respiration. Robert Hooke gave us Hooke's law in mechanics and the word "cell" in biology to designate the elementary entities of life. His famous book *Micrographia* (1664) has been reprinted by Dover Publications, New York (1960). Leonhard Euler wrote a definitive paper in 1775 on the propagation of waves in arteries. Thomas Young, who gave us the Young's modulus of elasticity, was a physician in London. He worked on the wave theory of light while he was concerned with astigmatism in lenses and in color vision. Poiseuille invented the mercury manometer to measure the blood pressure in the aorta of a dog while he was a medical student, and discovered Poiseuille's law of viscous flow upon graduation.

To von Helmholtz (Fig. 1.2:1) might go the title "Father of Bioenginering." He was professor of physiology and pathology at Königsberg, professor of anatomy and physiology at Bonn, professor of physiology at Heidelberg, and finally professor of physics in Berlin (1871). He wrote his paper on the "law of conservation of energy" in barracks while he was in military service fresh out of medical school. His contributions ranged over optics, acoustics, thermodynamics, electrodynamics, physiology, and medicine. He discovered the focusing mechanism of the eye and, following Young, formulated the trichromatic theory of color vision. He invented the phakoscope to study the changes in the lens, the ophthalmoscope to view the

Figure 1.2:1 Portrait of Hermann von Helmholtz. From the frontispiece to *Wissenschaftliche Abhandlungen von Helmholtz*. Leipzig, Johann Ambrosius Barth, 1895. Photo by Giacomo Brogi in 1891.

retina, the ophthalmometer for measurement of eye dimensions, and the stereoscope with interpupillary distance adjustments for stereo vision. He studied the mechanism of hearing and invented the Helmholtz resonator. His theory of the permanence of vorticity lies at the very foundation of modern fluid mechanics. His book *Sensations of Tone* is popular even today. He was the first to determine the velocity of the nerve pulse, giving the rate 30 m/s, and to show that the heat released by muscular contraction is an important source of animal heat.

The other names on the list are equally familiar to engineers. The physiologist Fick was the author of Fick's law of mass transfer. The hydrodynamicists Korteweg (1878) and Lamb (1898) wrote beautiful papers on wave propagation in blood vessels. Frank worked out a hydrodynamic theory of circulation. Van der Pol (1929) wrote about the modeling of the heart with nonlinear oscillators, and was able to simulate the heart with four Van der Pol oscillators to produce a realistic looking electrocardiograph.

This list perhaps suffices to show that there were, and of course are, people who would be equally happy to work on living subjects as well as inanimate objects. Indeed, what a scientist picks up and works on may depend a great deal on chance, and the biological world is so rich a field that one should not permit the opportunities there to slip by unnoticed. The following example about Thomas Young may be of interest to those who like to ponder about the threads of development in scientific thought. When he tried to understand the human voice, Thomas Young turned to the mechanics of vibrations. Let us quote Young himself (from his "Reply to the *Edinburgh Reviewers*" (1804), see *Works*, ed. Peacock, Vol. i, pp 192–215):

> When I took a degree in physic at Göttingen, it was necessary, besides publishing a medical dissertation, to deliver a lecture upon some subject connected with medical studies, and I choose for this Formation of the Human Voice, ... When I began the outline of an essay on the human voice, I found myself at a loss for a perfect conception of what sound was, and during the three years that I passed at Emmanuel College, Cambridge, I collected all the information relating to it that I could procure from books, and I made a variety of original experiments on sounds of all kinds, and on the motions of fluids in general. In the course of these inquiries I learned to my surprise how much further our neighbours on the Continent were advanced in the investigation of the motions of sounding bodies and of elastic fluids than any of our countrymen. And in making some experiments on the production of sounds, I was so forcibly impressed with the resemblance of the phenomena that I saw to those of the colours of thin plates, with which I was already acquainted, that I began to suspect the existence of a closer analogy between them than I could before have easily believed."

This led to his 'Principle of Interferences" (1801) which earned him lasting fame in the theory of light. How refreshing are these remarks! How often do we encounter the situation "at a loss for a perfect conception of what ... was." How often do we leave the vague notions untouched!

1.3 What's in a Name?

Biomechanics is mechanics applied to biology. We have explained in Sec. 1.1 that the word "mechanics" has been identified with the analysis of any dynamic system. To people who call themselves workers in applied mechanics, the field includes the following topics:

Stress and strain distribution in materials
Constitutive equations which describe the mechanical properties of materials
Strength of materials, yielding, creep, plastic flow, crack propagation, fracture, fatigue failure of materials; stress corrosion
Dislocation theory, theory of metals, ceramics
Composite materials
Flow of fluids: gas, water, blood, and other tissue fluids
Heat transfer, temperature distribution, thermal stresses
Mass transfer, diffusion, transport through membranes

Motion of charged particles, plasma, ions in solution
Mechanisms, structures
Stability of mechanical systems
Control of mechanical systems
Dynamics, vibrations, wave propagation
Shock, waves, and waves of finite amplitude

It is difficult to find any organ in any animal that does not involve some of these problems.

On the other hand, how did the word biology come about? The term *biology* was first used in 1801 by Lamarck in his *Hydrogéologie*, (see Merz, *History*, p. 217). Huxley, in his *Lecture on the Study of Biology*, [South Kensington (Dec. 1876), reprinted in *American Addresses*, 1886, p. 129] gave the following account of the early history of the word:

> About the same time it occurred to Gottfried Reinhold Treviranus (1776–1837) of Bremen, that all those sciences which deal with living matter are essentially and fundamentally one, and ought to be treated as a whole; and in the year 1802 he published the first volume of what he also called *Biologie*. Treviranus's great merit lies in this, that he worked out his idea, and wrote the very remarkable book to which I refer. It consists of six volumes, and occupied its author for twenty years—from 1802 to 1822. That is the origin of the term "biology"; and that is how it has come about that all clear thinkers and lovers of consistent nomenclature have substituted for the old confusing name of "natural history," which has conveyed so many meanings, the term "biology," which denotes the whole of the sciences which deal with living things, whether they be animals or whether they be plants.

In the present volume, we address our attention particularly to continuum mechanics in physiology. By physiology we mean the science dealing with the normal functions of living things or their organs. Originally the term had a much more broad meaning. William Gilbert (1546–1603), personal physician to Queen Elizabeth, wrote a book (1600) called *On the Magnet and on Magnetic Bodies and Concerning the Great Magnet, the Earth, a New Physiology*, which was the first major original contribution to science published in England (Singer, *History*, p. 188). It earned the admiration of Francis Bacon and of Galileo. Note the last word in the title, "physiology." The word *physiologia* was, in fact, originally applied to the material working of the world as a whole, and not to the individual organism.

1.4 Mechanics in Physiology

In Sec. 1.2 we listed a slate of giants in applied mechanics. We can equally well list a slate of giants in physiology who clarified biomechanics. For example, following William Harvey (1578–1658), we have

Marcello Malpighi (1628–1694)
Stephen Hales (1677–1761)