Biomechanics

Motion, Flow, Stress, and Growth

Other titles by the same author:

Biomechanics: Mechanical Properties of Living Tissues (1981)

Biodynamics: Circulation (1984)

Y.C. Fung

Biomechanics

Motion, Flow, Stress,
and Growth

With 254 Illustrations

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*Dedicated
to the
Memory of
My Father*
馮曜字重光
*Fung
Chung-
Kwang
(1896–
1952),
Educator,
Painter.*

*He painted
this scroll
in 1939.
He loved
monkeys
because
“they
are like
children.”*

Preface

Biomechanics aims to explain the mechanics of life and living. From molecules to organisms, everything must obey the laws of mechanics. Clarification of mechanics clarifies many things. Biomechanics helps us to appreciate life. It sensitizes us to observe nature. It is a tool for design and invention of devices to improve the quality of life. It is a useful tool, a simple tool, a valuable tool, an unavoidable tool. It is a necessary part of biology and engineering.

The method of biomechanics is the method of engineering, which consists of observation, experimentation, theorization, validation, and application. To understand any object, we must know its geometry and materials of construction, the mechanical properties of the materials involved, the governing natural laws, the mathematical formulation of specific problems and their solutions, and the results of validation. Once understood, one goes on to develop applications. In my plan to present an outline of biomechanics, I followed the engineering approach and used three volumes. In the first volume, *Biomechanics: Mechanical Properties of Living Tissues*, the geometrical structure and the rheological properties of various materials, tissues, and organs are presented. In the second volume, *Biodynamics: Circulation*, the physiology of blood circulation is analyzed by the engineering method. In the third volume, the present one, the methods of problem formulation, solution, and validation are further illustrated by studying the motion of man and animals, the internal and external fluid flow, the stress distribution in the bodies, strength of tissues and organs, and the relationship between stress and growth. Thus the three volumes form a unit, although each retains a degree of independence.

The plan of this book is as follows. In Chapter 1, Newton's laws of motion and the basic equations of solid and fluid mechanics are presented and illustrated by biological examples. In Chapter 2, the motion of a system of

connected elastic or rigid bodies is considered. Generalized coordinates, generalized forces, and Lagrange's equations are used. This method is especially useful in the analysis of the musculoskeletal system because it offers a systematic way of dealing with the many muscles involved in locomotion.

Then we consider external flow in Chapters 3 and 4, and internal flow in Chapters 5 through 9. External flow is the flow around bodies moving in wind and water, in locomotion, flying, and swimming. Internal flow is the flow of blood in blood vessels, gas in airways, water and other body fluid in interstitial space, urine in kidney, ureter and urethra. Although blood flow is treated in *Biodynamics* (Fung, 1984), a sketch of its salient features is included in Chapters 5 and 6 to make this volume somewhat self-contained, while some new topics are added. Chapter 7 treats the flow of gas in the lung. Chapter 8 derives the basic equations of fluid movement in the interstitial space between blood vessels and cells, as well as the transport mechanisms in cell membranes. Multiphasic mixtures are also discussed. Chapter 9 presents the analysis of fluid movement from capillaries to the interstitial space and lymphatics, the indicator dilution method of measurement, and transport by peristalsis.

The rest of the book is devoted to the biological effects of stress and strain. In Chapter 10 we set down the basic concepts of stress and strain in bodies subjected to large deformation. A simple introduction to the finite deformation theory is offered. I hope to acquaint the reader with the physical meaning of the most important formulas of the theory, and with the distinctions between Green's and Almansi's strains, and Cauchy's, Kirchhoff's, and Lagrange's stresses. With this easy introduction, I trust that the reader will be confident to use these quantities and formulas when dealing with soft tissues.

In Chapter 11, stress and strain in organs is studied. In Chapter 12, the strength of tissues and organs is considered. Trauma due to blunt impacts in airplane or automobile crashes is discussed.

In the last chapter, we consider the phenomena of growth and resorption of cells, tissues, and organs in relation to stress: phenomena such as hypertrophy due to high blood pressure, resorption due to too high or too low a stress, and normal growth with exercise in proper range. These phenomena are controlled by biological, chemical, and physical stimuli, including physical stress and strain. Furthermore, growth or resorption of tissues changes the zero-stress configurations of organs. Conversely, changes of zero-stress configurations are convenient indications of tissue remodeling.

The rapid progress of bioengineering makes a serious attempt at *tissue engineering* possible. A person's own cells may be grown rapidly in a polymer scaffold for use as tissue substitute in surgical repair of serious disease or trauma. Close attention to the study of growth in the future can be predicted.

Completeness is not claimed. Our subject is young, and progress is rapid. Seeking greater permanency, I have limited the scope of this book to the more fundamental aspects of biomechanics. For other aspects and handbook material, the reader must turn to the library. Liberal but selected lists of references are given in each chapter. Problems are proposed for solution, some of them

with references to articles in the literature. These problems will serve to broaden the scope of our discussion or point to further applications of the principles, or new directions of research.

When I began writing these books, I made a 10-year plan. I did not anticipate that it would take much longer. The first draft of the manuscript of this volume was completed in 1980. Successive revisions, simplifications, and amplifications were made to reflect the advancing frontiers of our subject, and to gain a greater clarity.

There are many people whose help I must acknowledge. First, on classical subjects I followed classical books, especially Sir James Lighthill's book on Biofluidynamics, and my friend Chia Shun Yih's book on Fluid Mechanics. Next, on biomechanics research I am indebted to many friends and colleagues who have influenced me greatly: Sidney Sobin, Michael Yen, Benjamin Zweifach, Geert Schmid-Schönbein, Hans Krumhaar, Dick Skalak, Savio Woo, Ted Yao-Tsu Wu, Maw Chang Lee, Zulai Tao, Charles C.J. Chuong, Evan Evans, Frank Yin, Paul Zupkas, and others. To Sid Sobin and Mike Yen, I must record my pleasure of having collaborated with them for more than 20 years. My students Jack Debes, Julius Guccione, Ghassan Kassab, Shu Qian Liu, Bruce Bedford, Carmela Rider, and Nina Tang read the final manuscript and gave me errata and other valuable suggestions. I also wish to express my thanks to the many authors and publishers who permitted me to quote from their publications and reproduce their figures and data in this book, especially to Professors Arnold Kuethe on flying, and James Hay on sports techniques. To my students at Caltech, UCSD, and several universities in China, I want to say thank you. You shaped this book by your questions, your enthusiasm, and your dismay. I am grateful to Perne Whaley for typing the manuscript.

La Jolla, California

Yuan-Cheng Fung

Caligraphy by
 鄭燮字板橋
Cheng Sih, alias
Banchiao (1693–1765)
“On Literary Style.”
Inscription says:
“Simplified as trees
in late Fall,
New as flowers
before Spring.”

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