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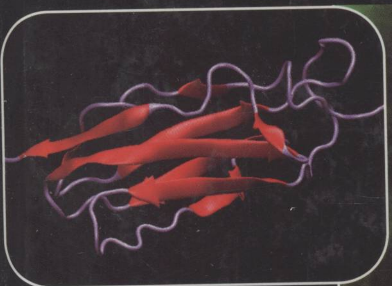
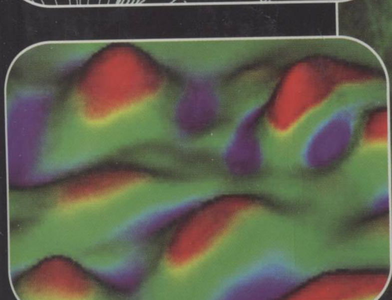
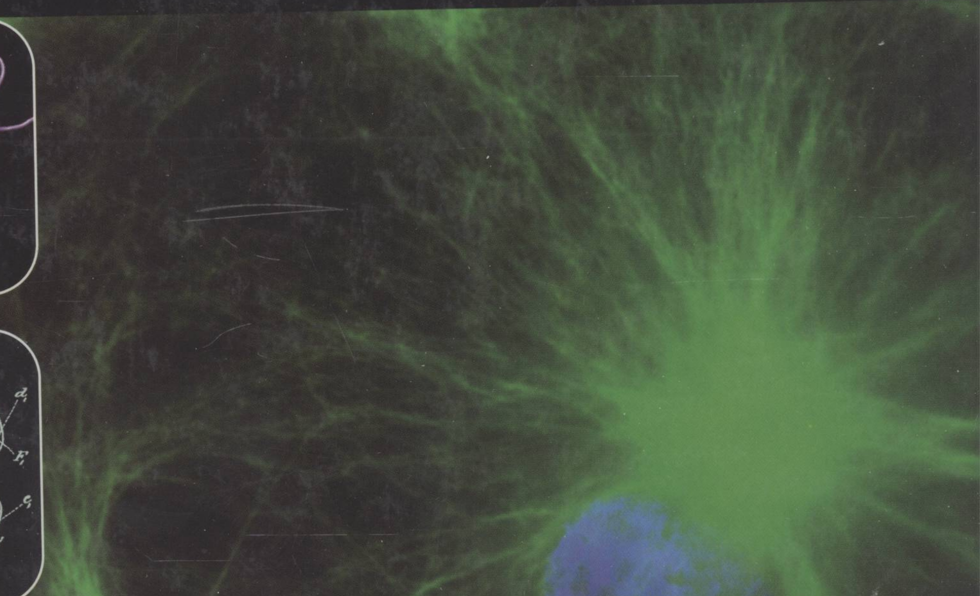
Introductory **Biomechanics**

From Cells to Organisms







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Introductory Biomechanics

From Cells to Organisms

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University of Toronto, Canada

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Introductory Biomechanics
From Cells to Organisms

Introductory Biomechanics is a new, integrated text written specifically for engineering students. It provides a broad overview of this important branch of the rapidly growing field of bioengineering. A wide selection of topics is presented, ranging from the mechanics of single cells to the dynamics of human movement. No prior biological knowledge is assumed and in each chapter, the relevant anatomy and physiology are first described. The biological system is then analyzed from a mechanical viewpoint by reducing it to its essential elements, using the laws of mechanics, and then linking mechanical insights back to biological function. This integrated approach provides students with a deeper understanding of both the mechanics and the biology than that obtained from qualitative study alone. The text is supported by a wealth of illustrations, tables, and examples, a large selection of suitable problems and many current references, making it an essential textbook for any biomechanics course.

C. Ross Ethier is a Professor of Mechanical and Industrial Engineering, the Canada Research Chair in Computational Mechanics, and the Director of the Institute of Biomaterials and Biomedical Engineering at the University of Toronto, with cross-appointment to the Department of Ophthalmology and Vision Sciences. His research focuses on biomechanical factors in glaucoma and on blood flow and mass transfer in the large arteries. He has taught biomechanics for over 10 years.

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Cambridge Texts in Biomedical Engineering provides a forum for high-quality, accessible textbooks targeted at undergraduate and graduate courses in biomedical engineering. It will cover a broad range of biomedical engineering topics from introductory texts to advanced topics including, but not limited to, biomechanics, physiology, biomedical instrumentation, imaging, signals and systems, cell engineering, and bioinformatics. The series will blend theory and practice, aimed primarily at biomedical engineering students but will be suitable for broader courses in engineering, the life sciences and medicine.

To my family, who make it all worthwhile.

C. ROSS ETHIER

To Deborah,
and to my parents, who inspired my love of learning.

CRAIG A. SIMMONS

About the cover

The cover contains images that together represent the broad scope of modern biomechanics. The figures are as follows:

- Main image: A fluorescent immunohistochemical image of an endothelial cell isolated from the surface of a pig aortic heart valve and grown in culture. Within the cell, the nucleus is stained blue and vimentin filaments are stained green. Vimentin is an intermediate filament protein of the cellular cytoskeleton that plays an important role in cellular mechanics.
- Left top: An intermediate stage from a simulation of the forced unfolding of repeats 4 and 5 of chain A of the protein filamin. Filamin is an actin cross-linking protein and therefore plays a role in the biomechanics of the cytoskeleton. The simulation was based on the crystal structure of part of filamin [1], and was carried out in NAMD [2] and visualized using the VMD package [3]. (Image courtesy of Mr. Blake Charlebois.)
- Left middle: A sketch by the Swiss anatomist Hermann von Meyer of the orientation of trabecular bone in the proximal human femur. This sketch was accompanied in the original article by a sketch of the principal stress trajectories in a crane having a shape similar to the femur. Together these sketches are believed to have inspired "Wolff's Law" of bone remodelling. From [4].
- Left lower: The distribution of mass transfer rates from flowing blood to cultured vascular endothelial cells. The contoured quantity (the Sherwood number) was computed by first measuring the topography of the endothelial cells using atomic force microscopy and then solving the convection-diffusion equation in the blood flowing over the cells. Mass transfer from blood to endothelial cells is important in cell-cell signalling. (Image courtesy of Mr. Ji Zhang.)

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Preface

For some years, we have taught an introductory course in biomechanics within the Department of Mechanical and Industrial Engineering at the University of Toronto. We have been unable to find a textbook suitable for the purpose of introducing engineers and others having a "hard science" background to the field of biomechanics. That is not to say that excellent books on biomechanics do not exist; in fact, there are many. However, they are typically at a level that is too advanced for an introductory course, or they cover too limited a subset of topics for purposes of an introductory course.

This book represents an attempt to fill this void. It is not meant to be an extensive treatise on any particular branch of biomechanics, but rather to be an introduction to a wide selection of biomechanics-related topics. Our hope is that it will aid the student in his or her introduction to the fascinating world of bioengineering, and will lead some to pursue the topic in greater detail.

In writing this book, we have assumed that the reader has a background in engineering and mathematics, which includes introductory courses in dynamics, statics, fluid mechanics, thermodynamics, and solid mechanics. No prior knowledge of biology, anatomy, or physiology is assumed, and in fact every section begins with a review of the relevant biological background. Each chapter then emphasizes identification and description of the essential aspects of the related biomechanics problems. Because of the introductory nature of this book, this has led in some cases to a great deal of simplification, but in all instances, we have tried to maintain a firm link to "biological reality."

We wish to thank Professor David F. James, of the Department of Mechanical and Industrial Engineering, University of Toronto. He first developed the introductory course in biomechanical engineering at the University and his course notes provided the inspiration for parts of this book. Professors James E. Moore Jr. and Takami Yamaguchi provided important material for Ch. 1. We have benefited greatly from interactions with our students, who sometimes are the best teachers, and our colleagues and mentors.

We shall be most grateful to students who, upon discovering errors in the text, bring them to our attention.

Contents

1 Introduction

Biomechanics is a branch of the field of bioengineering, which we define as the application of engineering principles to biological systems. Most bioengineering is applied to humans, and in this book the primary emphasis will be on *Homo sapiens*. The bioengineer seeks to understand basic physiological processes, to improve human health via applied problem solving, or both. This is a difficult task, since the workings of the body are formidably complex. Despite this difficulty, the bioengineer's contribution can be substantial, and the rewards for success far outweigh the difficulties of the task.

Biomechanics is the study of how physical forces interact with living systems. If you are not familiar with biomechanics, this might strike you as a somewhat esoteric topic, and you may even ask yourself the question: Why does biomechanics matter? It turns out that biomechanics is far from esoteric and plays an important role in diverse areas of growth, development, tissue remodeling and homeostasis. Further, biomechanics plays a central role in the pathogenesis of some diseases, and in the treatment of these diseases. Let us give a few specific examples:

- How do your bones "know" how big and strong to be so that they can support your weight and deal with the loads imposed on them? Evidence shows that the growth of bone is driven by mechanical stimuli [1]. More specifically, mechanical stresses and strains induce bone cells (*osteoblasts* and *osteoclasts*) to add or remove bone just where it is needed. Because of the obvious mechanical function played by bone, it makes good sense to use mechanical stress as the feedback signal for bone growth and remodeling. But biomechanics also plays a "hidden" regulatory role in other growth processes, as the next example will show.
- How do our arteries "know" how big to be so that they can deliver just the right amount of blood to their distal capillary beds? There is good evidence that this is determined in large part by the mechanical stress exerted on the artery wall by flowing blood. Endothelial cells lining the inner arterial surface sense this shear stress and send signals to cells deeper in the artery wall to direct the remodeling of the artery so as to enlarge or reduce its caliber [2].

- What about biomechanics in everyday life? Probably the most obvious application of biomechanics is in locomotion (walking, running, jumping), where our muscles generate forces that are transferred to the ground by bones and soft connective tissue. This is so commonplace that we rarely think about it, yet the biomechanics of locomotion is remarkably complex (watch a baby learning to walk!) and still incompletely understood.
- Locomotion happens on many scales, from whole organisms all the way down to individual cells. Unicellular organisms must be able to move so as to gather nutrients, and they have evolved a variety of clever strategies to accomplish this task [3]. In multicellular organisms, the ability of single cells to move is essential in processes such as repair of wounds, capture of foreign pathogens, and tissue differentiation. Force generation at the cellular level is a fascinating topic that is the subject of much active research.
- Cells can generate forces, but just as importantly, they can sense and respond to forces. We alluded to this above in the examples of bone remodeling and arterial caliber adjustment, but it is not only endothelial and bone cells that can sense forces. In fact, the ability of mechanical stress to elicit a biological response in cells seems to be the rule rather than the exception, and some cells are exquisitely specialized for just this task. One remarkable example is the hair cells in the ear. These cells have bundles of thin fibers (the *stereocilia*) that protrude from the apical cell surface and act as sensitive accelerometers; as a result, the hair cells are excited by sound-induced vibrations in the inner ear. This excitation produces electrochemical signals that are conducted by the auditory nerve to the auditory centers in the brain in a process that we call hearing [4,5].[1]
- The examples above show that biomechanics is important in homeostasis and normal function. Unfortunately, biomechanics also plays a role in some diseases. One example is glaucoma, an ocular disease that affects about 65 million people worldwide [6]. Normally the human eye is internally pressurized, a fact that you can verify by gently touching your eye through the closed eyelid. In most forms of glaucoma, the pressure in the eye becomes elevated to pathological levels, and the resulting extra biomechanical load somehow damages the optic nerve, eventually leading to blindness [7]. A second example is atherosclerosis, a common arterial disease in which non-physiological stress distributions on endothelial cells promote the disease process [8].
- What about biomechanics in the treatment of disease and dysfunction? There are obvious roles in the design of implants that have a mechanical function,

[1] Actually, the function of the hair cells is even more amazing than it first appears. The outer hair cells are active amplifiers, changing their shape in response to mechanical stimulation and thus generating sounds. The net effect is to apply a frequency-selective boost to incoming sounds and hence improve the sensitivity of the ear.

such as total artificial hips [9], dental implants [10], and mechanical heart valves [11]. In the longer term, we expect to treat many diseases by implanting engineered replacement tissue into patients. For tissues that have a mechanical function (e.g., heart valves, cartilage), there is now convincing evidence that application of mechanical load to the tissue while it is being grown is essential for proper function after implantation. For example, heart valves grown in a bioreactor incorporating flow through the valve showed good mechanical properties and function when implanted [12]. Cartilage subjected to cyclic shearing during growth was stiffer and could bear more load than cartilage grown without mechanical stimulation [13]. We expect that biomechanics will become increasingly important in tissue engineering, along the way leading to better fundamental understanding of how cells respond to stresses.

The above examples should give a flavor of the important role that biomechanics plays in health and disease. One of the central characteristics of the field is that it is highly interdisciplinary: to be called biomechanics, there must be elements of both mechanics and biology (or medicine). Advances in the field occur when people can work at the frontier of these two areas, and accordingly we will try to give both the "bio" and the "mechanics" due consideration in this book.

Another characteristic feature of biomechanics is that the topic is fairly broad. We can get a sense of just how broad it is by looking at some of the professional societies that fall under the heading of biomechanics. For example, in Japan alone, at least six different professional societies cover the field of biomechanics.[2] Obviously we cannot, in a single book, go into detail in every topic area within such a broad field. Therefore, we have given an introduction to a variety of topics, with the hope of whetting readers' appetites.

1.1 A brief history of biomechanics

We can learn more about the field of biomechanics by looking at its history. In one sense, biomechanics is a fairly young discipline, having been recognized as an independent subject of enquiry with its own body of knowledge, societies, journals, and conferences for only around 30–40 years. For example, the "Biomechanics and Human Factors Division" (later to become the "Bioengineering Division") of the American Society of Mechanical Engineering was established in late 1966. The International Society of Biomechanics was founded August 30, 1973; the European

[2] These are the Japanese Society of Biomechanics, the Bioengineering Division of the Japan Society of Mechanical Engineers, the Japan Society of Medical Electronics and Biological Engineering, the Association of Oromaxillofacial Biomechanics, the Japanese Society for Clinical Biomechanics and the Japanese Society of Biorheology.