PREFACE

COMPARATIVE BIOMECHANICS, MEANING A BROADLY BIOLOGICAL RATHER THAN a narrowly human subject, deals with the cheap, physical stuff—to rehabilitate a phrase from my youth. It worries about why trees so rarely fall over, why legged creatures switch from walking to running at particular speeds, how slugs slither, how flies fly, how samaras spin. In short, it starts with the ordinary activities of ordinary organisms, posing the questions a person might ask while exploring a coastline or tramping through a forest.

What draws its particular questions together is the kind of explanations to which they yield. Initially, at least, they draw on a physical and macroscopic world, a world closer to the purview of mechanical engineers than that of most contemporary biologists. The bad news is this unfamiliarity of its context. But that's a minor snag next to the good news—its wonderfully commonplace character. Comparative biomechanics invokes notions closer to one's everyday experience and intuitive sense of reality than does any other area of contemporary science. Gravity and elasticity have an immediacy that cells and molecules, let alone galaxies and subatomic particles, do not.

Although that physical world may be immediate and attractive, we have to face the fact that neither explaining nor quantifying it draws on well-used items in the biologist's intellectual toolbox. The present book tries to lead the reader into that world as gently as the author knows how; it tries both to make the case that biomechanics matters and that the subject need not be approached with fear, trepidation, and dark memories of first-year physics. It tries to demystify biomechanics, making it something to bear in mind, something to pursue more specifically when it proves relevant to a particular question, whatever the origin or context of the question. The field shouldn't be the private domain of initiates, isolated and insulated within its jargon and journals.

The primary purpose of the book is to provide a basic textbook for undergraduates and graduate students who may have taken an introductory biology course but who've had minimal exposure to physics and mathematics and none to engineering. It reflects about 25 years of offering—or co-teaching—such a course. My perception of the needs of students and investigators in the field has defined the level and scope of the book.

Based both on my aspirations and experience with the first edition, I intend a wider role for the present edition, in fact several of them. Even the course served a wider group, as about a third of the students came from engineering, and it usually attracted a small but diverse scattering of other people. But my correspondence made clear that "textbook" in the present sense didn't fully

describe the first edition's readership. Biologists outside the biomechanical community seemed to have found it a useful reference. People involved in human biomechanics—kinesiologists, exercise scientists, orthopedists—took notice of it. Engineers appeared to use it as a window on what we biologists of a biomechanical persuasion spend our time doing. An institute focused on biomimetics mined it for portentous ore. And the hands-on, macroscopic character of the material drew attention from science museums. For that matter, the book grew out of (by way of *Life's Devices,* a predecessor) a course for adult nonscientists that used the very commonplace character of biomechanical questions as a way to get them thinking in scientific terms rather than simply seeing science as a body of someone else's knowledge.

When I decided to have a go at a proper textbook, I sent e-mailings (e-missions or e-missives or e-missiles?) to all the people I knew who might be teaching comparative biomechanics to undergraduates. The overwhelmingly positive response came as no surprise—what had anyone to lose? What mattered more were all the useful suggestions, lists of references, and offers to test-run any preliminary version. A little worrisome, though, were the course outlines. With no standard book or long tradition, courses were divergent and eclectic; I envisioned a bunch of people waiting for the book, each with the expectation that it would follow a specific course description sent in a couple of years earlier.

And that brings up a problem that remains. Breaking with some canon is one thing, inadvertently creating a canon in a field blessedly unconstrained by one is quite another. So I must admit at the start, if more as warning than apology, its unavoidably idiosyncratic content. More deliberate is its equally idiosyncratic style. No generally accessible area of science better illustrates the way science is a process and a perpetual work-in-progress, and I've tried to give a sense of that reality with anecdotes, examples, and suggestions—but as best I could distinguishing the accepted from the opinionated. Similarly, I've included a fair dose of experimental particulars to connect the book to the reality of doing biomechanics, whether retrospectively or prospectively.

Content. Biomechanics covers an awesome diversity of things. The sheer mass of the book (and its 260,000 words) may strike the reader as some assurance of comprehensiveness (never mind comprehensibility). Do not be misled—major areas of perhaps equivalent relevance have been left out. Indeed, I've been driven nearly nuts deciding what to put in and what to leave out. My first rule has been to begin at the beginning, focusing on material that forms the background needed to go further into the subject. My second has been to pick material that tells useful stories, cases with general explanatory value. And my third has been to focus on topics that could be presented without presuming much background in the particulars of other areas of biology—and the various fields of biology have no end of particulars. And, good intentions aside, one tends to use material with which one is familiar, biasing coverage toward one's own work and that of associates.

As a result, the relative emphasis on different subjects doesn't reflect the relative attention they've received by investigators or my full judgment about relative importance. In particular, it has led to an underrepresentation of "hard" subjects, such as unsteady flows, computational approaches, and the work of some of the most impressive current investigators. As a further consequence, subjects whose understanding depends on a lot of morphological information have been given short shrift—however impressed I remain with what functional morphologists have done in recent years. Locomotion gets the

lion's share of current effort; it's not an equivalent presence in number of pages here. Concomitantly, animals get more attention than plants; I've no brief for equal time, but sap and wood matter at least as much as blood and bone. Paleobiomechanics gets ever more interesting, but I felt myself too far from the subject to have any decent perspective. And so on.

Organization. We're dealing with a subject lacking an obviously sequential character. So I've mostly made up the sequence of presentation myself, and I present it with no great conviction of its superiority, with a sense of fairly arbitrary decisions forced by the linearity of pagination. But I have tried to facilitate the use of the book by courses with different sequences, at least as far as I could with naturally interdependent topics. Part one serves a role that's both necessary and initiatory—although engineers may find most of it laughably primitive. In contrast, parts two and three can be done with either coming first or, for short courses, omitting one or the other. Part four forms a coda that can be used in its entirety, or in part, or augmented, or else ignored altogether. On a finer level, certain chapters can be omitted without laying traps that will catch the reader further along—in particular, chapters 10, 13, 14, 18, 22, 25, and, of course, 26. Gaining versatility, though, has cost some redundancy. Once again, I'm painfully conscious of the possibility that I may be de facto defining a canonical course in comparative biomechanics, and I want to impose as few constraints as possible.

Level. The course I gave prerequired basic college physics and calculus, which I could afford to do, because we required no less for our biology majors. But I've never been particularly taken with the choice of material of basic physics courses, and the book has had to cover for the way those courses avoided fluids, dimensionless numbers, nonrigid materials, and structures (beams and columns). Chapters 2 and 3 provide some extra background; more will be found in the appendices—enough, I hope, so even someone who has not taken a physics course can manage.

What's different in this second edition? The first chapter has been shortened, and quite a bit of the material in what were chapters 2–4 has been moved to appendices—both changes were made to move more quickly into the subject proper. Surface tension, shells, specific solid materials, viscoelasticity, and friction receive more attention. What had been chapter 5 is now chapters 4 and 5; what had been 16 is now 16 and 17. Most chapters now end with problems for students—or compulsive readers. And the references are considerably greater in number as well as more recent, the last recognizing that the 10 years between editions have seen a host of rich additions to our field.

A few other prefatory notes:

- The choice of symbols may strike the nonbiomechanic as inefficient or worse. I've tried to follow the conventions used in more specialized books, especially the ones by engineers. The awkward consequence is a marriage of various fields, traditions, and histories, in particular because solid and fluid mechanics have been pursued by different people.
- The extensive references to the primary literature in the text may be a bit unusual for books intended for undergraduates, but much of the biomechanical literature ought to be accessible to them. In addition, I want to encourage use of this book as an entry point into the field for anyone who wants one. I strongly recommend that the rapidly superannuating references be

popped into one or another forward-searching ("cited by") engine, such as Google Scholar or Web of Science.

- Nonbiologists might find it useful to buy some old (thus cheap) edition of an introductory biology textbook—all have copious indices and, even for terminological matters, will be more useful than a biological dictionary. Alternatively, instructors can accumulate a pile of loaners from the recipients of publisher's samples. My experience indicates that returns hit 100 percent when you suggest that return of the loaner is prerequisite for getting a grade.
- A collection of teaching resources may be obtained for the asking; for more information, please visit http://press.princeton.edu/titles/10046.html. These include suggestions for classroom demonstrations, small out-of-class projects, useful web sites, and so forth—plus an ongoing list of errors that have turned up in the text. Contributions to the collection will be welcomed. Most of that material can also be found under "biomechanics" on the web site of the Society for Integrative and Comparative Biology, http://www.sicb.org/dl/.
- Physicians take an oath by which they promise at least to do no harm; textbook writers should take an equivalent oath at least to tell no lies. For some subjects, that's no simple matter.

The number of people who have helped me in this endeavor goes beyond what I can conveniently list here. Students, other faculty members, other writers, and friends began contributing long before the book became a specific task and continued to respond to queries right up to submission time. And I kept no proper list. I note, with appreciation and good memories, that the first edition was sketched out while I was a guest at the Raman Research Institute in Bangalore, India—I'm grateful in particular to my host, V. Radhakrishnan ("Rad"). Several chapters were written at the Friday Harbor Laboratories, San Juan Island, of the University of Washington, where I enjoyed residence at the Whiteley Center—I must especially thank Arthur Whiteley and Dennis Willows. I wrote in a room called "Arthurs' Study"—the position of the apostrophe alludes to Arthurs Martin and Whiteley, both of whom, as it happens, appear in the present references. Gestation of the present edition took place at Croasdaile Village, in Durham, North Carolina, distracting me from proper participation in the community.

Most of the drawings here are the products of Annette deFerrari, although I've reused ones done by Susan Tanner Beety, Rosemary Calvert, Kate Davis, and Sally Schrohenloher. All the illustrations have been drawn specifically for this or my previous books, although a few represent only slight modifications of specific originals. Where single published sources have been used, acknowledgment of permission has been made in the legends.

Finally I want to thank the people at Princeton University Press, a publisher with whom I have had a long and productive association. This book would not have happened without the timely and effective urging of Alison Kalett. And Natalie Baan, Quinn Fusting, and Dimitri Karetnikov have pushed the project along with remarkable—and again effective—expeditiousness.