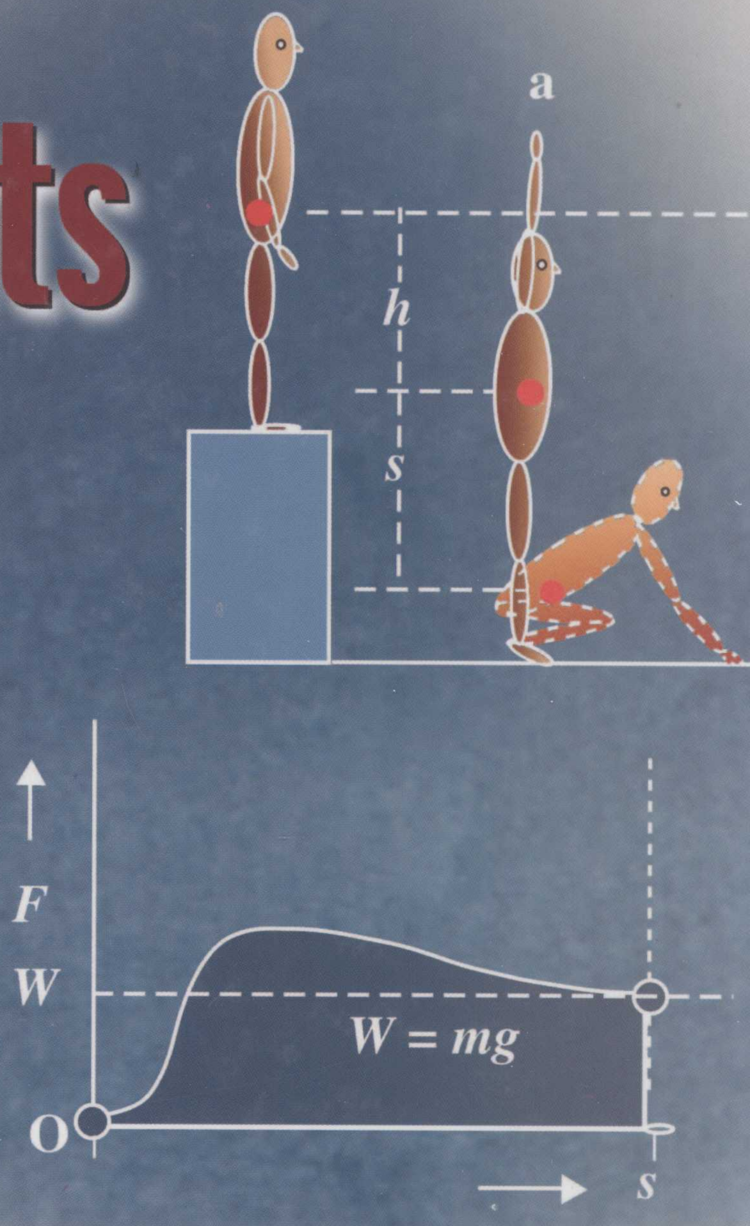
Biomechanical Analysis of Fundamental Human Movements

Arthur E. Chapman



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This book is dedicated to my wife,
who raised my children,
who in turn participated in many casual experiments
without their knowledge or permission,
and further to my daughter,
who has provided two more experimental subjects.

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to all my graduate students
who I believe are and will continue to be friends.

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gave me both intellectual and scientific grounding
in this area of lifelong interest.

Last of all,
I should like to dedicate this book to my parents,
both of whom knew how to kick a ball
but didn't know why scientifically
and sadly will never know.

Preface

Have you ever asked yourself, Why can't sprinters accelerate forever? Why can you land without injury from a height that is much greater than the height you can jump up to? Why is running a much more costly activity per distance traveled than walking? Why can't a pole-vaulter increase the height of the vault continuously by using poles of ever-increasing length? Why do bicycles have a range of gears? Why is it ungainly to walk without free movement of the arms? What are the energy and safety requirements of lifting a large load one time in comparison with lifting 1/10 of the total load in 10 repetitions? The answers are to be found in your mechanical properties, working according to the laws of mechanics in our gravitational field.

Human movement has existed for much longer than we have been able to talk about it. Despite the development of language, it was only recently in human existence that laws of movement of bodies, human and otherwise, were formalized. Now we are in a position to be able to take a scientific approach to the understanding of human movement. This area of study is biomechanics—a name that indicates the application of scientific principles and laws toward an understanding of biological systems. Specifically we are dealing with biomechanics of human movement, which in itself is a small part of the whole range of investigation in human biomechanics.

This book adheres to rigid mechanical and biological definitions and concepts. For example, force is recognized as that influence which accelerates a mass. Should there be no acceleration, either the force is zero or there must exist an equal and oppositely directed force (Newton's third law). It is true that application of a force increases the velocity of a thrown object. Yet this statement is inaccurate in the sense that we require more knowledge about the force in order to calculate velocity. In fact, it is either force multiplied by time (impulse) or force multiplied by the displacement of the force (work) that is required. Correct terminology must also be applied to our description of human motion. The term "hip flexion" has a specific meaning and refers to the movement of a joint. The phrase "flexing one's muscles" has no meaning in the biomechanical world.

The ability to determine the effect of some influence on motion or to calculate the speed of an action requires the language of a science known as mathematics. Without mathematics there can be no accurate numerical description of motion and no ability to relate biomechanical concepts. Numerical calculus is particularly important as a means of describing human motion. For example, force produces acceleration; and the relationship between acceleration, velocity, and displacement can be understood only if the concepts of differential and integral calculus are mastered.

No engineer would design a machine without an understanding of the mechanical properties of the motor driving it. Although we are not designing a human machine, knowledge of the mechanical properties of muscle enables us to understand why we do things in the way we do and what modifications we might make in the way we do something to enhance performance. Since muscle shows force–velocity and force–length relationships, its ability to produce acceleration depends on the instantaneous kinematic state (position and velocity) of the body.

An understanding of the mechanical properties of ligament, tendon, cartilage, and joint structure and articulation is also necessary. For example, cartilage can dissipate dangerous amounts of energy, and ligament and tendon can provide a temporary storage of energy that can be returned to the system when appropriate.

Audience and Approach

This book is written for those students who wish to understand human movement by means of scientific, quantitative biomechanical analysis. The information contained here should satisfy this wish as it provides an approach that is uncompromisingly mathematical and mechanical.

Earlier books in this area explained human movement by recourse to well-established mechanical laws. Such explanations were descriptions of how a variety of mechanical phenomena were exhibited in a variety of activities. The aim was to educate readers about the reasons we do things the way we do. This approach may be criticized as merely an academic exercise since we have been performing these movements without description for millennia. A further criticism is that these early books described the status quo of current human activities without facilitating an understanding of how movement may be modified. Yet such a development was a necessary precursor to more detailed study, as numerous important mechanical reasons for a particular type of movement were illustrated.

Many books on biomechanics tend to use examples of research that can appear to be rather disjointed. The problem with this type of compilation of information is that no formal approach to the study of human movement is either used or proposed. This book takes a systematic approach by examining the mechanical essentials of a task and then explaining how these essentials can be achieved by use of the biomechanical properties of the body. The purpose is to provide strategies and techniques for human performance and also biomechanical analysis of human movement from mathematical and mechanical viewpoints. Consequently this book is written for those individuals who either have a good grounding in mechanics or are prepared to learn mechanics. The information will be of use to teachers of human movement, to sport apparel and safety equipment designers, and to rehabilitation specialists. The current information will be useful to any person who wishes to understand the mechanical interaction of the human with the environment and the force, work, and energy either induced or required in such interaction. This material is essential for those who wish to perform advanced research in the area of human biomechanics. The material that is presented is necessary to allow the reader to advance from qualitative to quantitative understanding of human biomechanics; and it is the basis for calculation, or at the very least estimation, of the effects of adopting a change in technique in a particular activity. The mechanics, in conjunction with the information on properties of body structures, will enhance the reader's ability to estimate or calculate loads either applied to the body as a whole or induced in individual structures.

Since the early stage of this discipline, a great deal of research has been conducted for a wide range of reasons. Some of the reasons have been specific—for example, to identify the pattern of forces at the shoe-ground interface in running. Some implications of this work are in the design of running shoes and the avoidance of repetitive strain injuries in long distance running. Yet whatever the intention of the researcher, all of these investigations involve mechanics and mathematics.

Human biomechanics is a cross-disciplinary approach to understanding our biomechanical system through the laws of mechanics. Therefore information is provided on the structures involved in human movement such as bones, ligaments, cartilage, and muscles. The important properties of these structures are necessarily mechanical and include their viscoelastic characteristics and their properties of energy storage, release, and dissipation.

Muscle is given special attention as the force and work producer that is under our volition, as opposed to gravity, about which we can do nothing. Many of the mathematical techniques necessary to perform mechanical calculations are included in appendix B, but some are incorporated into the text in cases in which the material requires understanding of additional mechanics.

As in all textbooks, the question arises as to the depth of information that can be expected. This book is designed for upper-level undergraduate and graduate students of human movement. It should also be useful for those graduate students whose specialization is not biomechanics but who need to analyze human movement for other reasons; motor behaviorists are a good example.

How This Book Is Organized

The text is organized into two parts comprising 11 chapters. Part I includes three chapters covering the principles of biomechanics. Chapter 1, "Biomechanical Structures of the Body," deals with structures of the body including the skeletal framework and the properties of other tissues. The aim is to give the reader an appreciation of the biomechanical properties of the structures that either move the human "machine" or restrict its movement. Chapter 2, "Essential Mechanics and Mathematics," deals with the mechanics and mathematics necessary for our purpose. This order of presentation of the mechanical concepts differs from that of most mechanics textbooks, and it includes only information pertinent to our study. The aim is to develop mechanical concepts by means of a series of equations. Furthermore, readers will see that this material not only is mechanical but also includes the mathematics needed to manipulate the equations. Without mathematics, mechanics either makes little sense or is at best vague. Books that purport to teach biomechanics nonmathematically usually provide no more than a description of motion using mechanical terminology. To keep this chapter from becoming a lengthy mechanics primer, some mechanical concepts are dealt with in the chapters where they naturally arise.

Chapter 3, "Foundations of Movement," deals with those factors that move us, such as muscular force and gravity; those factors that enable us to move, such as friction; and the manner in which intersegmental motion occurs. Introductory mechanics usually deals with single rigid bodies. In our case we have a multisegmental body comprising head, upper arms, forearms, trunk, thigh, and so on. Obviously these segments move in relation to each other, and chapter 3 describes the manner in which this is accomplished. This relative motion, known as articulation, is one reason we can perform a wide range of activities, but also why we are sometimes in danger of injury. In other words, a machine with many moving parts is in greater danger of breaking down than is a single lump of matter.

Part II, "Fundamental Human Movements," is an examination of the mechanics of a wide range of fundamental human activities. While this part can be seen as the body of the book, readers will not be able to understand all the material unless they have completely mastered the preceding chapters. However, readers are encouraged to preview any one of the fundamental movements in order to appreciate what type of scientific information is necessary.

Devoting part II to the biomechanical analysis of fundamental human movements was an alternative to dealing with the intricacies of a variety of movements in a particular sport. The reason for this approach is that most, if not all, of our special activities (e.g., sporting and work) involve aspects of the fundamental movements. For example, running is a part of almost all of our sporting activities. A further reason is that many of our apparently simple, well-learned, and mundane movements often produce injury, as a result of either a single traumatic event or excessive repetition. The format for analysis of each fundamental activity involves a formal process in which the first step is to describe the primary *aim* of the activity. The next step is to convert the verbal description into a *mechanical* aim such as maximization of work or maximization of potential energy. Structures in the human body that can contribute to achievement of the mechanical aim are then identified, and the manner in which they can or should be used is determined based on knowledge of their properties. At this stage the *biomechanical* analysis of the movement is complete, and what follows is an examination of *variations* of the primary aim. For jumping, for example, the high jump, long jump, triple jump, and pole vault are examined for their particular requirements. Means of *enhancing* performance are examined with respect to changing the properties of body structures involved. A section on *safety* identifies potential injuries to body structures and then identifies strategies for avoidance of injury based on the manner in which the structures are used in the activity. Some worked *practical examples* are given to reinforce both the mathematical manipulation of biomechanical data and the process of solving a biomechanical problem. Finally, a chapter summary refers to the major points using common language rather than the technical language that predominates in the body of the chapter.

Chapters adhere to the following scheme for each of the fundamental movements:

1. *The aim:* This section identifies the primary mechanical aim of a given human activity from its initial verbal description.

2. *Mechanics:* In this section we identify the mechanical formulas which best describe how to achieve the mechanical aim. This second stage is both something of an art and a matter of convenience, since all mechanical formulas are related. For example, if we know force, time, mass, and displacement, we can deduce both momentum and energy. In some cases momentum rather than energy (or vice versa) may be the best way to capture the nature of the activity in question.

3. *Biomechanics:* This discussion identifies structures in the human body that can contribute to achievement of the mechanical aim and explains how these structures should or can be used based on knowledge of their properties.

4. *Variations:* This section examines variations of the primary aim. For example, for jumping, the particular requirements of the high jump, long jump, triple jump, and pole vault are identified.

5. *Enhancement:* This discussion focuses on ways in which the structures involved may be modified to enhance performance of the aim.

6. *Safety:* This section deals with how potential injuries to the structures may be identified and avoided. In some cases the questions of enhancement and safety are somewhat synonymous. In those cases safety is dealt with under the heading "Enhancement and Safety."

7. *Practical examples:* Worked examples are presented to demonstrate the choice of mechanical approach and the mathematical techniques that can be used to solve biomechanical problems, as well as to illustrate how biomechanics facilitates understanding of the nature of a given movement and its limitations. In many cases the examples can only approximate the biomechanics of the real situation because the muscle force produced depends upon the kinematics that the muscle itself produces. This leads to a complex situation that cannot be solved through application of the principles of calculus to an equation of the motion. This problem has been solved in the text through use of simulation of an activity whose solution requires numerical analysis. However, instruction on any other than basic numerical analysis is beyond the scope of this book.

The chosen format for this book is analysis of fundamental human movements because these movements have their application in a variety of everyday human situations. While the analysis uses examples from a variety of human situations, this is not a textbook on how to play a given game or how to work in a specific occupation. Many of these movements are combined and incorporated into a human situation, whether it is sporting or occupational or whether it has to do simply with survival. It is hoped that mastery of the fundamentals will provide a body of information and a method of analysis that can be applied to human tasks of interest to the reader.

The overall aim is to impart accurate scientific knowledge of a biomechanical nature in order to counter the misinformation, obfuscation, and ambiguity that surround this area of the study of human movement.

Special Features

The text is supplemented by several special elements. Within each chapter the reader will find Key Points, which summarize critical information; Recommended Readings; and Practical Examples as described for part II.

The Recommended Readings include sources of basic reference material on which this book is based, categorized according to discipline and application of biomechanics. The bibliography includes journal titles for those interested in delving deeper into a specific application, and conference proceedings that are accessible by modern electronic means.

In addition to a glossary, a bibliography, and a detailed index, several unique elements are included at the back of the book. Appendix A presents key symbols for mechanical variables, and appendix B presents mechanical formulas. Appendix C contains 68 problems that readers can tackle to test their grasp of biomechanical analysis; these are categorized by mechanical concept rather than by fundamental human movement. The topics include kinematics, forces and moments, impulse–momentum, and work–energy. The answers to the problems are provided in appendix D. Readers will have to develop the diagrams for each problem in the manner done for the worked examples in the text.

The author hopes that upon completion of this material, the reader will be armed with a full understanding of this branch of human biomechanics. Readers should then be able to identify the appropriate approach to investigating activities they are interested in. They should also be better armed with the ability to suggest novel ways of performing an activity. Last but not least, readers should be able to describe to others what is happening in a human movement, why it is happening, and what makes it happen. Readers' descriptions will employ correct usage of mechanical terms, and readers will appreciate that much popular use of mechanical terms is misleading at best and at worst incorrect.

Many books on human biomechanics have taken a mechanical concept and identified activities in which the concept is implicated. This approach is useful for learning mechanics through experience of well-recognized activities. The unique feature of this book is that the fundamental activity is of prime importance and the biomechanical concepts that best facilitate its understanding are identified.

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Contents

PART I

Introduction

When making sense of the biomechanics of human movement, we need three basic subsets of information. Chapter 1 concerns the manner in which the human system is constructed. Within this area we require information on the framework of the body, how parts of the framework are linked together, which structures aid the linkage, and which produce relative motion of the parts. If our interest is in safety, we also need to know the strength of the linking tissues and the mechanical conditions predisposing them to injury. The second subset of information, in chapter 2, deals with the conceptual and practical tools that facilitate biomechanical analysis. The mechanics give us an understanding of the way bodies move in our gravitational world, and the mathematics allow us to use mechanical equations to produce numbers representing movement. Chapter 3 concerns the foundations of movement. External agencies such as gravity and friction are considered. Mechanical properties of muscles are dealt with from the point of view of the internal forces that they create, how they predispose us to certain optimal patterns of movement, how they are used to generate maximal momentum and maximal kinetic energy, and how they facilitate redistribution of both momentum and energy among body parts. Chapter 3 ends with a discussion of the forces occurring between body parts and the analytical framework for their determination. Successful understanding of part I will allow the reader to tackle the analyses of fundamental human movements in part II.

CHAPTER 1

Biomechanical Structures of the Body

Study of the mechanics of a system must begin with knowledge of the size, shape, and inertial properties of the parts that compose it. Further knowledge is required on the kinematics and frictional characteristics of the mechanical linkage of connected parts. The study is completed by knowledge of the properties of the motive forces driving the system. This outline relates particularly to a system that does not change once constructed. Alternatively, the biomechanical system is subject to change. Its individual parts or segments, largely constructed of bone, muscle, and fat, are nonuniform and can change their size, shape, and inertial characteristics with age, use, and nutrition. The linkages or joints between segments have some interesting properties that can also change with these factors. Lastly, the motors or muscles driving the segments have complex properties that are subject to change. It is these animal motors that not only allow us to move, but also predispose us to certain patterns of movement depending upon the goals of our movement. This chapter concerns the structure of the human body primarily from the point of view that we are a moving machine capable of an enormous range of skills, but also capable of breakdown. The underlying theme is the biomechanics of the form and properties of the constituent parts of the human body. To this end we will confine ourselves to things biomechanical and leave the other wonderful features of human beings to others.

A question arises: How much do we need to know about the form and function of the body in order to perform biomechanical analysis? The answer is, "What are the goals of our investigation?" What we require in order to understand the biomechanical causes of lateral epicondylitis or "tennis elbow" is quite different from the knowledge we need to understand the biomechanical process of performing a handstand in gymnastics. Another question arises: What depth of knowledge is required? The answer in this case is, "How accurate do you want the results of your investigation to be?" In this chapter the aim is to present a body of biomechanical knowledge of the structure that is sufficient for understanding and analyzing a wide variety of fundamental human movements. A simpler statement might be that we need to know what to plug into our equations of motion so that we can tell a true story about human movement.

Not all of the material in this chapter is directly pertinent to the biomechanics of a single, fundamental human movement. For example, it is not necessary to know the ultimate strength of bones in order to understand how we jump. Such information is included because knowledge of the mechanical properties of biomechanical structures is important if we are to understand the effects of loads induced during fundamental activities. An exhaustive study of this area has been published by Nordin and Frankel (2001). The presentation in this chapter assumes that readers are familiar with the anatomical terminology for principal axes and planes; joint motion; and names of muscles, their locations, and points of origin and insertion.

The Frame

The frame or endoskeleton is the most rigid supporting structure in the body. This endoskeleton is the basic structure upon which the rest hangs. Long bones give us reach and leverage so that we can transport ourselves and manipulate objects that are at some distance from the mass of the body. Such aims are achieved by the long bones comprising the upper and lower limbs by means of enlargements at each end where they contact other bones to form an articulation, and at various other places along their length where tendons insert. The purpose of such enlargements is dealt with later in relation to their mechanical significance. Flat bones such as the iliac bone and the scapula have large surfaces where large areas of muscles can be inserted. Although the leverage of these muscles may be small, their size is an important part of their biomechanical energy-generation mechanism. This avoids the need for us to carry large muscles at the periphery. Such an arrangement would greatly increase the inertial properties of the body, and result in a concomitant increase in energy cost to the whole system during movement. The bones of the cranium are flat bones which protect the brain, yet they also perform the biomechanical function of providing a large surface of attachment for some muscles involved in feeding. Many other oddly shaped bones, such as the carpal bones of the wrist and their counterpart tarsal bones of the ankle, have important functions during our forceful mechanical interaction with the external world.

The bones of the frame are effectively rigid in comparison with the softer mechanical tissues. In reality, bones have elastic and other properties that are implicated in movements involving high-impact forces. These properties allow bending rather than breaking of bones, and as such contribute to energy dissipation when bones are loaded, as in falling. Unfortunately, when forces are too large or there is too much energy to absorb, bones can break. A further property of bone is that as a living tissue its cells are constantly being destroyed and created. This property is known as bone remodeling, in which both nutrition and applied forces play an important part. Without this feature any bone would wear out and lose its characteristic shape (see Currey, 1984).

■ Key Point

Bone shapes are implicated in joint leverage, the amount of muscle that can be attached, and the size of the articulation surface.

Articulations

Movement of one bone relative to another is known as articulation, so the joints are called articulations. Figure 1.1 shows a very rough approximation of the human knee joint linking the femur and tibia.

The knee joint provides a general example, as it displays most of the features of joints in general and is particularly subject to injury in many activities. Articulation occurs smoothly because the ends of the bones are covered in an especially smooth hyaline cartilage with low friction characteristics. You will be able to see this smooth surface on the ends of the bones of the next chicken leg you eat. In some joints there is also fibrocartilage, which not only aids in reducing joint friction but also modifies the shape of the articular surfaces. The knee joint contains two fibrocartilages; these are the structures removed when you have your

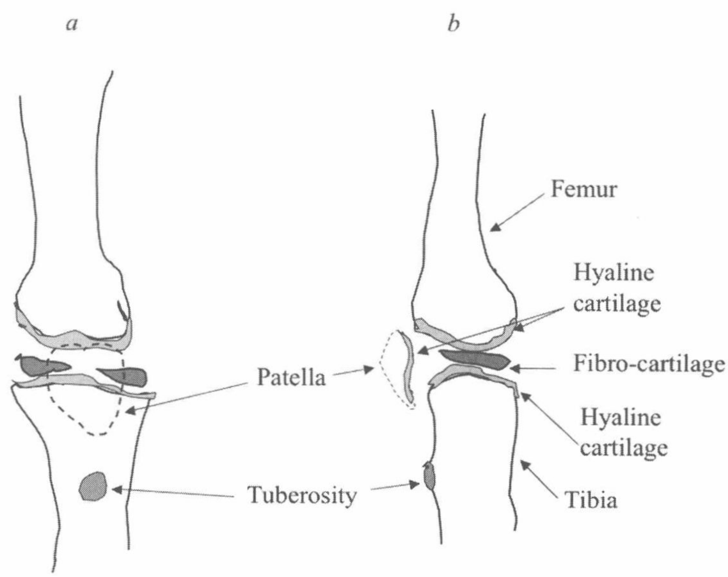

FIGURE 1.1 Bones and cartilages of the knee articulation, seen from *(a)* the front and *(b)* the side. The patella articulates upon the anterior aspects of the femoral condyles during movement.