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Preface

This book summarizes fundamental topics in biomechanics and provides procedures for biodynamic modeling.

In the last three or four decades, studies of biomechanics have expanded from simple topical applications of elementary mechanics to entire areas of study, occupying the attention of increasing numbers of scientists, engineers, and health care professionals. Today, studies and research in biomechanics exceed those in basic mechanics itself, even though basic mechanics underlies not only the study of biomechanics but many other fields as well.

Consequently, with today's knowledge base, a book or treatise on biomechanics can consider only a few of the many areas on the subject in any depth.

In this book, I have selected a few topics from the fundamentals of solid biomechanics with an emphasis on biodynamic modeling and on the analysis of human body models. The subject matter is a compilation of material drawn from a sequence of courses taught at the University of Cincinnati during the last 35 years or more.

This book is intended for students, researchers, and practitioners in various fields, with varying backgrounds, who are looking for a basic understanding of the principles of biomechanics analyses. The preparation needed is usually that acquired in the first years of undergraduate science and engineering curricula.

This book comprises 15 chapters together with an appendix containing a rather extensive listing of anthropometric data, a large glossary of terms and terminologies, and a bibliography for more in-depth studies.

Following a brief introductory chapter, this book presents a review of gross human anatomy and a summary of basic terminology currently in use. Chapters 3 through 5 describe methods of analysis from elementary mathematics to elementary mechanics, and on to fundamental concepts of the mechanics of materials.

Chapter 6 discusses the modeling of biosystems. Chapter 7 provides a brief overview of tissue biomechanics. Chapters 8 through 10 then introduce concepts of biodynamics and human body modeling, looking at the fundamentals of the kinematics, the kinetics, and the inertial properties of human body models.

Chapters 11 through 13 present a more detailed analysis of the kinematics, kinetics, and dynamics of these models. Chapter 14 discusses the numerical procedures for solving the governing dynamical equations.

Finally, in Chapter 15, the book concludes with a review of a few example applications of the biodynamic models. These include simple lifting, maneuvering in space, walking, swimming, and crash victim simulation. Each chapter contains its own list of references for additional study.

I am deeply appreciative of the encouragement and support of many friends, students, and colleagues in the preparation of this book over the past several years. I am especially appreciative of the vision and inspiration of Alvin Strauss and Chris Passerello who first brought the subject to my attention 40 years ago. The subsequent enthusiasm of students and of their focused studies in biomechanics was more than I had ever imagined possible. Their dedication inspired me to proceed with the writing of this book. These students include Roger Adelman, Eric Arthur, Brett Chouinard, John Connelly, Mina Dimov, Fadi El-Khatib, Joe Gallenstein, Cesar Grau, Mark Harlow, Dick Hessel, Stanley Huang, Dan Jones, George Khader, Jim Kamman, Tim King, David Lemmon, Chunghui Li, Fang Li, C.-Q. Liu, Chris Lowell, Sushma Madduri, Soumya Naga, Louise Obergefel, Chris Passerello, Jason Tein, Joe Tzou, Srikant Vallabhajosula, James Wade II, J. T. Wang, Tom Waters, Jim Winget, Michael Wu, and Sharon Yee.

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1

Introduction

What is biomechanics? Biomechanics is simply mechanics. Mechanics refers to those studies in engineering and applied physics concerned with forces and motion. Biomechanics is mechanics applied with living systems principally the human body.

While biomechanics is simply mechanics, and while mechanics can be a relatively simple subject (at least conceptually), the application with living systems is usually far from simple. Fabricated and inert systems are much less complex than living systems (or biosystems). With biosystems, the geometry is irregular and not easily represented by elementary figures or shapes. With biosystems, the material properties are inhomogeneous, anisotropic, and nonlinear. Indeed, biosystems are composed of solids, liquids, and gases with nonlinear viscoelastic and non-Newtonian characteristics. Biosystems present students and researchers with an uncountable number of challenging problems in modeling, simulation, and analysis. The aim of this book is to provide methods for simplifying and solving these problems.

1.1 Principal Areas of Biomechanics

Biomechanics may be conveniently divided into three principal areas: (1) performance, (2) injury, and (3) rehabilitation. Performance refers to the way living systems (primarily human beings) do things. It includes routine movements such as walking, sitting, standing, reaching, throwing, kicking, and carrying objects. It also refers to internal movement and behavior such as blood flow, fluid circulation, heart and muscle mechanics, and skeletal joint kinematics. In addition, performance connotes global activities such as oper-ating vehicles or tools, and sport mechanics.

Injury refers to failure and damage of biosystems as in broken bones, torn muscles, ligaments, and tendons, and organ impairment. Injury studies thus include evaluation of tissue properties. They also include studies of accidents and the design of protective devices.

Rehabilitation refers to the recovery from injury and disease. Rehabilitation thus includes all applications of mechanics in the health care industries encompassing such areas as design of corrective and assist devices, development of implants, design of diagnostic devices, and tissue healing mechanics.

1.2 Approach in This Book

Books could be written on each of these topics. Indeed, many have already been written (see Refs. [1–57]). It is thus impossible to encompass biomechanics in a single book. We therefore need to limit our scope to some extent. We have chosen to focus upon gross or whole-body biomechanics and associated analysis methods. That is, we will generally consider the overall system or the system in the large, as opposed to the internal workings of the system. We will also focus upon dynamic as opposed to static phenomena.

As the title suggests, a major portion of this book is devoted to fundamental methods of analysis. While research in biomechanics is closely related to advances in technology, it is believed that individual technological advances are often short-lived and that more long-term benefits are obtained by mastering the fundamental methods. Therefore, we include the text reviews of vector and matrix methods, and a summary of the methods of basic mechanics (statics, strength of materials, kinematics, kinetics, inertia, and dynamics). Readers already familiar with these topics may choose to simply skim over them.

We will use these fundamental methods to develop more advanced and computer-oriented methods. These include configuration graphs, lower body arrays, differentiation algorithms, partial velocity and partial angular velocity vectors, generalized speeds, and Kane's equations.

Finally, although our focus is gross motion simulation, we will still look at some topics in considerable depth to provide insight into those topics as well as to illustrate the developed analytical techniques. Throughout the text we will try to provide references for additional reading.

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2

Review of Human Anatomy and Some Basic Terminology

Most people are familiar with human anatomy—at least from an intuitive or gross perspective. Since our focus in this book is on gross biomechanics, such a general familiarity is sufficient for most of the discussions and analyses considered herein. Nevertheless, to be consistent in our terminology and to undergird our understanding of anatomical geometry, it is helpful to briefly review some of the terminology and the conventional biomechanics notation.

We begin with a presentation of conventions used in gross (or whole-body) modeling. We follow this with a review of the major bones and segments of the skeletal system. We then take a closer look at the cervical and lumbar spines and the principal connecting/articulating joints (shoulders, hips, elbows, knees, wrists, and ankles). We conclude with a consideration of the major muscle groups and with a presentation of anthropometric data.

2.1 Gross (Whole-Body) Modeling

Figure 2.1 contains a sketch of the human frame* where the dots represent major connecting joints. Figure 2.2 shows the same sketch with the human frame divided into its major segments or limbs. The resulting figure is a gross model of the human frame. We can further simplify this model by representing the segments by ellipsoids and frustums of elliptical cones as in Figure 2.3.

For analysis purposes, it is convenient to number and label the human model segments as in Figure 2.4. Also, in Figure 2.4, R represents an inertial (or Newtonian) reference frame in the system. It is often convenient to number or label R as body zero.

The human frame modeling in Figure 2.4 is sometimes called finitesegment modeling. The model itself is sometimes called a gross-motion simulator. We will use the model of Figure 2.4 in our analysis of human body kinematics and dynamics (see Table 2.1).

^{*} Using a Berol RapiDesign template: R-1050 human figure.



FIGURE 2.1 Sketch of the human frame.



FIGURE 2.2 Major segments of the human frame.



FIGURE 2.3 Modeling the human frame by ellipsoids and elliptical cones.



FIGURE 2.4 Numbering and labeling the human frame model.

TABLE 2.1

Body Segment Numbers for the Finite Segment Model of Figure 2.4

Segment Number	Segment Name	
0	Inertial reference frame	
1	Pelvis or lower-torso body	
2	Midriff or mid-torso body	
3	Chest or upper-torso body	
4	Left upper arm	
5	Left lower arm	
6	Left hand	
7	Neck	
8	Head	
9	Right upper arm	
10	Right lower arm	
11	Right hand	
12	Right upper leg or right thigh	
13	Right lower leg	
14	Right foot	
15	Left upper leg or left thigh	
16	Left lower leg	
17	Left foot	



FIGURE 2.5 Head/neck model.

Occasionally we may be interested in a more detailed modeling of the human frame-or more likely, a portion or part of the frame. For example, in injury studies we may be interested in head/ neck motion. Figure 2.5 shows a typical gross-motion model of the head and cervical vertebrae. Adjacent vertebrae can both translate and rotate relative to one another-at least, to some extent. Therefore, the soft tissue connecting the vertebrae are usually modeled by nonlinear springs and dampers. We will explore this further in later chapters.

Similarly, Figure 2.6 shows a model of the hand and wrist



FIGURE 2.6 Model of the hand and wrist.

which is useful for studying the gross kinematics (or movement) of the hand and its digits.

On many occasions, it is convenient to combine the use of a gross-motion model with the use of a more detailed model. For example, in neck injury studies of a crash victim, we may use a whole-body model as in Figure 2.4 to obtain the movement of the chest or upper-torso. Then, this upper torso movement may be used to determine more precise movement of the head and vertebrae through the head/neck model of Figure 2.5.

For these gross-motion models to be useful in kinematic and dynamic simulations, it is necessary to have accurate values for the physical (mass/inertia) and geometrical properties of the individual segments of the models. Also, it is necessary to have a good representation of the movement characteristics of the connecting joints. In many simulations a simple pin (or revolute) joint is a sufficient model. Other simulations may require a spherical (or ball-and-socket) model, and still others may require full, six degree of freedom movement. For even more precise modeling it may be necessary to use cam analyses.

The movement and constraints of the joints is governed by the soft tissue connecting the segments—that is, the ligaments, discs, tendons, and muscles. As noted earlier, this soft tissue is often modeled by semilinear and nonlinear springs and dampers.

While it is relatively easy to obtain reasonably accurate values for the physical and geometrical properties of the segments, it is much more difficult to obtain precise values for the coefficients and parameters of the joint spring and damper models. Indeed, improving the accuracy of the values of these coefficients and parameters is a topic of current research of many analysts.

2.2 Position and Direction Terminology

Consider a person in a standing position as in Figure 2.7. If a Cartesian coordinate system is placed in the person's torso it is common practice to have the *X*-axis forward, the *Z*-axis up, and the *Y*-axis to the person's left, as shown.



FIGURE 2.7 Coordinate axes for the body.

These axes define planes which are also useful in biomechanics analysis (Figure 2.8): the X–Y plane, called the transverse or horizontal plane, divides the body into upper and lower parts; the Y–Z plane, called the coronal or



FIGURE 2.8 Principal planes of the human body.

frontal plane, divides the body front to rear (anterior to posterior); and the Z-X plane, called the sagittal or median plane, divides the body left to right.

Similarly, *X*, *Y*, and *Z* axes may be affixed to the links and segments of the body selectively as illustrated in Figure 2.9. When the axes of these segments are mutually aligned (parallel) to one another and to the global *X*, *Y*, and *Z* axes of the torso, the body is said to be in the reference configuration.

The reference configuration may vary depending upon the intent of the analysis. For example, if we are interested in studying walking (gait) we may choose a reference configuration as in Figure 2.9. In this regard (for walking), the reference configuration has the planes of the hands facing inward or toward the median plane of the body. Alternatively, if we are interested in studying a vehicle operator we may choose a reference configuration representing a seated occupant with arms forward and up as in Figure 2.10.

With the torso being the largest segment of the human frame, the position and orientation of the other segments or limbs are usually measured relative to the torso. For example, the orientations of the head and neck are usually measured relative to each other and to the chest, as opposed to measuring their orientation relative to coordinate axes fixed in space.



(a) Front view

Coordinate axes of body segments.

FIGURE 2.9

(b) Side view



FIGURE 2.10 Reference configuration of a vehicle operator.

That is, it is usually more convenient to visualize and measure the orientations of the limbs relative to each other, and ultimately relative to the chest, as opposed to measuring absolute orientation in space.

The centrality of the torso is an intuitive concept. When people are asked to point to themselves, or to others, they invariably point to the chest.

The torso defines directions for the body: moving from the torso toward the head is usually regarded as upward (or superior) even if a person is lying down. Similarly, moving from the torso toward the feet is downward (or inferior). Also, limbs or portions of limbs away from the torso (such as fingers or toes) are said to be distal, whereas portions of limbs close to the torso (such as the shoulders) are said to be proximal.

Moving forward from the coronal plane is said to be the anterior direction. The rearward direction is called posterior. Similarly, moving away from the mid or sagittal plane is said to be lateral. Moving toward the sagittal plane is the medial direction, or medial side of a limb.

Figures 2.11 and 2.12 show these directions.* Tables 2.2 and 2.3, respectively, provide a summary description of the coordinate planes and direction terminology for the human body.



Superior/inferior and anterior/ posterior directions. **FIGURE 2.12** Lateral/medial and distal/proximal directions (Berol template).

^{*} Again using a Berol template.

Coordinate Planes of the Human Body in a Standing Position				
Name	Coordinate Axes	Description	Reference	
Transverse plane (horizontal plane)	X– Y (normal to Z)	Divides the body into upper and lower parts	Figure 2.8	
Coronal plane (frontal plane)	Y-Z (normal to X)	Divides the body front to rear	Figure 2.8	
Sagittal plane (medial plane)	Z– X (normal to Y)	Divides the body left to right	Figure 2.8	

TABLE 2.2

TABLE 2.3

Direction Terminology for the Human Body

Name	Description	Reference
Superior/inferior	Above/below or upper/lower	Figure 2.11
Anterior/posterior	Front/rear	Figure 2.11
Lateral/medial	Outside/inside	Figure 2.12
Distal/proximal	Away from/near to the chest	Figure 2.12

Terminology for Common Movements 2.3

Various movements of the limbs also have special terminology: Perhaps the most frequent of the limb movements is bending the arms at the elbows and the legs at the knees. Such bending is called flexion. Alternatively, straightening the arms or legs is called extension. In general, the bending of any limb or body part is called flexion and the straightening is called extension (Figures 2.13 and 2.14).

The concepts of flexion and extension are especially important in studying head and neck movement and injury. Bending the head forward, chin to chest, is flexion while bending the head rearward is called extension (Figure 2.15). The chest restricts the flexion but there is no comparable restriction to the extension. Thus, extension is generally more harmful than flexion.

The term extension can be misleading in that, in structural mechanics, extension refers to elongation, the opposite of shortening or compression. In body movement (kinesiology), however, extension is simply straightening, the opposite of flexion. With neck extension there may be either elongation or shortening of the neck [1].

When the head is moved to the side, ear to shoulder, the movement is called lateral bending. When the head is turned left or right the movement is called axial rotation, or simple rotation, or torsion, or twisting. Figure 2.16 shows these movements.



FIGURE 2.13 Arm flexion/extension (Berol template).

Some specific movements of the arms and legs are also of interest. When the forearm is rotated so that the palm of the hand faces downward it is called pronation. Rotation of the forearm so that the palm faces upward is called supination. Figure 2.17 shows these movements.

When the legs are brought together, as in clicking one's heels, the movement is called adduction (adding together). When the legs are separated or



FIGURE 2.14 Leg flexion/extension (Berol template).







(b) Extension

FIGURE 2.15

Head/neck flexion/extension (Berol template).





(a) Lateral bending

(b) Rotation (twisting)

FIGURE 2.16

Head/neck lateral bending and rotation (twisting) (Berol template).



FIGURE 2.17

Forearm rotation (right arm) (Berol template).



FIGURE 2.18

Adduction and abduction (Berol template).

spread apart, the movement is called abduction. Figure 2.18 depicts these movements.

When a person's legs are together more at the knees than at the feet (as in being knock-kneed) the position is called varus. When a person's legs are spread apart at the knees, more than at the feet (as in being bowlegged), the position is called valgus. Figure 2.19 depicts these positions.



FIGURE 2.19 Varus and valgus leg configuration (Berol template).



FIGURE 2.20 Plantarflexion and dorsiflexion foot movement (Berol template).

There are also some foot movements of interest. When one pushes the foot downward (as in accelerating a vehicle), the motion is called plantarflexion. The opposite motion, raising the toes upward, is called dorsiflexion. Figure 2.20 shows these movements.

Finally, when the soles of a person's feet are rotated outward, so as to cause a varus leg configuration, the motion is called eversion. Rotation of the feet inward so as to cause a valgus leg configuration is called inversion. Figure 2.21 shows these movements. Table 2.4 summarizes these common movements and their associated terminology.



FIGURE 2.21 Eversion and inversion of the feet (Berol template).

TABLE 2.4

Name	Description	Reference	
Flexion/extension	Bending/straightening	Figures 2.13 through 2.15	
Head lateral bending and rotation	Side-to-side movement and axial twisting	Figure 2.16	
Supination/pronation	Forearm movement with palm up/palm down	Figure 2.17	
Adduction/abduction	Leg bringing together/ spreading apart	Figure 2.18	
Varus/valgus	Leg positioning knees together/ knees apart	Figure 2.19	
Plantarflexion/dorsiflexion	Foot pushed down/raised up	Figure 2.20	
Eversion/inversion	Foot rotation outward/inward	Figure 2.21	

Common Movement Terminology for the Human Body

2.4 Skeletal Anatomy

Figure 2.22 shows a sketch of the human skeletal system, where the major bones are labeled. The femur (thigh bone) is the largest bone and the tibia (lower leg) and humerus (upper arm) are the next largest.



FIGURE 2.22 Human skeleton.



Figure 2.23 depicts the shape of the long bones. They are generally cylindrical with enlarged rounded ends. The long shaft is sometimes called the diaphysis and the rounded ends the epiphyses. The diaphysis is similar to a cylindrical shell with the outer wall composed of hard, compact bone (or cortical), and the cavity filled with soft spongy (or cancellous and sometimes called trabecular) bone [3,4]. The epiphyses with their enlarged shapes provide bearing surfaces for the joints and anchoring for the ligaments and tendons. The ligaments connect adjacent bones together and the tendons connect muscles to the bones.

Referring again to Figure 2.22, the skull is not a single bone but a series of shell-like bones knitted together as represented in Figure 2.24.

Referring yet again to Figure 2.22, the sternum (breast bone) is not a bone at all but is cartilage, as are those parts of the ribs attached to the sternum and spine.

Figure 2.25 shows a sketch of the spine. The spine is the principal supporting structure of the torso. It consists of four major parts: (1) the cervical spine (neck), (2) the thoracic spine (chest), (3) the lumbar spine (lower back), and (4) the sacrum (tail bones).

FIGURE 2.24





The spine is composed of annular bones (vertebrae) stacked upon one another and cushioned by discs—spongy, thick-walled annular fibrous structures with fluid interiors [5]. Figure 2.26 has a sketch of a typical vertebra from the cervical spine. The vertebrae are annular structures where the central opening, or foramen, accommodates the spinal cord.

Figure 2.27 provides a sketch of the cervical spine. It consists of seven vertebrae as shown. The cervical spine is the most flex-

ible of all the spine segments, enabling the



FIGURE 2.26 Typical cervical vertebra.



FIGURE 2.27 Sketch of the cervical spine.

global movement of the head. This flexibility, however, leaves the neck vulnerable to injury. Aggravating this vulnerability is the relatively fragile nature of the cervical vertebrae. They are small compared with the vertebrae of the thoracic and lumbar spines. But more than this, the foramen of the cervical vertebrae are large enough to accommodate the larger spinal cord of the neck.

The thoracic spine has 12 vertebrae, the lumbar spine has 5 vertebrae, and the sacrum has 5 fused vertebrae. The thoracic spine is supported by the ribs and is thus relatively well protected. The lumbar spine, however, is relatively unprotected and is thus a common source of injury, ailment, and pain.

2.5 Major Joints

In machine theory, joints are often classified by their degrees of freedom. The most common machine joint is the pin (the hinge or revolute joint) having one degree of freedom and as illustrated in Figure 2.28. Another one degree of freedom joint is the slider as in Figure 2.29. The most common three degree of freedom joint is the ball-and-socket, or spherical, joint as represented in Figure 2.30.

Bio-joints, or human body joints, are often represented or modeled by these mechanical joints. The elbows and knees are modeled as hinges and





FIGURE 2.30 Ball-and-socket or spherical joint.

the hips and shoulders are modeled as ball-and-sockets. A close examination of the limb movements at the elbows and knees, however, shows that the joints behave only approximately as hinges. Also, the shoulders and hips are only approximately spherical.

The spine movement may be modeled through a series of joints at the vertebral interfaces. Since the greatest flexibility is in the neck, the cervical joints are best represented by six degree of freedom joints, having both translation and rotation. Since there is less movement and almost no translation in the thoracic and lumbar spines, the movement in these spine segments may be represented through spherical joints.

2.6 Major Muscle Groups

The human body has three kinds of muscles: cardiac, smooth, and skeletal. Cardiac muscle is heart muscle and it occurs only in the heart. Smooth (or visceral) muscle occurs in the intestines, lungs, bladder, and other hollow organs. Skeletal muscle is the prominent visible muscle connected to the bones which moves the human frame. Skeletal muscle can be voluntarily controlled whereas cardiac and smooth muscle are involuntary. Skeletal muscles dominate our focus in global biomechanics. Figure 2.31 shows the major skeletal muscles.

Muscles contract and shorten. In this way they create and exert tension. By lengthening, however, they do not create compression. They pull but they do not push. Instead, they work in pairs: If a muscle causes limb flexion its counterpart will cause limb extension.

The muscles flexing and extending the arms are the biceps (flexion) and the triceps (extension). For the legs they are the hamstrings (flexion) and the quadriceps (extension).