Introduction

Humans have the capacity to produce a nearly infinite variety of postures and movements that require the structures of the human body to both generate and respond to forces that produce and control movement of the body's joints. Although it is impossible to capture all the kinesiologic elements that contribute to human musculoskeletal function at a given point in time, knowledge of at least some of the physical principles that govern the body's response to active and passive stresses is a prerequisite to an understanding of both human function and dysfunction.

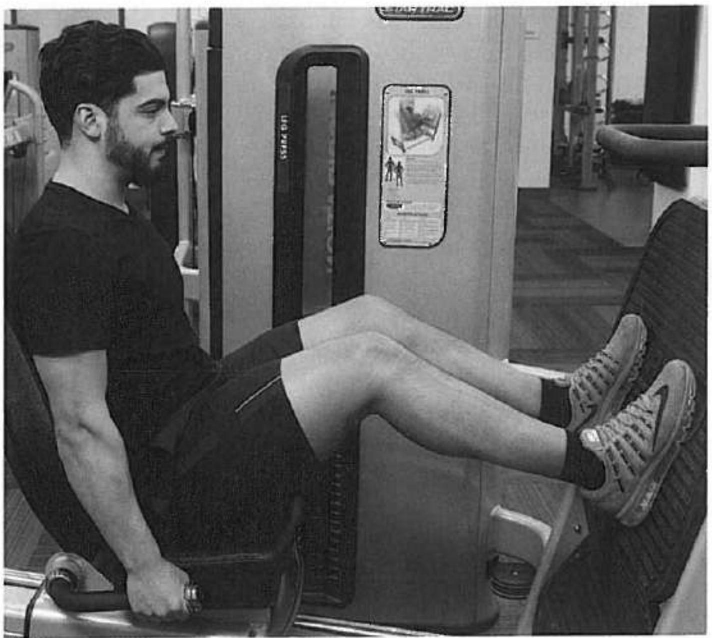
We will examine some of the complexities related to human musculoskeletal function by examining the roles of the bony segments, joint-related connective tissue structures, and muscles, as well as the external forces applied to those structures. We will develop a conceptual framework that provides a basis for understanding the stresses on the body's major joint complexes and the responses to those stresses. Case examples and clinical scenarios will be used to ground the reader's understanding in relevant applications of the presented principles. The objective is to cover the key biomechanical principles necessary to understand individual joints and their interdependent functions in posture and locomotion. Although we acknowledge the role of the neurological system in motor control, we leave it to others to develop an understanding of the theories that govern the roles of the controller and feedback mechanisms.

This chapter will explore the biomechanical principles that must be considered in the examination of the internal and external forces that produce or control movement. The focus will be largely on rigid body analysis; the next two chapters explore how forces affect deformable connective tissues (Chapter 2) and how muscles create and are affected by forces (Chapter 3). Subsequent chapters then examine the interactive nature of force, stress, tissue behaviors, and function through a regional exploration of the joint complexes of the body. The final two chapters integrate the function of the joint complexes into the comprehensive tasks of posture (Chapter 13) and gait (Chapter 14).

To maintain our focus on clinically relevant applications of the biomechanical principles presented in this chapter, the following patient application will provide a framework within which to explore the relevant principles of biomechanics.

Patient Application 1–1

John Alexander is 20 years old, 5 feet 9 inches (1.75 m) in height, and weighs 165 pounds (~75 kg or 734 N). John is a member of the university's lacrosse team. He sustained an injury when another player fell onto the posterior-lateral aspect of his right knee. Physical examination and magnetic resonance imaging (MRI) resulted in a diagnosis of a tear of the medial collateral ligament, a partial tear of the anterior cruciate ligament (ACL), and a partial tear of the medial meniscus. John agreed with the orthopedist's recommendation that a program of knee muscle strengthening was in order before moving on to more aggressive options such as surgery. The initial focus will be on strengthening the quadriceps muscle. The fitness center at the university has a leg-press machine **(Fig. 1–1A)** and a heavy ankle cuff weight **(Fig. 1–1B)** that John can use.



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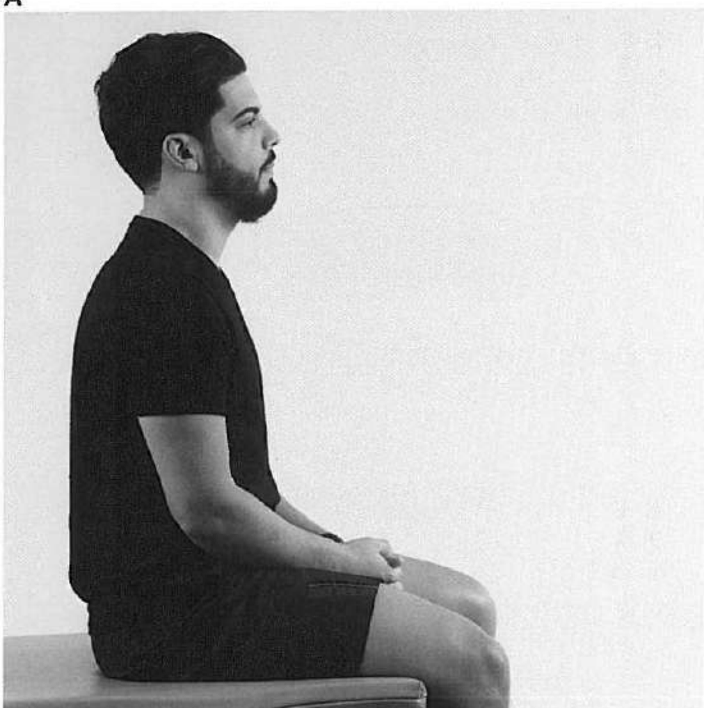

B

Figure 1–1 **A.** Leg-press exercise apparatus for strengthening hip and knee extensor muscles. **B.** Ankle weight for strengthening knee extensor muscles.

As we move through this chapter, we will consider the biomechanics of each of these rehabilitation exercise options in relation to John's injury and strengthening goals.

Human motion is inherently complex, involving multiple segments (bony levers) and forces that are most often applied to two or more segments simultaneously. To develop a conceptual model that can be understood and applied clinically, the common strategy is to focus on one segment at a time. For the purposes of analyzing John Alexander's issues, the focus will be on the leg-foot segment, treated as if it were one rigid unit acting at the knee joint. **Figure 1–2** is a schematic representation of the leg-foot segment in the leg-press and ankle weight scenarios. The leg-foot segment is the focus of the figure, although the contiguous components (distal femur, footplate of the leg-press machine, and the ankle weight) are maintained to give context. In some subsequent figures, the femur, footplate, and ankle weight are omitted for clarity, although the forces produced by these segments and objects will be shown. This limited visualization of a segment (or a selected few segments) can be referred to as a **free body diagram** or a **space diagram**. If proportional representation of all forces is maintained as the forces are added to the segment under consideration, it is known as a "free body diagram." If the forces are shown but a simplified understanding rather than graphic accuracy is the goal, then the figure is referred to as a "space diagram."[1] We will use space diagrams in this chapter and text because the forces are generally not drawn in proportion to their magnitudes for purposes of space efficiency.

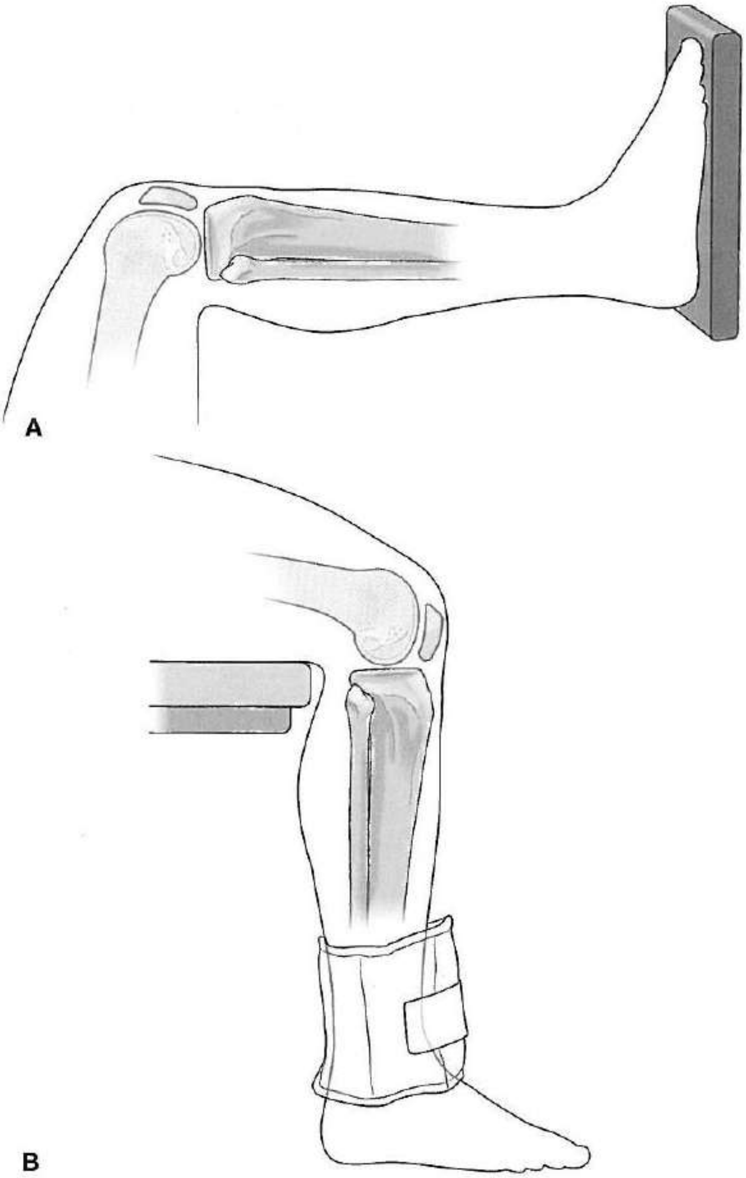

Figure 1–2 **A.** The leg-foot segment on the leg-press footrest. **B.** The leg-foot segment with an ankle weight.

As we begin to examine the leg-foot segment in either the ankle weight or leg-press exercise scenario, the first step is to describe the motion of the segment that is or will be occurring. This involves the area of biomechanics known as **kinematics.**

PART 1: Kinematics and Introduction to Kinetics

Descriptions of Motion

Kinematics includes the set of concepts that allows us to describe the **displacement** (the change in position over time) or motion of a segment without regard to the forces that cause that movement. The human skeleton is, quite literally, a system of segments or levers. Although bones are not truly rigid, we will assume that bones behave as rigid levers for purposes of simplification. There are five kinematic variables that fully describe the motion, or the displacement, of a segment: (1) the **type** of displacement (motion), (2) the **location** in space of the displacement, (3) the **direction** of the displacement of the segment, (4) the **magnitude** of the displacement, and (5) the **rate** of change in displacement (velocity) or the rate of change of velocity (acceleration).

Types of Displacement

Translatory and rotary motions are the two basic types of movement that can be attributed to any rigid segment. General motions are achieved by combining translatory and rotary motions.

Translatory Motion

Translatory motion (linear displacement) is the movement of a segment in a straight line. In human movement, isolated translatory movements are rare. However, a clinical example of an attempt at isolated translatory motion occurs during joint mobilization, whereby a clinician imposes a near linear motion (sliding) between two articular surfaces such as sliding the tibial plateau on the femur at the knee joint. In fact, translation of a body segment at an intact joint rarely occurs in human motion without some concomitant rotation (rotary motion) of that segment (even if the rotation is barely visible).

Rotary Motion

Rotary motion (angular displacement) is movement of a segment around a fixed axis **(center of rotation [CoR])** in a curved path. In true rotary motion, each point on the segment moves through the same angle, at the same time, at a constant distance from the center of rotation. True rotary motion can occur only if the segment is prevented from translating and is forced to rotate about a fixed axis. This rarely happens in human movement. In the example in **Figure 1–3**, all points on the leg-foot segment appear to move through the same angle at the same time around what appears to be a fixed axis. In actuality, none of the body segments move around truly fixed axes; all joint axes shift at least slightly during motion because segments are not sufficiently constrained to produce pure rotation.

General Motion

When nonsegmented objects are moved, combinations of rotation and translation **(general motion)** are common, although a number of terms can be used to describe the result.

Curvilinear (plane or planar) motion designates a combination of translation and rotation of a segment in *two dimensions* (parallel to a plane with a maximum of three degrees of freedom).[2–4] When this type of motion occurs, the axis about which the segment moves is not fixed but, rather, shifts in space as the object moves. The axis around which the segment appears to move in any part of its path is referred to as the **instantaneous center of rotation (ICoR), or instantaneous axis of rotation (IaR).** An object or segment that travels in a curvilinear path may be considered to be undergoing rotary motion around a fixed but quite distant CoR;[3,4] that is, the curvilinear path can be considered a segment of a much larger circle with a distant axis.

Three-dimensional motion is a general motion in which the segment moves across all three dimensions (planes). Just as curvilinear motion can be considered to occur around a single distant center of rotation, three-dimensional motion can be considered to be occurring around a **helical axis of motion (HaM), or screw axis of motion.**[3]

As already noted, the motion of a body segment is rarely sufficiently constrained by the ligamentous, muscular, or other bony forces acting on it to produce isolated rotary motion. Instead, there is typically at least a small amount of translation (and often a secondary rotation) that accompanies the primary rotary motion of a segment at a joint. Most joint rotations, therefore, take place around a series of instantaneous centers of rotation. The "axis" that is generally ascribed to a given joint motion (e.g., knee flexion) is typically a midpoint among these instantaneous centers of rotation rather than a truly fixed center of rotation. Because most body segments actually follow a curvilinear path, the true center of rotation is the point around which true rotary motion of the segment would occur and is generally quite distant from the joint.[3,4]

Location of Displacement in Space

The rotary or translatory displacement of a segment is commonly located in space by using the three-dimensional Cartesian coordinate system as a useful frame of reference. The origin of the x-axis, y-axis, and z-axis of the coordinate system for describing human movement is traditionally located at the **center of mass (CoM)** of the human body, assuming that the body is in **anatomic position** (facing forward in standing with palms forward) (**Fig. 1–4**). According to the common system described by Panjabi and White, the x-axis runs side-to-side in the body and is labeled as the **coronal axis**; the y-axis runs

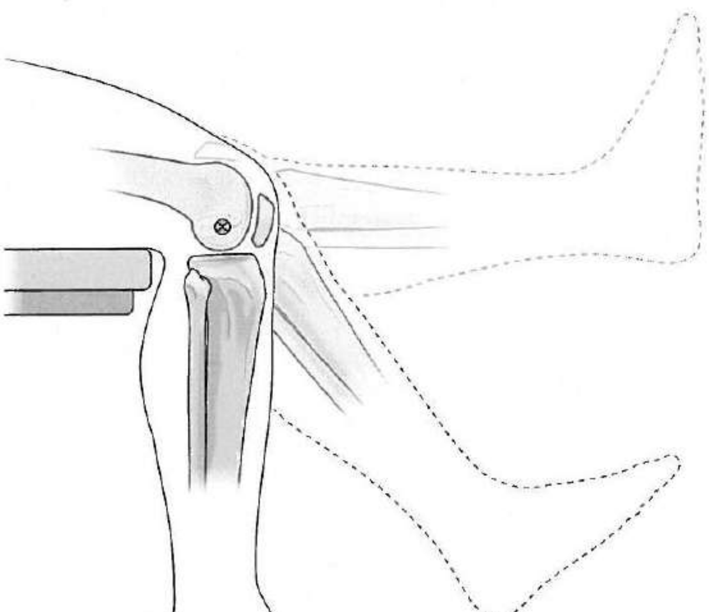

Figure 1–3 Rotary motion. Each point in the leg-foot segment moves through the same angle, at the same time, at a constant distance from the fixed (or relatively fixed) center of rotation or axis.

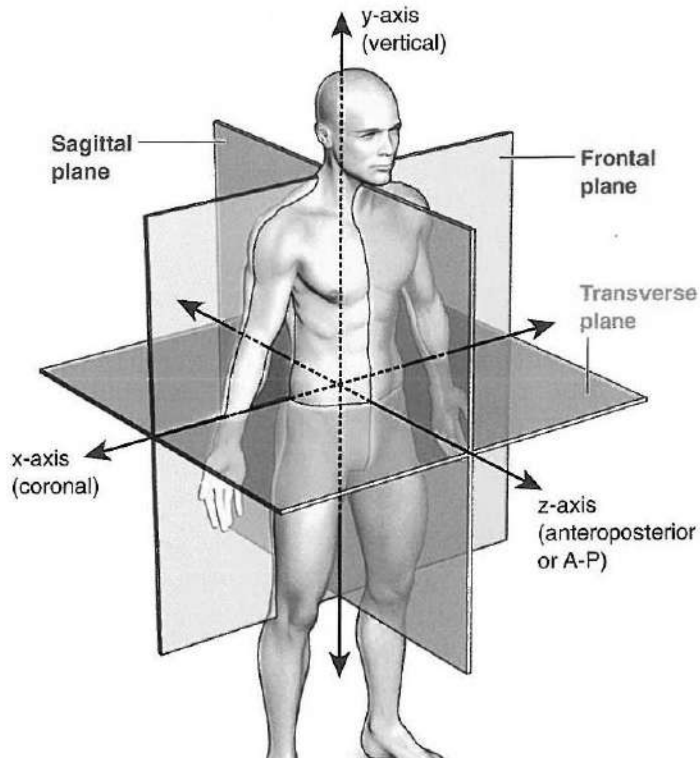

Figure 1–4 Body in anatomic position showing the x-axis, y-axis, and z-axis of the Cartesian coordinate system (the coronal, sagittal, and transverse planes, respectively).

up and down in the body and is labeled as the **vertical axis**; and the z-axis runs front to back in the body and is labeled as the **anteroposterior (A-P) axis.**[3] Motion of a segment can occur either *around* an axis (rotation) or *along* an axis (translation). An unconstrained segment can either rotate or translate around each of the three axes, resulting in six potential options for motion of that segment. The options for movement of a segment are also referred to as **degrees of freedom.** A completely unconstrained segment always has six degrees of freedom because it can rotate around the three axes (three degrees of freedom) as well as translate along the three axes (three additional degrees of freedom). Segments of the body, of course, are not unconstrained and—consequently—often have less than six degrees of freedom.

Rotation of a body segment is described not only as occurring around one of three possible axes but also as moving in or parallel to one of three possible **cardinal planes** (Fig. 1–4). As a segment rotates *around* a particular axis, the segment also moves in a plane that is perpendicular to its axis of rotation. Rotation of a body segment *around* the x-axis (coronal axis) occurs in the **sagittal plane**. Sagittal plane motions are most easily visualized as front-to-back motions of a segment (e.g., flexion/extension of the upper extremity at the glenohumeral joint).

Rotation of a body segment *around* the y-axis (vertical axis) occurs in the **transverse plane**. Transverse plane motions are most easily visualized as motions of a segment parallel to the ground (e.g., medial/lateral rotation of the lower extremity at the hip joint). Transverse plane motions at a joint often occur around an axis that passes through the length of the rotating long bone, resulting in an axis that is not truly vertically oriented. Consequently, the term **longitudinal** (or **long**) **axis** is often used instead of "vertical axis." Rotation of a body segment *around* the z-axis (A-P axis) occurs in the **frontal plane**. Frontal plane (also referred to as coronal plane) motions are most easily visualized as side-to-side motions of the segment (e.g., abduction/adduction of the upper extremity at the glenohumeral joint).

Rotation and translation of body segments are not limited to motion along or around cardinal axes or within cardinal planes. In fact, cardinal plane motions are the exception rather than the rule. Although useful for describing available motions at joints, cardinal planes and axes are an oversimplification of human motion. Much more commonly, a segment moves in three dimensions with two or more degrees of freedom.

Direction of Displacement

Even if displacement of a segment is confined to a single axis, the rotary or translatory motion of a segment around or along that axis can occur in two different directions (**Fig. 1–5**). For rotary motions, the direction of movement of a segment around an axis can be described as occurring in a clockwise or counterclockwise direction.

Flexion and **extension** are motions of a segment occurring around the same axis and in the same plane (uniaxial or uniplanar) but in opposite directions (**Fig. 1–5A**). Flexion and extension generally occur in the sagittal plane around a coronal axis, although exceptions exist (e.g., carpometacarpal flexion and extension of the thumb). **Abduction** and **adduction** of a segment occur around the A-P axis and in the frontal plane but in opposite directions (although carpometacarpal abduction and adduction of the thumb again serve as exceptions; **Fig. 1–5B**). Anatomically, abduction brings the segment away from the midline of the body, whereas adduction brings the segment toward the midline of the body. When the moving segment *is* part of the midline of the body (e.g., the trunk or the head), the rotary movement is commonly termed **lateral flexion** (to the right or left).

Medial (or **internal**) **rotation** and **lateral** (or **external**) **rotation** are opposite motions of a segment that generally occur around a vertical (or longitudinal) axis in the transverse plane (**Fig. 1–5C**). Anatomically, medial rotation occurs as the segment moves parallel to the ground and toward the midline, whereas lateral rotation occurs opposite to that. When the segment is part of the midline (e.g., the head or trunk), rotation in the transverse plane is simply called rotation to the right or rotation to the left. The exceptions to the general rules for naming motions must be learned on a joint-by-joint basis.

Magnitude of Displacement

The magnitude of rotary motion (or angular displacement) that a body segment can move through is known as its **range of motion (ROM).** The most widely used standardized clinical method of measuring available joint ROM is goniometry, with units given in degrees. If an object rotates through a complete circle, it has moved through 360°.

Translatory motion (displacement) of a segment is quantified by the linear distance through which the object or segment is displaced. The units for describing translatory motions are the same as those for length. The unit for the *Système International* system (SI) is the meter (or millimeter or centimeter); the corresponding unit in the U.S. system is the foot (or inch). This text will use the SI system but include a U.S. conversion when this appears to facilitate understanding (1 inch = 2.54 cm). Linear displacements of the entire body are often measured clinically. For example, the 6-minute Walk Test[5] (a test of functional status in individuals with cardiorespiratory problems) measures the distance in feet or meters that someone walks in 6 minutes.

Rate of Displacement

Although the magnitude of displacement is important, the rate of change in position of the segment (the displacement per unit time) is equally important. Displacement per unit time, regardless of direction, is known as **speed,** whereas displacement per unit time in a given direction is known as **velocity.** If the velocity is changing over time, the change in velocity per unit time is **acceleration.**

Linear velocity (velocity of a translating segment) is expressed as meters per second (m/sec) in SI units or feet per second (ft/sec) in U.S. units; the corresponding units for acceleration are meters per second squared (m/sec^2) and feet per second squared (ft/sec^2). Angular velocity (velocity of a rotating segment) is expressed as degrees per second (deg/sec), whereas angular acceleration is given as degrees per second squared (deg/sec^2).