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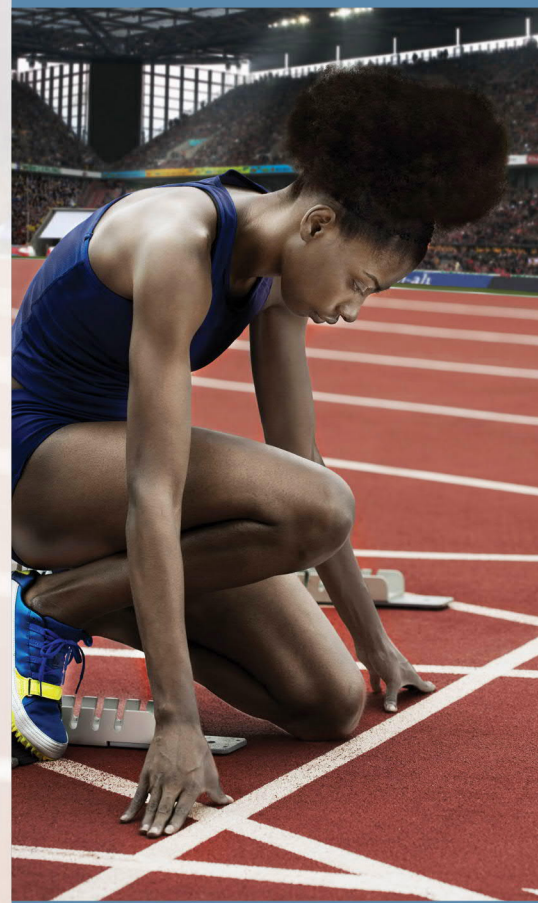
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Joint Structure and Function: Foundational Concepts

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Biomechanical Applications to Joint Structure and Function

Samuel R. Ward, PT, PhD, FAPTA | Bahar Shahidi, PT, DPT, PhD |
David B. Berry, PhD

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Introduction

Humans possess the remarkable ability to perform an almost limitless range of postures and movements. These actions depend on the body's ability to both generate and respond to forces that initiate and control the motion of its joints. Although it is not possible to capture all the kinesiological factors that contribute to human musculoskeletal function at any given moment, a foundational understanding of the physical principles that govern the body's response to both active and passive stresses is essential for understanding normal and impaired human movement.

In this chapter, we will examine the complexities of 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. The goal is to develop a conceptual framework for understanding the stresses placed on the body's major joint complexes and how those joints respond to such 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 last group of chapters will integrate the function of the joint complexes into the comprehensive tasks of posture (Chapter 13) and gait (Chapter 14) and then discuss how the forces imposed on the body may be altered in aquatic environments (Chapter 15).

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.

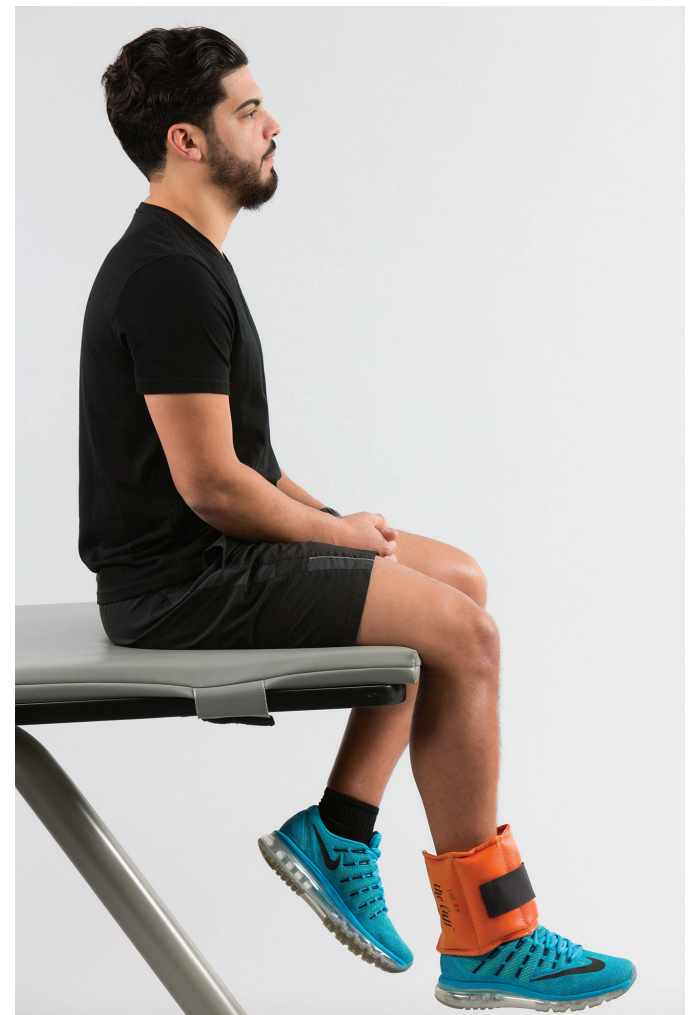


Patient Application 1-1

John Alexander is 20 years old, 5 ft 9 in. (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 (**Fig. 1-1**). 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.



A



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.

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 refers to the branch of mechanics that describes the motion or **displacement** (the change in position) of a segment over time, without regard to the forces that produce or influence 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.

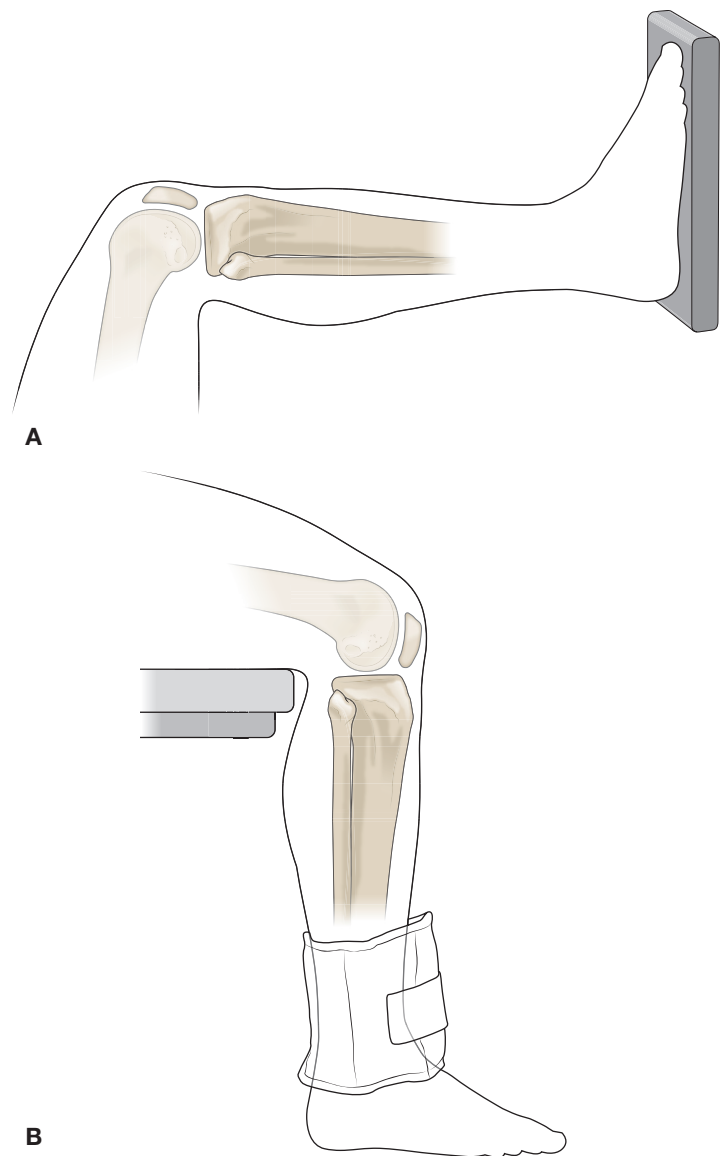


Figure 1-2 A. The leg-foot segment on the leg-press footrest. B. The leg-foot segment with an ankle weight.

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

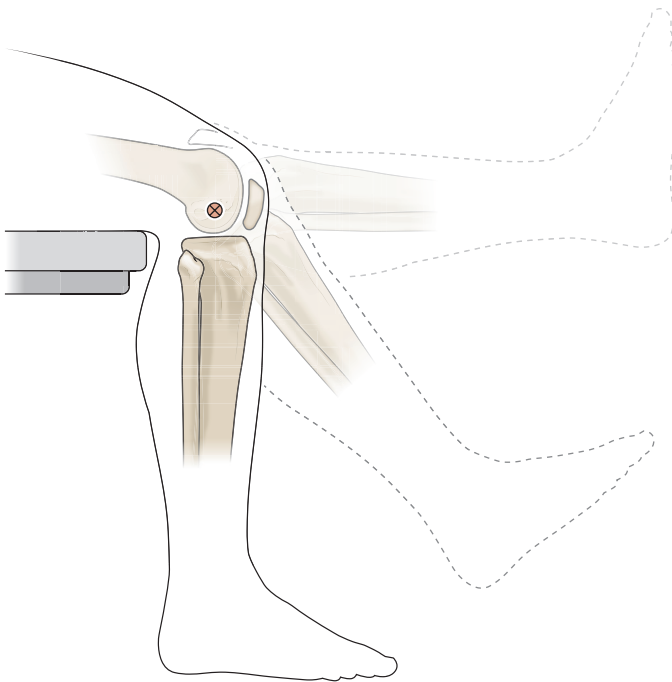


Figure 1-3 Rotary motion. Each point in the leg-foot segment moves through the same angle, at the same time, at a constant distance from the fixed (or relatively fixed) center of rotation or axis.

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 move, their motion typically involves a combination of rotation and translation, referred to as **general motion**.

Curvilinear motion (also called **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 at any point in 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 undergoing rotary motion around a fixed but quite distant CoR^{2,4}; that is, the curvilinear path can be considered one portion 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**.⁴

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.^{2,4}

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. In describing human movement, the intersection of the x-axis, y-axis, and z-axis of the coordinate system 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 front to back in the body and is labeled as the **anteroposterior (A-P) axis**; and the z-axis runs up and down in the body and is labeled as the **vertical axis**.⁴ 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 as occurring around one of three possible axes, but also as moving in or parallel to one of three possible **cardinal planes** (see **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 (A-P axis) occurs in the **frontal plane**. Frontal plane motions (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 of a body segment *around* the z-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).

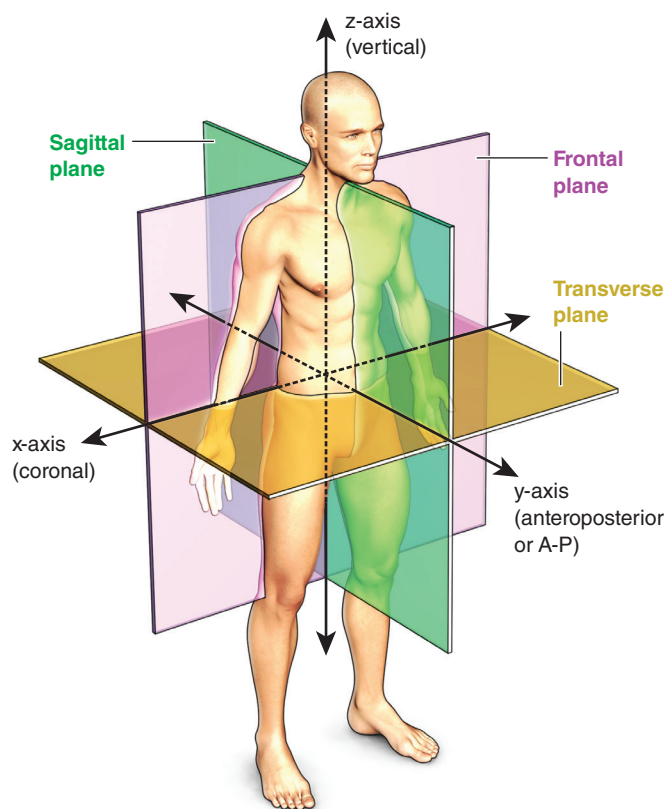


Figure 1-4 Body in anatomic position showing the x-axis, y-axis, and z-axis of the Cartesian coordinate system (for motion in the sagittal, coronal, and transverse planes, respectively).

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 axis** (or **long axis**) is often used instead of “vertical axis.”

The rotation and translation of body segments are not confined to movement along or around cardinal axes or within the cardinal planes. In fact, cardinal plane motions are the exception rather than the rule. Use of cardinal planes and axes is helpful for describing joint movements in a simplified manner, but tends to oversimplify the complexity of human motions. In reality, body segments typically move in three dimensions and often exhibit two or more degrees of freedom simultaneously.

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 in

opposite directions to each other (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 the anterior surface moves 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 in. = 2.54 cm). Linear displacements of the entire body are often measured clinically. For example, the 6-minute Walk Test⁵ (a test of functional status in an individual's gait) 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 termed **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/sec²) and feet per second squared (ft/sec²). 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/sec²).

An electrogoniometer or a three-dimensional motion analysis system can be used for documentation of the changes

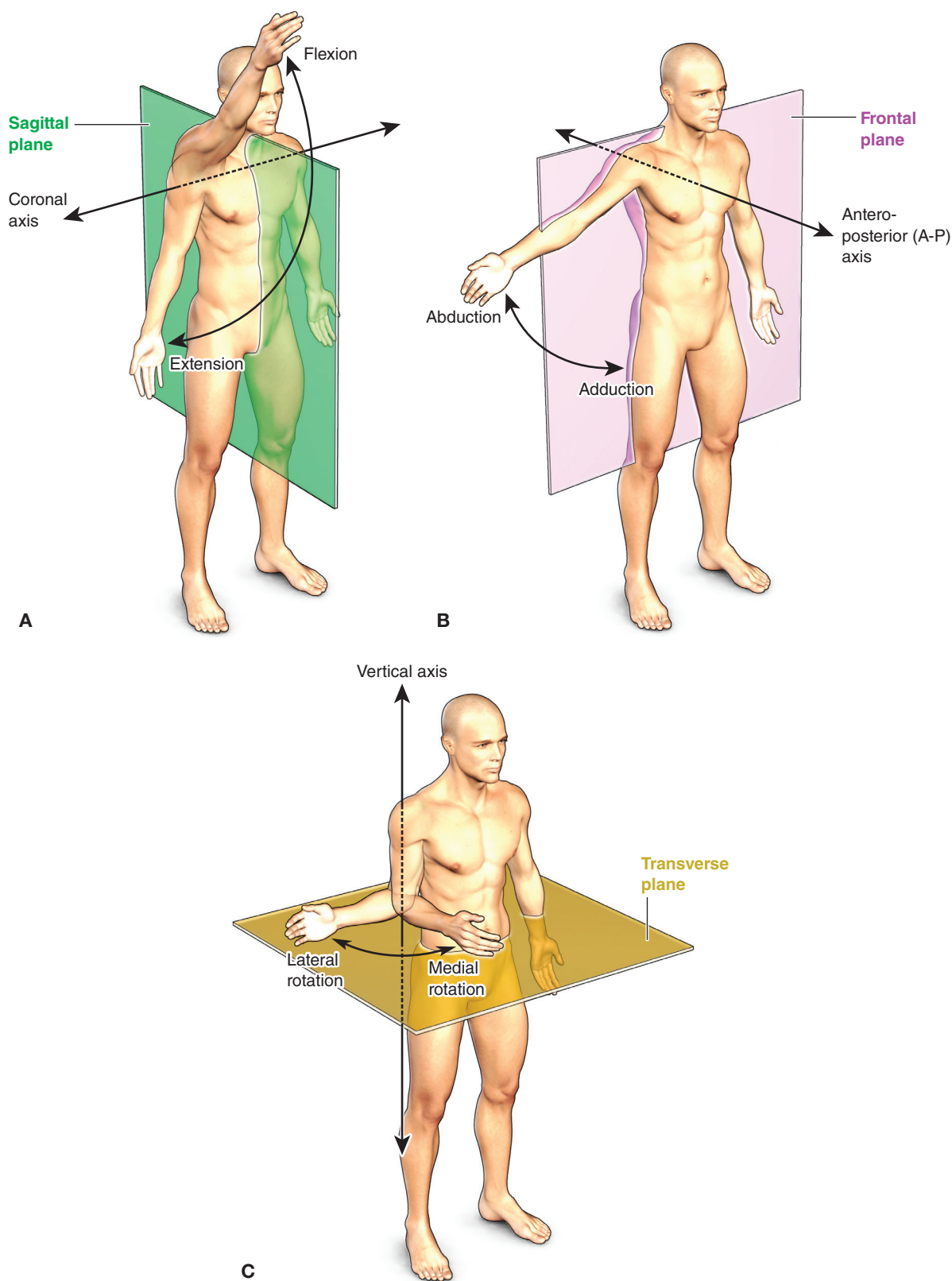


Figure 1-5 Anatomic definitions of motion. **A.** Flexion and extension are, respectively, forward (anterior) and backward (posterior) motions, typically around a coronal axis in the sagittal plane. **B.** Abduction and adduction are, respectively, movements away from the midline of the body and movement toward the midline of the body, typically around an A-P axis in the frontal plane. **C.** Medial and lateral rotation are, respectively, a “rolling” toward and away from the midline of the body, typically around a vertical (or longitudinal) axis in a transverse plane.

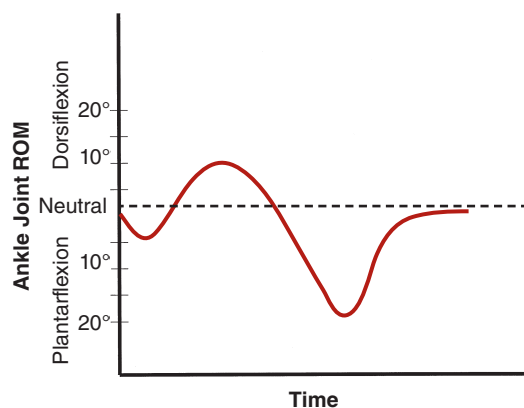


Figure 1-6 When a joint's range of motion is plotted on the y-axis (vertical axis) and time is plotted on the x-axis (horizontal axis), the resulting time-series plot portrays the change in joint position over time. The slope of the plotted line reflects the velocity of the joint change.

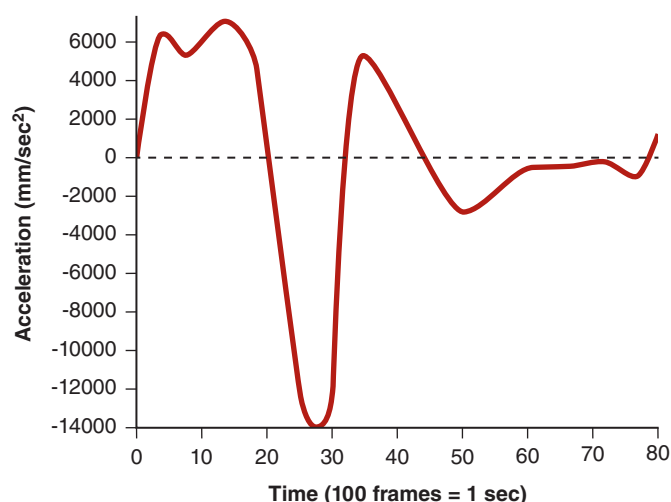


Figure 1-7 Movement of a point on a segment can be displayed by plotting the acceleration of the segment (y-axis) over time (x-axis). The slope and trend of the line represent increases or decreases in magnitude of acceleration as the movement continues. (Courtesy of Fethers L. Boston University, 2003.)

in displacement over time. The outputs of such systems are increasingly encountered when summaries of displacement information are presented. A computer-generated time-series plot, such as that in **Figure 1-6**, graphically portrays the angle between two bony segments (or the rotation of one segment in space) at each point in time as well as the direction of motion. The steepness of the slope of the graphed line represents the angular velocity. **Figure 1-7** plots the linear acceleration of a body segment (or a point on the body segment) over time without regard to changes in joint angle.

Introduction to Forces

Definition of Forces

Kinematic descriptions of human movement allow us to visualize and describe motion; however, they do not explain *why* that motion occurs. This requires a study of forces. Whether

a body or body segment is in motion or at rest depends on the forces acting upon it.

In its simplest form, a *force* can be defined as a push or a pull exerted by one object or substance on another. Whenever two objects contact each other, they will either push or pull on each other with some magnitude of force. The unit for a force (a push or a pull) in the SI system is the **newton (N)**; the unit in the U.S. system is the **pound (lb)**. The concept of a force as a push or pull can readily be used to describe the forces encountered in evaluating human motion.

Foundational Concepts 1-1 A Force

Although a force is most simply described as a push or a pull, it is also described as a “theoretical concept” because only its effects (e.g., acceleration) can be measured.² A force (*F*) on an object is directly proportional to both the acceleration (*a*) and to the mass (*m*) of that object; that is,

$$\text{Force} = (\text{mass})(\text{acceleration})$$

$$\text{or } F = (m)(a)$$

Because mass is measured in kilograms (kg) and acceleration in m/sec^2 , the unit for force is actually $\text{kg} \cdot \text{m/sec}^2$ or, more simply, the newton (N). A newton is the force required to accelerate 1 kg at 1 m/sec^2 ; the pound is correspondingly the amount of force required to accelerate a mass of 1 slug at 1 ft/sec^2 . A “slug” is a rarely used term for a unit of mass in the U.S. system.

External forces are pushes or pulls on the body that arise from sources outside the body. **Gravity (*g*)**, the attraction of the earth's mass to another mass, is an external force that under normal conditions constantly affects all objects. The **weight (*W*)** of an object is the pull of gravity on the object's mass with an acceleration of 9.8 m/sec^2 (or 32.2 ft/sec^2) in the absence of any resistance; that is:

$$\text{weight} = (\text{mass})(\text{gravity})$$

$$\text{or } W = (m)(g)$$

Because weight is a force, the appropriate unit is the newton (or pound). It is common to see weight given in **kilograms (kg)**, although this is technically incorrect because the kilogram is a unit of mass. In the U.S. system, the pound is commonly used to designate mass and is appropriately a force unit ($1 \text{ kg} = 2.2 \text{ lb}$).

Expanded Concepts 1-1 Force and Mass Unit Terminology

Force and mass units are often used incorrectly in the vernacular. The average person using the metric system expects a scale to show weight in kilograms rather than in newtons. In the United States, the average person correctly thinks of “weight” in pounds but also—incorrectly—considers the pound to be a unit of mass. Because people commonly tend to think of mass in terms of weight (the force of gravity acting on the mass of an object), the pound is often (incorrectly) used to represent the mass of an object in the United States.

One attempt to maintain common usage while clearly differentiating force units from mass units for scientific purposes is to designate “lb” and “kg” as mass units and to designate the corresponding force units

as “lbf” (pound-force) and “kgf” (kilogram-force).^{2,4} When the kilogram is used as a force unit:

$$1 \text{ kgf} = 9.8 \text{ N}$$

When the pound is used as a mass unit:

$$1 \text{ lb} = 0.031 \text{ slugs}$$

These conversions assume an unresisted acceleration of gravity of 9.8 m/sec^2 or 32.2 ft/sec^2 , respectively. It might be obvious to the reader who is unfamiliar with the kgf and the slug that these terms have not come into common usage.

The distinction between a measure of mass and a measure of force is important because mass is a scalar quantity (without action line or direction), whereas the newton and pound are measures of force and have vector characteristics. In this text, we will consistently use the terms *newton* and *pound* as force units and the term *kilogram* as the corresponding mass unit. The term *slug* is not in common usage and will not be used further in the text.

Because gravity is the most consistent and predictable force acting on the body, it should be the first consideration when analyzing the potential forces influencing a body segment. However, gravity is only one of an infinite number of external forces that can affect the body and its segments. Examples of other external forces that may exert a push or pull on the human body or its segments are wind (the push of air on the body), water (the push of water on the body), other people (the push or pull of an examiner on John Alexander’s leg), and other objects (the push of the floor on the feet, the pull of an ankle weight on the leg). A critical point is that the forces on the body or any one segment must come from something that is touching the body or segment. The major apparent exception to this rule is the force of gravity. However, we can circumvent this exception by using the notion that gravity (the pull of the earth) “contacts” all objects on earth, thereby allowing a standing rule that *all forces on a segment must come from something that is contacting that segment* (including gravity). The opposite also holds true: *Anything that contacts a segment must create a force on that segment*, although the magnitude may be small enough to disregard.

Foundational Concepts 1–2 Primary Rules of Forces

- All forces on a segment must come from something that is contacting that segment.
- Anything that contacts a segment *must* create a force on that segment (although the magnitude may be small enough to disregard).
- Gravity can be considered to be “touching” all objects.

Internal forces are those forces that act on structures of the body and arise from the body’s own structures (i.e., the contact of two structures within the body). A few common examples are the forces produced by the muscles (the pull of the biceps brachii on the radius), the ligaments (the pull of a ligament on the bones to which it attaches), and the bones (the push of one bone on another bone at a joint). Both internal and external forces can either facilitate or restrict movement. Internal forces, however, are most readily recognized as essential for *initiation* of movement. It should be apparent that

internal forces also control or counteract movement produced by external forces, as well as counteracting other internal forces. Much of the presentation and discussion in subsequent chapters of this text relate to the interactive role of internal forces in producing or controlling joint rotations as well as in maintaining the integrity (stability) of joint structures against the effects of external forces and other internal forces.

Force Vectors

All forces, regardless of the source or the object acted on, are **vector** quantities. A force is represented by an arrow (vector) that (1) has its base on the object being acted on (the point of application), (2) has a shaft and arrowhead in the direction of the force being exerted (direction/orientation), and (3) has a length representing the amount of force being exerted (magnitude). As we begin to examine force vectors (and at least throughout this chapter), the *point of application* (*base*) of each vector in each figure will be placed on the segment or object to which the force is applied—which is generally also the object under discussion.

The contact of a coffee cup on the forearm-hand and the pull of a muscle on the forearm-hand serve as examples of external and internal forces, respectively. **Figure 1–8** shows a forearm-hand segment with the hand holding a coffee cup (an external force). Because the cup contacts the forearm-hand segment, the cup must exert a force (in this case, downward) on the segment. The force, called cup-on-forearm/hand (CFh), is represented by a vector. The point of application on the forearm-hand segment is at the hand where the cup exerts its pull; the action line and direction indicate the direction of the pull and the angle of pull of the cup in relation to the forearm-hand; and the length is drawn to represent the magnitude of the pull (equivalent to the weight) of the cup. The force CFh is an external force because the weight of the cup is not part of the body, although it contacts the body. **Figure 1–9** shows the force of an elbow flexor (an internal force) pulling on the forearm-hand segment. The point of application is at the attachment of the muscle on the forearm, and the orientation and direction are toward the center of the muscle (a “pull” is always toward the source of the force). The force

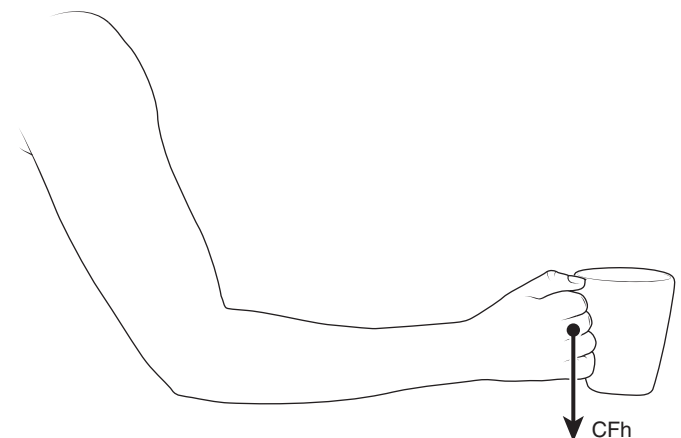


Figure 1–8 Vector representation of the pull of the weight of the cup on the forearm-hand segment (cup-on-forearm/hand [CFh]), with a magnitude proportional to the mass and equivalent to the weight of the cup.

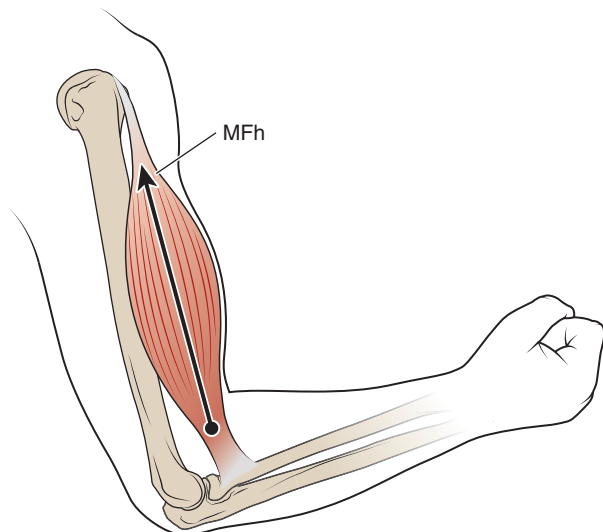


Figure 1-9 Vector muscle-on-forearm/hand (MFh) represents the pull of a muscle on the forearm-hand segment.

is called muscle-on-forearm/hand (represented by the vector MFh). Although the designation of a force as “external” or “internal” may be useful in some contexts, the rules for drawing (or visualizing) forces are the same for external forces, such as the cup, and internal forces, such as the muscle.

Vectors can represent either a push or a pull on a segment depending on the point of application and the source of the force. **Figure 1-10** shows the force vector of both a *push* and a *pull* of an external resistance on the forearm. In **Figure 1-10A**, the push vector is directed away from the source of the manual resistance; in **Figure 1-10B**, the pull vector is directed toward the source of the manual resistance. Whether a push or a pull, the vectors are similar and would have an identical effect on the forearm-hand segment if the magnitudes of the force were the same.

Foundational Concepts 1-3 Force Vectors

Force vectors are characterized by:

- A **point of application** on the object acted upon.
- An action line and **direction/orientation** indicating a *pull* toward the source object or a *push* away from the source object, at a given angle to the object acted upon.
- A length that represents, and may be drawn proportional to, its **magnitude** (the quantity of push or pull).
- A length that may be extended to assess the relation between two or more vectors or to assess the relation of the vector to adjacent objects or points.
- A force **name** that uses the “X-on-Y” where the first part of the force name (“X”) will always identify the *source* of the force and the second part of the force name (“Y”) will always identify the object or segment that is acted upon.

Force of Gravity

As already noted, gravity is one of the most consistent and influential forces that the human body encounters in posture and movement. For that reason, it is useful to consider gravity first when examining forces. As a vector quantity, the force of gravity can be fully described by point of application, action

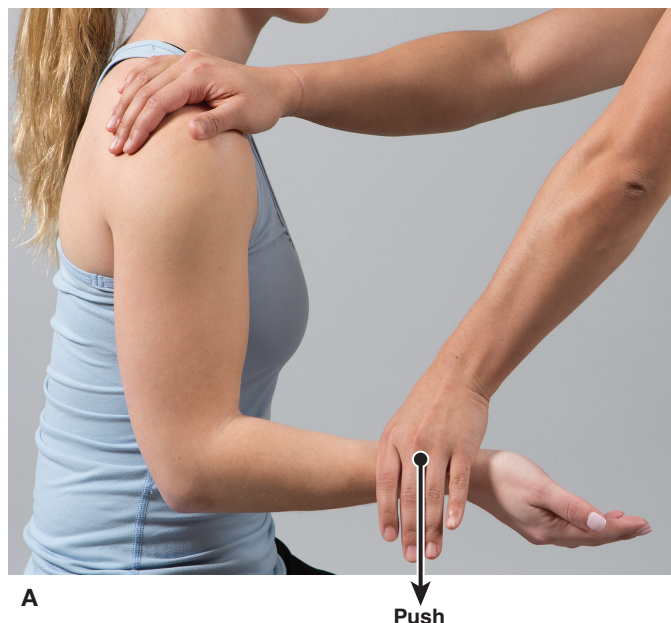


Figure 1-10 Push vs. pull forces. **A.** The clinician's manual resistance to the forearm is applied as a push, whereas in **B.** the clinician's manual resistance is applied to the forearm as a pull. Both vectors look similar and would be indistinguishable as a push vs. a pull if the clinician's hand was removed from each photo.

line/direction/orientation, and magnitude. The force of gravity acting on an object or segment is considered to have its point of application at the center of mass (CoM) or **center of gravity (CoG)** of that object or segment—the hypothetical point at which all the mass of the object or segment appears to be concentrated. Every object or segment can be approached as if it had a single center of mass.

In a symmetrical object, the center of mass is located in the geometric center of the object. In an asymmetrical object, the center of mass will be located toward the heavier end because the mass must be evenly distributed around the center of mass. In cases where the center of mass conceptually lies outside the object, it is still the point from which the force