CHAPTER 2

DESCRIBING THE SYSTEM AND ITS MOTION



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LEARNING OBJECTIVES

1. Define the term *system*.
2. Understand basic anatomical terminology.
3. Explain how the system and the movement environment interact.

CONCEPTS

2.1 Introduction to the System

2.2 Anatomical Terminology

2.3 System Orientation

2.4 Motion at Segmental Links

2.5 The Movement Environment

2.6 Types of Movement

CONNECTIONS

2.7 Exercise Physiology

2.8 Motor Behavior

2.9 Pedagogy

2.10 Adapted Motion

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Disagreements about observed events occur often in the world of sports, even in the presence of trained officials. Anyone who has watched a sporting event has probably seen two referees or umpires make opposite calls on the same play: A tennis umpire overrules a line judge, three football officials disagree on a call during the same play, a first-base umpire 20 meters away is asked to call a batter's motion by the home-plate umpire who is standing less than 2 meters from the batter. In sports such as diving, gymnastics, and ice-skating, panels of judges are asked to score sport skills that may have been performed at extremely rapid rates. With the advent of instant replay, viewers may find out that all of the officials were incorrect. However, veteran officials generally make the correct call, even when action occurs quickly. They are trained to look for critical elements while filtering out irrelevant information. What do you think are the critical elements to notice if a soccer player is injured during play? How would you describe the situation to a paramedic who arrives several minutes later?

Accurately observing and describing motion is especially difficult because the human body can perform so many different motions in extremely short periods. Careful observation and description are necessary in all movement-related disciplines. Exercise physiologists tend to observe skills in the context of muscle contraction and a task's metabolic needs. The student of motor control watches the same skill and thinks of the nervous system resources used to accomplish the highly complex motion. Motor development theorists are concerned with skill capability related to age, whereas motor learning experts think in terms of learning the task. Teachers and coaches must create methods for teaching the skill to other people and may have to adapt the motion for students with special needs. The common theme in all of these fields is observation and description.

As fledgling biomechanists, you will be introduced to a new language that will help you better understand and describe human movement and its complexity. This chapter will also help you recognize the salient features of motor skills, sport activities, and the motion of implements and objects that humans use and propel. With a common and consistent language and a trained eye for describing motion, you'll gain a deeper understanding of the role that biomechanics plays in sports and everyday life. The goal of this chapter is to give you the tools necessary to specifically describe the system of interest, the motion of the system, the location of the system within the environment, and the type of motion exhibited. With some practice, you will begin to look at motion in an entirely different way, noticing detailed aspects of movement that you may have previously ignored.

CONCEPTS

2.1 INTRODUCTION TO THE SYSTEM

To understand biomechanics and to begin biomechanical analysis, we must begin with an understanding of a clearly defined system of interest. A **system** is any structure or organization of related structures whose state of motion is of analytical interest. We tend to immediately assume that the system is an entire human, which may be true in some circumstances. However, the system may be only one part of the person or even some object that the human has kicked or thrown. A system is a simple concept, but the importance of defining it clearly should not be underestimated.

Let's use the following example for the remainder of this discussion: A biomechanist is interested in studying injury to find the most effective methods of prevention and treatment. In this situation, simply saying "people get injured playing soccer" is not especially useful. To be studied effectively, both the system and the circumstances must be clearly specified. In this particular case, we must begin with the system. What injury is the researcher studying? Is it damage to the knee, ankle, foot, or some other body part? If the researcher is concerned with the knee, then the system may be the tibiofemoral joint or simply the femur or the

System Any structure or organization of related structures whose state of motion is of analytical interest.

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tibia. What is the age of the system? An injury may occur more frequently in a particular age group. For example, Osgood-Schlatter disease is an inflammation of the attachment site of the patellar tendon to the tibial tuberosity. This condition is typically observed in children and adolescents who regularly engage in activities that involve jumping. If age is a concern, then the system may be redefined as the tibiofemoral joint of 13-year-olds. What is the gender of the system? If the game is female soccer, then the quadriceps angle (Q-angle) may be important because females possess a wider pelvis than males. It could be that the femur and the tibia do not make appropriate contact (tibiofemoral incongruence). We may also be concerned with the relative lengths of various limbs forming the injured joint. The injury could also be the result of muscular imbalances around the joint of interest (e.g., the ratio of hamstring to quadriceps strength). Any of these concerns could change the specified system.

Remember that you may be the only person who has observed the system. Therefore, observing the system carefully and being as specific as possible when describing the system to others is critical. Every detail of the system will make a difference in identification. In the movement-related sciences, we must clearly describe the physical characteristics of the system and its state of motion because others may not have observed the event. Also, we must practice our observation skills because many of the motions that we witness happen at extremely rapid rates. We will begin with the discipline that studies the physical characteristics of systems; next, we'll discuss the motion of the systems.

Anthropometry

Anthropometry is the discipline that studies measurements of the body and body segments in terms of height, weight, volume, length, breadth, proportion, inertia, and other properties related to shape, mass, and mass distribution. Anthropometrics basically describe the shape of the system. A comprehensive presentation of the field of anthropometrics is beyond the scope of this text. However, the student of biomechanics should always be aware of how varying body shape and limb proportions affect motion. So the purpose of this section is to draw attention to the natural variability in human shape and illustrate how it can affect movement (Figure 2.1).

Anthropometry The discipline that studies measurements of the body and body segments in terms of height, weight, volume, length, breadth, proportion, inertia, and other properties related to shape, mass, and mass distribution.



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Figure 2.1 **Variability in human form.** How might these differences affect their sport performance?

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For example, many competitive swimmers tend to have long torsos and short legs. Also, evidence suggests that great sprinters have short femurs in proportion to their tibia length. What body type makes for the most successful weight lifter? What about the length of the weightlifter's segments? What about great gymnasts? What is it about their bodies that aids in success? Inherent physical ability, even when combined with hours of intense training, can only go so far. Some of that physical capability comes simply from body shape. Because of the biomechanical effects of genetically determined body shape, particular activities are inherently easier for certain people.

For example, a majority of elite volleyball and basketball players are taller than the average, and the majority of elite female gymnasts are less than 5 feet tall. When people are comfortable with a particular sport activity, they tend to select that activity over others and potentially become successful within that sport. People also tend to opt out of sports in which they are not so comfortable. As a result of this sport self-selection by body type, we tend to see similarities in body features among athletes within a given sport. So any time that we are analyzing a particular movement, we must take into account the "build" of the person involved (i.e., the shape of the system).

A few anthropometric measurements students are usually familiar with even before a biomechanics course are height and weight, body mass index (BMI), somatotype, and waist-to-hip ratio. Height and weight are relatively simple measures but are still important, especially when considered along with other variables. But many pieces of information should be taken into account simultaneously. For example, if we are given only the information that the opponents in a wrestling match both weigh 47.5 kg, we can make no real judgments. However, if we also know that their heights are 1.5 m and 1.8 m, we can also assume some major differences in stature exist that could affect the match. If we also know that the wrestlers have similar body compositions, we can safely assume that the shorter of the two is probably stronger because more of his or her total body mass is composed of muscle tissue.

Statural Expressions

Equations and ratios have been developed that use multiple pieces of anthropometric data simultaneously to make assessments about health, stature, and athleticism. One such frequently used ratio is the **body mass index (BMI)**:

$$BMI = \frac{kg}{m^2} \tag{2.1}$$

where

kg = kilograms of body mass
m = height in meters

The most familiar use of BMI is its association with disease risk (i.e., as BMI increases, the risk of a variety of diseases also rises). One limitation to BMI is that it does not consider body composition—that is, relative amounts of fat and muscle. So care should be taken when interpreting the BMI value, because the numerator of the fraction can be affected by factors other than fat (i.e., other lean tissues such as muscle), which frequently leads to athletes being misclassified as having a high risk for disease. For the purposes of this text, BMI can still be a useful measure for giving some idea of an athlete's stature. For example, think about the BMI of a sumo wrestler versus that of a cross-country runner. In other words, particular BMI values are highly suitable for a given sport.

Body mass index (BMI) Ratio of body mass to height used to describe stature.

Ponderal index (PI) Ratio used to describe stature.

The **ponderal index (PI)** is a measure of stature similar to BMI but not as well known outside the fields of

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anthropometrics and biomechanics. Many methods for calculating PI have been suggested. The ratio used in this text is as follows:

$$PI = \frac{kg}{m^3} \tag{2.2}$$

where

kg = kilograms of body mass
m = height in meters

The PI yields a different numerical value, but it is used similarly to BMI (i.e., a person who weighs less relative to height has a lower PI). Again, in an era of athletics that encourages muscularity, one should use caution in making assumptions about the health of athletes using PI. However, we can use ratios such as BMI and PI to begin to take a closer look at the shape of the system. Some other expressions of PI that have been used are PI = $10^3 \times (\sqrt[3]{W}/H)$, where height is in centimeters; and PI = $H/\sqrt[3]{W}$, where height is in meters. A logical rationale exists for each recommended PI equation, and the semantics of the equations and their usefulness are controversial. However, normalization values such BMI and PI should be used only as guides when describing or interpreting the characteristics of a system. In terms of biomechanical analysis, parameters such as BMI and PI are meaningful only within a tightly narrow context. Highly technical kinematic and kinetic analyses of movement require more specific values such as segmental mass centers, mass distributions, and moments of inertia, all of which are covered in greater detail in subsequent chapters. For now, consider that expressions such as BMI and PI are associated not only with health status but also with success in some sporting events.

Somatotyping is another system for body classification that has been used for many years both quantitatively and qualitatively (Figure 2.2).

Somatotyping is a system of body-type description that uses the classification of people into three basic categories:

1. **ectomorphic**, being linear and relatively thin for height, which is also called *linear*;

Somatotyping System of body-type description based on weight and muscularity relative to height.

Ectomorphic Somatotype described as being linear and relatively thin for height.

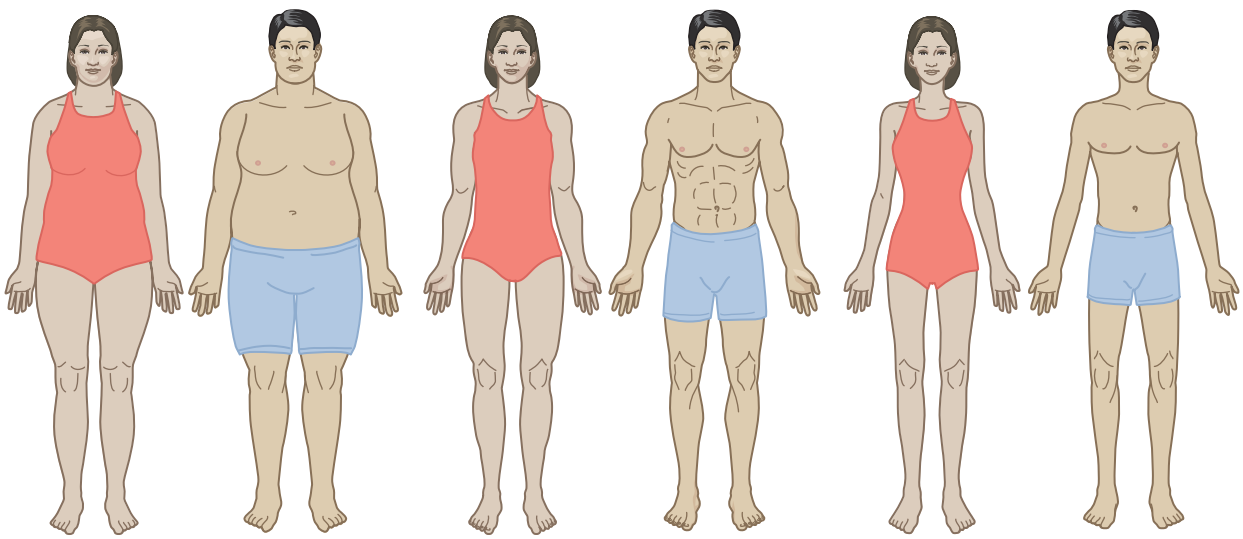


Figure 2.2 **The basic somatotypes: endomorph, mesomorph, and ectomorph.** In what sport can you imagine each individual participating?

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2. **mesomorphic**, being muscular, strong, and possessing weight relatively proportional to height, which is also called *athletic*; and
3. **endomorphic**, which is rounder and relatively heavy for height.

A person does not have to fit perfectly into any given category but can possess varying degrees and combinations of traits from all three categories. As previously mentioned, a quantitative (points-based) system exists for classifying the degree to which a person possesses qualities of each category. However, most people tend to use this system in a more qualitative manner by visually categorizing a person. Even qualitatively, it can be assumed that most athletes are going to have a significant mesomorphic component blended with one of the other categories, depending on the sport. For example, an offensive lineman in football could be considered to have qualities of both the mesomorphic and endomorphic categories. In contrast, a combination of the ectomorphic and mesomorphic categories better describes a wrestler in a light weight class. In which category do you think a sumo wrestler would fall?

Rather than classifying or describing the entire body, biomechanical analysis is often more productive if we look at the anthropometrics of various individual parts of the body in relation to each other. Learning to pay close attention to individual body segments is important because of the variations in angular kinematics produced by varying limb proportions.

Body Segment Proportions

The ratio of waist to hip circumferences is another anthropometric measure that is often used to assess health risk. A person with a larger ratio (more "apple shaped") is at higher risk for disease than a person with a lower ratio ("pear shaped"). Even though the **waist-to-hip ratio** is associated with various disease states, the student of biomechanics should be aware of the difference in location of the whole body center of gravity that accompanies the change in distribution of weight from either above or below the waist. Consider the injured soccer player. What is the likely difference in waist-to-hip ratio for a female versus a male soccer player? Is this piece of information relevant in terms of the injury?

Many comparisons of system body-segment parameters are associated with various aspects of performance. One such comparison is that of limb proportion in the **crural index (CI)**:

$$CI = \frac{\text{length of the tibia}}{\text{length of the femur}} \times 100 \qquad (2.3)$$

As you can see from the equation, an animal with a large CI possesses a long distal segment (segment farther from the body) in proportion to the proximal segment (segment closer to the body) (Figure 2.3). As you will discover in later chapters, this quality provides the animal with an advantage in terms of running and jumping.

Mesomorphic Somatotype described as being muscular, strong, and possessing weight relatively proportional to height.

Endomorphic Somatotype described as being rounder and relatively heavy for height.

Waist-to-hip ratio Ratio of waist circumference to hip circumference often associated with disease risk.

Crural index Ratio of the length of the tibia to the length of the femur.

Crural index is just one example of segmental comparison. You can find other advantageous trends within sports such as long arms in successful baseball pitchers and high torso-to-leg-length ratios in swimmers (i.e., two people of the same height do not necessarily have the same leg length). As previously mentioned, all of these anthropometric variables have some biomechanical influence on a person's ability to succeed within a given sport.

Having looked at some ways of evaluating the system itself and its characteristics, we can turn to the movement situation and the environment in which the system is moving. In following sections of this chapter, we will learn how to clearly define the movement space. Here we also begin

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Figure 2.3 **Two sprinters: human and cheetah.** Notice the proportions of the leg segments. Can you think of some other great sprinters in the animal kingdom?

to develop some understanding that the system of interest is not necessarily a separate entity from the environment with which it interacts. Using the example of the injured soccer player, our system may be defined as the tibiofemoral joint of teenage female soccer players. However, if we are researching types of injuries, we need to know, for example, whether the injury occurred on natural grass or an artificial surface. We also need to ask questions such as, What exactly was the situation? In what position was the system? Was it a cutting maneuver, a start, a stop? Was another player involved? Was the injury to the anterior or posterior cruciate ligament?

As can be seen from the preceding examples, the system is a specifically defined entity engaged in a particular movement situation within a specified space. Biomechanists must use common multidisciplinary terminology to perform research after the fact or to simply be able to specifically define the system, the movement situation, and the environment to someone who was not present. Now let's focus on specific definitions of movements and movement space.

2.2 ANATOMICAL TERMINOLOGY

To describe motion of the human body with consistency, researchers must have a common reference system and use consistent terminology. Much of the vocabulary used in biomechanics (and in most other movement-related disciplines) is derived from the field of anatomy. Comprehensive coverage of anatomical terminology is beyond the scope of this text, and anatomical terms vary slightly depending on the book. So the terms presented in this section represent the most common and widely used across disciplines (Floyd, 2018; Oatis, 2017; VanPutte, Regan, & Russo, 2017; Watkins, 2010).

Anatomical Position

The **anatomical position** is a commonly used reference point for the body itself; it refers to a person standing erect with all joints extended, feet parallel, palms facing forward, and fingers together (Figure 2.4).

Anatomical position Reference position defined by standing erect with all joints extended, feet parallel, palms facing forward, and fingers together.

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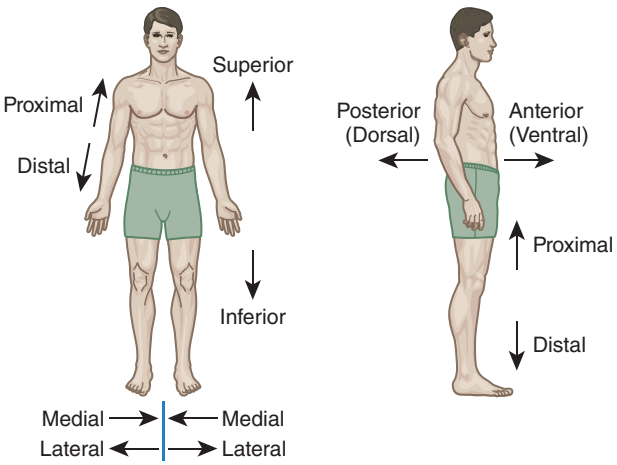


Figure 2.4 **The anatomical reference position with directions indicated.** When you give directions do you give a reference point?

Note that locations, movements, and relative positions of anatomical structures are always described according to the anatomical position whether or not the person is actually in the anatomical position at the time of description.

Directional Terms

Along with the anatomical position, directional terminology can be used for a more complete description of a movement or structural location. Remember that directional terms are usually used to describe *relative* location or position. The following is a list of the most commonly used directional terms:

- *Superior* and *inferior* are used to describe being toward or closer to the head and feet, respectively. For example, the knee is superior relative to the ankle but inferior to the hip. *Cephalo* or *cranial* may be used instead of *superior*, and *caudal* is sometimes used in place of *inferior*.
- *Anterior* means toward the front of the body, and *posterior* means toward the rear of the body. The pectoralis muscles are anterior to the heart. Alternative terms for anterior and posterior are *ventral* and *caudal*, respectively.
- *Medial* and *lateral* indicate position or movement toward and away from the midline of the body, respectively. One of the quadriceps muscles is closer to the midline, and one is farther away from the midline: thus, the names *vastus medialis* and *vastus lateralis*.
- *Proximal* means closer to the attachment of a limb to the body, and *distal* indicates having a position farther from the attachment of the limb to the body. The carpals are proximal to the phalanges.
- *Superficial* and *deep* describe relative proximity to the surface of the body. The gastrocnemius is superficial to the soleus.

2.3 SYSTEM ORIENTATION

Now that we have reviewed the anatomical reference position and directional terminology, we can introduce the fundamental orientation concepts of biomechanics. These particular concepts are useful for specifically describing motion of the body system and its segments in relation to the movement environment.

Planes of System Motion

Planar motion of a system or system segment is described as occurring in a plane. Geometrically, a plane is a flat two-dimensional (2-D) surface. So motion "in a plane" technically refers to the movement of that segment "describing" an imaginary plane. Movements can generally be classified as *uniplanar* (occurring in one plane, or two-dimensional) or *multiplanar* (occurring in more than one plane, or being three dimensional, or 3-D). Although most natural human motions occur in more than one plane, most segmental movements occur along one individual plane. Of course not all of the possible planes of motion are named, but an understanding of the concept of motion occurring in a plane is necessary for describing movements of the body as well as for comprehending many concepts you will encounter later. A **cardinal plane** is a plane that passes directly through the midline of the body (i.e., divides the mass of the body in half).

Cardinal plane Plane that passes directly through the midline of the body.

The three cardinal planes of motion are *sagittal*, *frontal*, and *transverse*. These planes are orthogonal, or

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perpendicular, to each other (Figure 2.5). The **sagittal plane** (also called *median* or *anteroposterior*) is vertical and divides the body in half along the midline into right and left masses. It runs superior to inferior and anterior to posterior. The **frontal plane** (also called *coronal* or *lateral*) is another vertical plane, but it divides the body in half along the midline into anterior and posterior masses. It runs superior to inferior and side to side. The **transverse plane** (also called *horizontal*) passes through the body horizontally and divides it into superior and inferior masses. It passes anterior to posterior and side to side.

Because the cardinal planes pass directly through the midline of the body and many body segments are lateral to the midline, most motions do not actually occur in one of the cardinal planes. Most motions should actually be pictured as taking place in one of the infinite number of planes parallel to the cardinal planes. In other words, a motion can be in a *sagittal* plane (such as knee extension) or a *coronal sagittal* plane (such as performing an abdominal crunch). In addition, a motion of the system may occur in a plane that is not parallel to one of the cardinal planes (e.g., a golf swing). These movements are said to describe *diagonal* or *oblique* planes (Figure 2.6).

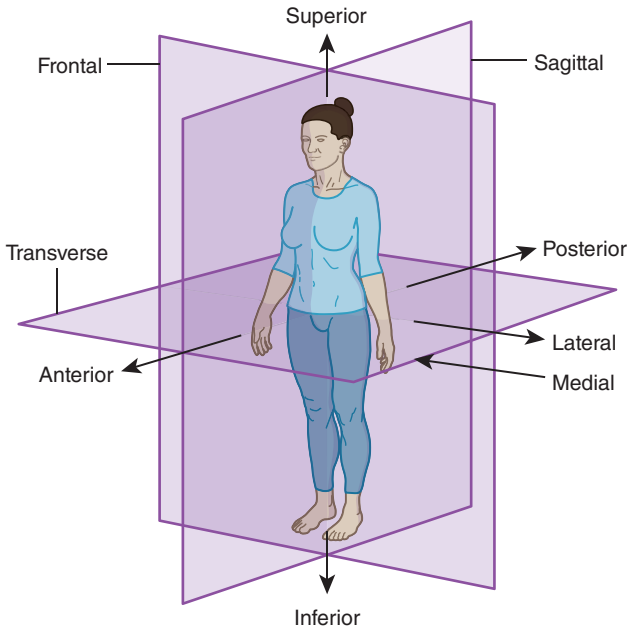


Figure 2.5 **The cardinal planes of motion: sagittal, frontal, and transverse.** Can you think of motions that occur in each of these planes?

Axes of System Motion

If we imagine the plane of motion as a wheel, the axis of rotation should be envisioned as the axle around which that wheel turns. In other words, a segmental movement describes a plane (*planar* motion) that rotates around a theoretical axis (*axial* motion). Just as there are three cardinal planes, there are three axes of rotation: *mediolateral*, *anteroposterior*, and *superoinferior*.

Each axis of rotation should be imagined as a line (axle) that is perpendicular to one of the described planes (Figure 2.7). Many variations of names for the axes are seen in textbooks. In this text, the axes are named for the anatomical directions in which they pass. Note, however, that some texts name an axis because it is parallel to a plane, or name it according to the intersection of the two planes by which it is formed. The **mediolateral axis** (also called *bilateral*, *frontal*, *frontal-horizontal*, *frontal-transverse*, and *transverse*) passes horizontally side to side and is perpendicular to the sagittal plane. The **anteroposterior axis** (also called *sagittal*, *sagittal–horizontal*, and *sagittal–transverse*) runs horizontally from front to back and is perpendicular to the frontal plane of motion. The **superoinferior axis** (also called *frontal–sagittal*, *longitudinal*, and *vertical*) passes up and down and is perpendicular to the transverse plane. Also, because there are diagonal (or oblique) planes of motion, diagonal axes of rotation exist perpendicular to each of those planes. Using our preceding examples, knee extension and flexion occur around a mediolateral axis, and a golf swing occurs around a diagonal axis.

Sagittal plane Vertical plane dividing the body into right and left halves.

Frontal plane Vertical plane dividing the body into anterior and posterior halves.

Transverse plane Horizontal plane dividing the body into superior and inferior halves.

Mediolateral axis Axis that passes horizontally side to side and is perpendicular to the sagittal plane.

Anteroposterior axis Axis that runs horizontally from front to back and is perpendicular to the frontal plane of motion.

Superoinferior axis Axis that passes up and down and is perpendicular to the transverse plane.

Planes, Axes, and the Center of Gravity

Understanding the cardinal planes of motion and axes of rotation can aid elementary comprehension of certain

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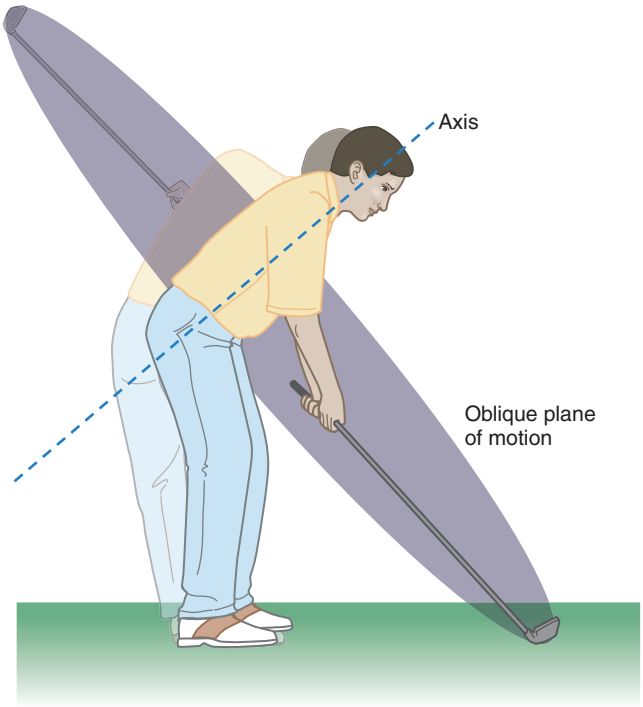


Figure 2.6 **Golf swing with an oblique plane.** What are some other sports motions that occur in oblique planes?

frequently used concepts in the field of biomechanics. As mentioned in the previous section, the cardinal planes divide the body into equal mass halves. Also, axes are formed by the intersections of two planes. Because the cardinal planes bisect the body, they must also pass through the **center of mass** (the point that represents the average location of a system's mass). Gravitational pull is concentrated at the center of mass. So at least in the vertical axis, the center of mass can be considered synonymous with the **center of gravity** (the point at which the force of gravity seems to be concentrated). In other words, the center of mass (or center of gravity) of the system is at the intersection of the three cardinal planes. As you will see in a Chapter 3, all forces can be represented with a line that possesses specific characteristics. Gravity can be represented with a line called the **line of gravity** that passes through the center of mass.

The line of gravity can be envisioned as the line at which the two vertical cardinal planes intersect (Figure 2.8). The center of mass and center of gravity are further elucidated as new concepts are introduced throughout the text.

Spatial Frames of Reference

To fully describe motion of the body system and its segments, we must be able to specifically define its position or location in space. This goal is achieved by establishing one or more frames of reference within a **Cartesian** or **rectangular coordinate system** (named for mathematician and philosopher René Descartes). An **origin (O)** and two or three orthogonal axes (each passing through the origin and defining one spatial dimension) are used to define a Cartesian coordinate frame of reference. For example, one of the most common rectangular coordinate systems uses two orthogonal axes that divide a plane into four quadrants (Figure 2.9).

The origin is a stationary point in the environment from which all measurements are made. For example, if you wanted to give someone directions to your home, you wouldn't begin from an arbitrary undefined point. The two of you would first agree on a starting point that is mutually understood and predefined. In biomechanics, we define the origin with the coordinates (0, 0) in two dimensions and (0, 0, 0) in three dimensions. Because most natural motions of the body occur in three dimensions, a 3-D coordinate frame of reference is used frequently throughout this text.

As previously mentioned, two or more perpendicular axes pass through the origin. Each axis represents a direction of motion. Many coordinate axis frames are used in different textbooks and research journals. The frame of reference we choose to use is merely a preference; the important factors are that it be clearly defined and that it is convenient for the specified purpose. For consistency, the convention adopted by the International Society of Biomechanics (ISB) is used throughout this text. We use a 3-D coordinate frame, so we need three axes: *x*-axis direction, *y*-axis direction, and *z*-axis direction (Figure 2.10).

Center of mass The point that represents the average location of a system's mass.

Center of gravity The point at which the force of gravity seems to be concentrated.

Line of gravity A vertical line representing gravity that passes though a system's center of mass.

Cartesian or rectangular coordinate system A frame of reference defined by an origin and two or three orthogonal axes, each passing through the origin and defining one spatial dimension.

Origin (O) A stationary point in the environment, from which all measurements are made.

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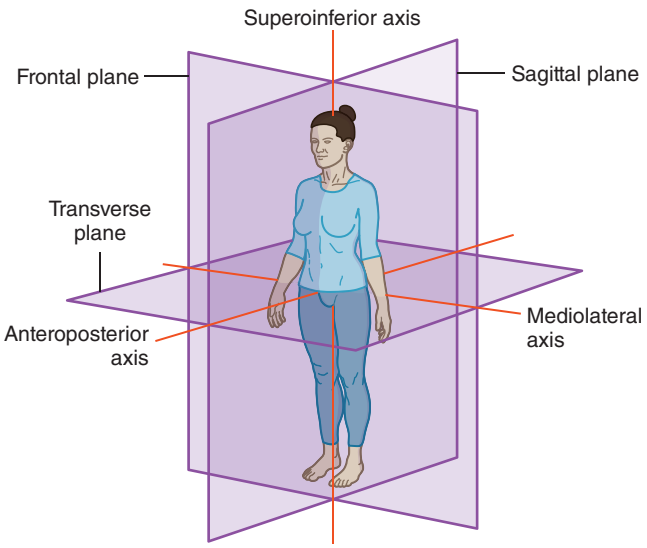


Figure 2.7 **The axes of rotation: mediolateral, anteroposterior, and superoinferior.** Nodding the head occurs around which axis?

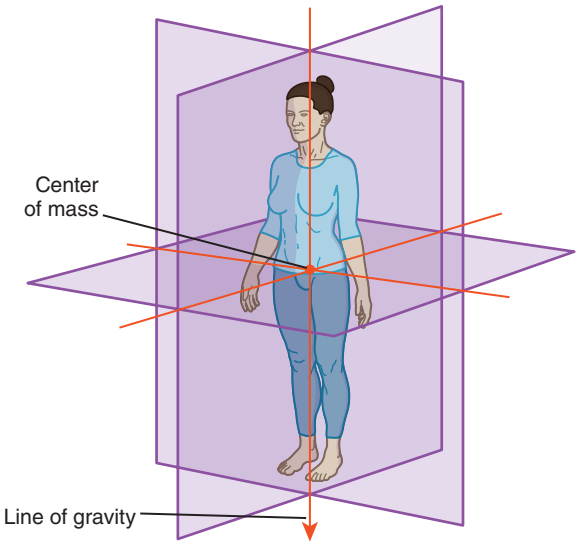


Figure 2.8 **The center of mass and line of gravity.** How could you locate your center of gravity?

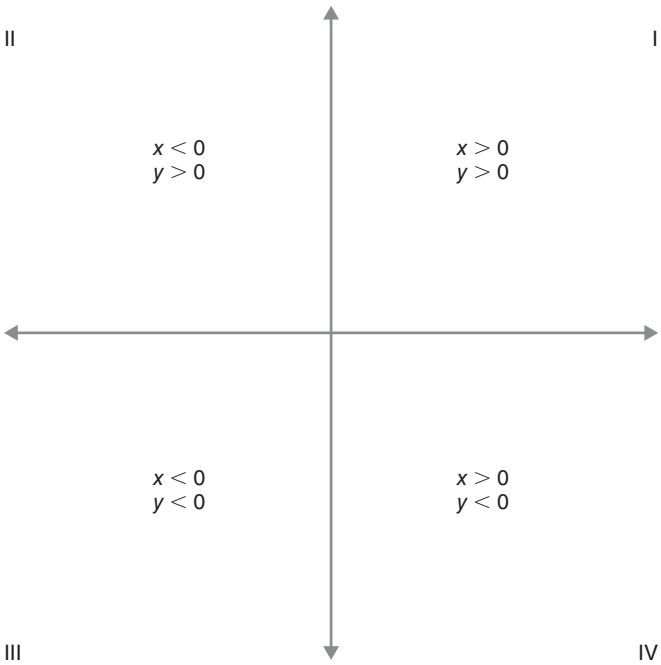


Figure 2.9 **The four quadrants of a 2-D coordinate system.** In what quadrant is a point that has x and y coordinates that are both negative?

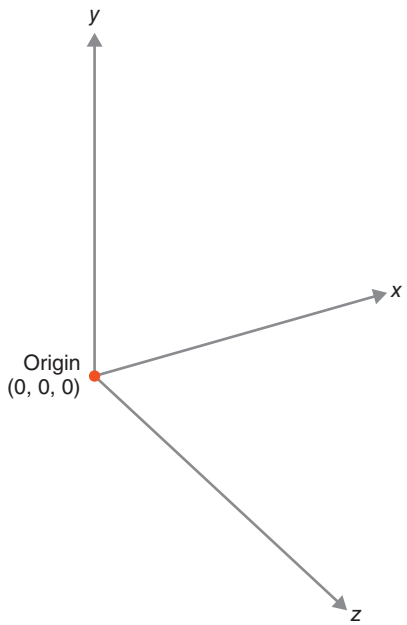


Figure 2.10 **A right-handed 3-D global coordinate frame.** Imagine the frame as a corner of the room in which you are located. Where are you located relative to the origin?

The x-axis direction (direction of progression) runs horizontally forward and backward relative to the system, with forward designated as positive and backward designated as negative. The vertical direction is the y-axis, which is perpendicular to the x-axis and runs superiorly (positive) and inferiorly (negative). The z-axis direction is horizontal and orthogonal to the x and y directions, running medially and laterally relative to the system. The positive z-axis direction is lateral or to the right, and

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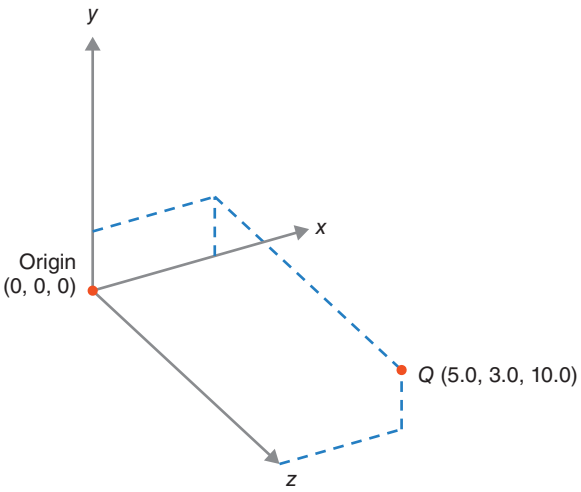


Figure 2.11 **The coordinates of a point Q located within the global coordinate frame.** Try to imagine the location of this point if you are located within the frame facing the *x* direction.

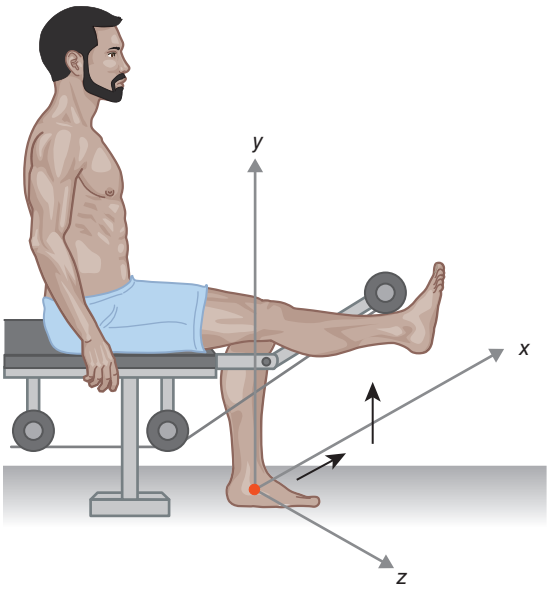


Figure 2.12 **Directions of motion of a point within a coordinate frame of reference.** In what directions would a runner move on a circular track?

Global reference frame A fixed frame of reference that allows the location of any point to be specified with respect to a defined origin.

Local reference frame A frame of reference attached to and moving with the system of interest.

the negative *z*-axis direction is medial or to the left of the system. So within a 2-D Cartesian coordinate frame of reference, a point Q with the coordinates (6, 8) can be located by moving 6 units in the positive *x* direction (forward) and 8 units in the positive *y* direction (upward).

If the frame of reference is 3-D (Figure 2.11), a point Q may possess the coordinates (5, 3, 10), which can be located by moving 5 units in the positive *x*, 3 units in the positive *y*, and 10 units in the positive *z* direction (right). So if a point is on one axis, its location can be fully designated with one coordinate. The location of a point in a *plane* formed by two axes requires two coordinates, and three coordinates are required for a point in 3-D *space*. So we can fully define the location of a point in space with a coordinate reference frame, or we may simply want to indicate the direction of motion of a point (Figure 2.12).

Notice that the coordinate axis frames defined above are *right-handed* (which is common). In other words, the *z*-axis is pointing to the right relative the plane formed by the *x*- and *y*-axes. You can further visualize this convention using your own hand. Begin by placing your right-hand palm up and making a fist. Now extend your index finger to point toward the positive *x* direction and extend (abduct) your thumb to point toward the positive *z* direction. Finally, extend your middle finger just to the extent that it is perpendicular to the other two. In other words, the middle finger points upward or positive in the *y* direction.

The same position can be used by your left hand to represent a *left-handed* coordinate frame, with the third axis pointing to the left of the plane formed by the other two axes. The reference frame is called *oblique* when the axes are not orthogonal. If we include oblique reference frames, an infinite number can be established. As previously stated, the ISB convention is used throughout this text for consistency. However, different reference frames are commonly used, not only within the field of biomechanics but also in engineering, mathematics, and physics. One common convention used in 3-D biomechanical analysis is one in which the *x*- and *y*-axes are orthogonal to each other in the transverse plane, and the *z*-axis is vertical instead of horizontal (Robertson et al., 2014). With all of the possibilities in mind, you can now understand the importance of clearly predefining the coordinate reference frame.

Fixed axes relative to the system, one of which is parallel to the ground, define the reference frame just described. This type of reference frame is called *global* (also *absolute*, *fixed*, *stationary*, and *inertial* or *Newtonian*). A **global reference frame** allows the position of any single point to be specified with respect to the defined origin. In other words, this frame is used to describe movement of the *entire* system as a whole relative to the start. However, to clearly describe the orientation of the entire system or the individual segments of the system (as opposed to defining the system as a single point moving in space), we must construct another reference frame within our global frame that moves with the system. This second frame is called the **local reference frame** (also *anatomical*,

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cardinal, moving, relative, segmental, and *somatic*) and has an origin and axes attached to the body. The origin of the local reference frame is established at the center of mass of the system or a system segment. The axes are orthogonal, have the same handedness as the global frame, and are aligned with those of the global frame when the system is in the anatomical position (Figure 2.13).

Depending on the needs of the observer, movement can be further defined by attaching multiple local coordinate frames to the system (Robertson et al., 2014; Zatsiorsky, 1998). For example, one local frame may be oriented similarly to the global frame and maintain that orientation while moving with the system. This type of frame is used to describe change in system orientation relative to its original orientation and is sometimes called *moving*. A second local frame (sometimes called *somatic* or body) may be fixed within the system that changes its orientation in space when system orientation is changed (describing change in position of one segment of the system relative to another).

To gain insight into the difference between global and local reference frames and the information that each provides, let's use the example of observing a person driving a car. If you view the person driving the car from a global reference frame defined as the surface of Earth, you observe them to be moving in the positive *x* direction. However, the person is not necessarily moving in the positive *x* direction *relative to the car*. More specifically, viewed from the global frame, the driver's hands are moving in the positive *x* direction because they are attached to the driver. But relative to a local frame of reference, the driver's hands are on the steering wheel. The steering wheel allows the hands to move only up and down, not forward and backward. So, motion varies widely depending on your point of view. Therefore, establishing more than one reference frame provides multiple points of view that help to fully describe the event.

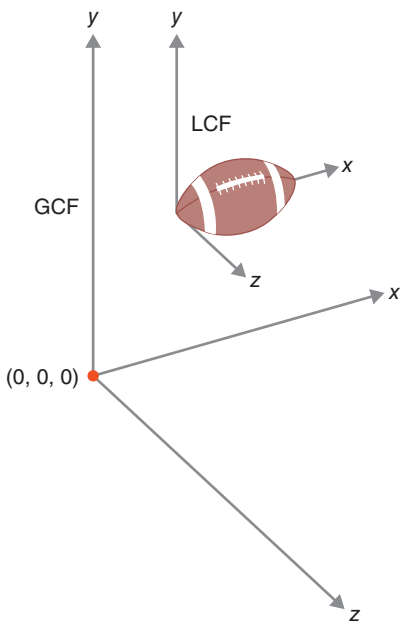


Figure 2.13 **Local coordinate frame located within the global coordinate frame.** Can you think of some sports in which a local coordinate frame would be necessary?

Tumbling in gymnastics is a great example of using multiple coordinate frames in sport to completely describe the motion of a system (Figure 2.14).

The only information relative to a global reference frame is that the system (gymnast) is moving forward (positive in the *x* direction), which is a huge understatement in terms of this skill. We need to further describe motion of the system in terms of rotation around the *x*-, *y*-, and *z*-axes of a local reference frame. The rotations around the *x*-, *y*-, and *z*-axes are also called **roll**, **yaw**, and **pitch**, respectively. In addition, the act of tumbling is being produced by changes in relative body segment positions. So a third axis frame is needed that helps to describe segmental motions. For example, the gymnast is moving forward and momentarily upward (global: $x+$ and $y+$ directions), may be rolling in midair (local moving: *y* and *z* directions around the *x*-axis), and have legs in a tuck because of knee flexion (local knee somatic: *x* and *y* directions around the *z*-axis). You can clearly see that motion of a system can be described with much greater detail and accuracy if multiple levels of reference frames are used.

Degrees of Freedom

Degrees of freedom (DOF) are literally the number of parameters that are "free" to vary. In biomechanical terms, DOF are the number of independent ways in which a system can move or the number of values required to completely describe system motion relative to the established

Roll A combination of rotation and translation in which each point on a surface contacts a unique location on the other surface.

Yaw Rotation of a system around the *y*-axis.

Pitch Rotation of a system around the *z*-axis.

Degrees of freedom (DOF) The number of independent ways in which a system can move.

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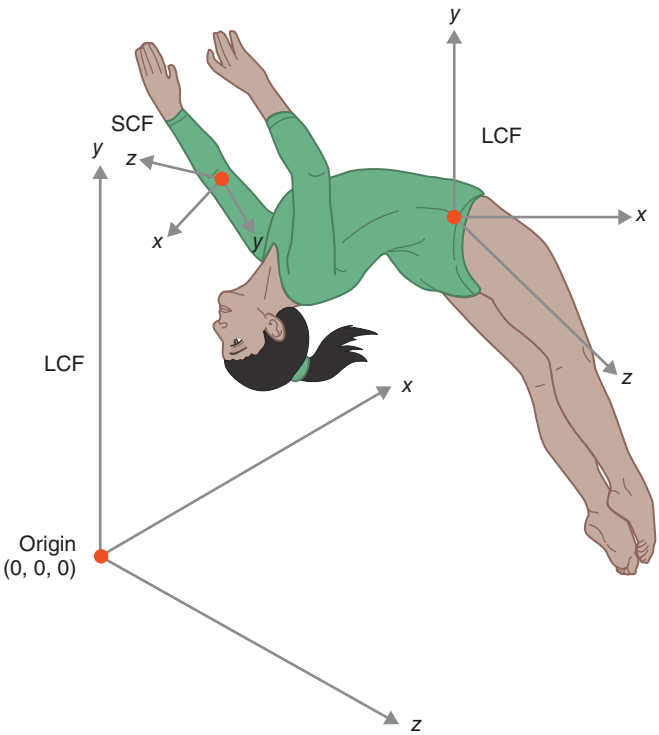


Figure 2.14 **Gymnast with global, local, and somatic reference frames indicated.** Which coordinate frame(s) are the most important in this situation?

coordinate reference frame. Two-dimensional (planar) motion has three degrees of freedom (some combination of movement in two possible directions and rotation around one axis). However, six DOF are required to describe 3-D system movements: a rigid segment freely suspended in space can move in three directions (three parameters required to specify the location of the segmental center of mass) and rotate around three axes (three values needed to describe segment orientation). If any constraints are imposed on the system, they must be subtracted from the six possible degrees of freedom. For example, a ball-and-socket joint such as the hip can rotate around any axis but cannot under normal circumstances move out along any of the three directions without dislocating (i.e., it is constrained in three of six possible movements types). Therefore, the DOF for a ball-and-socket joint is three (DOF = six minus three constraints). The human body is a system of segments. Any rigid segment in space has six DOF, therefore a system of n rigid segments has $6 \times n$ DOF. In systems such as the human body, joints connect the segments. These joint connections (and their skeletal features) impose constraints by limiting motion in certain planes or axes, so the number of DOF decreases (DOF in a jointed segmental system = $6n$ – number of constraints) (Zatsiorsky, 1998). So, even though the human system is made up of many segments (each of which would theoretically have six DOF), any particular segment or part of the system is constrained in one or more ways. Whereas planes, axes, and directions are ways of describing motion of the system (or a segment of the system), DOF give information as to *available* motion of the system or system segment.

2.4 MOTION AT SEGMENTAL LINKS

The human skeleton is linked together at various types of joints. So if the human body is the system of interest, then we must be able to describe the relative motion that occurs between two segments of the system. Once again, descriptions of joint motions vary slightly depending on the discipline or textbook. Therefore, the motions defined in the following sections represent generalizations of terminology used across various movement disciplines (Floyd, 2018; Oatis, 2017; VanPutte et al., 2017; Watkins, 2010).

Traditionally, intersegmental motions are termed *joint actions* and are introduced as new vocabulary to memorize. But one purpose of this book is to introduce as early as possible the use of biomechanical concepts to analyze movement. To make using these concepts easier and to aid understanding of skeletal movements, we will use a free-body diagram. A **free-body diagram** is a simplified representation of the system *free* of the movement environment. This type of minimalist rendering is often a stick figure or geometrical model of the system with the center of mass and points of contact with the environment depicted (Figure 2.15).

The center of mass must be represented because it is the point at which the force of gravity is concentrated. Points of contact with the environment are important because these are areas where the system is acted on by external forces. In situations in which a joint (segmental link) in the body is the system of interest (Figure 2.16), internal forces such as muscle forces and forces at the link itself (joint reaction forces) are usually represented along with the center of mass and environmental contact points (external forces).

Free-body diagram A simplified representation of a system free of the movement environment.

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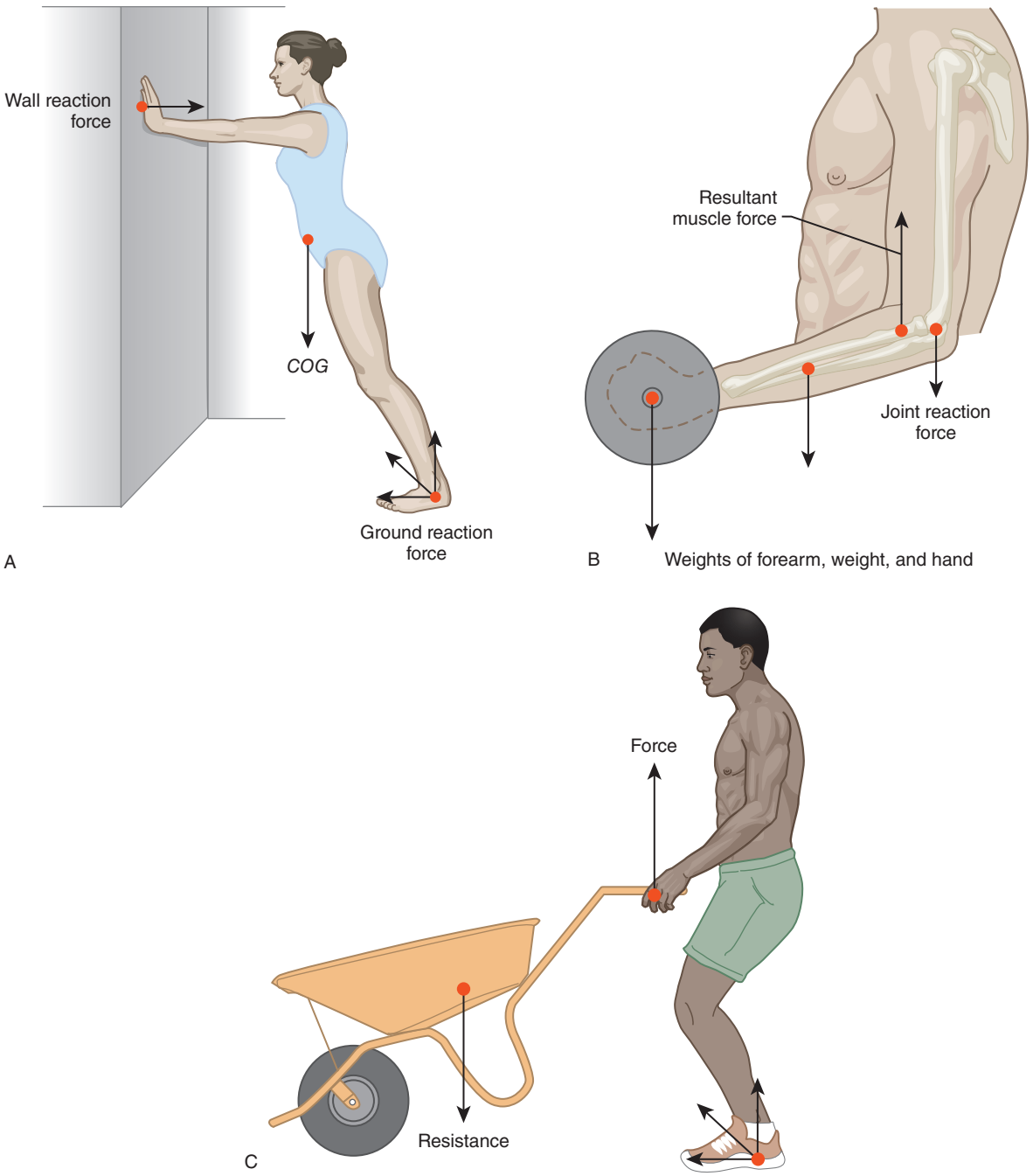


Figure 2.15 **Free-body diagrams of common activities.** Draw a free-body diagram of your current position.

Arrows showing the directions in which they act represent the forces in free-body diagrams. The specific characteristics of force representation with arrows are discussed in Chapter 3. We have not begun to elucidate all of the possible forces acting internally or externally to the system, so free-body diagrams in this chapter consist of the system alone. As you will see in subsequent chapters, the human body is a highly complicated system that can be engaged in highly complex movements. Free-body diagrams help visualize the many complex facets of a movement situation in a simplistic form for analysis. In essence, sometimes we must "suspend reality" and create a representation of only the most important aspects

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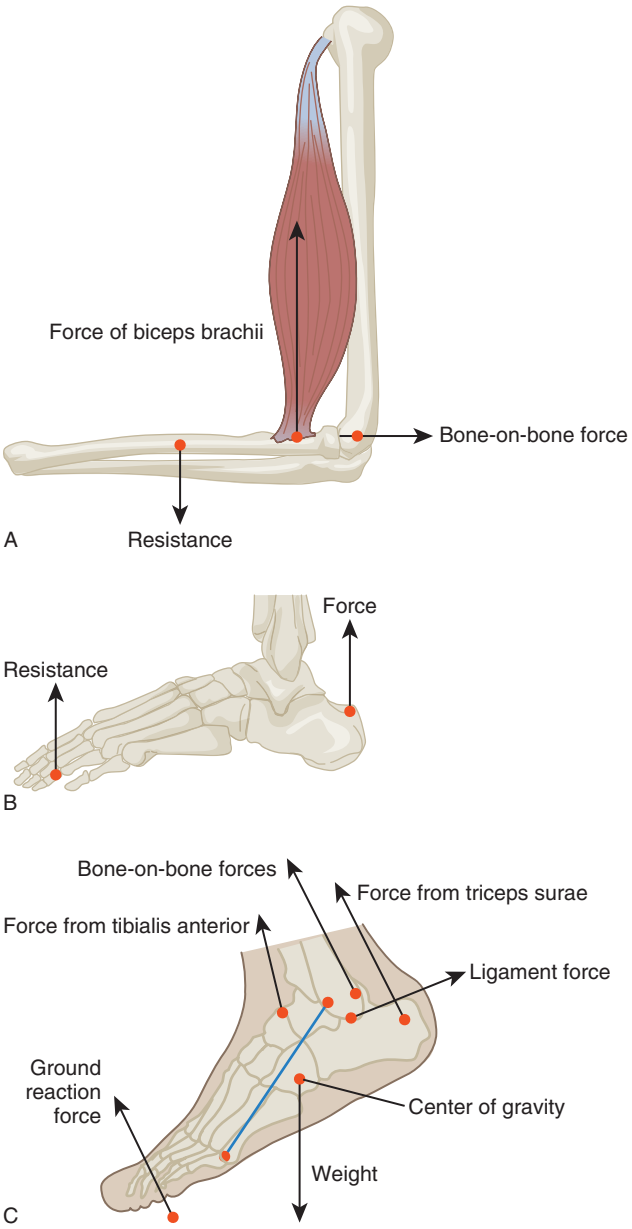


Figure 2.16 **Anatomical free-body diagrams.** Draw a free-body diagram of the hand during the performance of a push-up exercise.

Flexion Segmental motion in a sagittal plane, around a mediolateral axis, and away from the anatomical position.

Extension Returns a segment to the anatomical position in a sagittal plane around a mediolateral axis and is described as increasing the angle at the joint.

of the motion. Even though the segmental link movements that follow are relatively simple, using free-body diagrams at this point enables you to engage in the initial stages of biomechanical analysis by becoming accustomed to the visualization necessary in the field of biomechanics.

Motions in Sagittal Planes

Most body segmental links (joints) possess degrees of freedom in the sagittal plane: ankle (talocrural), elbow, hip, interphalangeal, intervertebral, knee, shoulder (glenohumeral), and wrist. Of course, the relative motion of two segments in the sagittal plane occurs around a mediolateral axis and is in reference to the anatomical position (Figure 2.17).

For example, **flexion** of a joint results in segmental motion in a sagittal plane, around a mediolateral axis, and away from the anatomical position. Flexion is sometimes described as causing a decrease in joint angle. The angle that should be visualized in this convention is the angle formed by the segment of interest and the frontal plane while in the anatomical position. Specialized terms are used for flexion at the ankle: *dorsiflexion* deviates the foot from the anatomical position such that it moves in a sagittal plane toward the anterior tibia, whereas *plantar flexion* is the opposite motion in a sagittal plane away from the anatomical position resulting in the foot moving toward the posterior surface of the tibia (e.g., pointing the toe). **Extension** returns the segment to the anatomical position in a sagittal plane around a mediolateral axis and is described as increasing the angle at the joint. If extension is continued to the point that it exceeds the anatomical position, the movement is termed *hyperextension*. *Hyperflexion* is technically also possible but is prevented by joint structure (contact of one segment with another) in most non-injured joints. However, hyperflexion does occur in a healthy shoulder joint when it is flexed beyond vertical.

Motions in Frontal Planes

Body segmental links that are capable of frontal plane motion (around an anteroposterior axis) are the foot (subtalar and transverse tarsal joints), hip, intervertebral, metacarpophalangeal, shoulder, and wrist (Figure 2.18). Once again, all anatomical motions are described relative to the anatomical position.

Motion of the axial skeleton (at the intervertebral joints) in the frontal plane around an anteroposterior axis is termed *lateral flexion*. For example, leaning the trunk to one side and tilting the head are both lateral flexions.

The hip, metacarpophalangeal, and shoulder (glenohumeral) joints are capable of abduction and adduction.

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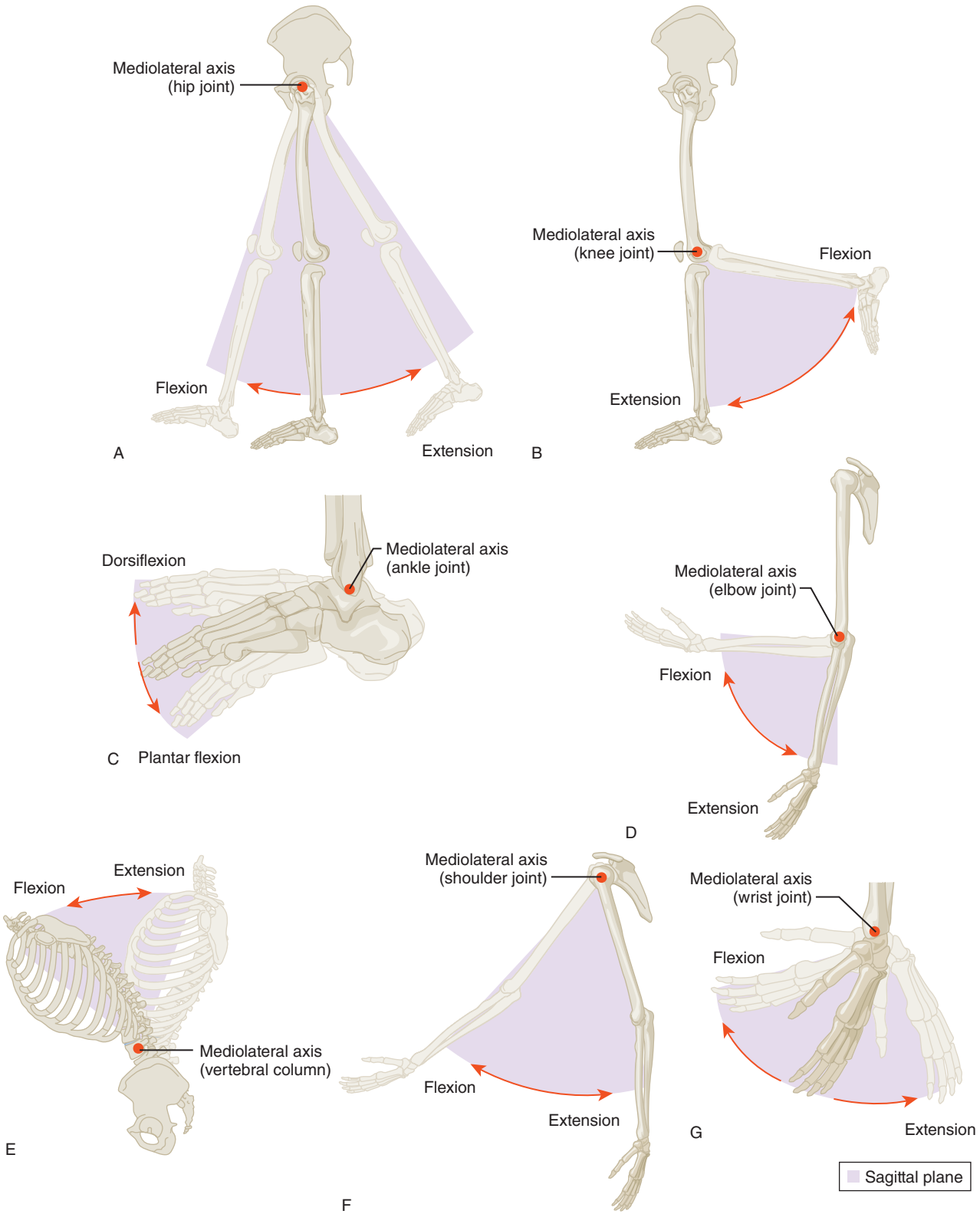


Figure 2.17 **Motions in sagittal planes.** Think of resistance training exercises that occur in sagittal planes.

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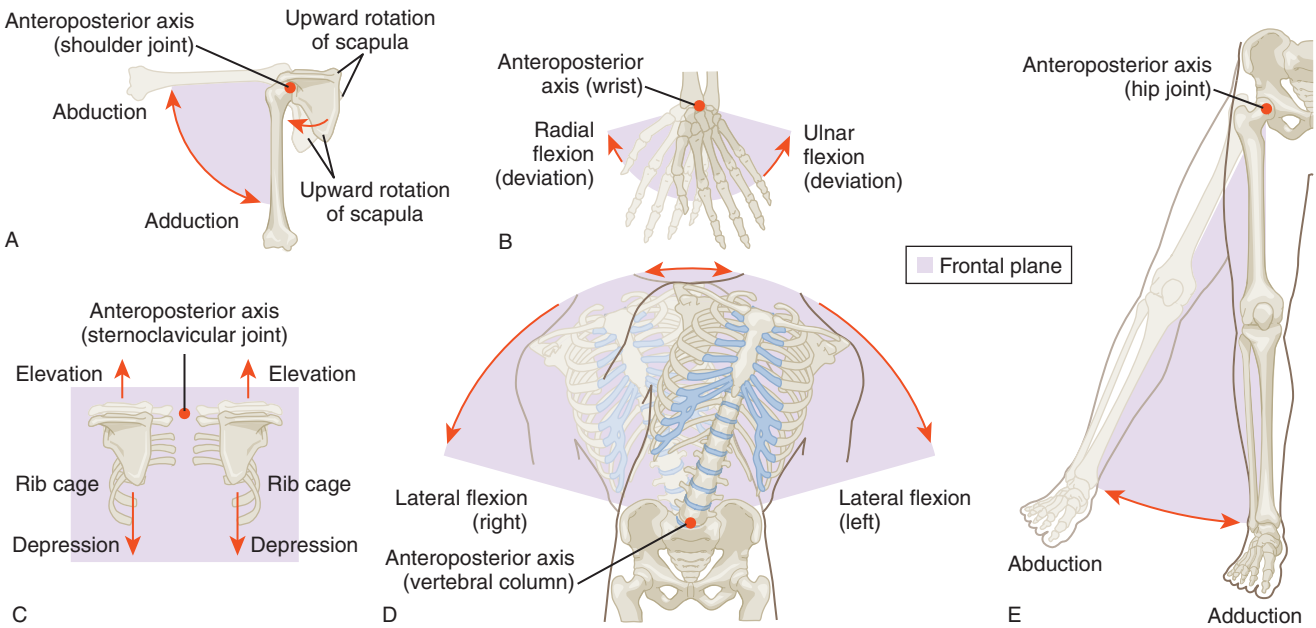


Figure 2.18 **Motions in frontal planes.** What exercises occur in frontal planes?

Abduction is the frontal plane movement analogous to flexion. In other words, **abduction** is motion in a frontal plane and around an anteroposterior axis that moves the segment away from the anatomical position. In contrast, **adduction** is frontal plane motion that returns the segment to the anatomical position. Jumping jacks is an exercise example of repetitive abduction and adduction of the shoulders and hips. Abduction of the metacarpophalangeal joints can be visualized by standing in the anatomical position and then spreading the fingers.

Because the number of degrees of freedom at the shoulder is large, many specialized movement terms are necessary to fully describe its motion. As previously mentioned, the glenohumeral joint of the shoulder is capable of flexion and extension in the sagittal plane and abduction and adduction in the frontal plane. However, when motions of the shoulder are being described, we must consider more than just the glenohumeral joint. For example, the scapula (shoulder blade) is capable of four motions in the frontal plane. Two of these motions are actually associated with sternoclavicular joint motion and are therefore considered motions of the shoulder girdle: *elevation* is the term for motion of the scapula superiorly, and inferior movement of the scapula is called *depression*. The other two motions of the scapula in the frontal plane are associated with acromioclavicular joint motion and are named for changes in orientation of the glenoid fossa of the scapula. The orientation of the glenoid fossa changes when the arms are raised above the head. Movement of the scapula in a frontal plane that causes the glenoid fossa to rotate upward (inferior angle of the scapula moving laterally away from the vertebral column) is called *upward rotation*. *Downward rotation* is movement of the shoulder that results in the glenoid fossa rotating downward (scapula rotating in a frontal plane, around an anteroposterior axis, with the inferior angle moving medially toward the vertebral column).

Specialized terms also exist for frontal plane motion of the foot at the subtalar and transverse tarsal joints. **Eversion** is frontal plane motion around an anteroposterior axis

Abduction Motion in a frontal plane and around an anteroposterior axis that moves the segment away from the anatomical position.

Adduction Frontal plane motion that returns the segment to the anatomical position.

Eversion Frontal plane motion around an anteroposterior axis such that the sole of the foot rotates outward or laterally.

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such that the sole of the foot rotates outward or laterally. If the sole of the foot is rotated medially the motion is termed **inversion**. Take care with these terms, because they are often confused with ankle pronation and supination, which in this chapter are discussed with motions that occur in oblique or multiple planes.

Deviation is a term used for frontal plane motion around an anteroposterior axis at the wrist. If the thumb is moved closer to the radius (relative to the anatomical position), the movement is called *radial deviation* (also abduction and radial flexion). *Ulnar deviation* is frontal plane motion at the wrist that results in hand motion toward the ulna (adduction and ulnar flexion).

Motions in Transverse Planes

Skeletal segmental links with DOF in the transverse plane (around a superoinferior axis) directly from the anatomical position are the hip, intervertebral, shoulder, and radioulnar (Figure 2.19).

The axial skeleton (intervertebral joints) is capable of transverse plane motion at both the neck and trunk. *Rotation to the left* and *rotation to the right* are transverse plane motions accomplished by simply turning the head or twisting the torso to the left or right.

Internal rotation and external rotation are motions that are available at the hip and shoulder. For example, *internal rotation* at the shoulder (also called *inward* or *medial rotation*) is motion of the arm segment around a superoinferior axis that rotates it from the palms-forward anatomical position to a posture in which the palms are facing more medially and finally posteriorly. *External rotation* (outward or lateral) is the opposite motion in which the segment is returned to or beyond the anatomical position in a transverse plane (e.g., rotating the leg segment at the hip such that the toes point outward or laterally.

In addition to rotations, the shoulder is also capable of two other transverse plane motions. The shoulder girdle can be protracted and retracted. *Protraction* is movement of the shoulder girdle anteriorly away from the spine. Protraction is accompanied by abduction of

Inversion Frontal plane motion around an anteroposterior axis such that the sole of the foot rotates inward or medially.

Deviation Frontal plane motion around an anteroposterior axis at the wrist.

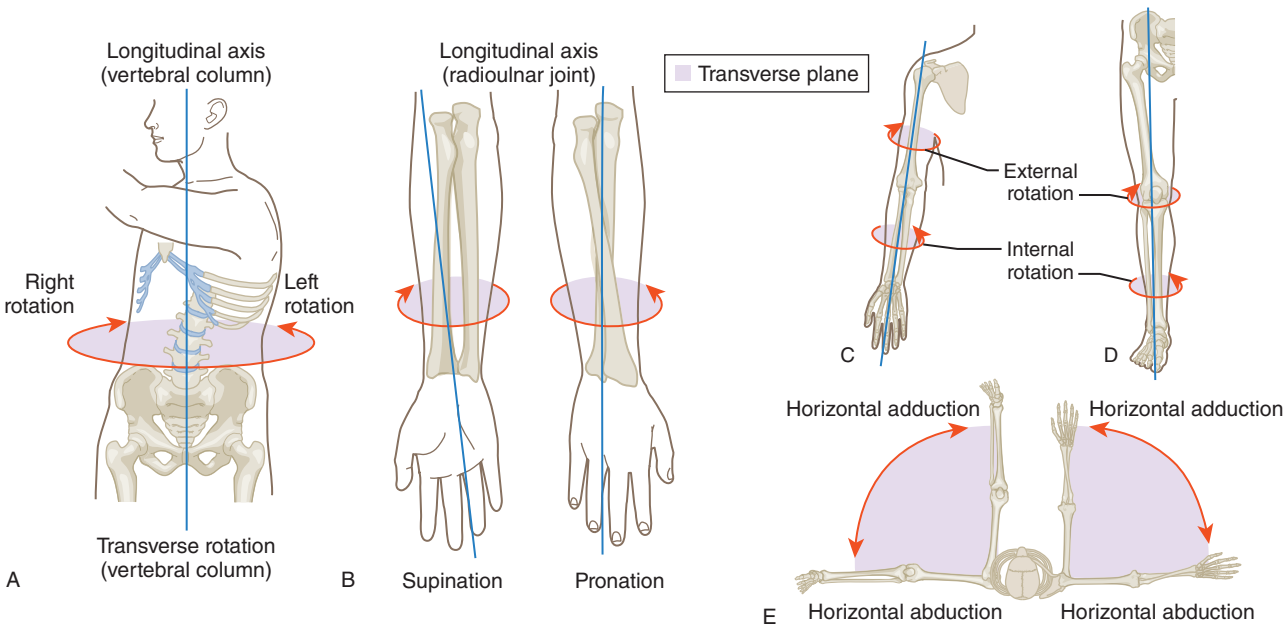


Figure 2.19 **Motions in transverse planes.** Think of daily activities that occur in transverse planes.

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the scapula. *Retraction* is movement of the shoulder girdle posteriorly toward the spine and is accompanied by adduction of the scapula.

The radioulnar joint of the forearm is capable of pronation and supination. In the anatomical position, the radioulnar joint is in supination. **Pronation** is rotation at the radioulnar joint around a superoinferior axis that causes the palm to turn toward the body (medially and posteriorly). Do not confuse this action with internal rotation. Internal rotation occurs at the hip or shoulder; pronation occurs specifically at the radioulnar joint and is an independent action from rotation (i.e., you can rotate the palm medially without moving at the shoulder joint at all). Of course **supination** is the transverse plane motion that returns the radioulnar joint toward the anatomical position (palm moves anteriorly). Again, supination is independent of external rotation at the shoulder.

Rotation to the left and right, internal and external rotation, and pronation and supination can all occur directly from the anatomical position. Some transverse plane motions are possible if a segment is first moved into the transverse plane. For example, the frontal plane motions of abduction and adduction can occur in the transverse plane if the shoulder or hip is flexed first. If the hip or shoulder is flexed until a segment is moved into the transverse plane and then rotated laterally around a superoinferior axis, the movement is called *horizontal* or *transverse abduction* (also called *horizontal extension*). *Horizontal* or *transverse adduction* (horizontal flexion) is the opposite motion in which the segment is rotated around a superoinferior axis and through a transverse plane toward the midline of the body (medially).

Motions in Oblique and Multiple Planes

Some segmental link motions do not fit into the cardinal planes and axes described. For example, you have learned that planes and axes can be oblique. Therefore, if a segment is moved into an oblique plane before the motion of interest occurs, the segmental link motion is also oblique or diagonal (e.g., oblique abduction). In addition, movements can occur in more than one plane of motion, and some motions occur in planes but not around axes.

One segmental link motion that occurs in more than one plane (around more than one axis) is called *circumduction* (Figure 2.20).

Circumduction is possible at any joint in which the proximal end of the segment can remain fixed while the distal end of the segment is capable of describing a circle (so that the segment as a whole describes a cone). Because circumduction is a complex motion in multiple planes and axes, the joints that are capable of circumduction are the ones that have DOF in terms of flexion, extension, abduction, and adduction (hip, intervertebral, metacarpophalangeal, shoulder, talocalcaneal, and wrist).

Two other motions that do not quite fit into a clearly defined planar category are ankle and foot pronation and supination. Pronation of the ankle and foot requires simultaneous ankle dorsiflexion, forefoot abduction, and subtalar eversion. Supination is simultaneous ankle plantar flexion, forefoot adduction, and subtalar inversion (Floyd, 2018).

Although all of the segmental link motions mentioned to this point occur in planes and around axes, motion can occur in a plane but not around an axis. These nonaxial movements occur when a system segment is being moved as the result of an adjacent axial joint motion. For example, if you perform a bench press in weight lifting, the hands are moved in a plane but not around an axis. Can you name the plane? The planar motion of the hands in this example is caused by axial motions at the elbows and shoulders.

Pronation Rotation at the radioulnar joint around a superoinferior axis that causes the palm to turn toward the body (medially and posteriorly).

Supination Transverse plane motion that returns the radioulnar joint toward the anatomical position (palm moves anteriorly).

Use of Terminology

To avoid confusion, we need to refer back to the previous discussions of planes, axes, directions, and segmental

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motions. As can be seen, the cardinal planes (sagittal, frontal, and transverse) and axes (mediolateral, anteroposterior, superoinferior) are especially useful for describing musculoskeletal movement *from the anatomical position*. Because the anatomical position is a constant starting reference point, it is accompanied by cardinal axes (and planes) that are always the same. However, natural motion does not often begin in the anatomical position. For example, one can describe the movements of *individual body parts* of a tennis player in reference to the anatomical position, but it does not make sense to describe the position on the court of the *entire tennis player* (system) in reference to the anatomical position. So we need the ability to establish frames of reference outside of the body and independent of the anatomical position. In addition, we need to define multiple frames of reference. Cartesian coordinate frames of reference are versatile. The *x*, *y*, and *z* are not only *axes* that can be used in place of the cardinal axes but also can form a frame of reference in terms of *planes* and *directions* of motion of both individual segments and the entire system. For example, hip and knee extension and flexion occur around a mediolateral axis. This motion would be accompanied by motion of the femur and tibia in a sagittal plane (in reference to the anatomical position). What about motion of the foot or entire body (system) as a result of repetitive hip and knee flexion and extension? Hip and knee extension and flexion could be described in relation to the previously defined Cartesian coordinate frames of reference: hip and knee motion are occurring around *z*-axes, resulting in motion of the femur and tibia in planes formed by the *x*- and *y*-axes. Movement at the hip and knee results in foot motion in the $x\pm$ (forward and backward) and $y\pm$ (upward and downward) directions. The total resultant motion of the entire system center of gravity is $y\pm$ and $x\pm$ (Figure 2.21).

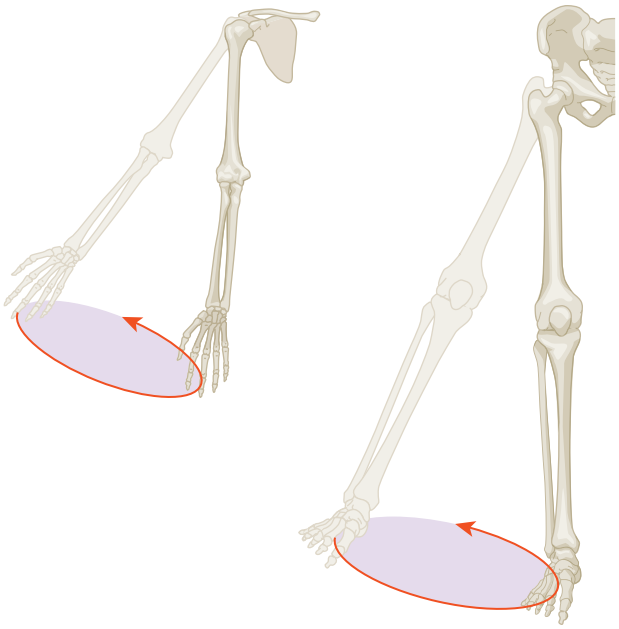


Figure 2.20 **Motion in oblique and multiple planes.** Name some oblique plane sports motions.

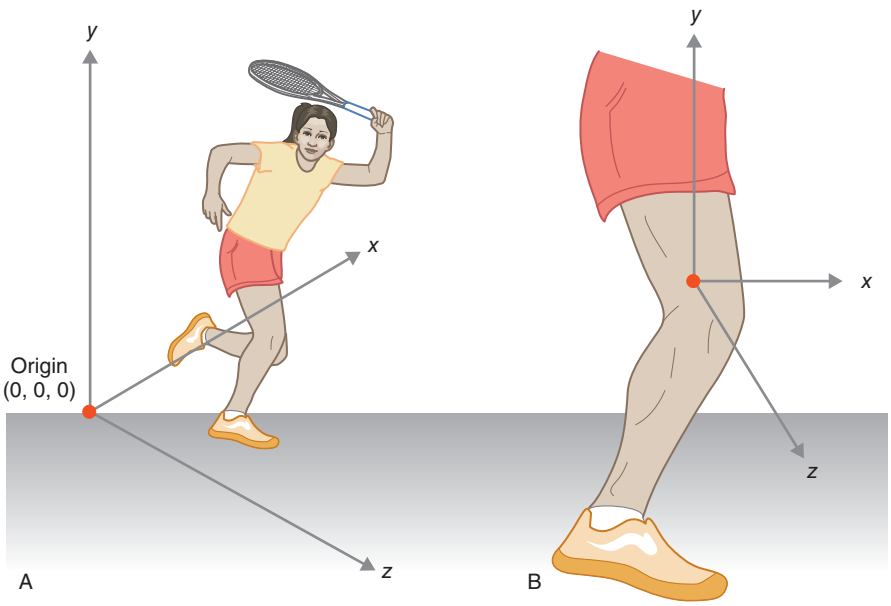


Figure 2.21 **Athlete and associated reference systems.** In what direction does the tennis ball move?

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In addition to enhanced descriptive ability, Cartesian coordinate frames have an origin but do not require a specific starting body position to describe motion at any given point in time (i.e., the above description did not require any comparison to the anatomical position). So even though some terminology in the disciplines of anatomy and biomechanics is redundant, having several different conventions allows highly detailed interdisciplinary description of system movement.

2.5 THE MOVEMENT ENVIRONMENT

During a game of soccer, the ball is kicked for several different reasons and in different ways, including passes, clears, and shots on goal. At times the ball is in motion when struck by the foot, and at other times it is stationary. The movement—or lack thereof—of the ball is an environmental factor that must be taken into account when performing each kick. The nature of the skill is *open to change* when the ball is in motion, which is quite different than when the skill is performed with the ball at rest. The following section describes these two major environmental categories in which movements are performed. Note that some seemingly closed skills may take on properties of an open skill when external environmental factors have the potential to affect the outcome. In essence, a continuum of options exists between closed and open skills. Skills performed under the most constant conditions are at one end, and those with the most variable conditions are at the other.



Figure 2.22 **Basketball free throw.** Think of some other closed sports skills.
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Closed Skills

A skill is defined as **closed** when it is performed under standard environmental conditions (Figure 2.22). A basketball free throw is a good example; the goal is always at the exact same height, the free throw line is the same distance from the goal, and the ball is a standard size and weight.

Other examples include soccer penalty shots, putting in golf, bowling, archery, throwing horseshoes, and batting in T-ball. Notice that in each of these skills, the possibility of an external environmental influence is present. For instance, although the soccer penalty kick is taken from a standard distance and position, with a standard size ball at a standard size target, certain factors influence how the skill is performed. The playing surface (grass or artificial), position and tendencies of the goalkeeper, or wind may all affect how a player performs the skill. Putting on a golf green also presents factors that may affect the ball after the stroke is taken, such as the grain of the grass and changes in elevation, but the skill of striking the ball is constant. Few sport skills could be considered entirely closed or free from any environmental influence.

Closed skill Skill performed under standardized or predictable environmental conditions.

Open skill Skill performed in a changing or unpredictable environment.

Open Skills

When movement must be altered because of the changing dynamics of the activity, environment, or object of interest, a skill is considered **open** (Figure 2.23).

Referring back to the game of soccer, you may have realized by now that most skills are not performed under

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static or standard conditions; the ball is in motion most of the time. To be successful, players must react to the ball in this constantly changing environment. Dribbling and passing could be considered closed skills when performed in isolation during practice, but these skills are not designed to be used in isolation. During a game, no two passes are likely to be identical, and dribbling is a dynamic skill that changes constantly depending on defensive pressure, open spaces, position of teammates, and the velocity of the player with the ball. Some sport and recreation skills are performed in less changeable environments, and some are performed in conditions that are highly unpredictable and constantly changing.



Figure 2.23 **Soccer header.** What are some closed skills in soccer?
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2.6 TYPES OF MOVEMENT

Linear and Angular Motion

The term *motion* has been used many times thus far in our description of the system. We must now be more specific and clarify exactly what is meant by the word *motion*. **Motion** can be defined as a change in position with respect to both spatial (relative to points in space) and temporal (relative to time) frames of reference. In other words, a system moves in a given space and that movement requires a given amount of time. No change in motion occurs without force. For now, we will simply define a **force** as something that possesses the capability to cause a change in motion or shape of the system (i.e., a "pull" or "push"). Motion is relative, so the frame of reference is extremely important. **Relative motion** is the motion of one object with respect to a reference object. For example, if you are standing still it could be said that you are motionless relative to Earth. However, Earth is in orbit around the sun and moving through the galaxy. So although you may not be moving relative to Earth, you are in motion relative to other planets. A more specific example is two hockey players skating next to each other at 5 kilometers per hour (km/hr). They are both moving at 5 km/hr relative to the rink, but neither is moving relative to the other (0 km/hr). If another hockey player then skates past them at 15 km/hr, this third player is moving at 15 km/hr relative to the rink and 10 km/hr relative to the other two players (the numbers are subtracted if both objects are moving in the same direction). On the other hand, one player could be skating at 15 km/hr toward another player moving at 10 km/hr. In this case, their relative motion is 25 km/hr (the numbers are added if two objects are moving in opposite directions). In addition to motion being relative it can be defined as *translation*, *rotation*, or *general* (translation and rotation simultaneously).

Translation is motion *along* one of the *x*-, *y*-, or *z*-axes in which all points of the system move (change position) at the same time, in the same direction, and the same distance with respect to the defined reference frame despite their location on the system. During translation, all points on the system are moving at the same time, so their path can be represented as one point (e.g., the center of gravity) traveling along a line from one place to another. Therefore, translation is

Motion A change in position with respect to both spatial and temporal frames of reference.

Force Something that possesses the capability to cause a change in motion or shape of the system.

Relative motion The motion of one object with respect to a reference object.

Translation Motion along one of the *x*-, *y*-, or *z*-axes; linear motion.

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also called *linear motion*. The linear path of a system in translation can be straight or curved. If the path of the system is a straight line (i.e., no change occurs in direction of motion), the motion is termed *rectilinear translation*. An example of rectilinear motion is the movement of an object when you drop it.

The object would travel in a straight line toward Earth. The change in linear position of the system in a straight line or its *linear displacement* (*d*) is described in terms of linear measurement units (e.g., millimeters, centimeters, meters, and kilometers). *Curvilinear translation* is the same as rectilinear in terms of the points on the system moving together, but in this case the path of the representative point is curved (in an arc) instead of straight (i.e., direction of system motion is changing). An example of curvilinear motion is a ski jumper. As soon as the jumper leaves the ramp, wind resistance slows him down and gravity pulls him toward Earth. Therefore, the resultant path of the ski jumper is an arc (curvilinear). Because the shortest distance between two points is a straight line, the actual path of the system in curvilinear motion is a greater distance than the linear displacement measured relative to the frame of reference.

Rotation occurs when the system is restricted to move *around* a fixed axis and therefore in a circular path (such as the segmental link motions described previously). Because the path of motion of one point on a rotating system or system segment describes a circle (and therefore the location of one segment relative to another forms an angle), rotation is also called *angular motion*. In the case of rotation, all points on the rotating segment have the same *angular displacement* (θ; the Greek letter theta), measured in degrees or radians. However, each point on a rotating segment has a different curvilinear displacement depending on its distance from the axis of rotation, which is called the *radius of rotation* (Figure 2.24).

Rotation Motion around a fixed axis and therefore in a circular path; angular motion.

For example, all points on the forearm and hand segments travel 45 degrees *angularly* ($\theta = 45°$) if the elbow is flexed 45°; but individual points representing the center of mass of the forearm, the wrist, and the distal phalanges all describe arcs of varying lengths (i.e., travel different *curvilinear* distances).

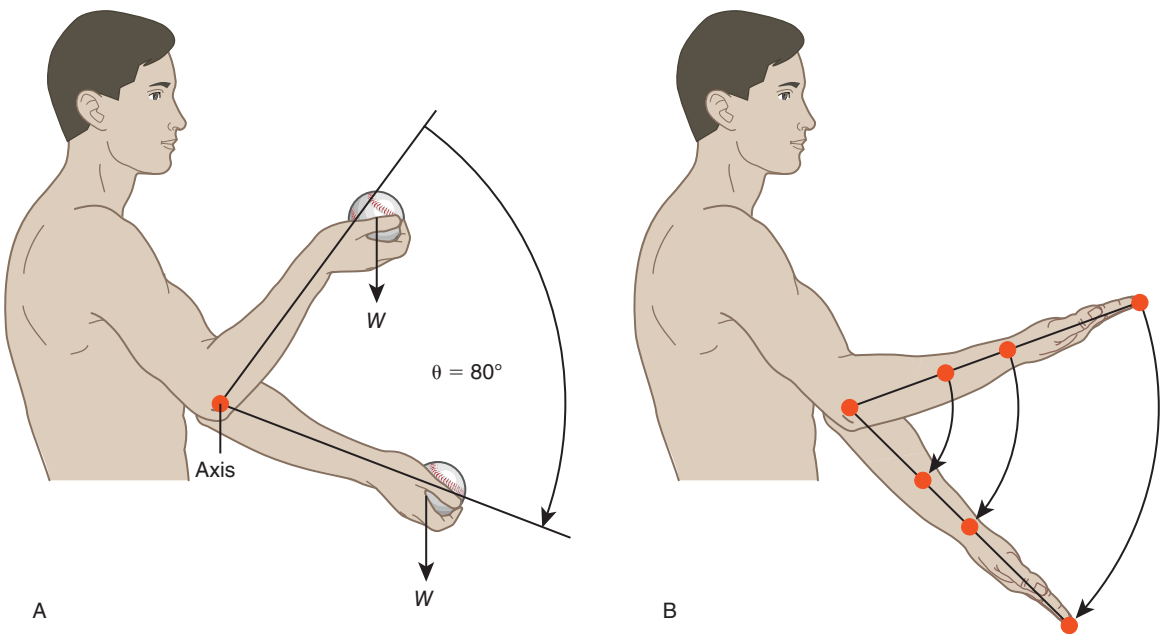


Figure 2.24 **Radius of rotation for various points on the arm.** What happens to the radius of rotation if an athlete uses an implement instead of the hand for striking?

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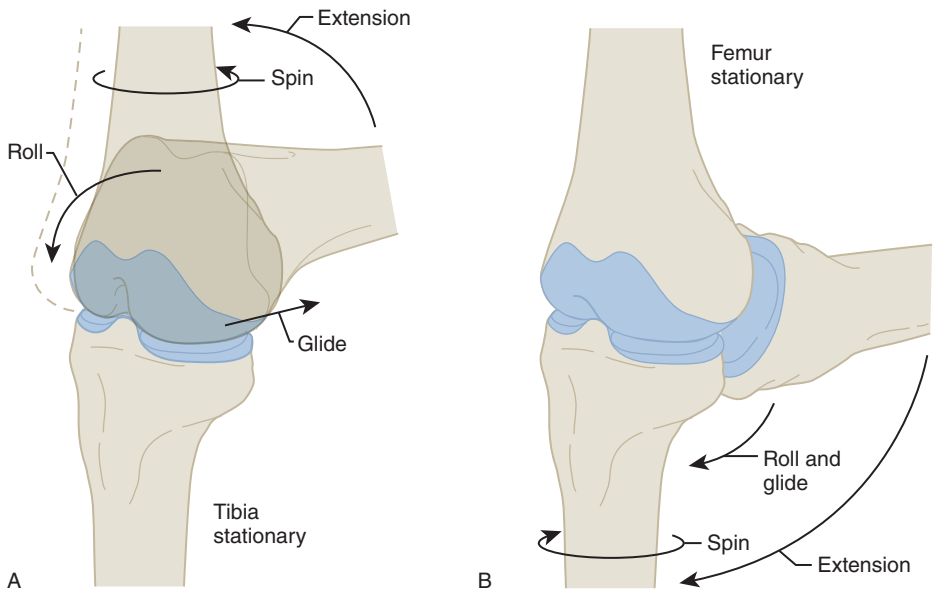


Figure 2.25 **Knee spin, roll, and glide.** Are there any joints in which pure spin occurs?

As previously described, nonaxial segmental motions are produced as a result of adjacent axial motions. In the human system, this motion is actually translation as a result of rotation. This combination of translation and rotation is called *general motion*. Specifically, the entire system or a segment of the system can be linearly displaced (translate) as a result of angular displacement at a segmental link (rotation at joints). For example, a person (the whole system) can run forward (translate) because of actions at the hips, knees, and ankles (joint rotation). Motion at segmental links (joints) is actually a great example of combining translation and rotation. We tend to think of joint movement as pure rotation. However, motion at most synovial joints is actually general in nature. If one segment in the skeletal system moves relative to another with pure rotation (no translation) it is called *spin*. **Spin** occurs if all points on one articulating surface (such as the ulna) come in contact with one point on another articulating surface (the humerus). Contrast this motion with **glide** (sliding) or pure translation, in which a point on one surface glides (or skids) over many points of an opposing surface. **Roll** (a combination of rotation and translation) occurs when each point on a surface contacts a unique location on the other surface (Figure 2.25).

Many natural joint motions are a combination of gliding and rolling. In the preceding tibiofemoral joint example, knee flexion causes the tibia to roll and glide posteriorly on the femur (the femur is in posterior roll and anterior glide). Knee extension causes the opposite situations of femoral anterior roll and posterior glide.

Discrete, Continuous, and Serial Skills

Skills can be classified into general categories by how they appear. Movement has traditionally been defined into three categories; *discrete, continuous*, and *serial*. This text identifies four categories of movement to alleviate some of the confusion that arises when skills don't seem to precisely fit the definition of one of the three traditional categories. A term that is often used synonymously with serial is *repeated discrete*, but it can be argued that these terms describe distinct categories.

Spin Occurs if all points on one articulating surface come in contact with one point on another articulating surface.

Glide Sliding or pure translation in which a point on one surface glides or skids over many points of an opposing surface.

Roll Rotation of a system around the *x*-axis.

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Figure 2.26 **A tennis player performs a discrete skill.** Why is pitching a discrete skill?
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Figure 2.27 **Cycling.** Think of some other continuous skills.
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Discrete skill Motion that has a definite beginning and end-point.

Continuous skill Cycles of motion performed repeatedly with no well-defined beginning or end points.

Repeated discrete Cycles of motion that are seemingly continuous but require a recovery phase between propulsive actions.

Serial skill Movement that comprises a series of discrete motions.

Discrete

A movement is labeled a **discrete skill** when it has a definite beginning and end point (Figure 2.26). Examples of discrete skills are basketball free throws, baseball pitches, a penalty kick in soccer, and the volleyball or tennis serve. Although discrete skills have identifiable start and end points, they may also be initiated or followed by other movements. The long jump, high jump, and pole vault are all discrete skills that directly follow a moving approach. The moving approach to all three track and field jumping events is usually running, which is identified as a continuous movement. The flip turn in swimming is also a discrete skill that follows a continuous skill of freestyle or backstroke swimming.

Continuous skills are distinguished as cycles of motion performed repeatedly with no well-defined beginning or end points (Figure 2.27).

Examples include walking, swimming, bicycle riding, wheelchair "hand-cycle" racing, and in-line skating. Continuous movements can be stopped and started anywhere in the pattern. A critical identifier of continuous movements is the fact that at the finish of one cycle, the body is already in position to perform the next repetition.

Repeated Discrete

Some movements appear continuous but deserve a separate category of classification. Rowing is often labeled a continuous event, but at the end of a stroke the body is not in a position to perform the next stroke.

Between each pull there must be a recovery phase to put the rower in position to pull again. Therefore, a skill of this type is better labeled as **repeated discrete** (Figure 2.28). Another example in this category is traditional wheelchair racing. As in rowing, the propulsion phase leaves the athlete in a down-and-forward position from which she is not ready to push again without recovering to an upright position. Many assembly line jobs also fall into this category because workers rarely finish one repetition of their designated task in position to begin the next.

Serial

Some movements appear to be somewhat continuous in nature but are really a combination of discrete motions; these are called **serial skills**. In track and field, the triple jump is an excellent example of a serial movement Figure 2.29.

A continuous movement (run-up) initiates the activity; then the athlete performs three discrete actions

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without any stop between them (a hop, a step, and a jump), creating a new complex movement. An uneven parallel bar routine in gymnastics provides another good example. Points are deducted if a gymnast loses momentum during a routine, so it may seem to be a continuous activity. However, the routine is composed of series of discrete skills that are connected together into a constantly flowing pattern.



Figure 2.28 **A rower sculling.** Why is this skill repeated discrete instead of continuous?
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Gross and Fine Motor

Depending upon which textbook you are reading, movements are classified as gross or fine motor based on either the size of the muscle groups responsible for the action or for the precision of control necessary for the action. **Gross movements** generally result from major muscle group activity involving large muscles.

Movements classified as gross motor require little precision and include most fundamental skills such as walking, running, throwing for distance, skipping, and weight lifting. **Fine movements** are precise and generally controlled by small muscle groups or individual muscles (Figure 2.30). Examples include writing, playing the piano, threading a needle, and typing. Sometimes large muscle groups are asked to perform precise movements, and conversely, small muscles may be contracted with little regard for precision. For this reason, movement is classified as gross or fine *motor*, based on the precision of motion that the task requires.

Two examples that use common muscles or groups of muscles can help explain why precision of movement should be the best indicator for distinguishing between gross and fine motor skills. The quadriceps is a large four-muscle complex that performs multiple gross motor tasks during daily activity. Most actions that the quadriceps muscles perform require little precision: walking, climbing stairs, running, and jumping. However, the quadriceps muscles are asked to function with varying degrees of precision during some tasks. They function eccentrically

Gross movement Motion that is the result of large muscle group activity and requires little precision.

Fine movement Motion that is precise and generally controlled by small muscle groups.



Figure 2.29 **A triple jump.** Why is the triple jump not considered to be repeated discrete?
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Figure 2.30 **Power lifting and texting.** Are there some precise skills performed by large muscle groups?

in lowering the body from standing to sitting position, a movement that requires more precise control to avoid falling heavily into the seat. Drivers of autos with manual transmissions take quadriceps precision to an even higher level. Any time the car is stationary, a driver must depress the clutch with his left leg (a gross motor skill requiring little precision), then *slowly* retract the leg to engage the clutch smoothly and avoid stalling the engine. This engagement point occurs in a relatively small range of motion and is controlled by a large muscle group.

At the opposite end of the spectrum are the small muscles that control side-to-side eye movement. These muscles are diminutive relative to the quadriceps and generally perform highly precise movements—such as allowing your eyes to move from word to word as you read this sentence. If you've never done it, watch a friend's eyes as he or she reads a paragraph; you'll be able to see each tiny movement as the eyes advance to a new word or line. These eye movements are called *saccades*, and they occur even when we are asked to follow an object in constant motion with our eyes such as watching a baseball travel from a bat into the outfield. These saccades require highly precise control to follow moving objects and are considered a fine motor skill. How could these muscles ever be considered gross motor effectors? Consider the case of a golfer who follows an instructor's advice: keep your head down and eyes on the ball until after you make contact. The ball leaves the club face traveling at high velocity, then the golfer must "find the ball" by moving her eyes rapidly in the approximate direction of ball flight. This saccade should be considered a gross movement, because the initial objective is to catch up to the ball. Once the ball is identified in flight, the muscle contractions become fine motor again as the eyes focus on and track it using small saccades.

Most sport and recreational activities require a combination of fine and gross motor skills. At times, the same skill may require different degrees of precision, depending on the environmental context. The car driver who had to let the clutch out smoothly from a stop does not have to be as precise when shifting between two gears while the car is in motion. An accomplished piano player can change the nature of a piece by playing the same notes, at the same tempo, but varying the pressure with which she depresses the keys. Complex tasks may include movements that require large and small muscle groups working together. For example, dart throwing combines fine finger control with gross control of the triceps to propel the dart toward the board. Therefore, movements can fall along a continuum from fine to gross, even within the same activity. This textbook identifies movements on this continuum based on the precision of movement rather than the size of the muscle or muscle group.

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Kinetic Chain

In trying to describe motion of the system, using simplified models (such as the free-body diagrams referred to previously) is sometimes helpful. Thus far in the process of defining the system and describing its movements, we have modeled the human body system as having multiple segments connected at links (joints). If one imagines this system of segments and links as several interconnected chains, some specialized motion situations become easier to analyze and understand. For example, why does timing matter in throwing a baseball? Why does injury in one joint often lead to injury in another? Detailed understanding of the answers to these questions will come later. But even at this point, one can gain some basic insight into system motion if one understands the concept of a kinetic chain. At the basic structural and movement levels, a **kinetic chain** is simply a system of linked rigid bodies subject to force application. Remember that because all of the segments in the chain are linked together, motion at one link in the chain affects force transfer and therefore motion at one or more other links in the chain. For example, maximal medial rotation at the shoulder interferes with elbow flexion (i.e., degrees of freedom changes because of obstruction by the body). At the system performance level, a kinetic chain is an optimally timed sequence of link motions involving inter segmental force transmission. Kinetic chains vary in their particular characteristics because segmental links are all structurally different and movement situations are highly individualistic.

One type of classification for kinetic chains is their complexity. For example, in the arm kinetic chain, each segment participates in no more than two linkages (i.e., the hand is linked to the forearm; the forearm is linked to the hand and upper arm; and the upper arm is linked to the forearm and the shoulder) and is called a **serial** or **simple kinetic chain**.

A kinetic chain can also be complex (or branched). A **complex kinetic chain** is one in which a segment is linked to more than two other segments (Figure 2.31). For example, the human torso (if modeled as one segment) has two links at the hips, one at the neck, and two at the shoulders.

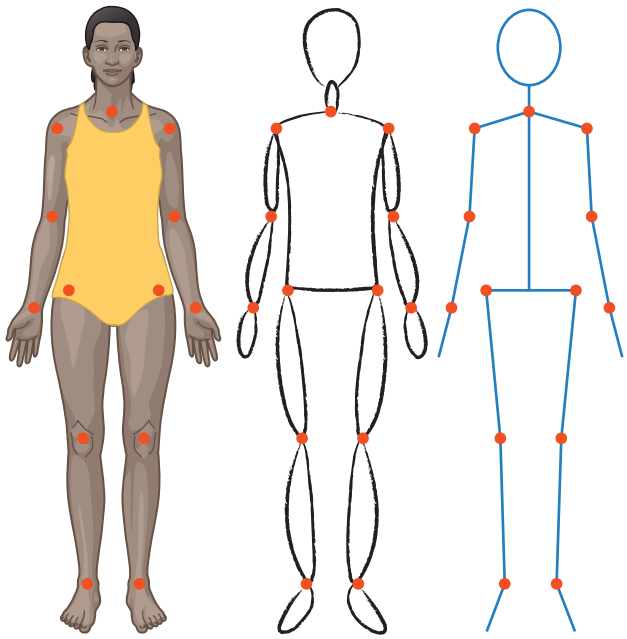


Figure 2.31 **A complex kinetic chain.**

Whether a kinetic chain is serial or complex is important in terms of total mobility of the chain and control of movement by the motor system. **Mobility** is the total DOF of a kinetic chain. Recall from our discussion of degrees of freedom that the number of segments and the number of links to other segments changes the total number of degrees of freedom (Zatsiorsky, 1998). Also, motion at one link can affect total chain DOF. In addition, more sophisticated methods of motor control are necessary as the chain becomes more mobile (gains degrees of freedom).

One of the most important considerations for kinetic chain classification, in terms of application to rehabilitation and sports training, is whether the chain is open or closed. Remember that, although the words are the same, this concept is not the same as an open or closed skill. The following are definitions of open and closed chain movements, which may or may not be performed in an open or closed environment.

Kinetic chain System of linked rigid bodies subject to force application.

Serial or simple kinetic chain Kinetic chain in which each segment participates in no more than two linkages.

Complex kinetic chain Kinetic chain in which a segment is linked to more than two other segments.

Mobility The total degrees of freedom of a kinetic chain.

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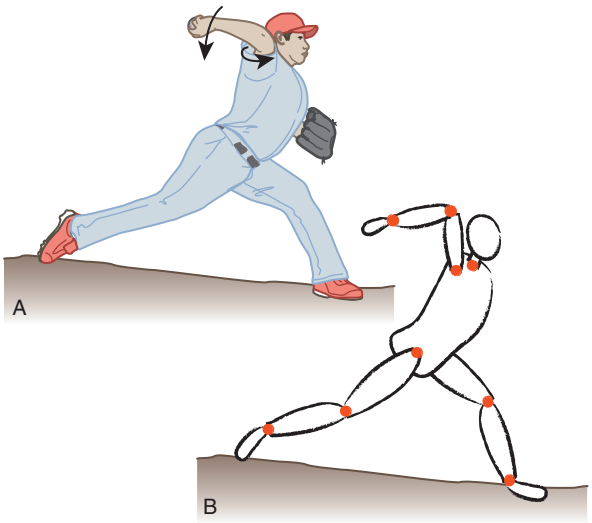


Figure 2.32 **A baseball pitcher as a complex open kinetic chain.** Are there some sports situations that are not complex open chain?

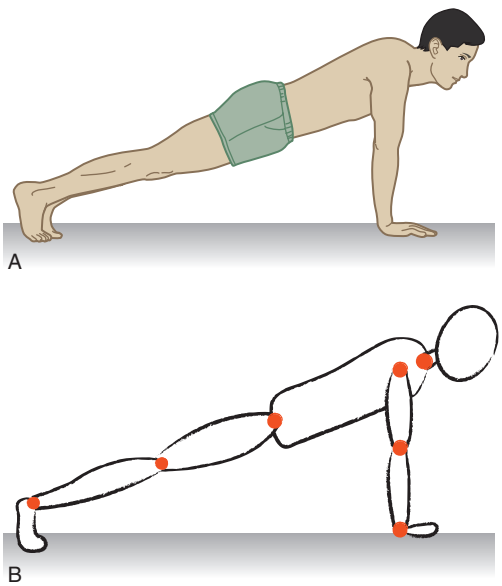


Figure 2.33 **A push-up exercise as a closed kinetic chain.** Name some other exercises that are closed chain.

Open kinetic chain Kinetic chain in which motion can occur at one link in the chain without cooperative motion at other links.

Closed kinetic chain Kinetic chain in which motion at one link is only possible with cooperative movement at other links.

Open Kinetic Chains

An **open kinetic (kinematic) chain** is one in which the most distal (or terminal) segment is free ("open") to move. Another classification is that motion can occur at one link (joint) in the chain without cooperative motion at other links. Therefore, open kinetic chains have greater mobility (more DOF). The force is usually applied at a more proximal segment (or proximal end of the same segment) to initiate motion. The force then can be transferred throughout other links in the chain. Of course, open kinetic chains vary in number of linked segments and complexity. An example of a serial kinetic chain motion with minimal segments is a barbell curl exercise.

The terminal hand segment holding the barbell is free to move. The force of the elbow flexors is applied to the proximal end of the forearm segment. In this example, the elbow is free to flex without motion at the shoulder or wrist. The advantage of such open kinetic chain exercise movements is that emphasis can be placed on one muscle or specific group of muscles (in this case, the elbow flexors—biceps brachii, brachialis, and brachioradialis). Throwing skills are open kinetic chain motions that are complex and have many participating segments (Figure 2.32).

Throwing is also an example of the need for optimal timing of force generation and intersegmental force transmission within a kinetic chain. For example, proficient throwing involves force generation and transfer from the base segments (legs) to the hips, then torso, humerus, forearm, and finally the hand. Notice in throwing that proper timing of segmental participation produces lag. In other words, the hips are rotating forward, while the upper torso is still rotating in the opposite direction (lagging behind). Then as the upper torso rotates forward, the humerus lags, and so on. The final result is a motion of the entire kinetic chain that is similar to that of a whip.

The proximal end of the whip is the area where force is initially applied. The initial force results in a wave of increasing velocity that travels toward the distal end of the whip. This sequence of actions, properly timed, results in rapid speed at the tip of the whip. Similarly, the goal of proficient throwing is extremely high speed in the distal hand segment of the chain, which can be transferred to the thrown object.

Closed Kinetic Chains

In a **closed kinetic (or kinematic) chain**, the distal segment is stationary ("closed"), and therefore the total chain has less mobility (fewer DOF). In other words, the distal segment is in contact with the reference frame or portion of the reference frame (e.g., Earth or another object) that provides enough resistance to prohibit free motion. Therefore, motion at one joint is only possible with cooperative movement at other joints.

A push-up exercise is an example of a closed kinetic chain motion (both the toes and the palms are in contact with the surface of the environment). In this example, motion at the elbow can only occur if movement also occurs at the shoulder and wrist joints (Figure 2.33). But

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classifying a movement as closed can sometimes be more difficult than it would seem. For example, squatting is a closed kinetic chain movement even though the head is free to move (and is in fact being moved up and down). The movement is classified as closed because the distal segment is the foot, and it is in contact with an immovable reference frame. This example is an instance in which thinking of cooperative joint motion is highly effective. During squatting, the knee can move only if motion occurs at the hip and ankle. Sometimes it is less confusing if one also considers the more proximal segments at which force is being applied to initiate the movement. Most of the force for movement in the squat example is applied to the femur and tibia by the hip and knee extensors (i.e., force application occurs proximal to the foot segment). It also helps to think of what *would* have happened if the foot had not been in contact with the immoveable reference frame. If the hip and knee extensors were contracted in the absence of foot contact with any surface, then the distal foot segment *would* have moved away from the body. But in the case of a squat, the body is forced to move away from the distal segment and is therefore classified as a closed kinetic chain.

The disadvantage in performance of closed chain motions is that one cannot focus so much on a specific muscle or muscle group. For example, in a squat exercise, both the hip and knee extensors are active. Closed kinetic chain motions have some advantages in terms of athletic training and rehabilitation. One advantage is that closed kinetic chain motions for training are more functional and sport specific because many sports skills are performed with the feet fixed.

Functional Kinetic Chains

The human system is a multisegmented complex kinetic chain during functional activities. Functional activities can basically be considered activities of daily living (or applied activities) as opposed to isolated motions performed in a closed environment (such as those observed in common exercise routines). If the system is a complex chain, then some links likely are engaged in open kinetic chain motions while other links are involved in closed kinetic chain motions. So a **functional kinetic chain** is a complex kinetic chain in which some links are involved in open chain motion and others are engaged in closed chain motion, which together produce a functional activity. One example of a functional activity is human locomotion (Figure 2.34).

Human gait can be divided into a stance (or weight-bearing) phase and a swing (or non-weight-bearing) phase. During locomotion, one foot is in contact with the ground (closed kinetic chain motion), while the other foot is free to swing forward (open kinetic chain motion). Locomotion is just one of the myriad activities classified as functional. Functional kinetic chains are also used in the performance of device and home management, self-care, and most sports skills.

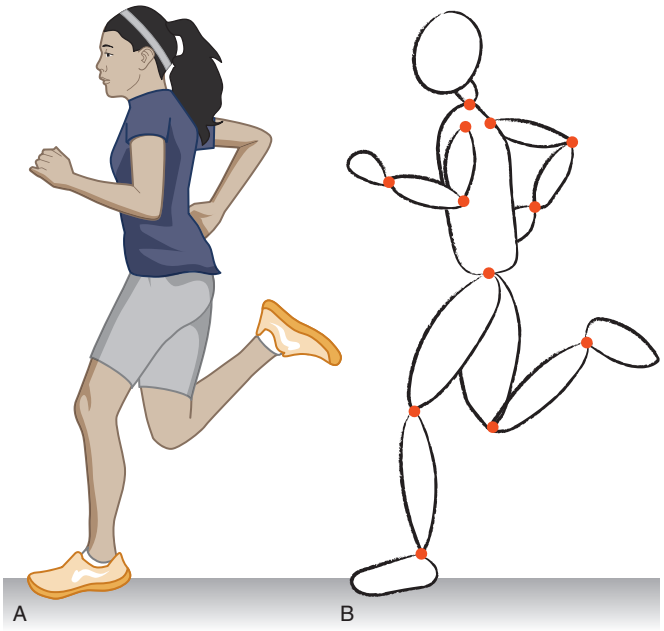


Figure 2.34 **A runner as a functional kinetic chain.**

Compensatory Motion

Comprehending kinetic chain concepts is necessary to completely understand both normal and abnormal human movement. Remember that motion at one link in the kinetic chain affects motion at one or more other links. Therefore, musculoskeletal abnormality such as

Functional kinetic chain A complex kinetic chain in which some links are involved in open chain motion and others are engaged in closed chain motion.

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injury or muscular imbalance at one segment or link in the chain can force other links to adapt their motion. These **compensatory movements** are adaptations at normal kinetic chain links as a result of abnormal motion at another link so that a task can still be accomplished. Awareness of compensatory movement is important for two reasons: (1) the task will now probably require more energy than before because it is no longer being carried out with use of the most efficient movement pattern (i.e., the pattern that minimizes muscle force requirements); and (2) changes in force-loading patterns on the compensating links can eventually lead to musculoskeletal abnormalities in other areas of the chain. In other words, compensatory motion arising from injury or muscular imbalance not only makes activities more difficult but also will possibly result in other injuries.

Compensatory movements Adaptations at normal kinetic chain links as a result of abnormal motion at another link.



FOCUS ON RESEARCH

As we proceed through the textbook, we hope it will become clear that the concepts in biomechanics are surprisingly related to many aspects of our daily lives. For example, millions of women wear high heels on a daily basis probably without the term *biomechanics* ever coming to mind. However, the relationship between wearing high heels, muscle activity, and dynamics of human walking was examined in a study by Simonsen et al. (2012).

First, we must explain several pieces of research equipment that are frequently used to study many aspects of biomechanics. One common tool for studying biomechanics is three-dimensional motion capture (3D MOCAP for short). The 3D MOCAP process records the motion of the system of interest using multiple cameras (often with high frame rates), each having a different view. Analyzing the videos via special software allows re-creation of the motion in a virtual 3-D Cartesian coordinate system and then the calculation of many static and dynamic parameters. Next, force platforms or force plates are instruments often recessed into the floor that are capable of measuring the forces exerted by a system moving on or across them. The force plates can measure the forces in all three directions of the Cartesian coordinate system discussed earlier. Simultaneous use of MOCAP with the force plates allows for calculation of many aspects of statics and dynamics that will be discussed throughout the book. Finally, electromyography (EMG) is the process of using a special instrument with electrodes to record the electrical signals generated by muscle fibers when activated. The signals can then be analyzed to evaluate muscle activation level, abnormalities, recruitment parameters, and so on.

Simonsen et al. (2012) used all of the just cited equipment to examine muscle activity and walking dynamics while wearing high heels (9 cm). Dynamics of the hip, knee, and ankle were measured using MOCAP along with force plates. EMG was used to measure activity of the following muscles of the leg: soleus, gastrocnemius medialis, tibialis anterior, vastus medialis, vastus lateralis, rectus femoris, biceps femoris, and semimembranosus. The researchers found that in the first half of the stance phase of walking on high heels, knee extensor moment peak was doubled. It was also found that the knee joint was flexed significantly more in the first half of the stance phase. A significant increase in knee and hip joint abductor moments in the frontal plane was also observed. Those differences, along with increases in several EMG parameters, led the authors to speculate about walking on high heels. The researchers conclude that the large increased knee joint extensor moment could be caused by the observed increased knee joint flexion during the stance phase along with increased EMG in the quadriceps muscle. Along with the significant increase in knee joint

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abduction moment in the frontal plane, the results may be indicative of a large increase in bone-on-bone forces in the knee joint while walking in high-heeled shoes. The authors also hypothesize that their findings may help explain the higher incidence of osteoarthritis in the knee joint observed in women when compared to men.

Notice the study involves planes of motion as well as directions of a Cartesian coordinate system. In addition, the study is directly related to the concept of compensatory movements in the kinetic chain. Because the ankle, knee, and hip are all links in the kinetic chain, a change in one will cause compensation in the others. In the case of high heels, changing the angle of the foot during walking leads to changes in knee joint dynamics and muscle activity patterns, resulting in potentially damaging forces at the knee joint. Unfortunately, compensatory motions often lead to or result from injuries.

CONNECTIONS

2.7 EXERCISE PHYSIOLOGY

At the most basic level, our field is about movement. Both biomechanists and exercise physiologists are interested in studying that movement, but the perspectives differ. As described in the previous sections, joint (segmental link) motions are described in terms of relative movement of two segments. Motions of the skeletal system are made possible through contraction of skeletal muscle. A biomechanist will tend to focus on the motion that results from muscle contraction, whereas an exercise physiologist will likely focus on the physiological processes (such as metabolism) occurring within the muscle that allow the contraction to take place. Now let's discuss some specific variations in perspective as they relate to the musculoskeletal system.

In general, a muscle has two points of attachment: a proximal attachment (sometimes called an *origin*) that tends to be at a relatively immoveable location, and a distal attachment (sometimes called an *insertion*) that tends to be on a relatively moveable segment. The two attachments of the muscle (and therefore two segments) are brought closer together during muscle contraction, with the less stable end being moved closer to the more stable (Figure 2.35).

The attachment that is most stable is not always obvious. For example, the distal attachment of the biceps brachii is brought closer to the more proximal attachments during the performance of a bicep curl exercise; however, the opposite is true when performing a pull-up exercise.

Biomechanical concepts can be used to study the resultant motion caused by contraction of a muscle with particular points of attachment. Biomechanics can also help explain the mechanical behavior of and potential injury to biological tissues such as bone, ligaments, and tendons that are affected by the muscle contraction. Principles of exercise physiology are also used to study biological tissues of the musculoskeletal system. However,

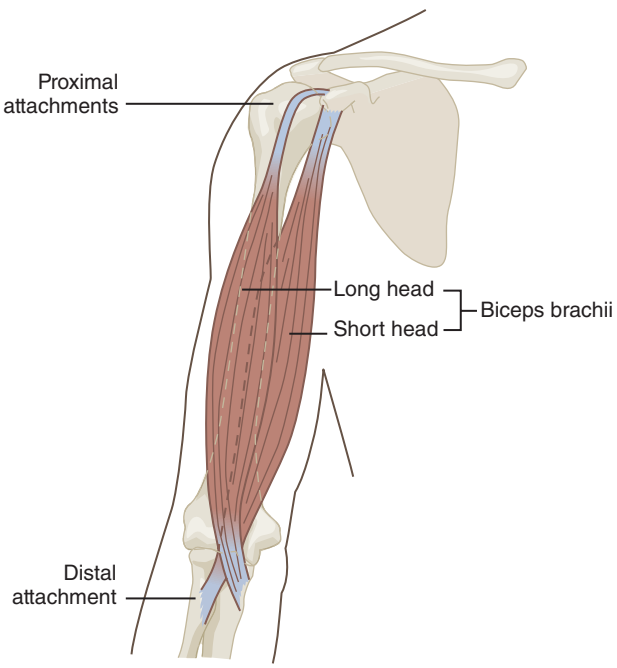


Figure 2.35 **The origin and insertion of the biceps brachii muscle.** Name some muscles that are only capable of one action.

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the physiologist may be concerned with the specific cellular processes by which bones, ligaments, and tendons become stronger in response to muscle contraction. For instance, bone becomes stronger and denser in response to weight-bearing exercise. A biomechanist may be concerned with impact sustained by the musculoskeletal system during exercise sessions on varying surfaces, whereas a physiologist may be interested in how and what type of exercise is most effective for increasing the density of bone to prevent or treat osteoporosis.

It was already noted that joints of the body vary in their number of degrees of freedom. Therefore, having a wide range of muscles and muscle attachments available is necessary to move the segments of our skeletal system through all of the available degrees of freedom. In some cases, providing DOF at a segmental link is accomplished by more muscles. For example, the glenohumeral joint is classified as ball and socket and therefore has three degrees of freedom (rotation around any axis). However, do not mistake this fact to mean that the joint can perform only three actions. For example, flexion and extension are two rotations around a single axis. In addition, two different actions can occur around the same axis if the arm is not in the anatomical position at initiation of the observed motion. For example, both internal rotation (from the anatomical position) and horizontal adduction occur around a superoinferior axis. As a result of this increased mobility, 11 different muscles are necessary to provide all available degrees of freedom at the glenohumeral joint. The biomechanist may approach this situation by asking which muscle or muscles out of the many are most active at a given joint position, or which biomechanical factors are associated with a loss in mobility. An exercise physiologist might be more interested in whether fatigue in one of the muscles could predispose other muscles to injury.

In contrast to using multiple muscles, having a single muscle perform more than one function can also provide added DOF. For example, the biceps brachii can cause elbow flexion and forearm supination, as well as aid in shoulder flexion. Because many muscles act at each joint, and each one of those muscles has multiple functions, some redundancy of muscle action occurs. For example, four different muscles are involved in shoulder flexion; six muscles are used for wrist and phalangeal flexion, and seven muscles extend the cervical spine. Why so much redundancy? Having more than one muscle involved in an action strengthens the motion and enhances control. So not only does the human musculoskeletal system have many movement options, but also many of those motions can be highly precisely controlled. Once again, a biomechanist may be interested in exact movement patterns, joint positions, or velocities associated with contraction of a particular multifunctional muscle. In contrast, an exercise physiologist may be more interested in the exact cellular mechanisms that cause a change in that single muscle's function at different joint angles.

Finally, let's not forget that energy is needed for muscles to move the joints through all of the DOF necessary for exercise. The energy necessary for muscle contraction is produced by the metabolic systems, and the muscle contractions themselves are controlled by the neurological system. So the muscular system is the connection between the physiological, neurological, and skeletal systems. In fact, the systems are so interrelated that distinguishing whether a research project has been conducted by a biomechanist or exercise physiologist (or both) is often difficult. For example, in a study published in the journal *Medicine & Science in Sports & Exercise* (Roy & Stefanyshyn, 2006), the researchers observed that subjects running in shoes with a stiff midsole rather than a control (unmodified) midsole experienced a metabolic energy savings of approximately 1%. A subject such as midsole stiffness would often be found in the realm of biomechanical interest because it is related to forces acting in the foot. The metabolic cost of physical activity is frequently associated with exercise physiology because it is a cellular-level process. However, this study is a prime example of the need for interdisciplinary research in the movement-related disciplines. In biomechanics, the major concerns are the motion of the system itself and the forces involved in the movement situation. But one must always be aware that because the muscles cause the skeletal link movements, a physiological change within a muscle (e.g., fatigue) leads to a biomechanical outcome (e.g., a different running pattern).

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2.8 MOTOR BEHAVIOR

As you have learned, the neurological system controls the muscles that are responsible for motion at the links of the skeletal system segments. So the observed biomechanical outcomes of the system are a coordinated effort under the control of the brain and spinal cord. Therefore, all of the different motions that have been described in this chapter are under the control of the motor system.

Motor Control

In terms of motor control, expressing how a motion is perceived is sometimes more effective than trying to describe the motion. For example, we have discussed Cartesian coordinate frames, which are constructed of orthogonal, or perpendicular, axes passing through an origin. These reference frames are a great way to describe a motion. However, we also discussed oblique reference frames in which the axes are nonorthogonal. In fact, an oblique reference frame is actually better representation of motion perception by the brain and sensory organs. For example, movement of the head can be *described* in terms of motion within a Cartesian coordinate frame. Motions (e.g., roll, yaw, and pitch) of the head are perceived by the semicircular canals of the vestibular system.

Although the semicircular canals are oriented in each of the major planes (sagittal, frontal, and transverse), they are not perfectly orthogonal to each other. This conformation means that the axes of the semicircular canals form an oblique coordinate reference frame within which motions are perceived. Therefore, the model of motor control of the head involves several transformations of Cartesian coordinates to oblique coordinates and oblique coordinates to Cartesian coordinates (Pellionisz, 1984; Zatsiorsky, 1998).

As the previous discussion illustrates, control of the system can be extremely complicated. Each human joint (link) possesses multiple degrees of freedom, and multiple muscles move each joint through those DOF. In fact, the human system possesses so many degrees of freedom that explaining the methods by which the motor system can learn, initiate, and control such smoothly coordinated motions, with so many variables to coordinate, can be difficult.

Russian biomechanist and physiologist Nikolai Bernstein (1897–1966) theorized that simply too many DOF must be controlled at the conscious level, and he put forth the idea that learning a motor skill is actually the process of solving the above "degrees of freedom problem." Bernstein divided learning into three stages (Schmidt & Lee, 2011):

1. *Freezing* degrees of freedom in which constraints are added to the movement so that fewer independent segments must be controlled, therefore simplifying the skill enough to allow crude performance;
2. *releasing* or removing constraints on degrees of freedom then occurs as the learner becomes more comfortable, which results in increased effectiveness of skill performance; and
3. *exploiting* the natural properties of degrees of freedom, a stage in which the learner becomes proficient in the movement by taking advantage of the various mechanical advantages inherent to the human system.

Motor Development

Development of walking patterns, from beginning to mature, provides evidence supporting Bernstein's theory that humans learn basic motor skills by decreasing the degrees of freedom during initial attempts, then freeing up additional degrees of freedom as they progress toward more mature and efficient patterns. When toddlers first attempt upright bipedal locomotion, they display several

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Figure 2.36 **A beginning walker.** Restricting degrees of freedom simplifies the activity.
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characteristics that identify them as beginning walkers. They instinctively increase their base of support by spreading their legs and pointing their toes outward, flexing the knees minimally, rotating the pelvis as little as possible, and carrying the hands and arms stiffly in a "high-guard" position (Figure 2.36).

The lack of pelvic rotation, lack of flexion in the knees, and lack of arm swing evident in immature attempts at walking suggest that the human body restricts degrees of freedom to simplify the movement. As toddlers become more comfortable and efficient walkers through practice, additional degrees of freedom are added to allow longer and more accurate strides. Mature walkers demonstrate pelvic rotation and knee flexion and not only lower their arms to the side but also swing them contralaterally. This restricted to less-restricted movement pattern seems to be used when learning many fundamental skills such as hopping, skipping, striking, kicking, and more.

Motor Learning

When we learn complex movements later in life, excessive degrees of freedom are often the problem. In contrast to a toddler learning a fundamental skill, beginners attempting new and complex skills tend to use more motion than the skill requires. In essence, too many degrees of freedom are allowed at first but are reduced as performers become more efficient through practice. Juggling provides a good example of this process. The only body parts moving while a professional juggler performs a simple three-ball cascade are the lower arms, with slight movement at the shoulder joint. Contrast this technique to that of a novice juggler, who exhibits exaggerated shoulder motion in more than one plane, flexes and extends at the waist in more than one plane, and often moves her feet to correct for inaccurate tosses. As a novice improves, the movement, or degrees of freedom, seen in the lower body and waist diminishes, and the motion of the upper extremities becomes less exaggerated.

2.9 PEDAGOGY

Physical education teachers can improve performance of fundamental and complex motor skills by increasing or decreasing the degrees of freedom necessary for efficient movement. Children in preschool through second grade should be given plenty of opportunities to practice fundamental skills, with the teacher providing feedback designed to encourage increasing degrees of freedom of movement.

Older students learning more complex skills should also be allowed the maximum number of repetitions possible while being encouraged and given feedback to decrease the degrees of freedom. This approach promotes more efficient movement patterns that maximize power and minimize error. Secondary school students (middle and high school) and adults learning the game of golf can all benefit from formal instruction. Beginning golfers almost always add movements that are neither relevant—nor conducive—to sending a golf ball along an intended path with maximum velocity. Rather than rotating around the spine, beginners often sway laterally away from the target and then have to sway back toward the ball precisely the same amount if they want the club face to meet the ball exactly as it did when they addressed the ball. Amateur players who aspire to lower handicaps would do well to emulate professionals who have removed all but the essential degrees of freedom of motion in their swings.

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2.10 ADAPTED MOTION

Most successful physical education teachers would agree that the word *adapted* is an adjective that describes everything they do, not just working with children who have formally identified disabilities. Each class that arrives in the gym will likely include students who range from beginners to advanced performers, and teachers must adapt their lessons, equipment, and teaching style to the needs of each one. Although the adapted physical education sections in this text focus primarily on those students with physical or cognitive challenges, the ideas and information are easily transferable to adapting physical education for any student that you teach.

Students with a variety of with physical challenges participate in physical education, physical therapy, and occupational therapy to increase their chances for success in sport, recreation, or activities of daily living. Muscle function lost because of amputation or diseases such as muscular dystrophy often require people to relearn movement patterns using different muscle groups, including modifying movement through different joints. In essence, degrees of freedom have been lost, and other links in the kinetic chain must learn to adapt to restore motion. Adapted physical education teachers often work closely with physical and occupational therapists to help people create new kinetic chains when normal movement becomes impossible. One example is learning to walk or run with a prosthetic after an amputation. Depending on the site of the surgery—above or below critical joints such as the knee and elbow—the muscles used to propel the body can differ significantly from those on the unaffected side. In essence, the prosthetic itself become part of the chain, and alterations to movement patterns are learned to compensate for it.

SUMMARY

Precise observation and accurate description of motion are necessities in all movement-related disciplines. A system is any object or group of objects whose motion is of analytical interest. The system can have numerous physical qualities, all of which can influence the characteristics of its motion. The physical qualities of the system are described by the field of anthropometrics. Directional terminology is shared among different fields to provide a common language for description of system motion.

Many movement terms are used to fully describe the movement of a system. System motion occurs in a plane and around an axis. The cardinal planes (frontal, sagittal, and transverse) bisect the body, and each has an associated orthogonal axis. Coordinate reference frames are used to describe motion of the system relative to the environment. The total number of movement options available to a system is its degrees of freedom.

Motion of the system within a predictable environment is called *closed*, whereas motion within a potentially changing environment is called *open*. Motion within that particular environment can be linear or rotational. Linear is motion *along* one of the *x*-, *y*-, or *z*-axes in which all points of the system move (change position) at the same time, in the same direction, and the same distance with respect to the defined reference frame despite their location on the system. Angular motion occurs if the system is restricted to move around an axis.

Skills performed by the system can be classified as *discrete*, *continuous*, or *serial*, depending on whether a definite beginning and end point can be identified and how many different movements make up the skill. A skill can be classified as gross or fine motor dependent on the level of precision required.

A kinetic chain is a system of linked rigid bodies subject to force application. Kinetics chains are classified according to complexity and whether cooperative motion is necessary among the links in the chain. The human system is a kinetic chain and must therefore adapt motions if one link in the chain becomes nonfunctional. The human kinetic chain has many degrees of freedom and therefore requires highly complex control mechanisms.

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REVIEW QUESTIONS

1. What structures make up the system in the situation of a soccer injury? What about in a sumo wrestling match?
2. Sumo wrestler Akebono has a body mass of 236 kg and a height of 203 cm. What is his BMI? Find a classification table for BMI and classify Akebono in terms of disease risk. In what somatotype category does he fit? Why are these classifications not necessarily a bad thing for Akebono?
3. Explain the crural index and provide an example of an athlete or animal in which this value is high.
4. In what direction or directions does a runner move with reference to a global reference system?
5. In what direction or directions does the lower leg of a runner move in relation to the thigh?
6. What is the plane in which a runner's arms move?
7. As the runner's arms move in that plane, around which axis does the shoulder joint move?
8. How many degrees of freedom are available in planar motion? How many DOF are available in 3-D movements of the system? How many DOF does a ball-and-socket joint such as the shoulder possess?
9. What type of skill is a basketball free throw? Explain your answer.
10. If I drop an object, what type of motion will it exhibit? What if I throw the same object?
11. Classify running as one of the following types of motion: translation, rotation, or general. Explain your answer.
12. Provide examples of discrete, repeated discrete, continuous, and serial skills.
13. Provide simple and complex examples of open and closed kinetic chain motions. In which category is throwing?

EQUATIONS

Body mass index $$BMI = \frac{kg}{m^2} \quad (2.1)$$

Ponderal index $$PI = \frac{kg}{m^3} \quad (2.2)$$

Crural index $$CI = \frac{\text{length of the tibia}}{\text{length of the femur}} \times 100 \quad (2.3)$$

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