CHAPTER 1

Getting Started

DONALD A. NEUMANN, PT, PHD

TOPICS AT A GLANCE

INTRODUCTION

What Is Kinesiology?

The origins of the word *kinesiology* are from the Greek *kinesis*, to move, and *ology*, to study. *Kinesiology of the Musculoskeletal System: Foundations for Physical Rehabilitation* serves as a guide to kinesiology by focusing on the anatomic and biomechanical interactions within the musculoskeletal system. The beauty and complexity of these interactions have inspired the work of two great artists: Michelangelo Buonarroti (1475–1564) and Leonardo da Vinci (1452–1519). Their work likely inspired the creation of the classic text *Tabulae Sceleti et Musculorum Corporis Humani* published in 1747 by the anatomist Bernhard Siegfried Albinus (1697–1770). A sample of this work is presented in Figure 1–1.

The primary intent of this book is to provide students and clinicians with a *foundation for the practice of physical rehabilitation*. A detailed review of the anatomy of the musculoskeletal system, including its innervation, is presented as a background to the structural and functional aspects of movement and their clinical applications. Discussions are presented on both normal conditions and abnormal conditions that result from disease and trauma. A sound understanding of kinesiology allows for the development of a rational evaluation, a precise diagnosis, and an effective treatment of musculoskeletal disorders. These abilities represent the hallmark of high quality for any health professional engaged in the practice of physical rehabilitation.

This text of kinesiology borrows heavily from three bodies of knowledge: anatomy, biomechanics, and physiology. *Anatomy* is the science of the shape and structure of the human body and its parts. *Biomechanics* is a discipline that uses principles of physics to quantitatively study how forces interact within a living body. *Physiology* is the biologic study of living organisms. This textbook interweaves an extensive review of musculoskeletal anatomy with selected principles of biomechanics and physiology. This approach allows the kinesiologic functions of the musculoskeletal system to be reasoned rather than purely memorized.

The remainder of this chapter provides fundamental biomechanical concepts and terminology related to kinesiology. The glossary at the end of the chapter summarizes much of the essential terminology. A more in-depth and quantitative approach to the biomechanics applied to kinesiology is presented in Chapter 4.

KINEMATICS

Kinematics is a branch of mechanics that describes the *motion* of a body, without regard to the forces or torques that may produce the motion. In biomechanics, the term *body* is used rather loosely to describe the entire body, or any of its parts or segments, such as individual bones or regions. In general, there are two types of motions: translation and rotation.

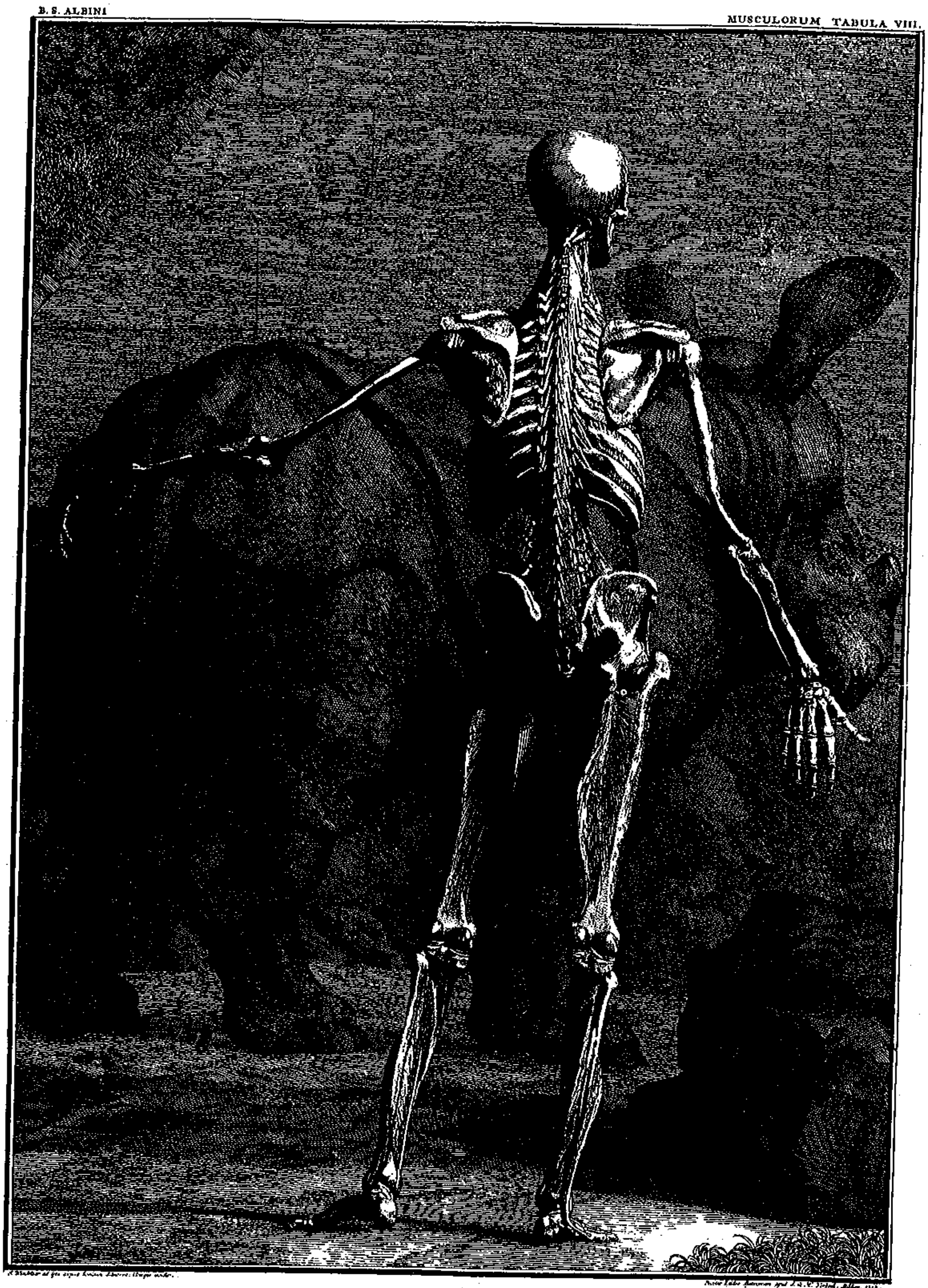


FIGURE 1–1. An illustration from the anatomy text *Tabulae Sceleti et Musculorum Corporis Humani* (1747) by Bernhard Siegfried Albinus.

Translation Compared with Rotation

Translation describes a linear motion in which all parts of a rigid body move parallel to and in the same direction as every other part of the body. Translation can occur in either a *straight line (rectilinear)* or a *curved line (curvilinear)*. While walking, for example, a point on the head moves in a general curvilinear manner (Fig. 1–2).

Rotation, in contrast, describes a motion in which an assumed rigid body moves in a circular path about some pivot

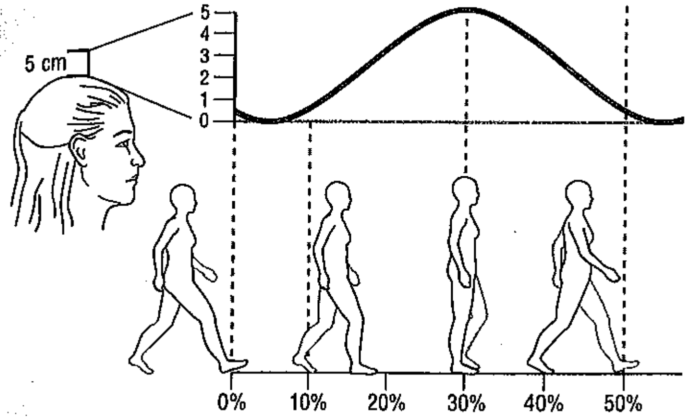


FIGURE 1–2. A point on the top of the head is shown translating upward and downward in a curvilinear fashion while walking. The X axis shows the percentage of completion of one entire gait (walking) cycle.

point. As a result, all points in the body simultaneously rotate in the same angular direction (e.g., clockwise and counterclockwise) across the same number of degrees.

Movement of the human body, as a whole, is often described as a translation of the body's *center of mass,* located generally just anterior to the sacrum. Although a person's center of mass translates through space, it is powered by muscles that *rotate* the limbs. The fact that limbs rotate can be appreciated by watching the path created by a fist while flexing the elbow (Fig. 1–3). (It is customary in kinesiology to use the phrases "rotation of a joint" and "rotation of a bone" interchangeably.)

The pivot point for the angular motion is called the *axis of rotation.* The axis is at the point where motion of the rotating body is zero. For most movements of the body, the axis of rotation is located within or very near the structure of the joint.

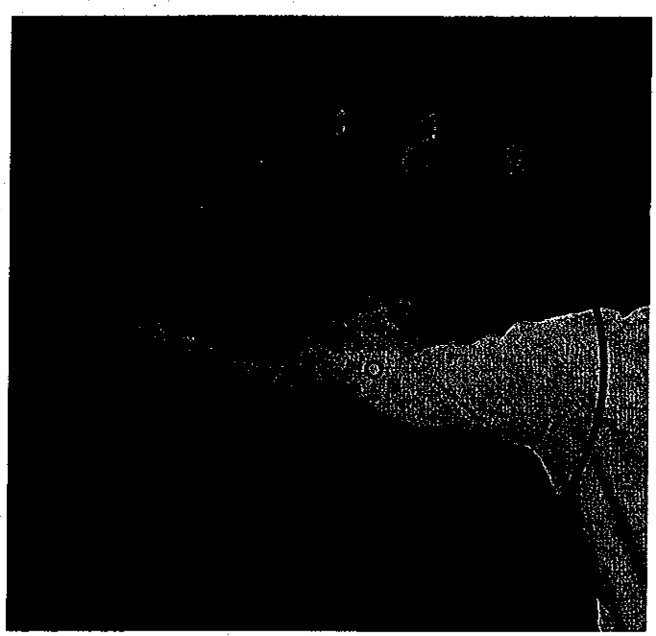


FIGURE 1–3. Using a stroboscopic flash, a camera is able to capture the rotation of the forearm. If not for the anatomic constraints of the elbow, the forearm could, in theory, rotate 360 degrees about an axis of rotation located at the elbow (red circle).

TABLE 1–1. Common Conversions Between Units of Kinematic Measurements

1 meter (m) = 3.28 feet (ft)	1 ft = .305 m
1 m = 39.37 inches (in)	1 in = .0254 m
1 centimeter (cm) = .39 in	1 in = 2.54 cm
1 m = 1.09 yards (yd)	1 yd = .91 m
1 kilometer (km) = .62 miles (mi)	1 mi = 1.61 km
1 degree = .0174 radians (rad)	1 rad = 57.3 degrees

Movement of the body, regardless of translation or rotation, can be described as active or passive. *Active movements* are caused by stimulated muscle. *Passive movements,* in contrast, are caused by sources other than muscle, such as a push from another person, the pull of gravity, and so forth.

The primary variables related to kinematics are position, velocity, and acceleration. Specific units of measurement are needed to indicate the quantity of these variables. Units of meters or feet are used for translation, and degrees or radians are used for rotation. In most situations, *Kinesiology of the Musculoskeletal System* uses the *International System of Units,* adopted in 1960. This system is abbreviated SI, for Système International, the French name. This system of units is widely accepted in many journals related to kinesiology and rehabilitation. The kinematic conversions between the more common SI units and other measurement units are listed in Table 1–1.

Osteokinematics

PLANES OF MOTION

Osteokinematics describes the *motion of bones* relative to the three cardinal (principal) planes of the body: sagittal, frontal, and horizontal. These planes of motion are depicted in the context of a person standing in the *anatomic position* as in Figure 1–4. The *sagittal plane* runs parallel to the sagittal suture of the skull, dividing the body into right and left sections; the *frontal plane* runs parallel to the coronal suture of the skull, dividing the body into front and back sections. The *horizontal (or transverse) plane* courses parallel to the horizon and divides the body into upper and lower sections. A sample of the terms used to describe the different osteokinematics is shown in Table 1–2. More specific terms are defined in the chapters that describe the various regions of the body.

AXIS OF ROTATION

Bones rotate about a joint in a plane that is perpendicular to an *axis of rotation.* The axis is typically located through the convex member of the joint. The shoulder, for example, allows movement in all three planes and, therefore, has three axes of rotation (Fig. 1–5). Although the three orthogonal axes are depicted as stationary, in reality, as in all joints, each axis shifts throughout the range of motion. The axis of rotation remains stationary only if the convex member of a

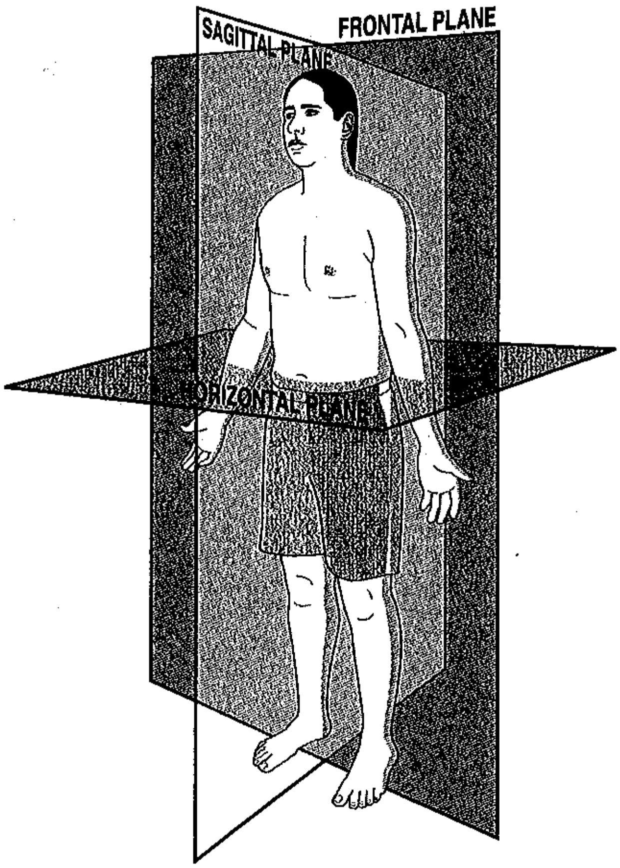


FIGURE 1–4. The three cardinal planes of the body are shown as a person is standing in the anatomic position.

joint were a perfect sphere, articulating with a perfectly reciprocally shaped concave member. The convex members of most joints, like the humeral head at the shoulder, are imperfect spheres with changing surface curvatures. The issue of a migrating axis of rotation is discussed further in Chapter 2.

DEGREES OF FREEDOM

Degrees of freedom are the number of independent movements allowed at a joint. A joint can have up to three degrees of angular freedom, corresponding to the three dimensions of space. As depicted in Figure 1–5, for example,

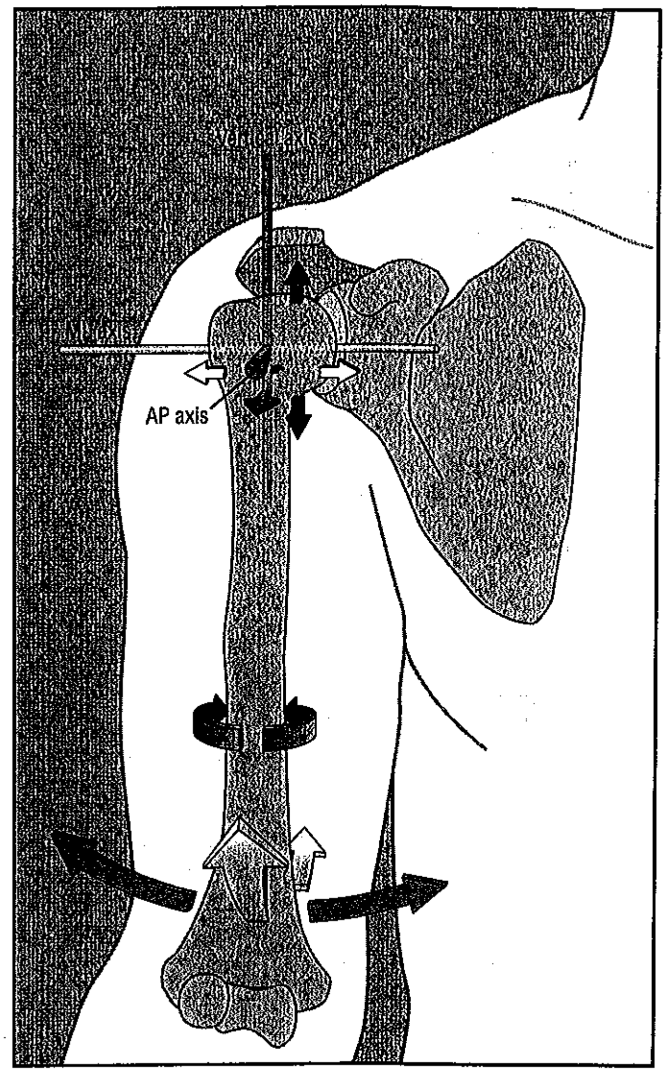


FIGURE 1–5. The right glenohumeral (shoulder) joint highlights three orthogonal axes of rotation and associated planes of angular motion: flexion and extension (white curved arrows) occur about a medial-lateral (ML) axis of rotation; abduction and adduction (red curved arrows) occur about an anterior-posterior (AP) axis of rotation; and internal and external rotation (gray curved arrows) occur about a vertical axis of rotation. Each axis of rotation is color-coded with its associated plane of movement. The straight arrows shown parallel to each axis represent the slight translation potential of the humerus relative to the scapula. This illustration shows both angular and translational degrees of freedom. (See text for further description.)

TABLE 1–2. A Sample of Common Osteokinematic Terms

Sagittal Plane	Frontal Plane	Horizontal Plane
Flexion and extension	Abduction and adduction	Internal (medial) and external (lateral) rotation
Dorsiflexion and plantar flexion	Lateral flexion	Axial rotation
Forward and backward bending	Ulnar and radial deviation	
	Eversion and inversion	

Many of the terms are specific to a particular region of the body. The thumb, for example, uses different terminology.

the shoulder has three degrees of angular freedom, one for each plane. The wrist allows two degrees of freedom, and the elbow only one.

Unless specified differently throughout this text, the term degrees of freedom indicates the number of permitted *planes of angular motion* at a joint. From a strict engineering perspective, however, degrees of freedom applies to angular as well as translational movements. All synovial joints in the body possess at least some translation, driven actively by muscle, or passively owing to the natural laxity within the structure of the joint. The slight passive translations that occur in most joints are referred to as *accessory motions* and are defined in three linear directions. From the anatomic position, the directions correspond to those of the three axes of rotation. In the relaxed glenohumeral joint, for example, the humerus can be passively translated anterior-posteriorly, medial-laterally, and superior-inferiorly (see Fig. 1–5). At many joints, especially the knee and ankle, the amount of translation is used clinically to test the integrity of ligaments.

OSTEOKINEMATICS: A MATTER OF PERSPECTIVE

In general, the articulations of two body segments constitute a joint. Movement at a joint can therefore be considered from two perspectives. (1) the proximal segment can rotate against the relatively fixed distal segment, and (2) the distal segment can rotate against the relatively fixed proximal segment. These two perspectives are shown for knee flexion in Figure 1–6. A term such as knee flexion, for example, describes only the *relative motion* between the thigh and leg. It does not describe which of the two segments is actually rotating. Often, to be clear, it is necessary to state the bone that is considered the primary rotating segment. As in Figure 1–6, for example, the terms tibial-on-femoral movement or femoral-on-tibial movement adequately describe the osteokinematics.

Most routine movements performed by the upper extremities involve distal-on-proximal segment kinematics. This reflects the need to bring objects held by the hand either toward or away from the body. The proximal segment of a joint in the upper extremity is usually stabilized by muscles or gravity, whereas the distal, relatively unconstrained, segment rotates.

Feeding oneself or throwing a ball are two common examples of distal-on-proximal segment kinematics employed by the upper extremities. The upper extremities are certainly capable of performing proximal-on-distal segment kinematics, such as flexing and extending the elbows while performing a pull-up.

The lower extremities routinely perform both distal-on-proximal and proximal-on-distal segment kinematics. These kinematics reflect, in part, the two primary phases of walking: the *stance phase*, when the limb is planted on the ground under the load of body weight, and the *swing phase*, when the limb is advancing forward. Many other activities, in addition to walking, use both kinematic strategies. Bending the knee in preparation to kick a ball, for example, is a type of distal-on-proximal segment kinematics (Fig. 1–6*A*). Descending into a squat position, in contrast, is an example of proximal-on-distal segment kinematics (Fig. 1–6*B*). In this last example, a relatively large demand is placed on the quadriceps muscle of the knee to control the gradual descent of the body.

The terms open and closed kinematic chain are frequently used in the physical rehabilitation literature and clinics to describe the concept of relative segment kinematics.[4,10] A kinematic chain refers to a series of articulated segmented links, such as the connected pelvis, thigh, leg, and foot of the lower extremity. The terms "open" and "closed" are typically used to indicate whether the distal end of an extremity is fixed to the earth or some other immovable object. An *open kinematic chain* describes a situation in which the distal segment of a kinematic chain, such as the foot in the lower limb, is *not fixed* to the earth or other immovable object. The distal segment, therefore, is free to move (see Fig. 1–6*A*). A *closed kinematic chain* describes a situation in which the distal segment of the kinematic chain is *fixed* to the earth or another immovable object. In this case, the proximal seg-

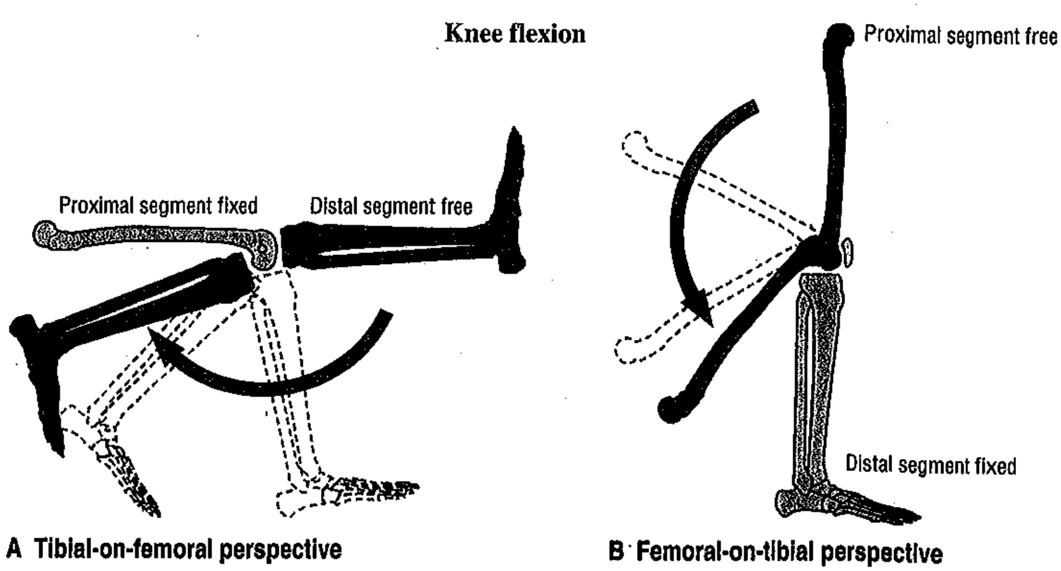


FIGURE 1–6. Sagittal plane osteokinematics at the knee show an example of (*A*) distal-on-proximal segment kinematics and (*B*) proximal-on-distal segment kinematics. The axis of rotation is shown as a circle at the knee.

ment is free to move (see Fig. 1–6*B*). These terms are employed extensively to describe methods of applying resistance to muscles and ligaments, especially in the knee.[2,3]

Although very convenient terminology, the terms open and closed kinematic chains are often ambiguous. From a strict engineering perspective, the terms open and closed kinematic chains apply more to the *kinematic interdependence* of a series of connected rigid links, which is not exactly the same as the previous definitions given here. From this engineering perspective, the chain is "closed" if *both ends* are fixed to a common object, much like a closed circuit. In this case, movement of any one link requires a kinematic adjustment of one of more of the other links within the chain. "Opening" the chain by disconnecting one end from its fixed attachment interrupts this kinematic interdependence. This more precise terminology does not apply universally across all health-related and engineering disciplines. Performing a one-legged partial squat, for example, is often referred to clinically as the movement of a closed kinematic chain. It could be argued, however, that this is a movement of an open kinematic chain because the contralateral leg is not fixed to ground (i.e., the circuit formed by the total body is open). To avoid confusion, this text uses the terms open and closed kinematic chains sparingly, and the preference is to explicitly state which segment (proximal or distal) is considered fixed and which is considered free.

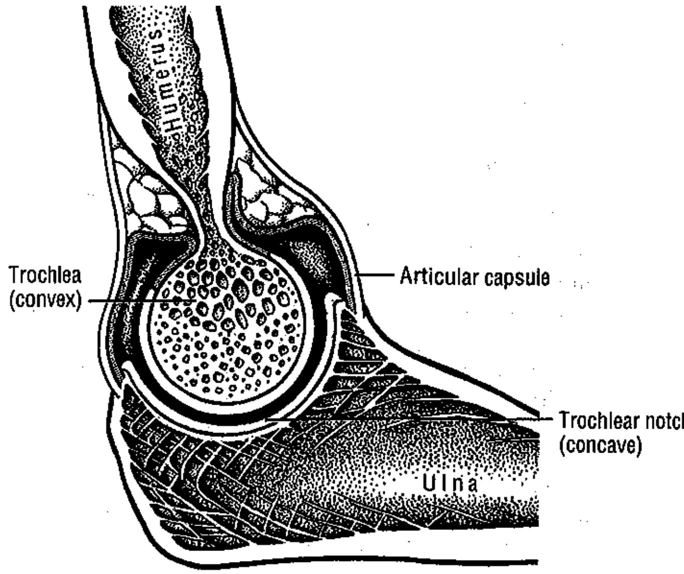


FIGURE 1–7. The humeroulnar joint at the elbow is an example of a convex-concave relationship between two articular surfaces. The trochlea of the humerus is convex, and the trochlear notch of the ulna is concave.

Arthrokinematics

TYPICAL JOINT MORPHOLOGY

Arthrokinematics describes the *motion* that occurs between the *articular surfaces* of joints. As described further in Chapter 2, the shapes of the articular surfaces of joints range from flat to curved. Most joint surfaces, however, are curved, with one surface being relatively convex and one relatively concave (Fig. 1–7). The convex-concave relationship of most articulations improves their congruency, increases the surface area for dissipating contact forces, and helps guide the motion between the bones.

FUNDAMENTAL MOVEMENTS BETWEEN JOINT SURFACES

Three fundamental movements exist between joint surfaces: roll, slide, and, spin.[11] These movements occur as a convex surface moves on a concave surface, and vice versa (Fig. 1–8). Although other terms are used, these are useful for visualizing the relative movements that occur within a joint. The terms are formally defined in Table 1–3.

Roll-and-Slide Movements

One primary way that a bone rotates through space is by a *rolling* of its articular surface against another bone's articular surface. The motion is shown for a convex-on-concave surface movement at the glenohumeral joint in Figure 1–9*A*. The contracting supraspinatus muscle rolls the convex humeral head against the slight concavity of the glenoid fossa. In essence, the roll directs the osteokinematic path of the abducting shaft of humerus.

A rolling convex surface typically involves a concurrent, oppositely directed slide. As shown in Figure 1–9*A*, the inferior-directed *slide* of the humeral head offsets most of the potential superior migration of the rolling humeral head. The offsetting roll-and-slide kinematics is analogous to a tire on a car that is spinning on a sheet of ice. The potential for the

TABLE 1–3. Three Fundamental Arthrokinematics: Roll, Slide, and Spin

Movement	Definition	Analogy
Roll*	*Multiple points* along one rotating articular surface contact *multiple points* on another articular surface.	A tire rotating across a stretch of pavement
Slide†	A *single point* on one articular surface contacts *multiple points* on another articular surface.	A stationary tire skidding across a stretch of icy pavement
Spin	A *single point* on one articular surface rotates on a *single point* on another articular surface.	A rotating toy top on one spot on the floor

*Also termed rock.
†Also termed glide.

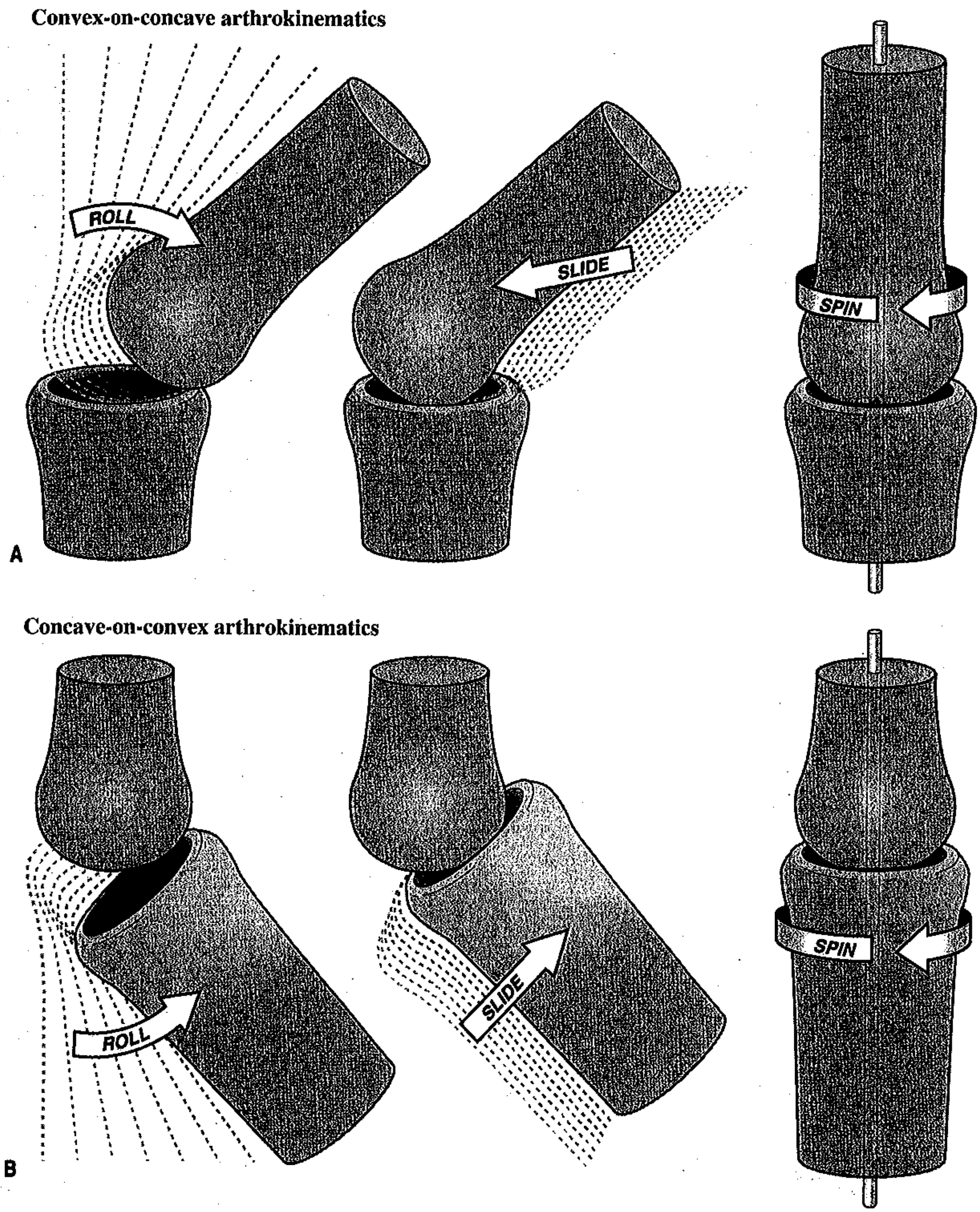


FIGURE 1–8. Three fundamental movements between joint surfaces: roll, slide, and spin. *A*, Convex-on-concave arthrokinematics; *B*, concave-on-convex arthrokinematics.

tire to rotate forward on the icy pavement is offset by a continuous sliding of the tire in the opposite direction to the intended rotation. A classic pathologic example of a convex surface rolling *without* an off-setting slide is shown in Figure 1–9*B*. The humeral head translates upward and impinges the delicate tissues in the subacromial space. The migration alters the relative location of the axis of rotation, thereby changing the leverage of the muscles that cross the glenohumeral joint. As shown in Figure 1–9*A*, the concurrent roll and slide maximizes the angular displacement of the abducting humerus, and minimizes the net translation between joint surfaces. This mechanism is particularly important in joints in which the articular surface area on the convex member exceeds that of the concave member.

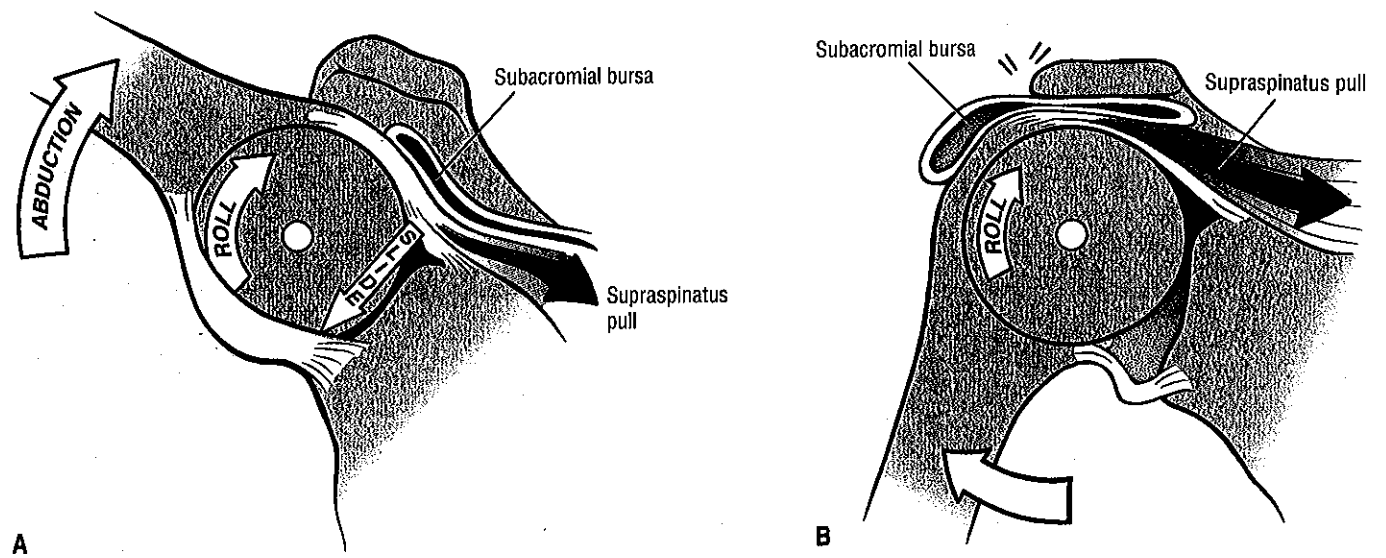


FIGURE 1–9. Arthrokinematics at the glenohumeral joint during abduction. The glenoid fossa is concave, and the humeral head is convex. *A*, Roll-and-slide arthrokinematics typical of a convex articular surface moving on a relatively stationary concave articular surface. *B*, Consequences of a roll occurring without a sufficient off-setting slide.

Spin

Another primary way that a bone rotates is by a *spinning* of its articular surface against the articular surface of another bone. This occurs as the radius of the forearm spins against the capitulum of the humerus during pronation of the forearm (Fig. 1–10). Other examples include internal and external rotation of the 90-degree abducted glenohumeral joint and flexion and extension of the hip. Spinning is the primary mechanism for joint rotation when the longitudinal axis of the long bone intersects the surface of its articular mate at right angles.

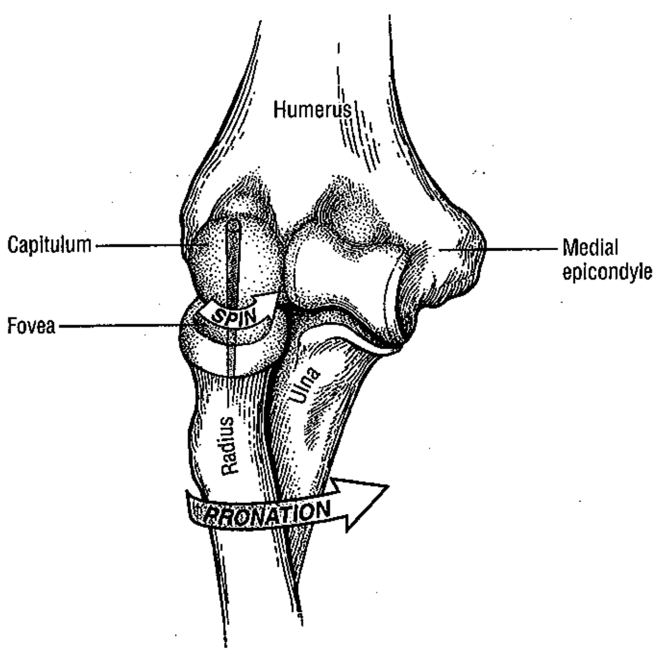


FIGURE 1–10. Pronation of the forearm shows an example of a spinning motion between the head of the radius and the capitulum of the humerus.

Motions That Combine Roll-and-Slide and Spin Arthrokinematics

Several joints throughout the body combine roll-and-slide with spin arthrokinematics. A classic example of this combination occurs during flexion and extension of the knee. As shown during femoral-on-tibial knee extension (Fig. 1–11*A*), the femur spins internally slightly, as the femoral condyle rolls and slides relative to the fixed tibia. These arthrokinematics are also shown as the tibia extends relative to the fixed femur in Figure 1–11*B*. In the knee, the spinning motion that occurs with flexion and extension occurs automatically and is mechanically linked to the primary motion of extension. As described in Chapter 13, the obligatory spinning rotation is based on the shape of the articular surfaces at the knee. The conjunct rotation helps to securely lock the knee joint when fully extended.

PREDICTING AN ARTHROKINEMATIC PATTERN BASED ON JOINT MORPHOLOGY

As previously stated, most articular surfaces of bones are either convex or concave. Depending on which bone is moving, a convex surface may rotate on a concave surface or vice versa (compare Fig. 1–11*A* with 1–11*B*). Each scenario presents a different roll-and-slide arthrokinematic pattern. As depicted in Figure 1–11*A* and 1–9*A* for the shoulder, during a *convex-on-concave movement*, the convex surface rolls and slides in *opposite directions*. As previously described, the contradirectional slide offsets the translation tendency inherent to the rolling convex surface. During a *concave-on-convex movement*, as depicted in Figure 1–11*B*, the concave surface rolls and slides in *similar directions*. These two principles are very useful for visualizing the arthrokinematics during a movement. In addition, the principles serve as a basis for

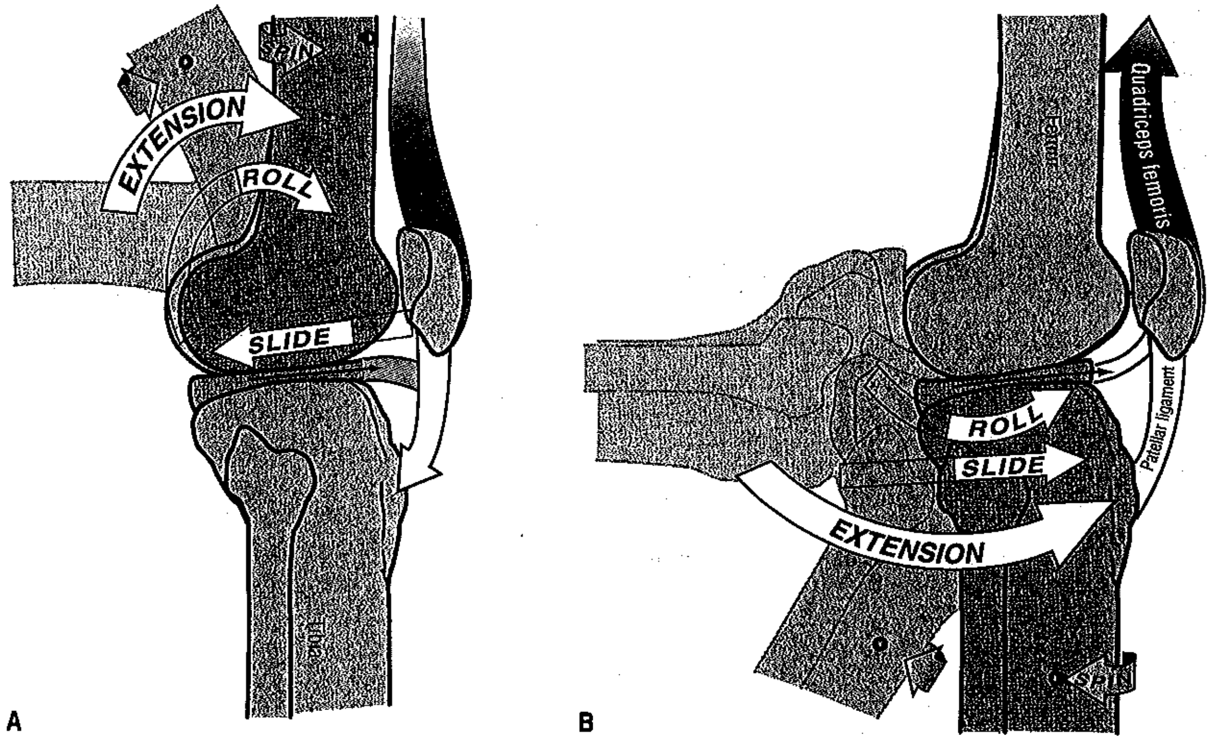


FIGURE 1–11. Extension of the knee demonstrates a combination of roll-and-slide with spin arthrokinematics. The femoral condyle is convex, and the tibial plateau is slightly concave. *A*, Femoral-on-tibial (knee) extension. *B*, Tibial-on-femoral (knee) extension.

some manual therapy techniques. External forces may be applied by the clinician that assist or guide the natural arthrokinematics at the joint. For example, in certain circumstances, glenohumeral abduction can be facilitated by applying an inferior-directed force at the proximal humerus, simultaneously with an active-abduction effort. The arthrokinematic principles do, however, require a knowledge of the joint surface morphology.

Arthrokinematic Principles of Movement

1. For a *convex-on-concave surface movement*, the convex member rolls and slides in *opposite directions*.
2. For a *concave-on-convex surface movement*, the concave member rolls and slides in *similar directions*.

CLOSE-PACKED AND LOOSE-PACKED POSITIONS AT A JOINT

The pair of articular surfaces within most synovial joints "fit" best in only one position, usually in or near the very end range of a motion. This position of maximal congruency is referred to as the joint's *close-packed position*. In this position, most ligaments and parts of the capsule are pulled taut, providing an element of natural stability to the joint. Accessory motions are minimal in a joint's close-packed position.

For many joints in the lower extremity, the close-packed position is associated with a habitual function. At the knee, for example, the close-packed position is full extension—a position that is typically approached while standing. The combined effect of the maximum joint congruity and stretched ligaments helps to provide transarticular stability to the knee.

All positions other than a joint's close-packed position are referred to as the joint's *loose-packed positions*. In these positions, the ligaments and capsule are relatively slackened, allowing an increase in *accessory movements*. The joint is generally least congruent near its mid range. In the lower extremity, the loose-packed positions of the major joints are biased toward flexion. These positions are generally not used during standing, but frequently are preferred by the patient during long periods of immobilization, such as extended bed rest.

KINETICS

Kinetics is a branch of mechanics that describes the effect of forces on the body. The topic of kinetics is introduced here as it applies to the musculoskeletal system. A broader and more detailed explanation of this subject matter is provided in Chapter 4.

From a kinesiologic perspective, a *force* can be considered as a "push or pull" that can produce, arrest, or modify movement. Forces therefore provide the ultimate impetus for movement and stabilization of the body. As described by Newton's second law, the quantity of a force (F) can be measured by the product of the mass (m) that received the push or pull, multiplied by the acceleration (a) of the mass. The formula $F = ma$ shows that, given a constant mass, a force is directly proportional to the acceleration of the mass—measuring the force yields the acceleration and vice versa. A force is zero when the acceleration of the mass is zero and vice versa.

Based on the SI, the unit of force is a *newton* (N): 1 N = 1 kg × 1 m/sec². The English equivalent to the newton is the pound (lb): 1 lb = 1 slug × 1 ft/sec² (4.448 N = 1 lb).

SPECIAL FOCUS 1-1

Body Weight Compared with Body Mass

A kilogram (kg) is a unit of *mass* that indicates the number of particles within an object. A kilogram is *not* a unit of force or weight. Under the influence of gravity, however, a 1-kg mass weighs 9.8 N. This is the result of gravity acting to accelerate the 1-kg mass toward the center of earth at a rate of about 9.8 m/s². If a person weighs 150 lb, gravity is pulling the center of mass of the person toward the center of earth with a force equal to 150 lb (667 N).

Often, however, the weight of the body is expressed in kilograms. The assumption is that the acceleration due to gravity acting on the body is constant and, for practical purposes, is ignored. Technically, however, the weight of a person varies inversely with the square of the distance between the mass of the person and the center of the earth. A person on the summit of Mt. Everest at 29,035 ft (≈8,852 m) weighs slightly less than a person with identical mass at sea level.[5] The acceleration due to gravity on Mt. Everest is 9.782 m/s² compared with 9.806m/s² at sea level.[4]

Musculoskeletal Forces

IMPACT OF FORCES ON THE MUSCULOSKELETAL TISSUES: INTRODUCTORY CONCEPTS AND TERMINOLOGY

The same forces that move and stabilize the body also have the potential to deform and injure the body. The manner by which forces or loads are most frequently applied to the musculoskeletal system is illustrated in Figure 1–12. (See the glossary at the end of this chapter for definitions.) Healthy tissues are able to resist changes in their shape. The tension force that stretches a healthy ligament, for example, is met by an intrinsic tension generated within the elongated tissue. Any tissue weakened by disease or trauma may not be able to adequately resist the application of the loads depicted in Figure 1–12. The proximal femur weakened by osteoporosis, for example, may fracture from the impact of a fall owing to *compression or torsion (twisting), shearing* or *bending* of the neck of the femur.

The inherent ability of connective tissues to tolerate loads can be observed experimentally by plotting the amount of force required to deform an excised tissue.[6] Figure 1–13 shows the tension generated by an excised ligament that has been stretched to a point of mechanical failure. The vertical axis of the graph is labeled *stress*, a term that denotes the internal resistance generated as a tissue resists its deformation, divided by its cross-sectional area. The horizontal axis is labeled *strain*, which is the ratio of the tissue's deformed length to its original length.[8] A similar procedure may be performed by *compressing*, rather than by stretching, an excised slice of cartilage or bone, for example, and then plotting the amount of stress within the tissue.

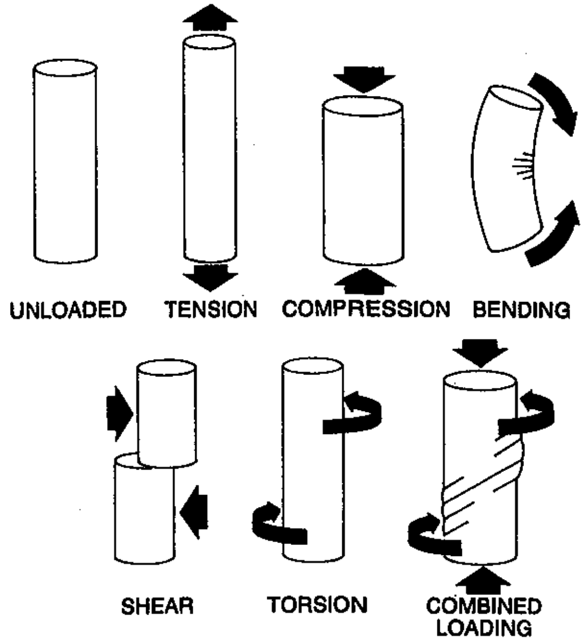


FIGURE 1–12. The manner by which forces or loads are most frequently applied to the musculoskeletal system is shown. The combined loading of torsion and compression is also illustrated. (With permission from Nordin M, Frankel VH: Biomechanics of bones. Basic Biomechanics of the Musculoskeletal System, 2nd ed. Philadelphia, Lea & Febiger, 1989.)

Figure 1–13 shows five zones (A to E). In *zone A*, the slightly stretched or elongated ligament produces only a small amount of tension. This nonlinear region of low tension reflects the fact that the collagen fibers within the ligament must first be drawn taut before significant tension is measured. *Zone B* shows the linear relationship between stress and strain in a normal ligament. The ratio of stress to strain in an elastic material is a measure of its *stiffness*. All normal tissues within the musculoskeletal system exhibit some degree of stiffness. The clinical term "tightness" usually implies a pathologic condition of abnormally high stiffness.

Zone B in Figure 1–13 is often referred to as the *elastic zone* of the stress-strain plot. The amount of stretch (strain) applied to the ligament in this zone is significant and likely experienced during many natural movements of the body. Within this zone, the tissue returns to its original length or shape once the deforming force is removed. The area under the curve (red) represents *elastic deformation energy*. Most of the energy utilized to deform the tissue is released when the force is removed. Even in a static sense, elastic energy can do useful work for the body. When stretched even a moderate amount within the elastic zone, ligaments and other connective tissues surrounding muscles perform important joint stabilization functions.

Zone C in Figure 1–13 shows a mechanical property of stretched connective tissue called *plasticity*. At this extreme

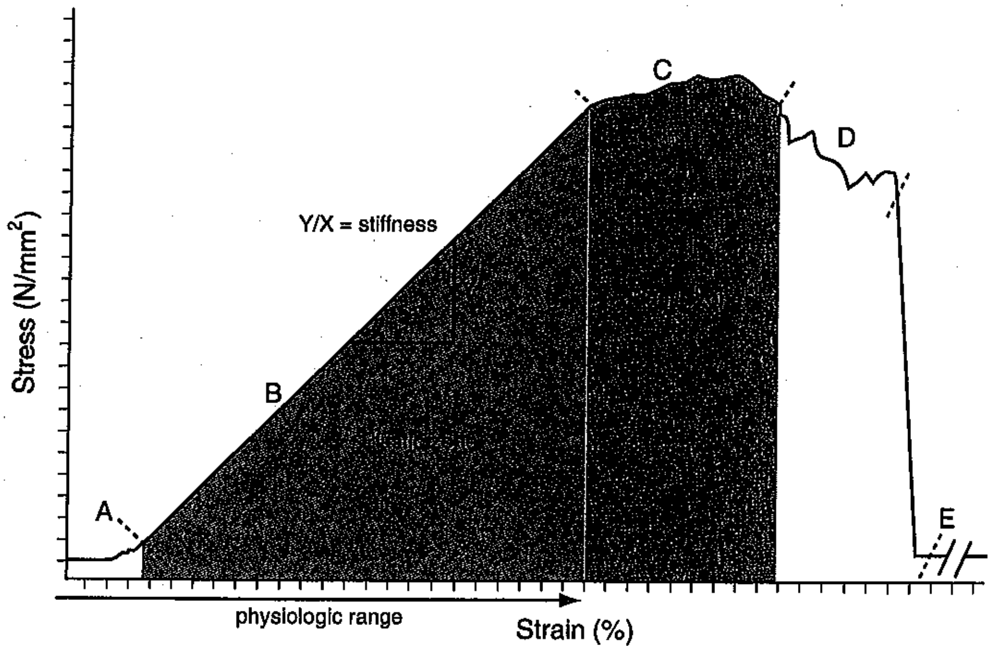


FIGURE 1–13. The stress-strain curve of an excised ligament is shown that has been stretched to a point of mechanical failure (disruption). The ligament is considered an elastic tissue. *Zone A* shows the nonlinear region. *Zone B* (elastic zone) shows the linear relationship between stress and strain, demonstrating the *stiffness* of the tissue. *Zone C* indicate the mechanical property of *plasticity*. *Zones D* and *E* demonstrate the points of progressive mechanical failure of the tissue. (Modified with permission from Neumann DA: Arthrokinesiologic considerations for the aged adult. In Guccione AA (ed): Geriatric Physical Therapy, 2nd ed. Chicago, Mosby-Year Book, 2000.)

and abnormally large stretch, the tissue generates only marginal increases in tension as it continues to elongate. At this point, the ligament is experiencing microscopic failure and remains permanently deformed. The area under the curve (gray) represents *plastic deformation energy*. Unlike the elastic deformation energy (region B), the plastic energy is not recoverable in its entirety when the deforming force is released. As elongation continues, the ligament reaches its initial point of failure in *zone D* and complete failure in *zone E*.

The graph in Figure 1–13 does *not* indicate the variable of time. Tissues in which the stress-strain curve changes as a function of time are considered *viscoelastic*. Most tissues within the musculoskeletal system demonstrate at least some degree of viscoelasticity (Fig. 1–15). One phenomenon of a viscoelastic material is creep. As demonstrated by the tree branch in Figure 1–15, *creep* describes a progressive strain of a material when exposed to a constant load over time. The phenomenon of creep explains why a person is taller in the morning than at night. The constant compression caused by body weight on the spine throughout the day literally squeezes fluid out of the intervertebral discs. The fluid is reabsorbed at night while the sleeping person is in a non-weight-bearing position.

The stress-strain curve of a viscoelastic material is also sensitive to the *rate* of loading of the tissue. In general, the slope of a stress-strain relationship when placed under tension or compression increases throughout its elastic range as the rate of the loading increases.[8] The rate-sensitivity nature of viscoelastic connective tissues may protect surrounding structures within the musculoskeletal system. Articular cartilage in the knee, for example, becomes stiffer as the rate of compression increases,[7] such as during running. The increased stiffness affords greater protection to the underlying bone at a time when joint forces are greatest.

INTERNAL AND EXTERNAL FORCES

The principal forces acting to move and stabilize the musculoskeletal system can be conveniently divided into two sets: internal and external. *Internal forces* are produced from structures located *within* the body. These forces may be "active" or "passive." Active forces are generated by stimulated muscle, generally under volitional control. Passive forces, in contrast, are typically generated by tension in stretched periarticular connective tissues, including the intramuscular connective tissues, ligaments, and joint capsules. Active forces produced by muscles are typically the largest of all internal forces.

External forces are typically produced by forces acting from *outside* the body. These forces usually originate from either *gravity* pulling on the mass of a body segment or an external load, such as that of luggage or "free" weights, or *physical contact*, such as that applied by a therapist against the limb of a patient. Figure 1–16*A* shows an opposing pair of internal and external forces: an internal force (muscle), pulling the forearm, and an external (gravitational) force, pulling on the center of mass of the forearm. Each force is depicted by an arrow that represents a vector. By definition, a *vector* is a quantity that is completely specified by its magnitude and its direction. (Quantities such as mass or

SPECIAL FOCUS 1–2

Productive Antagonism: The Body's Ability to Convert Passive Tension into Useful Work

As previously described, connective tissue produces tension when stretched. Since tension is a force, it has the ability to do work. Several examples are presented throughout this text in which the tension produced by stretched connective tissues performs useful functions. This phenomenon is called *productive antagonism* and is demonstrated for a pair of muscles in the simplified model in Figure 1–14. As shown in the middle, part of the energy produced by active contraction of muscle A is transferred and stored as an elastic energy in the stretched connective tissues within muscle B. The elastic energy is released as muscle B actively contracts to drive the nail into the board (lower). Part of the contractile energy produced by muscle B is used to stretch muscle A, and the cycle is repeated.

This transfer and storage of energy between opposing muscles is useful in terms of overall metabolic efficiency. This phenomenon is often expressed in different ways by multiarticular muscles (i.e., muscles that cross several joints). Consider the rectus femoris, a muscle that flexes the hip and extends the knee. During the upward phase of jumping, for example, the rectus femoris contracts to extend the knee. At the same time, the extending hip stretches the active rectus femoris across the front of the hip. As a consequence, the overall shortening of the rectus femoris is minimized, thereby maintaining a low level of useful passive tension within the muscle.

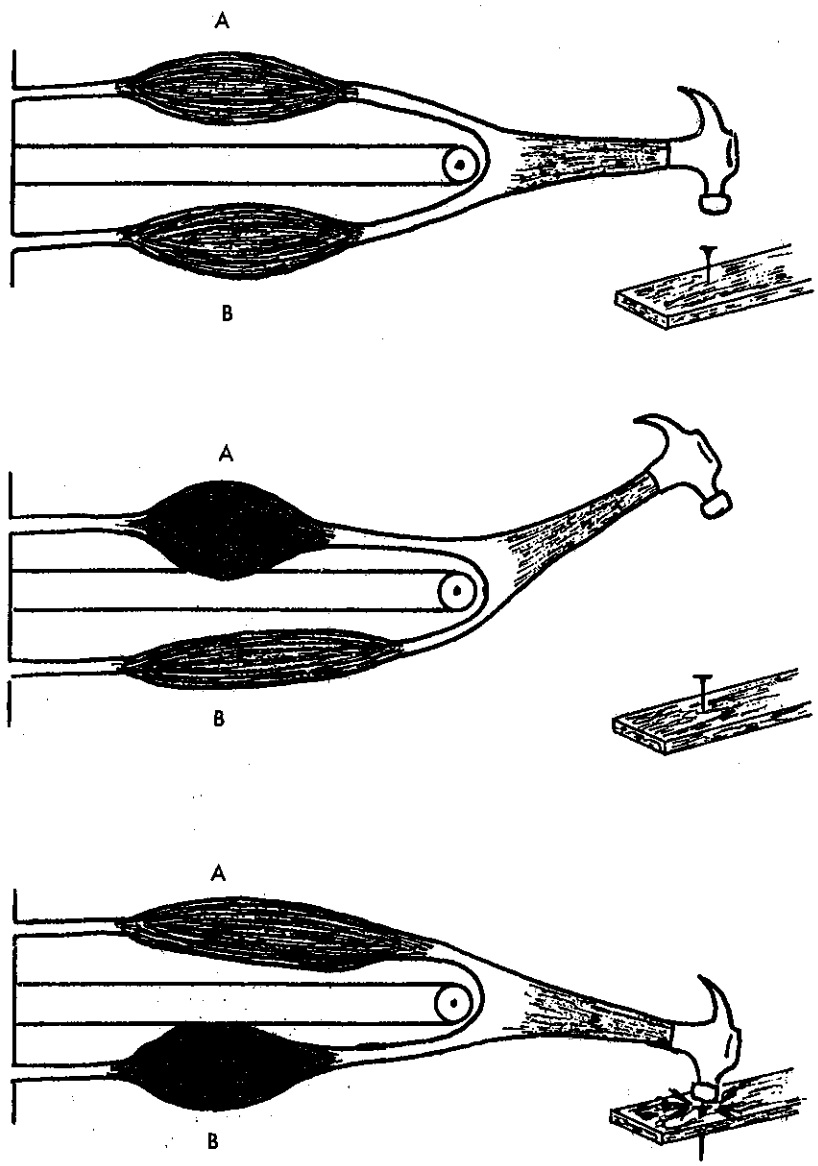


FIGURE 1–14. A simplified model showing a pair of opposed muscles surrounding a joint. Muscles A and B in the *top* are shown in their relaxed state. In the *middle*, muscle A (red) is contracting to provide the force needed to lift the hammer in preparation to strike the nail. In the *lower* view, muscle B (red) is contracting, driving the hammer against the nail, while simultaneously stretching muscle A. (Modified with permission from Brand PW: Clinical Biomechanics of the Hand. St Louis, CV Mosby, 1985.)

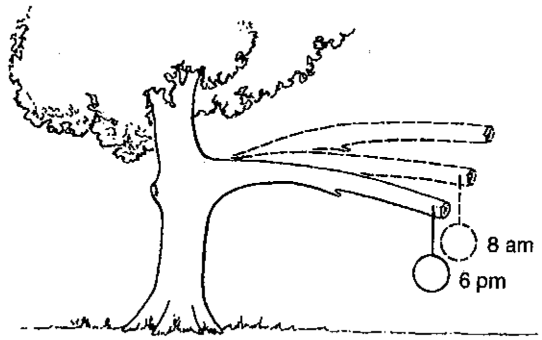


FIGURE 1–15. The branch of the tree is demonstrating a time-dependent property associated with a *viscoelastic material*. Hanging a load on the branch at 8 AM creates an immediate deformation. By 6 PM, the load has caused additional deformation in the branch. (With permission from Panjabi MM, White AA: Biomechanics in the Musculoskeletal System. New York, Churchill Livingstone, 2001.)

speed are scalars not vectors. A scalar is a quantity that is completely specified by its magnitude and has no direction.)

In order to completely describe a vector in a biomechanical analysis, its magnitude, direction, sense, and point of application must be known. The forces depicted in Figure 1–16*A* indicate these four factors.

1. The *magnitude* of each force vector is indicated by the length of the shaft of the arrow.

2. The *direction* of both force vectors is indicated by the spatial orientation of the shaft of the arrows. Both forces are oriented vertically, commonly referred to as the Y direction. The direction of a force can also be described by the angle formed between the shaft of the arrow and a reference line. Throughout this text, the direction of a muscle force and the direction of gravity are commonly referred to as their *line-of-force* and *line-of-gravity*, respectively.

3. The *sense* of each force vector is indicated by the orientation of the arrowhead. In the example depicted in Figure 1–16*A*, the internal force acts upward in a *positive Y sense;* the external force acts downward in a *negative Y sense.*

4. The *point of application* of the vectors is where the base of the vector arrow contacts the part of the body. The point of application of the muscle force is where the muscle inserts to the bone. The *angle-of-insertion* describes the angle formed between a tendon of a muscle and the long axis of the bone to which it inserts. In Figure 1–16*A*, the angle-of-insertion is 90 degrees. The angle-of-insertion changes as the elbow rotates into flexion or extension. The point of application of the external force depends on whether the force is the result of gravity or the result of a resistance applied by physical contact. Gravity acts on the *center of mass* of the body segment (see Fig. 1–16*A*, dot at the forearm). The point of application of a resistance generated from physical contact can occur anywhere on the body.

Factors Required to Completely Describe a Vector in Most Biomechanical Analyses

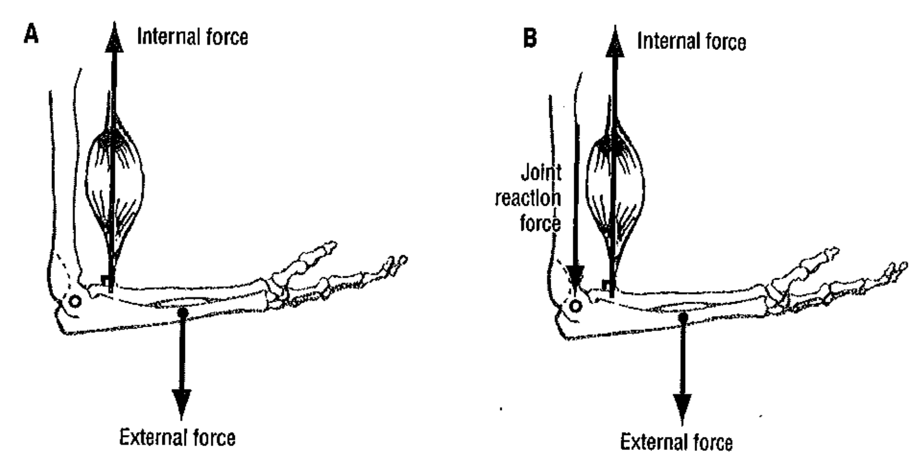
- Magnitude
- Direction (line-of-force or line-of-gravity)
- Sense
- Point of application

As a push or a pull, all forces acting on the body cause a potential translation of the segment. The direction of the translation depends on the net effect of all the applied forces. Since in Figure 1–16*A* the muscle force is three times greater than the weight of the forearm, the net effect of both forces would accelerate the forearm vertically upward. In reality, however, the forearm is typically prevented from accelerating upward by a *joint reaction force* produced between the surfaces of the joint. As depicted in Figure 1–16*B*, the distal end of the humerus is pushing *down* with a reaction force against the proximal end of the forearm. The magnitude of the joint reaction force is equal to the difference between the muscle force and external force. As a result, the sum of all vertical forces acting on the forearm is balanced, and net acceleration of the forearm in the vertical direction is zero. The system is therefore in *static linear equilibrium*.

Musculoskeletal Torques

Forces exerted on the body can have two outcomes. First, as depicted in Figure 1–16*A*, forces can potentially translate a body segment. Second, the forces, if acting at a *distance* from

FIGURE 1–16. A sagittal plane view of the elbow joint and associated bones. *A*, Internal (muscle) and external (gravitational) forces are shown both acting vertically, but each in a different sense. The two vectors each have a different magnitude and different points of attachment to the forearm. *B*, Joint reaction force is added to prevent the forearm from accelerating upward. (Vectors are drawn to relative scale.)



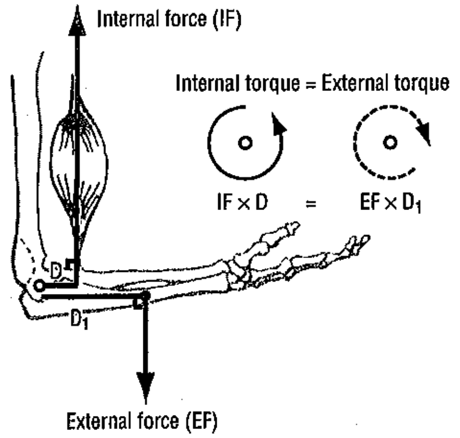


FIGURE 1–17. The balance of internal and external torques acting in the sagittal plane about the axis of rotation at the elbow (small circle) is shown. The *internal torque* is the product of the internal force multiplied by the internal moment arm (D). The internal torque has the potential to rotate the forearm in a counterclockwise direction. The *external torque* is the product of the external force (gravity) and the external moment arm (D_1). The external torque has the potential to rotate the forearm in a clockwise direction. The internal and external torques are equal, demonstrating a condition of static rotary equilibrium. (Vectors are drawn to relative scale.)

the axis of rotation at the joint, produce a potential rotation of the joint. The shortest distance between the axis of rotation and the force is called a *moment arm.* The product of a force and its moment arm is a *torque* or a moment. Torque can be considered as a rotatory equivalent to a force. A force pushes and pulls an object in a linear fashion, whereas a torque rotates an object about an axis of rotation.

Torques occur in planes about an axis of rotation. Figure 1–17 shows the torques produced within the sagittal plane by the internal and external forces introduced in Figure 1–16. The *internal torque* is defined as the product of the internal force (muscle) and the internal moment arm. The *internal moment arm* (see Fig 1–17,D) is the distance between the axis of rotation and the perpendicular intersection with the internal force. As depicted in Figure 1–17, the internal torque has the potential to rotate the forearm in a counterclockwise, or flexion, direction.

The *external torque* is defined as the product of the external force (gravity) and the external moment arm. The *external moment arm* (see Fig 1–17,D_1) is the distance between the axis of rotation and the perpendicular intersection with the external force. The external torque has the potential to rotate the forearm in a clockwise, or extension, direction. The internal and external torques happen to be equal in Figure 1–17, and therefore no rotation occurs at the joint. This condition is referred to as *static rotary equilibrium.*

Muscle and Joint Interaction

The term *muscle and joint interaction* refers to the overall effect that a muscle force may have on a joint. This topic is revisited repeatedly throughout this textbook. A force produced by a muscle that has a moment arm causes a torque, and a potential to rotate the joint. A force produced by a muscle that lacks a moment arm (i.e., the muscle force passes *through* the axis of rotation) will not cause a torque or a rotation. The muscle force is still important, however, because it usually provides a source of stability to the joint.

> **SPECIAL FOCUS 1-3**
>
> **Torque Makes the World Go 'Round**
>
> Torques are experienced by everyone, in one way or another. Muscles and gravity are constantly competing for dominance of torque about the axis of rotation at joints. The direction of rotation of a bone about a joint can indicate the more dominant torque. Furthermore, manual contact forces applied against objects in the environment are frequently converted to torques. Torques are used to unscrew a cap from a jar, turn a wrench, swing a baseball bat, and open a door. In the last example, the door is opened by the product of the push on the door knob multiplied by the perpendicular distance between the door knob and the hinge. Trying to open a door by pushing only a couple of centimeters from the hinge of the door is very difficult, even when applying a large pushing force. In contrast, a door can be opened with a slight push, provided the push is applied at the door knob, which is purposely located at a distance far from the hinge. *A torque is the product of a force and its moment arm.* Both variables are equally influential.
>
> Torques are involved in most therapeutic situations with patients, especially when physical exercise or strength assessment is involved. A person's "strength" is the product of their muscle's force, and, equally important, the distance between the muscle's line-of-force and the axis of rotation. As explained further in Chapter 4, the length of a muscle's moment arm changes constantly throughout a range of motion. This partially explains why a person is naturally stronger in certain parts of a joint's range of motion.
>
> Clinicians frequently apply manual resistance against their patients as a means to assess, facilitate, and challenge a particular muscle activity. The *force* applied against a patient's extremity is usually perceived as an external *torque* by the patient's musculoskeletal system. A clinician can challenge a particular muscle group by applying an external torque by way of a small manual force exerted a great distance from the joint or a large manual force exerted close to the joint. Either means can produce the same external torque against the patient. Modifying the force and external moment arm variables allows different strategies to be employed based on the strength and skill of the clinician.

TYPES OF MUSCLE ACTIVATION

A muscle is considered activated when it is stimulated by the nervous system. A muscle produces a force through three types of activation: isometric, concentric, and eccentric. The physiology of the three types of activation is described in greater detail in Chapter 3 and briefly summarized subsequently.

Isometric activation occurs when a muscle is producing a force while maintaining a constant length. This type of activation is apparent by the origin of the word isometric (from the Greek *isos,* equal; and *metron,* measure or length). During an isometric activation, the internal torque produced at a joint is equal to the external torque; hence, there is no muscle shortening or rotating at the joint (Fig. 1–18*A*).

Concentric activation occurs as a muscle produces a force as it contracts (shortens) (Fig. 1–18*B*). Literally, concentric means "coming to the center." During a concentric activation, the internal torque at the joint exceeds the opposing external torque. This is reflected by the fact that the muscle contracted and accelerated a rotation of the joint in the direction of the activated muscle.

Eccentric activation, in contrast, occurs as a muscle produces an active force while being elongated. The word eccentric literally means "away from the center." During an eccentric activation, the external torque about the joint exceeds the internal torque. In this case, the joint rotates in the direction dictated by the relatively larger external torque, such as that produced by the cable in Figure 1–18*C*. Many common activities employ eccentric activations of muscle. Slowly lowering a cup of water to a table, for example, is caused by the pull of gravity on the forearm and water. The activated biceps slowly elongates in order to control their descent. The triceps muscle, although considered as an elbow "extensor," is most likely inactive during this particular process.

The term "contraction" is often used synonymously with "activation," regardless of whether the muscle is actually shortening, lengthening, or remaining at a constant length. The term "contract" literally means to be *drawn together* and, therefore, its use can be confusing when describing either an isometric or eccentric activation. Technically, a contracting muscle occurs during a concentric activation only.

A MUSCLE'S ACTION AT A JOINT

A *muscle's action at a joint* is defined as its potential to cause a torque in a particular rotation direction and plane. The actual naming of a muscle's action is based on an established nomenclature, such as flexion or extension in the sagittal plane, abduction or adduction in the frontal plane, and so forth. The terms "muscle action" and "joint action" are used interchangeably throughout this text, depending on the context of the discussion. If the action is associated with a nonisometric muscle activation, the resulting osteokinematics may involve distal-on-proximal segment kinematics, or vice versa, depending on the relative stability of the two segments that comprise the joint.

Kinesiology allows one to determine the action of a muscle, without relying purely on memory. Suppose the student desires to determine the action of the *posterior deltoid* at the glenohumeral (shoulder) joint. In this particular analysis, two assumptions are made. First, it is assumed that the humerus is the freest segment of the joint, and that the scapula is fixed, although the reverse assumption could have been made. Second, it is assumed that the body is in the anatomic position at the time of the muscle activation.

The first step in the analysis is to determine the planes of rotary motion (degrees of freedom) allowed at the joint. In this case, the glenohumeral joint allows rotation in all three planes (see Fig. 1–5). Figure 1–19*A* shows the potential for the posterior deltoid to rotate the humerus in the frontal plane. The axis of rotation at the joint passes in an anterior-posterior direction through the humeral head. In the anatomic position, the line-of-force of the posterior deltoid passes inferior to the axis of rotation. By assuming that the scapula is stable, the posterior deltoid would rotate the humerus toward adduction, with a strength equal to the product of the muscle force multiplied by its internal moment arm. This same logic is next applied to determine the muscle's action in the horizontal and sagittal planes. As depicted in Figure 1–19*B* and *C*, it is apparent that the muscle is also

Three types of muscle activation

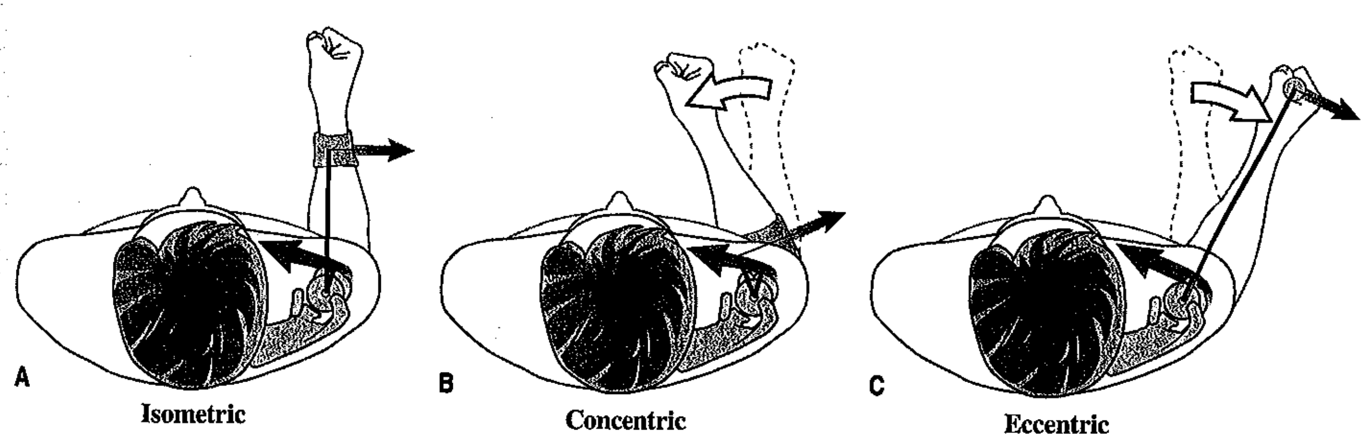


FIGURE 1–18. Three types of muscle activation are shown as the pectoralis major actively attempts to internally rotate the shoulder (glenohumeral) joint. In each of the three illustrations, the internal torque is the product of the muscle force (red) and its moment arm; the external torque is the product of the force in the cable (gray) and its moment arm. Note that the external moment arm and, therefore, the external torque is different in each illustration. *A,* Isometric activation is shown as the internal torque matches the external torque. *B,* Concentric activation is shown as the internal torque exceeds the external torque. *C,* Eccentric activation is shown as the external torque exceeds the internal torque. (Vectors are *not* drawn to scale.)

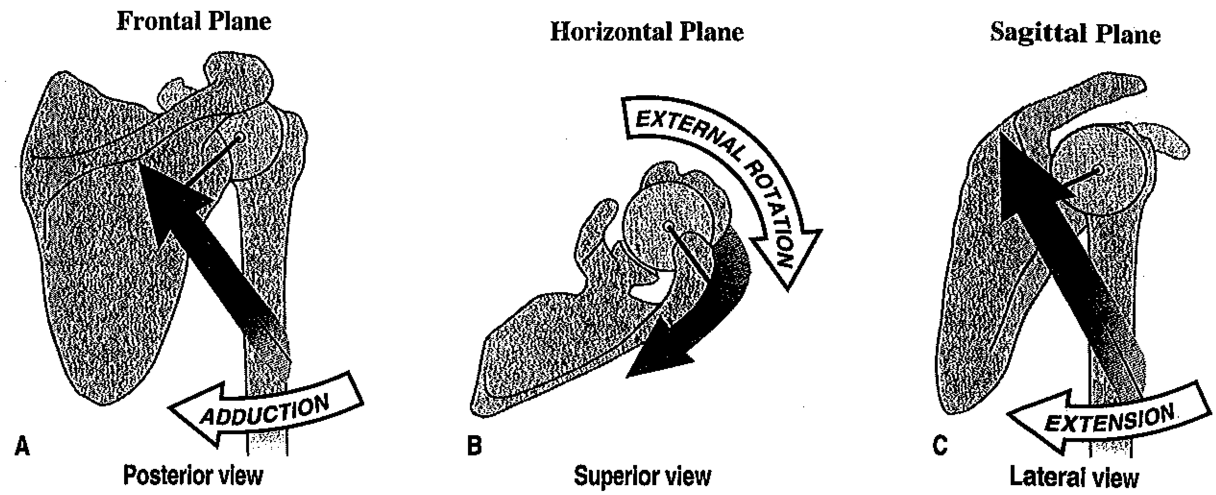


FIGURE 1–19. The multiple actions of the posterior deltoid are shown at the glenohumeral joint. *A*, Adduction in the frontal plane. *B*, External rotation in the horizontal plane. *C*, Extension in the sagittal plane. The internal moment arm is shown extending from the axis of rotation (small circle through humeral head) to a perpendicular intersection with the muscle's line-of-force.

an external (lateral) rotator and an extensor of the glenohumeral joint.

The logic so presented can be used to determine the action of *any muscle* in the body, at any joint. If available, an articulated skeleton model and a piece of string that mimics the line-of-force of a muscle is helpful in applying this logic. This exercise is particularly helpful when analyzing a muscle whose action switches, depending on the position of the joint. One such muscle is the posterior deltoid. From the anatomic position, the posterior deltoid is an *adductor* of the glenohumeral joint. If the arm is lifted (abducted) fully overhead, however, the line-of-force of the muscle shifts just to the *superior side* of the axis of rotation. As a consequence, the posterior deltoid actively abducts the shoulder. This shift can be visualized with the aid of Figure 1–19*A*. The example shows how one muscle can have opposite actions, depending on the position of the joint at the time of muscle activation. It is important, therefore, to establish a reference position for the joint when analyzing the actions of a muscle. One common reference position is the anatomic position (see Fig. 1–4). Unless otherwise specified, the actions of muscles described throughout Sections II to IV are based on the assumption that the joint is in the anatomic position.

Terminology Related to the Actions of Muscles

The following terms are often used when describing the actions of muscles:

1. The *agonist* is the muscle or muscle group that is most directly related to the initiation and execution of a particular movement. For example, the tibialis anterior is the agonist for the motion of dorsiflexion of the ankle.
2. The *antagonist* is the muscle or muscle group that is considered to have the opposite action of a particular agonist. For example, the gastrocnemius and soleus muscles are considered the antagonists to the tibialis anterior.
3. A pair of muscles are considered *synergists* when they cooperate during the execution of a particular movement. Actually, most meaningful movements of the body involve multiple muscles acting as synergists. Consider, for example, the flexor carpi ulnaris and flexor carpi radialis muscles during flexion of the wrist. The muscles act synergistically because they cooperate to flex the wrist. Each muscle, however, must neutralize the other's tendency to move the wrist in a side-to-side (radial and ulnar deviation) fashion. Paralysis of one of the muscles significantly affects the overall action of the other.

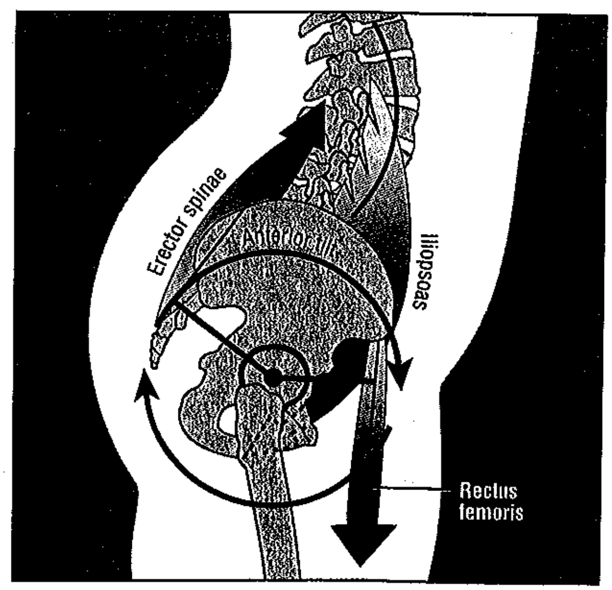


FIGURE 1–20. Side view of the force-couple formed between two representative hip flexor (rectus femoris and iliopsoas) muscles and back extensor (erector spinae) muscles, as they contract to tilt the pelvis in an anterior direction. The internal moment arms used by the muscles are indicated by the dark black lines. The axis of rotation runs through both hip joints.

Another example of muscle synergy is described as a muscular force-couple. A muscular *force-couple* is formed when two or more muscles simultaneously produce forces in different linear directions, although the torques act in the same rotary direction. A familiar analogy of a force couple occurs between the two hands while turning a steering wheel of a car. Rotating the steering wheel to the right, for example, occurs by the action of the right hand pulling down and the left hand pulling up on the wheel. Although the hands are producing forces in different linear directions, they cause a torque on the steering wheel in a common rotary direction. The hip flexor and low back extensor muscles, for example, form a force-couple to rotate the pelvis in the sagittal plane about both hip joints (Fig. 1–20).

Musculoskeletal Levers

THREE CLASSES OF LEVERS

A lever is a simple machine consisting of a rod suspended across a pivot point. The seesaw is a classic example of a lever. One function of a lever is to convert a force into a torque. As shown in the seesaw in Figure 1–21, a 672-N (about 150-lb) man sitting 0.91 m (about 3 ft) from the pivot point produces a torque that balances a boy weighing half his weight, who is sitting twice the distance from the pivot point. In Figure 1–21, the opposing torques are equal:

$$BW_m \times D = BW_b \times D_1.$$

As indicated, the boy has the greatest leverage (D_1). *Leverage* describes the relative moment arm length possessed by a particular force.

Internal and external forces produce torques throughout the body through a system of bony levers. The most important forces involved with musculoskeletal levers are those produced by muscle, gravity, and physical contacts within the environment. Levers are classified as either *first, second,* or *third class.*

First-Class Lever. As depicted in Figure 1–21, the first-class lever has its axis of rotation positioned *between* the opposing forces. An example of a first-class lever in the body is the head-and-neck extensor muscles that control the posture of the head in sagittal plane (Fig. 1–22*A*). As in the seesaw example, the head is held in equilibrium when the product of the muscle force (MF) multiplied by the internal moment arm (IMA) equals the product of head weight (HW) multiplied by its external moment arm (EMA). In first-class levers, the internal and external forces typically act in similar

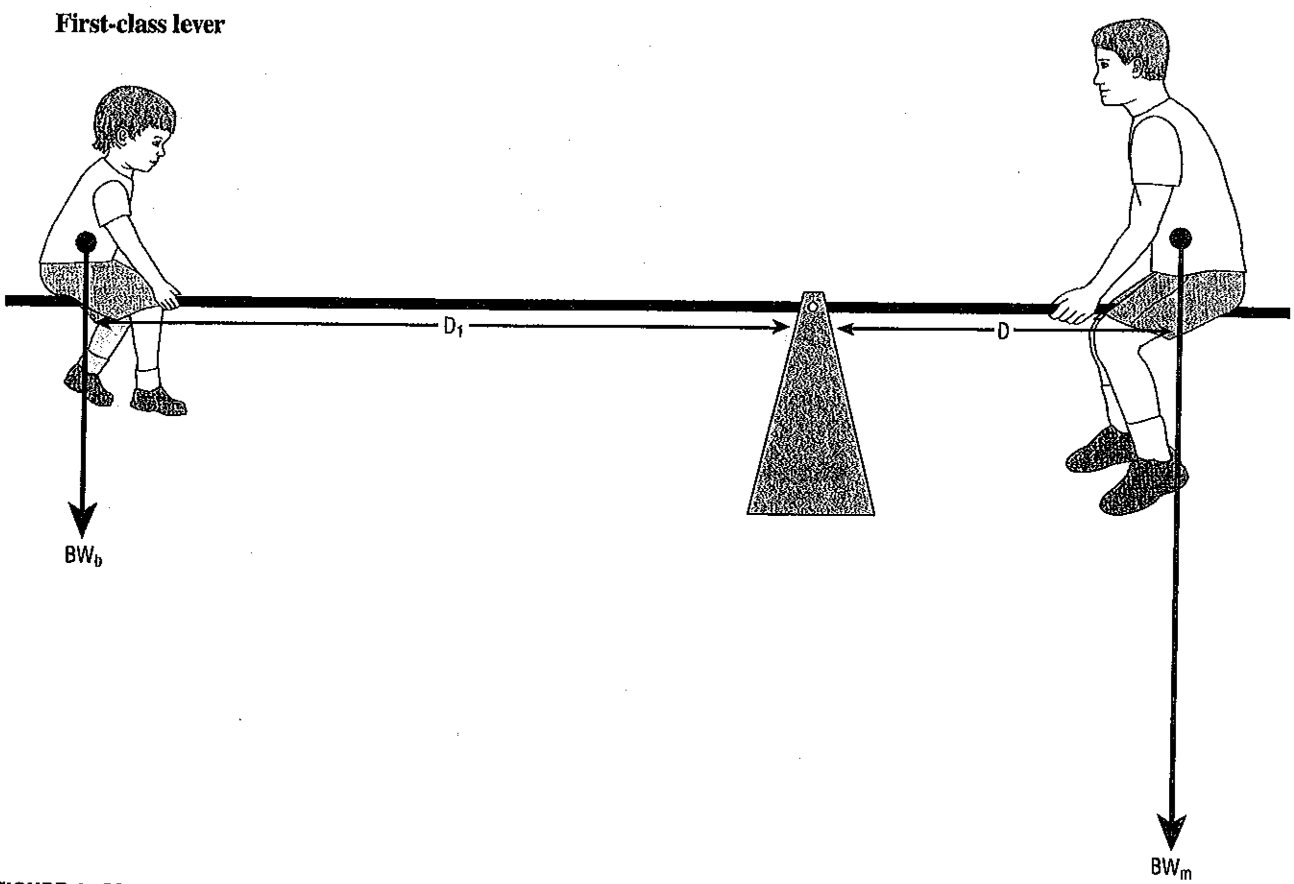
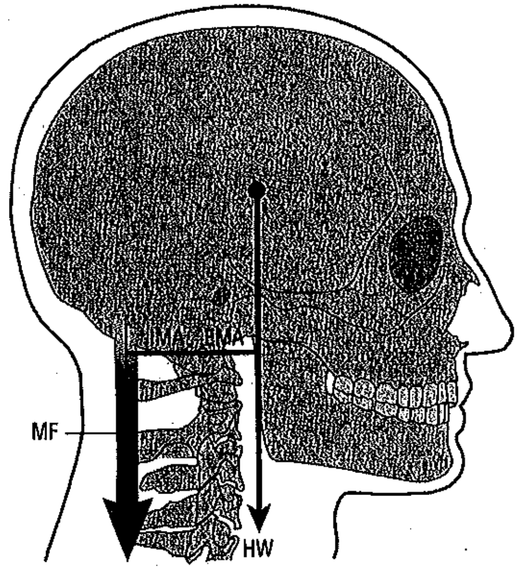


FIGURE 1–21. A seesaw is shown as a typical first-class lever. The body weight of the man (BW_m) is 672 N (about 150 lb). He is sitting .91 m (about 3 ft) from the pivot point (D). The body weight of the boy (BW_b) is only 336 N (about 75 lb). He is sitting 1.82 m (about 6 ft) from the pivot point (D_1). The seesaw is balanced since the clockwise torque produced by the man is equal in magnitude to the counterclockwise torque produced by the boy: 672 N × .91 m = 336 N × 1.82 m.

First-class lever



A

Data for first-class lever:
Muscle force (MF) = unknown
Head weight (HW) = 46.7 N (10.5 lbs)
Internal moment arm (IMA) = 4.0 cm
External moment arm (EMA) = 3.2 cm
Mechanical advantage = 1.25

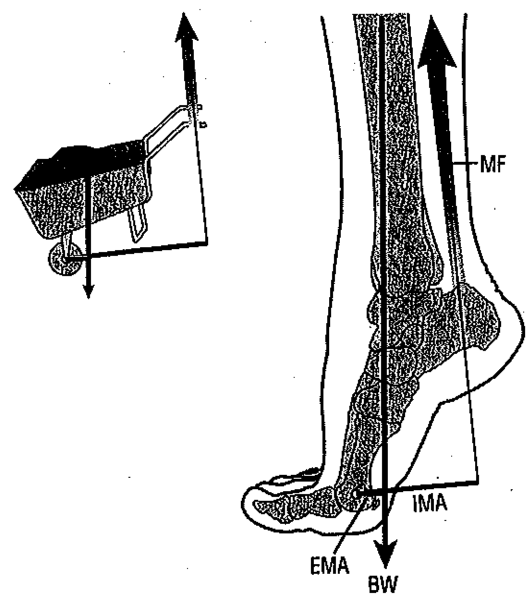
MF × IMA = HW × EMA

$MF = \frac{HW \times EMA}{IMA}$

$MF = \frac{46.7\ N \times 3.2\ cm}{4.0\ cm}$

MF = 37.4 N (8.4 lbs)

Second-class lever



B

Data for second-class lever:
Muscle force (MF) = unknown
Body weight (BW) = 667 N (150 lbs)
Internal moment arm (IMA) = 12.0 cm
External moment arm (EMA) = 3.0 cm
Mechanical advantage = 4.0

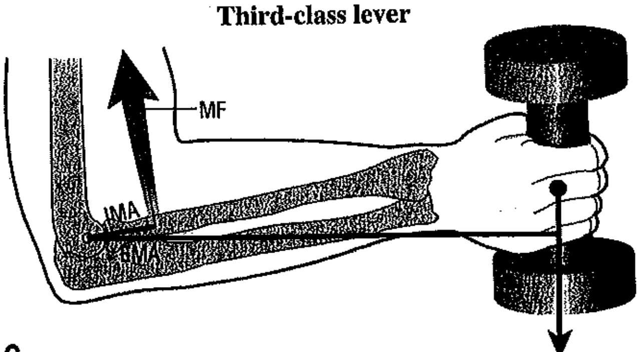
MF × IMA = BW × EMA

$MF = \frac{BW \times EMA}{IMA}$

$MF = \frac{667\ N \times 3.0\ cm}{12.0\ cm}$

MF = 166.8 N (37.5 lbs)

Third-class lever



C

Data for third-class lever:
Muscle force (MF) = unknown
External weight (EW) = 66.7 N (15 lbs)
Internal moment arm (IMA) = 5.0 cm
External moment arm (EMA) = 35.0 cm
Mechanical advantage = .143

MF × IMA = EW × EMA

$MF = \frac{EW \times EMA}{IMA}$

$MF = \frac{66.7\ N \times 35.0\ cm}{5.0\ cm}$

MF = 467.0 N (105.0 lbs)

FIGURE 1–22. Anatomic examples are shown of first- (*A*), second- (*B*), and third- (*C*) class levers. (The vectors are *not* drawn to scale.) The data contained in the boxes to the right show how to calculate the muscle force required to maintain static rotary equilibrium. Note that the mechanical advantage is indicated in each box. The muscle activation is isometric in each case, with no movement occurring at the joint.

linear directions, although they produce torques in opposing rotary directions.

Second-Class Lever. A second-class lever has two unique features. First, its axis of rotation is located at one end of a bone. Second, the muscle, or internal force, possesses greater leverage than the external force. As illustrated in Figure 1–22*B*, a calf muscle group uses a second-class lever to produce the torque needed to stand on tiptoes. The axis of rotation for this action is through the metatarsophalangeal joints. The internal moment arm used by calf muscles greatly exceeds the external moment arm used by body weight. Second-class levers are rare in the musculoskeletal system.

Third-Class Lever. As in the second-class lever, the third-class lever has its axis of rotation located at one end of a bone. The elbow flexor muscles use a third-class lever to produce the flexion torque required to support a barbell (Fig. 1–22*C*). Unlike the second-class lever, the external weight supported by a third-class lever always has greater leverage than the muscle force. The third-class lever is the most common lever used by the musculoskeletal system.

MECHANICAL ADVANTAGE

The *mechanical advantage* (MA) of a musculoskeletal lever is defined as the ratio of the internal moment arm to the external moment arm. Depending on the location of the axis of rotation, the first-class lever can have an MA equal to, less than, or greater than one. Second-class levers always have an MA greater than one. As depicted in the boxes associated with Figure 1–22*A* and *B*, lever systems with an MA greater than one are able to balance the torque equilibrium equation by an internal (muscle) force that is *less than* the external force. Third-class levers always have an MA less than one. As depicted in Figure 1–22*C*, in order to balance the torque equilibrium equation, the muscle must produce a force much *greater than* the opposing external force.

Mechanical Advantage (MA) is equal to the Internal Moment Arm/External Moment Arm

- First-class levers may have an MA less than 1, equal to 1, or more than 1.
- Second-class levers always have an MA more than 1.
- Third-class levers always have an MA less than 1.

The majority of muscles throughout the musculoskeletal system function with a mechanical advantage of much *less than one*, and, actually, it may be more appropriate to call this a mechanical disadvantage! Consider, for example, the biceps at the elbow, the quadriceps at the knee, and the supraspinatus and deltoid at the shoulder. Each of these muscles attaches to bone relatively close to the joint's axis of rotation. The external forces that oppose the action of the muscles typically exert their influence considerably *distally* to the joint, such as at the hand or the foot. Consider the force demands placed on the supraspinatus and deltoid muscles to maintain the shoulder abducted to 90 degrees while holding an external weight of 35.6N (8 lb) in the hand. For the sake of this example, assume that the muscles have an internal moment arm of 2.5 cm (about 1 in) and that the center of mass of the external weight has an external moment arm of 50 cm (about 20 in). (For simplicity, the weight of the limb is ignored.) The 1/20 MA requires that the muscle would have to produce 711.7N (160 lb) of force, or *twenty times* the weight of the external load! As a general principle, skeletal muscles produce forces several times larger than the external loads that oppose them. Depending on the shape of the muscle and configuration of the joint, a certain percentage of the muscle force produces large compression or shear forces at the joint surfaces. Periarticular tissues, such as articular cartilage, fat pads, and bursa, must partially absorb or dissipate these large *myogenic (muscular-produced) forces*. In the absence of such protection, joints may partially degenerate and become painful and chronically inflamed. This presentation is the hallmark of severe osteoarthritis.

Dictating the "Trade-off" between Force and Distance

As previously described, most muscles are obligated to produce a force much greater than the resistance applied by the external load. At first thought, this design may appear flawed. The design is absolutely necessary, however, when the large distances and velocities experienced by the more distal points of the extremities are considered.

Work is the product of force times distance (see Chapter 4). In addition to converting a force to a torque, a musculoskeletal lever converts the work of a contracting muscle to the work of a rotating bone. The mechanical advantage of a musculoskeletal lever dictates how the work is converted—through either a relatively large force exerted over a short distance or a small force exerted over a large distance. Consider the small mechanical advantage of 1/20 described earlier for the supraspinatus and deltoid muscles. This mechanical advantage implies that the muscle must produce a force 20 times greater than the weight of the external load. What must also be considered, however, is that the muscles need to contract only 5% (1/20) the distance that the center of mass of the load would be raised by the abduction action. A very short contraction distance of the muscles produces a very large angular displacement of the arm.

Although all points throughout the abducting arm share the same *angular* displacement and velocity, the more distal points on the arm move at an even greater *linear* displacement and velocity. The ability of a short contraction range to generate large velocities of the limb may have an important physiologic advantage for the muscle. As explained in Chapter 3, a muscle produces its maximal force within only a relatively narrow range of its overall length.

In summary, most muscle and joint systems in the body function with a mechanical advantage of less than one. The muscles and underlying joints must, therefore, "pay the price" by generating and dispersing relative large forces, respectively, even for seemingly low-load activities. Obtaining a high linear velocity of the distal end of the extremities is a necessity for generating large contact forces against the environment. These high forces can be used to rapidly accelerate objects held in the hand, such as a tennis racket, or to accelerate the limbs purely as an expression of art and athleticism, such as dance.

SPECIAL FOCUS 1-4

Surgically Altering a Muscle's Mechanical Advantage: Dealing with the Trade-off

A surgeon may perform a muscle-tendon transfer operation as a means to partially restore the loss of internal torque at a joint. Consider, for example, complete paralysis of the elbow flexor muscles following poliomyelitis. Such a paralysis can have profound functional consequences, especially if it occurs bilaterally. One approach to restoring elbow flexion is to surgically reroute the fully innervated triceps tendon to the anterior side of the elbow (Fig. 1–23). The triceps, now passing anteriorly to the medial-lateral axis of rotation at the elbow, becomes a flexor instead of an extensor. The length of the internal moment arm for the flexion action can be exaggerated, if desired, by increasing the perpendicular distance between the transferred tendon and the axis of rotation. By increasing the muscle's mechanical advantage, the activated muscle produces a *greater torque per level of muscle force.* This may be a beneficial outcome, depending on the specific circumstances of the patient.

An important mechanical trade-off exists whenever a muscle's mechanical advantage is increased. Although a greater torque is produced per level muscle force, a given amount of muscle shortening results in a *reduced angular displacement of the joint.* As a result, a full muscle contraction may produce an ample torque, however, the joint may not complete its full range of motion. In essence, the active range of motion "lags" behind the muscle contraction. The reduced angular displacement and velocity of the joint may have negative functional consequences. This mechanical trade-off needs to be considered before the muscle's internal moment arm is surgically exaggerated. Often, the greater torque potential gained by increasing the moment arm functionally "outweighs" the loss of the speed and distance of the movement.

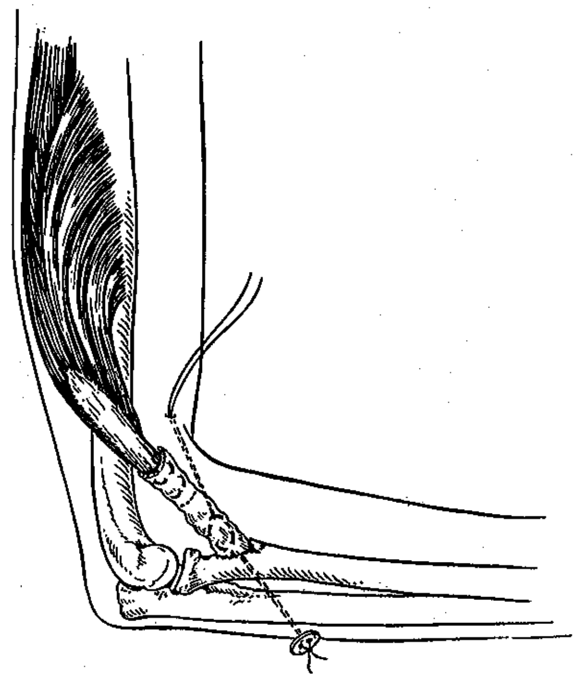


FIGURE 1–23. An anterior transfer of the triceps following paralysis of the elbow flexor muscles. The triceps tendon is elongated by a graft of fascia. (From Bunnell S: Restoring flexion to the paralytic elbow. J Bone Joint Surg 33A:566, 1951.)

GLOSSARY

Acceleration: change in velocity of a body over time, expressed in linear (m/s²) and angular (°/s²) terms.

Accessory movements: slight, passive, nonvolitional movements allowed in most joints (also called "joint play").

Active force: push or pull generated by stimulated muscle.

Active movement: motion caused by stimulated muscle.

Agonist muscle: muscle or muscle group that is most directly related to the initiation and execution of a particular movement.

Angle-of-insertion: angle formed between a tendon of a muscle and the long axis of the bone to which it inserts.

Antagonist muscle: muscle or muscle group that has the action opposite to a particular agonist muscle.

Arthrokinematics: motions of roll, slide, and spin that occur between the articular surfaces of joints.

Axis of rotation: an imaginary line extending through a joint about which rotation occurs (also called the piv point or the center of rotation).

Axial rotation: angular motion of an object in a directic perpendicular to its longitudinal axis, often used to d scribe a motion in the horizontal plane.

Bending: effect of a force that deforms a material at rigl angles to its long axis. A bent tissue is compressed on i concave side and placed under tension on its convex sid A bending moment is a quantitative measure of a ben Similar to a torque, a bending moment is the product the bending force and the perpendicular distance betwee the force and the axis of rotation of the bend.

Center of mass: point at the exact center of an objec mass (also referred to as center of gravity when conside ing the weight of the mass).

Close-packed position: unique position within most join of the body where the articular surfaces are most congr ent, and the ligaments are maximally taut.

Compression: application of one or more forces that press an object or objects together. Compression tends to shorten and widen a material.

Concentric activation: activated muscle that shortens as it produces a force.

Creep: a progressive strain of a material when exposed to a constant load over time.

Degrees of freedom: number of independent movements allowed at a joint. A joint can have up to three degrees of translation and three degrees of rotation.

Displacement: change in the linear or angular position of an object.

Distal-on-proximal segment kinematics: type of movement in which the distal segment of a joint rotates relative to a fixed proximal segment (also called an open kinematic chain).

Distraction: movement of two objects away from one another.

Eccentric activation: activated muscle that is elongating as it produces a force.

Elasticity: property of a material demonstrated by its ability to return to its original length after the removal of a deforming force.

External force: push or pull produced by sources located outside the body. These typically include gravity and physical contact applied against the body.

External moment arm: distance between the axis of rotation and the perpendicular intersection with an external force.

External torque: product of an external force and its external moment arm (also called external moment).

Force: a push or a pull that produces, arrests, or modifies a motion.

Force-couple: interaction of two or more muscles acting in different linear directions, but producing a torque in the same rotary direction.

Force of gravity: potential acceleration of a body to the center of the earth due to gravity.

Friction: resistance to movement between two contacting surfaces.

Internal force: push or pull produced by a structure located within the body. Most often internal force refers to that produced by an active muscle.

Internal moment arm: distance between the axis of rotation and the perpendicular intersection with a muscle (internal) force.

Internal torque: product of an internal force and its internal moment arm.

Isometric activation: activated muscle that maintains a constant length as it produces a force.

Joint reaction force: push or pull produced by one joint surface against another, usually for the purpose of maintaining static linear equilibrium of a joint and associated bones.

Kinematics: branch of mechanics that describes the motion of a body, without regard to the forces or torques that may produce the motion.

Kinematic chain: series of articulated segmented links, such as the connected pelvis, thigh, leg, and foot of the lower extremity.

Kinetics: branch of mechanics that describes the effect of forces on the body.

Leverage: relative moment arm length possessed by a particular force.

Line-of-force: direction of a muscle's force.

Line-of-gravity: direction of the gravitational pull on a body.

Load: general term that describes the application of a force to a body.

Longitudinal axis: axis that extends within and parallel to a long bone or body segment.

Loose-packed positions: places within most joints of the body where the articular surfaces are least congruent, and the ligaments are slackened.

Mass: quantity of matter in an object.

Mechanical advantage: ratio of the internal moment arm to the external moment arm.

Muscle action: potential of a muscle to produce an internal torque within a particular plane of motion and rotary direction (also called *joint action* when referring specifically to a muscle's potential to rotate a joint). Terms that describe a muscle action are flexion, extension, pronation, supination, and so forth.

Osteokinematics: motion of bones relative to the three cardinal, or principal, planes.

Passive force: push or pull generated by sources other than stimulated muscle, such as tension in stretched periarticular connective tissues, physical contact, and so forth.

Passive movement: motion produced by a source other than activated muscle.

Plasticity: property of a material demonstrated by remaining permanently deformed after the removal of a force.

Pressure: force divided by a surface area (also called stress).

Productive antagonism: phenomenon in which relatively low-level tension within stretched connective tissues performs a useful function.

Proximal-on-distal segment kinematics: type of movement in which the proximal segment of a joint rotates relative to a fixed distal segment (also referred to as a closed kinematic chain).

Roll: multiple points along one rotating articular surface contact multiple points on another articular surface. (Also called rock.)

Rotation: angular motion in which a rigid body moves in a circular path about a pivot point or an axis of rotation.

Scalar: quantity, such as speed and temperature, that is completely specified by its magnitude and has no direction.

Segment: any part of a body or limb.

Shear: forces on a material that act in opposite but parallel directions (like the action of a pair of scissors).

Shock absorption: ability to dissipate forces.

Slide: single point on one articular surface contacts multiple points on another articular surface. (Also called glide.)

Spin: single point on one articular surface rotates on a single point on another articular surface (like a toy top).

Static linear equilibrium: state of a body at rest in which the sum of all forces is equal to zero.

Static rotary equilibrium: state of a body at rest in which the sum of all torques is equal to zero.

Stiffness: ratio of stress (force) to strain (elongation) within an elastic material.

Strain: ratio of a tissue's deformed length to its original length.

Stress: force generated as a tissue resists deformation, divided by its cross-sectional area (also called pressure).

Synergists: two muscles that cooperate to execute a particular movement.

Tension: application of one or more forces that pulls apart or separates a material. (Also called a distraction force.) Used to denote the internal stress within a tissue as it resists being stretched.

Torsion: application of a force that twists a material about its longitudinal axis.

Translation: linear motion in which all parts of a rigid body move parallel to and in the same direction as every other point in the body.

Vector: quantity, such as velocity or force, that is completely specified by its magnitude and direction.

Velocity: change in position of a body over time, expressed in linear (m/s) and angular (degrees/s) terms.

Viscoelasticity: property of a material expressed by a changing stress-strain relationship over time.

Weight: gravitational force acting on a mass.

SUMMARY

Many of the basic biomechanical principles and essential terms and concepts used to communicate the subject matter of kinesiology are provided. Chapters 2 to 4 give additional background on the essential topics of kinesiology. This material then sets the foundation for the more anatomic-based chapters, starting with the shoulder complex in Chapter 5.

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