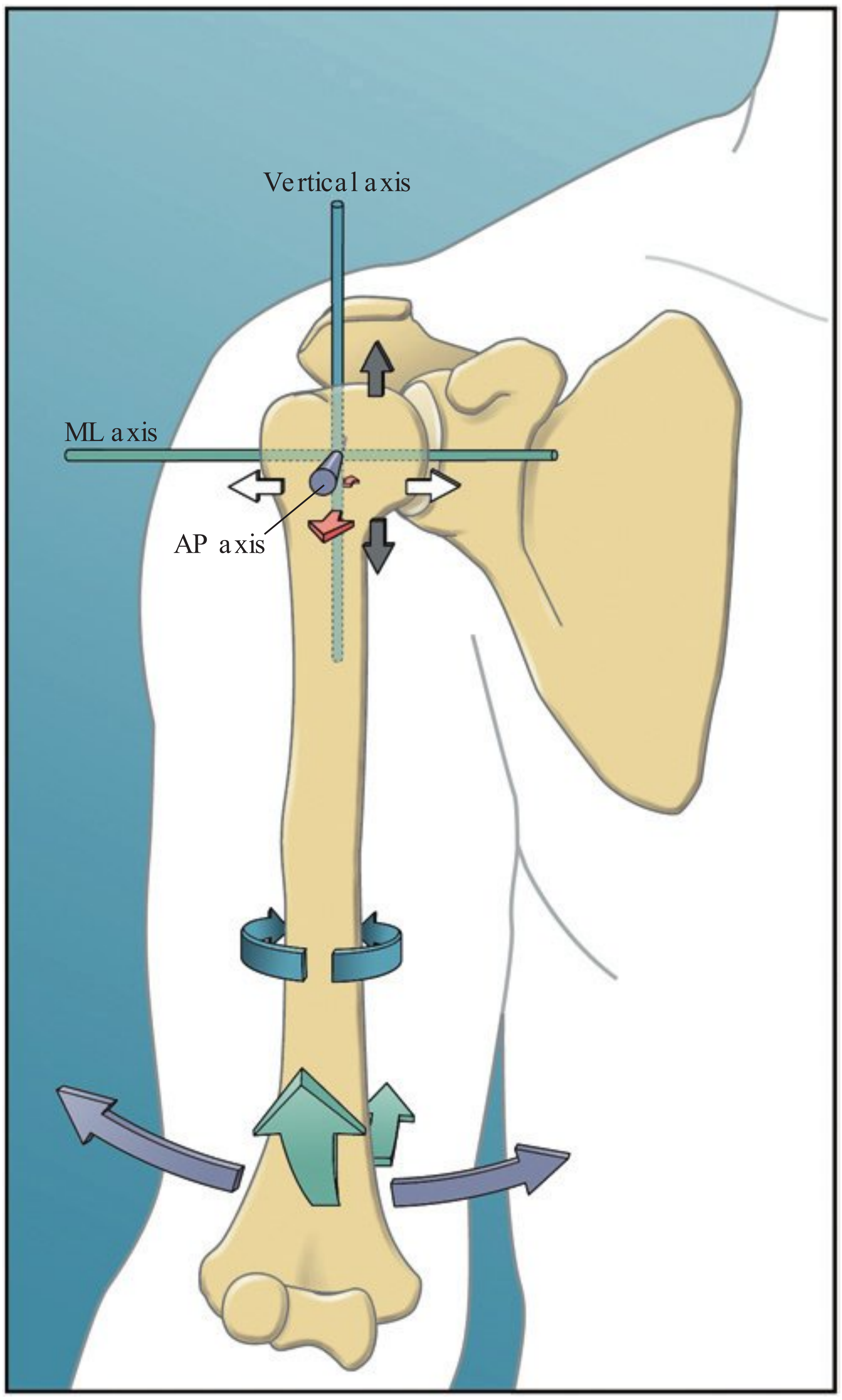


FIG. 1.5 The right glenohumeral (shoulder) joint highlights three orthogonal axes of rotation and associated planes of angular motion: flexion and extension *(green curved arrows)* occur around a medial-lateral *(ML)* axis of rotation; abduction and adduction *(purple curved arrows)* occur around an anterior-posterior *(AP)* axis of rotation; and internal rotation and external rotation *(blue curved arrows)* occur around a vertical axis of rotation. Each axis of rotation is color-coded with its associated plane of movement. The short, 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.)

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 apply to translational (linear) as well as angular movements. All synovial joints in the body possess at least some translation, driven actively by muscle or passively because of the natural laxity within the structure of the joint. The slight passive translations that occur in most joints are referred to as *accessory movements* (or joint "play") and are commonly defined in three linear directions. From the anatomic position, the spatial orientation and direction of accessory movements can be described relative to the three axes of rotation. In the relaxed glenohumeral joint, for example, the humerus can be passively translated slightly: anterior-posteriorly, medial-laterally, and superior-inferiorly (see short, straight arrows near proximal humerus in Fig. 1.5). At many joints, the amount of translation is used clinically to test the health of the joint. Excessive translation of a bone relative to the joint may indicate ligamentous injury or abnormal laxity. In contrast, a significant reduction in translation (accessory movements) may indicate pathologic stiffness within the surrounding periarticular connective tissues. Abnormal translation within a joint typically affects the quality of the active movements, potentially causing increased intra-articular stress and microtrauma.

OSTEOKINEMATICS: A MATTER OF PERSPECTIVE

In general, the articulation of two or more bony or limb segments constitutes 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. (In reality, both perspectives can and often do occur simultaneously; although for ease of discussion and analysis, this situation is often omitted within this text.) The two kinematic perspectives are shown for knee flexion in Fig. 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 rotating segment. As in Fig. 1.6, for example, the terms *tibial-on-femoral movement* and *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, gravity, or its inertia, whereas the distal, relatively unconstrained, segment rotates.

Feeding oneself and throwing a ball are 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 one performs a pull-up.

The lower extremities routinely perform both proximal-on-distal *and* distal-on-proximal 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. Flexing the knee in preparation to kick a ball, for example, is a type of distal-on-proximal segment kinematics (see Fig. 1.6A). Descending into a squat position, in contrast, is an example of proximal-on-distal segment kinematics (see Fig. 1.6B). In the latter 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 chains* are frequently used in the physical rehabilitation literature and clinics to describe the concept of relative segment kinematics. 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 another immovable object. The distal segment therefore is free to move (see Fig. 1.6A).

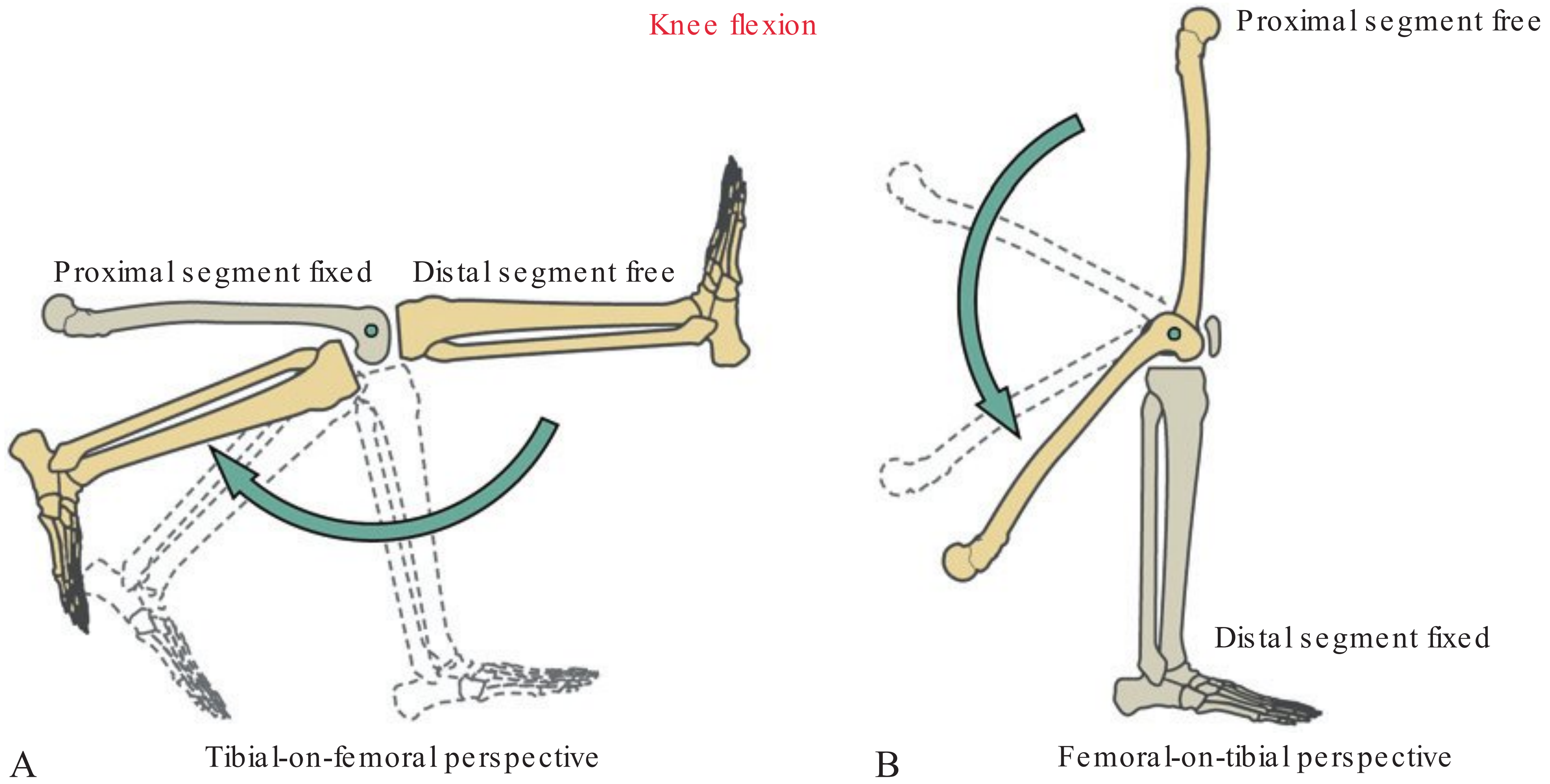


FIG. 1.6 Sagittal plane osteokinematics at the knee show an example of (A) distal-on-proximal segment kinematics and (B) proximal-on-distal segment kinematics. The axis of rotation is shown as a circle at the knee.

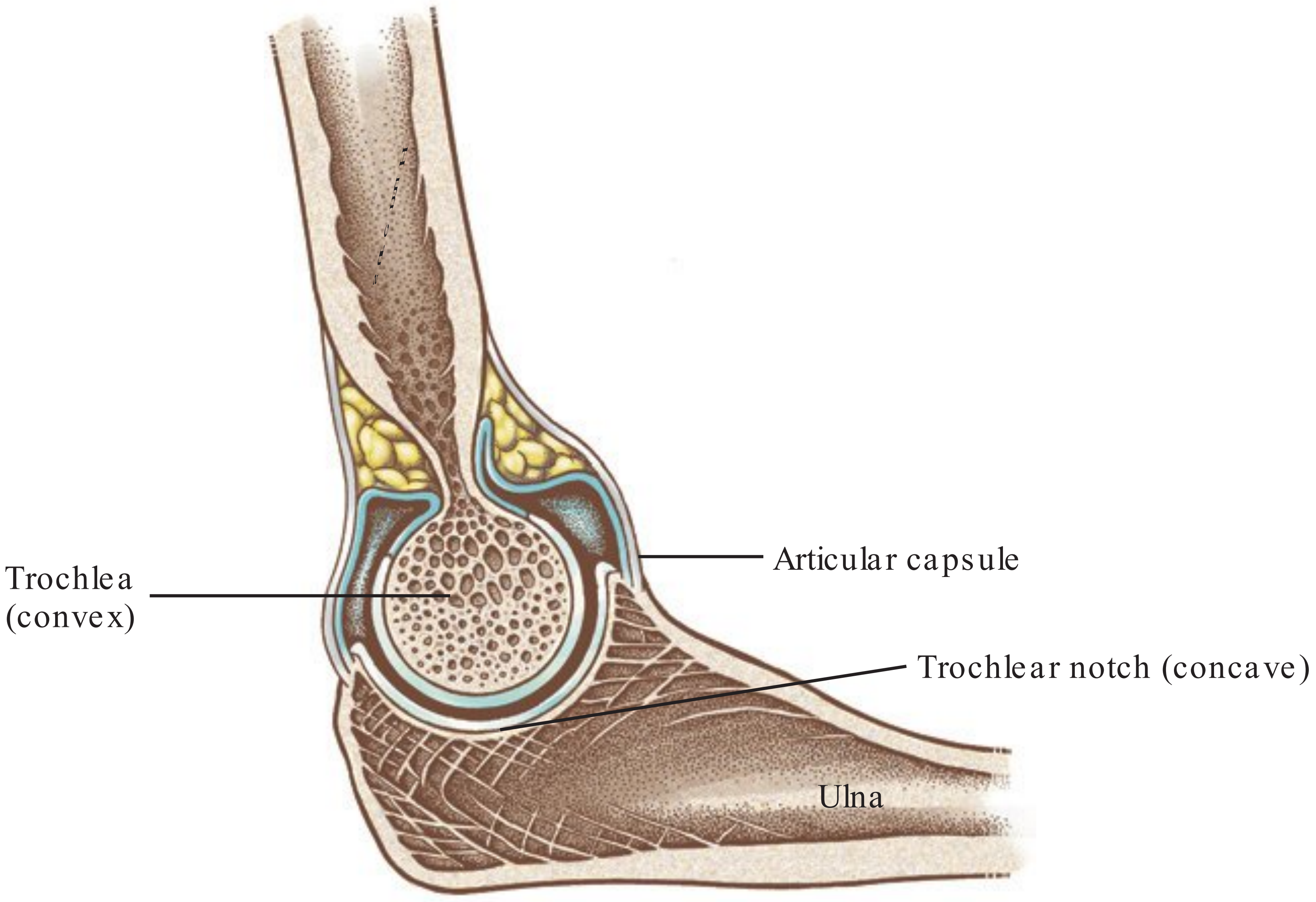


FIG. 1.7 The humero-ulnar joint at the elbow is an example of a convex-concave relationship between two articular surfaces. The trochlea of the humerus is convex, and the trochlear notch of the ulna is concave.

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 segment is free to move (see Fig. 1.6B). These terms are employed extensively to describe methods of applying resistive exercise to muscles, especially to the joints of the lower limb.

Although very convenient terminology, the terms *open* and *closed kinematic chains* are often ambiguous. From a strict engineering perspective, the terms 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 or 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.

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 at least slightly curved, with one surface being relatively convex and one relatively concave (Fig. 1.7). The convex-concave relationship of most articulations improves their congruency (fit), increases the surface area for dissipating contact forces, and helps guide the motion between the bones.

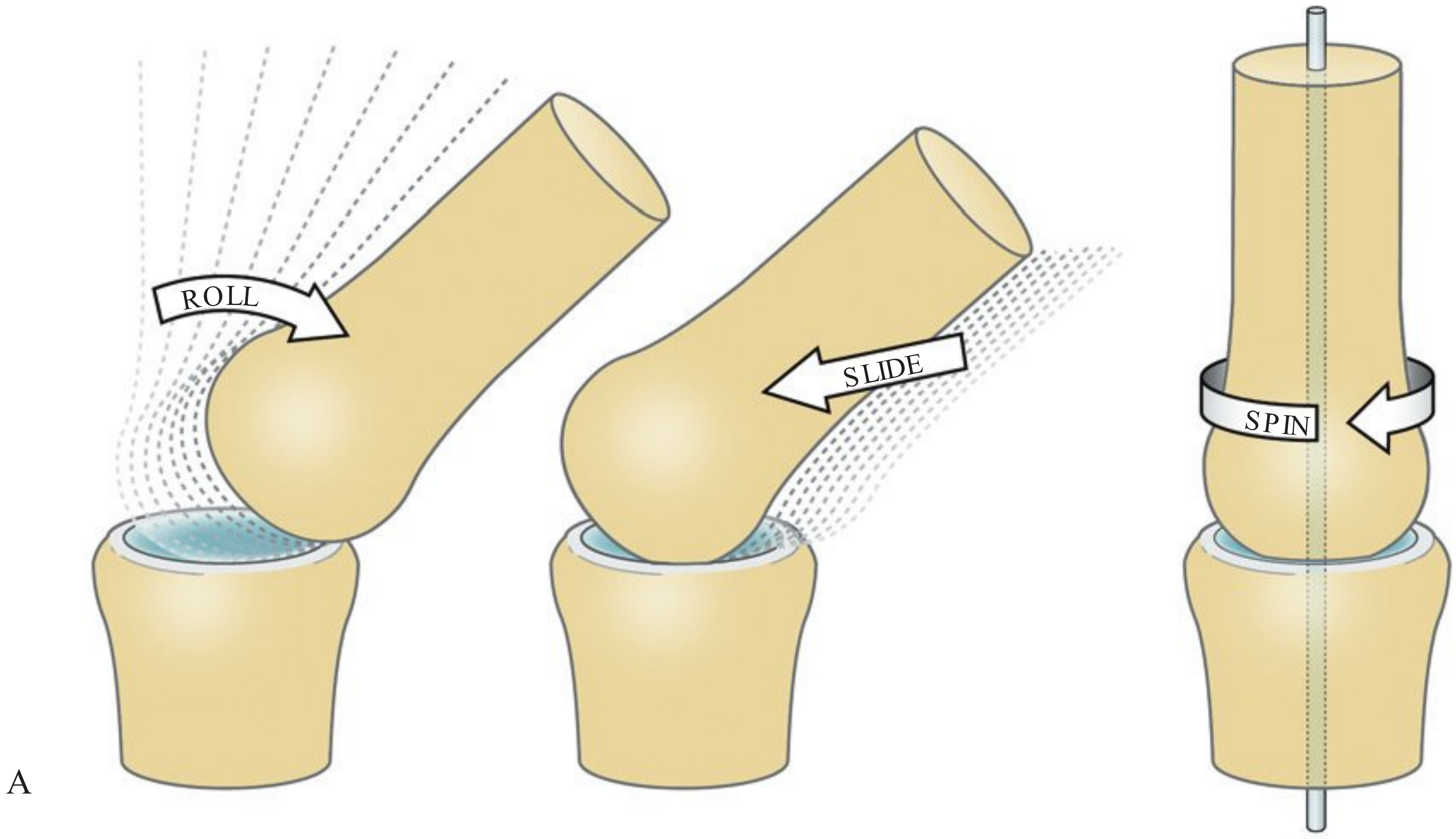
FUNDAMENTAL MOVEMENTS BETWEEN JOINT SURFACES

Three fundamental movements exist between curved joint surfaces: roll, slide, and, spin. 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

Convex-on-concave arthrokinematics



Concave-on-convex arthrokinematics

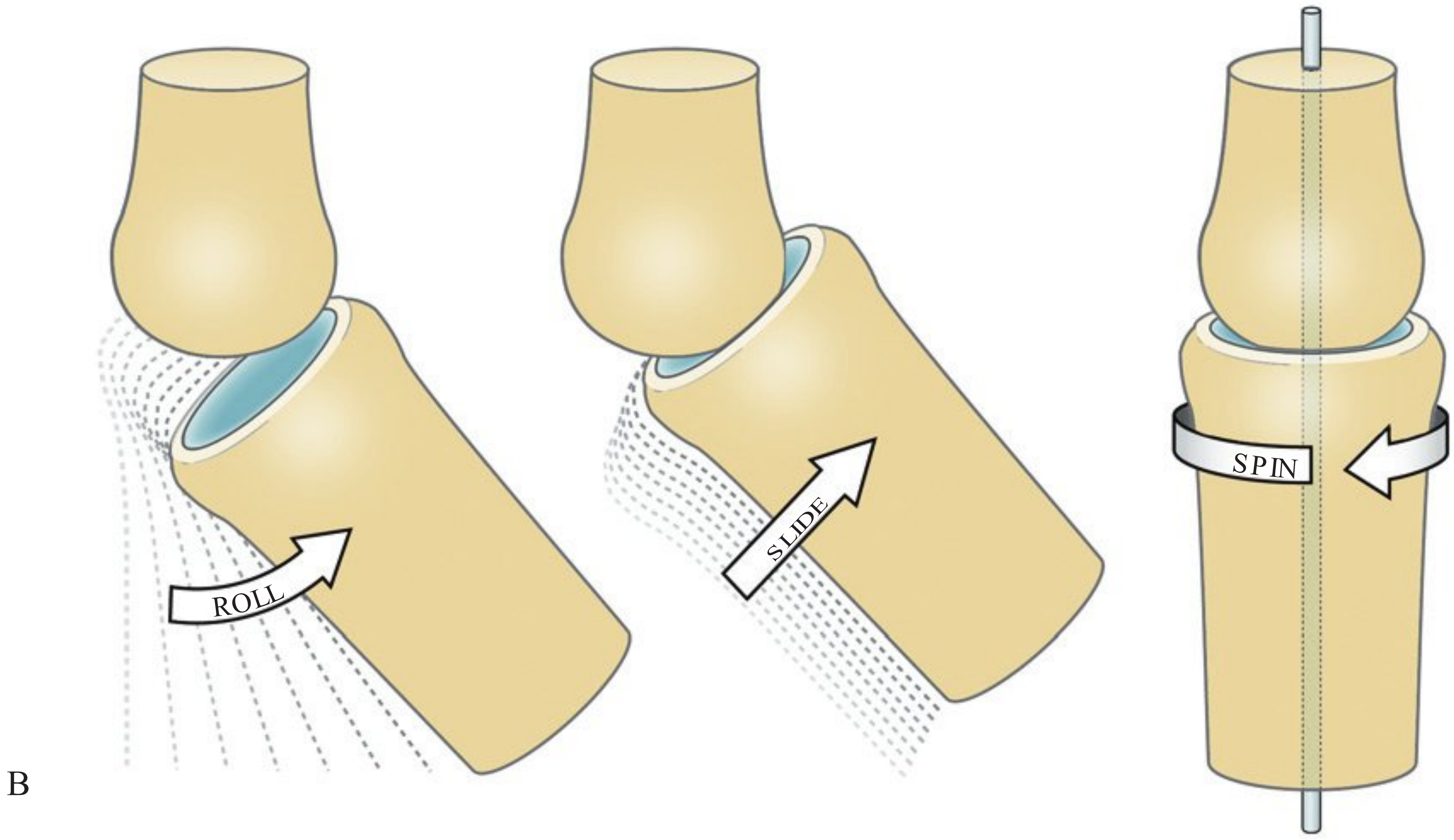


FIG. 1.8 Three fundamental arthrokinematics that occur between curved joint surfaces: roll, slide, and spin. A, Convex-on-concave movement. B, Concave-on-convex movement.

SPECIAL FOCUS 1.3

Muscle-Produced Torques across a Joint: An Essential Concept in Kinesiology

How muscles produce torques across joints is one of the most important (and often difficult) concepts to understand in kinesiology. An understanding of this concept can be helped by considering a simple analogy between a muscle's potential to produce a torque (i.e., rotation) and the action of a force attempting to swing open a door. The essential mechanics in both scenarios are surprisingly similar. This analogy is described with the assistance of Fig. 1.18A–B.

Fig. 1.18A shows top and side views of a door mounted on a vertical hinge (depicted in blue). Horizontally applied forces

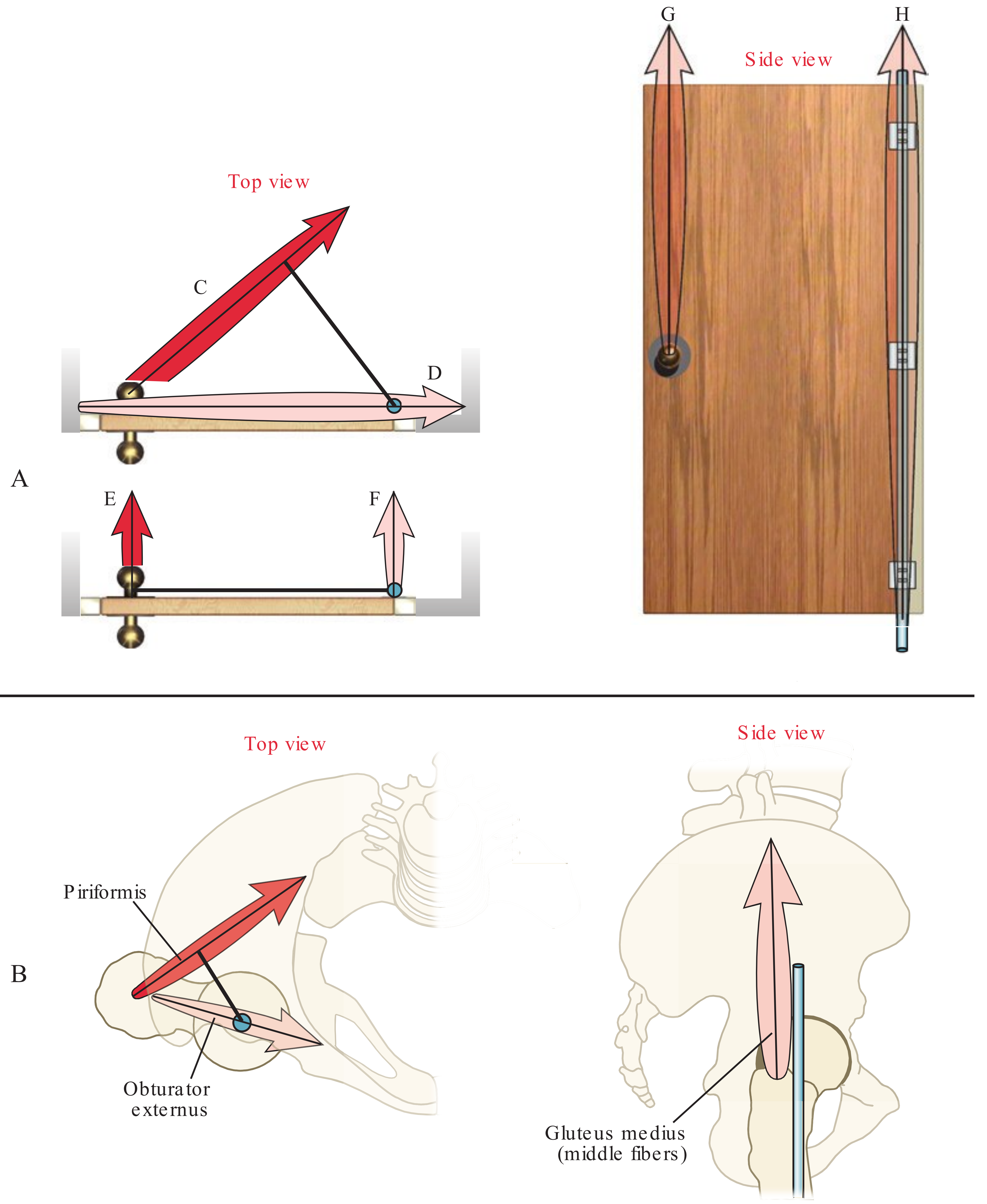


FIG. 1.18 Mechanical analogy depicting the fundamental mechanics of how a force can be converted into a torque. A, Six manually applied forces are indicated *(colored arrows),* each attempting to rotate the door in the horizontal plane. The vertical hinge of the door is shown in blue. The moment arms available to two of the forces (on the left) are indicated by dark black lines, originating at the hinge. B, Three muscle-produced forces are depicted *(colored arrows),* each attempting to rotate the femur (hip) in the horizontal plane. The axes of rotation are shown in blue, and the moment arm as a dark black line. As described in the text, for similar reasons, only a selected number of forces is actually capable of generating a torque that can rotate either the door or the hip. For the sake of this analogy, the magnitude of all forces is assumed to be the same.

SPECIAL FOCUS 1.3

Muscle-Produced Torques across a Joint: An Essential Concept in Kinesiology—cont'd

(C to F) represent different attempts at manually pulling open the door. Although all forces are assumed equal, only forces C and E (applied at the doorknob) are actually capable of rotating the door. This holds true because only these forces meet the basic requirements of producing a torque: (1) each force is applied in a plane perpendicular to the given axis of rotation (hinge in this case), and (2) each force is associated with a moment arm distance (dark black line originating at the hinge). In this example the torque is the product of the pulling force times its moment arm. Force E will produce a greater torque than force C because it has the longer moment arm (or greater leverage). Nevertheless, forces C and E both satisfy the requirement to produce a torque in the horizontal plane.

Forces D and F, however, cannot produce a torque within the horizontal plane and therefore are not able to rotate the door, regardless of their magnitude. Although this may seem intuitively obvious based on everyone's experience closing or opening doors, the actual mechanical reasoning may not be so clear. Forces D and F are directed through the axis of rotation (the hinge in this case) and therefore have a zero moment arm distance. Any force multiplied by a zero moment arm produces zero torque, or zero rotation. Although these forces may compress or distract the hinge, they will not rotate the door.

Forces G and H, shown at the right in Fig. 1.18A, also cannot rotate the door. Any force that runs parallel with an axis of rotation cannot produce an associated torque. A torque can be generated only by a force that is applied perpendicular to a given axis of rotation. Forces G and H therefore possess no ability to produce a torque in the horizontal plane.

To complete this analogy, Fig. 1.18B shows two views of the hip joint along with three selected muscles. In this example the muscles are depicted as producing forces in attempt to rotate the femur within the horizontal plane. (The muscle forces in these illustrations are analogous to the manually applied forces applied to the door.) The axis of rotation at the hip, like the hinge on the door, is in a vertical direction (shown in blue). As will be explained, even though all the muscles are assumed to produce an identical force, only one is capable of actually rotating the femur (i.e., producing a torque).

The force vectors illustrated on the left side of Fig. 1.18B represent the lines of force of two predominantly horizontally aligned muscles at the hip (the piriformis and obturator externus). The piriformis is capable of producing an external rotation torque within the horizontal plane for the same reasons given for the analogous force C applied to the door (Fig. 1.18A). Both forces are applied in a plane perpendicular to the axis of rotation, and each possesses an associated moment arm distance (depicted as the dark line). In sharp contrast, however, the obturator externus muscle cannot produce a torque in the horizontal plane. This muscle force (as with the analogous force D acting on the door) passes directly through the vertical axis of rotation. Although the muscle force will compress the joint surfaces, it will not rotate the joint, at least not in the horizontal plane. As will be described in Chapter 12, which studies the hip, changing the rotational position of the joint often creates a moment arm distance for a muscle. In this case the obturator externus may generate external rotation torque at the hip, although relatively small.

The final component of this analogy is illustrated on the right of Fig. 1.18B. The middle fibers of the gluteus medius are shown attempting to rotate the femur in the horizontal plane around a vertical axis of rotation (depicted as a blue pin). Because the muscle force acts essentially parallel with the vertical axis of rotation (like forces G and H acting on the door), it is incapable of generating a torque in the horizontal plane. This same muscle, however, is very capable of generating torque in other planes, especially the frontal.

To summarize, a muscle is capable of producing a torque (or rotation) at a joint only provided it (1) produces a force in a plane perpendicular to the axis of rotation of interest, and (2) acts with an associated moment arm distance greater than zero. Stated from a different perspective, an active muscle is incapable of producing a torque if the force either pierces or parallels the associated axis of rotation. This applies to all axes of rotation that may exist at a joint: vertical, anterior-posterior (AP), or medial-lateral (ML). These principles will be revisited many times throughout this textbook

Muscle and Joint Interaction

The term *muscle and joint interaction* refers to the overall effect that a muscle force may have on a joint. 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 will not cause a torque or a rotation. The muscle force is still important, however, because it usually provides a source of stability and sensory information to the joint.

TYPES OF MUSCLE ACTIVATION

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

Isometric activation occurs when a muscle is producing a pulling 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 within a given plane at a joint is equal to the external torque; hence, there is no muscle shortening or rotation at the joint (Fig. 1.19A).

Concentric activation occurs as a muscle produces a pulling force as it contracts (shortens) (see Fig. 1.19B). Literally, *concentric* means "coming to the center." During a concentric activation, the

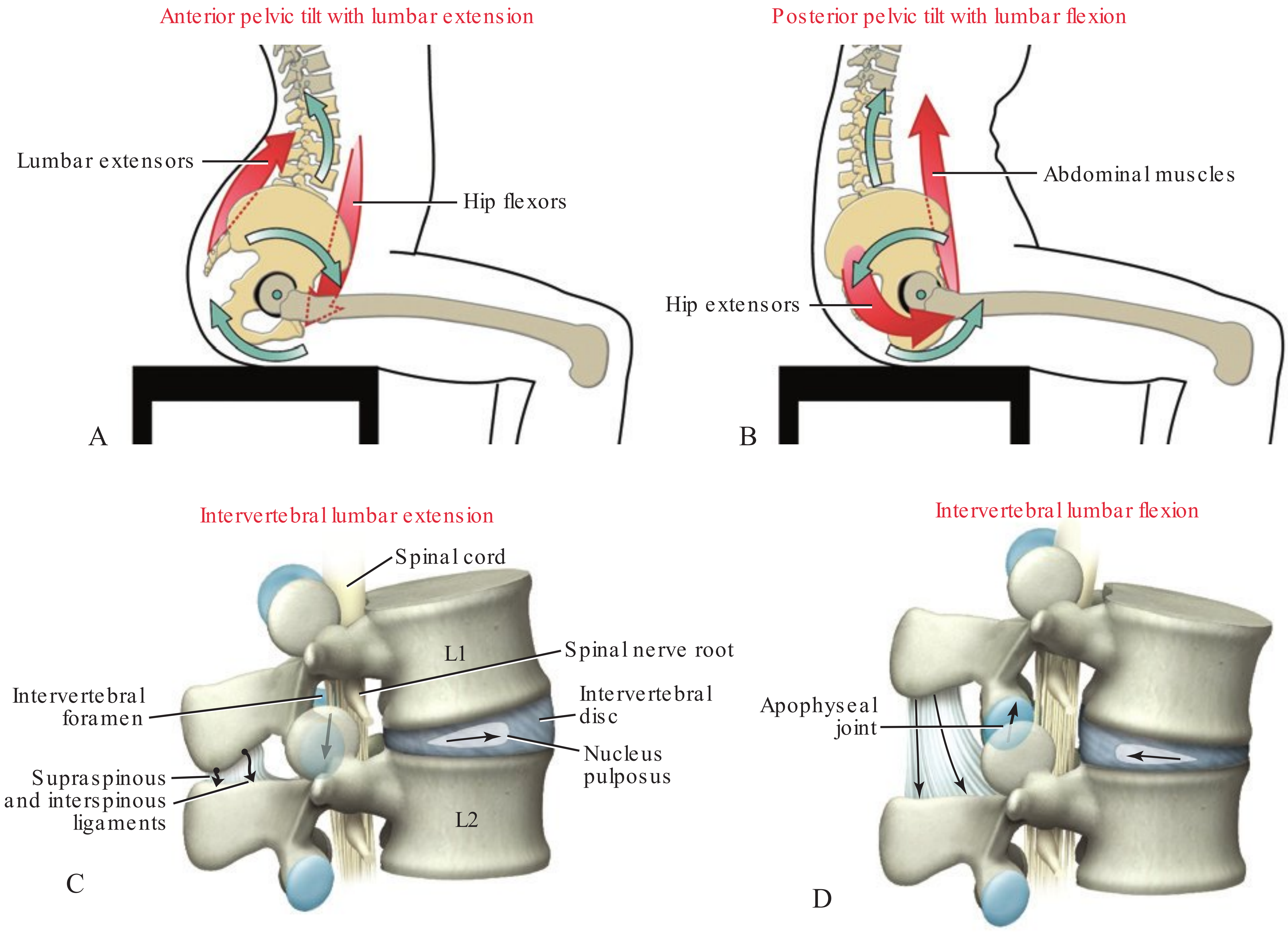


FIG. 9.63 Anterior and posterior tilting of the pelvis and its effect on the kinematics of the lumbar spine. (A and C) *Anterior pelvic tilt* extends the lumbar spine and increases the lordosis. This action tends to shift the nucleus pulposus anteriorly and reduces the diameter of the intervertebral foramen. (B and D) *Posterior pelvic tilt* flexes the lumbar spine and decreases the lordosis. This action tends to shift the nucleus pulposus posteriorly and increases the diameter of the intervertebral foramen. Muscle activity is shown in red.

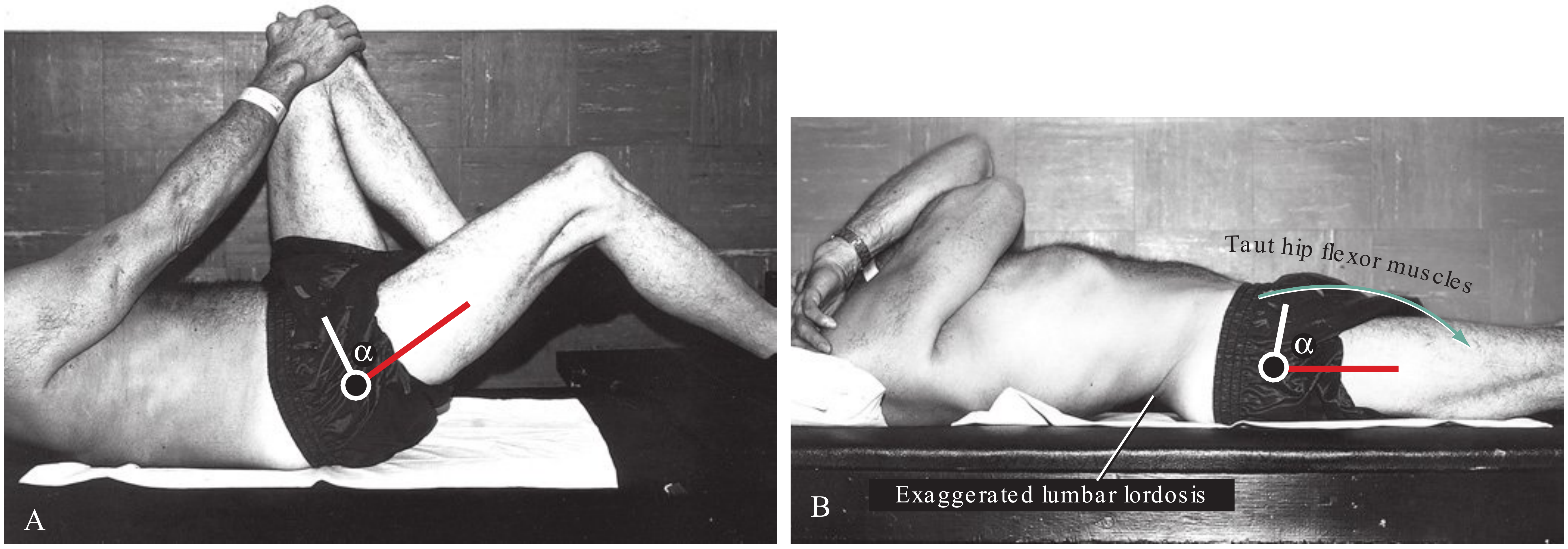


FIG. 9.64 The relationship between taut hip flexor muscles, excessive anterior pelvic tilt, and exaggerated lumbar lordosis in a person with marked right hip osteoarthritis. The medial-lateral axis of rotation of the hip is shown as an open white circle. (A) A right hip flexion contracture is shown by the angle (α) formed between the femur *(red line)* and a *white line* representing the iliac crest of the pelvis. The left normal hip is held flexed to keep the pelvis as posteriorly tilted as possible. (B) With both legs allowed to lie against the mat, tension created in the taut and shortened right hip flexors tilts the pelvis anteriorly, exaggerating the lumbar lordosis. The increased lordosis is evident by the hollow in the low back region. The hip flexion contracture is still present but is masked by the anteriorly tilted position of the pelvis. (Photograph from the archives of the late Mary Pat Murray, PT, PhD, FAPTA, Marquette University.)

SPECIAL FOCUS 9.8

More about the Herniated Nucleus Pulposus

The formal name for a herniated or prolapsed disc is a herniated nucleus pulposus. Herniations typically involve a posterior-lateral or posterior migration of the nucleus pulposus toward the very sensitive neural tissues (i.e., the spinal cord, cauda equina, ventral or dorsal nerve roots, or exiting spinal nerve roots). In vivo research strongly suggests that the herniated material is not just the nucleus but also fragments of dislodged vertebral endplates.[190] The term herniated nucleus pulposus (or disc) therefore may not be totally correct. However, because the term is so well embedded in the literature it will be used throughout this chapter.

Not all herniated discs are as remarkable as that illustrated in Fig. 9.60. In relatively mild cases the displaced nucleus migrates posteriorly but remains well within the confines of the annulus fibrosus. More moderate cases, however, may progress to a point at which the nuclear material, although still remaining within the posterior annulus, bulges or protrudes beyond the circumference of the posterior rim of the vertebral body. In more severe cases this nuclear material completely herniates through the annular wall (or posterior longitudinal ligament) and extrudes into the epidural space (depicted in Fig. 9.60). In some cases the extruded material may become lodged in the epidural space—frequently referred to as sequestration of the herniated disc. Extruded or sequestered herniations may have a better prognosis than a protruded or bulging disc. Once displaced into the spinal canal, the herniated nucleus attracts macrophages that can assist with resorption of the displaced material.[112] Even a small amount of resorption can significantly reduce the mechanical pressure placed on the neural tissues. This mechanism may partially explain why, in some persons, pain associated with a herniated disc may resolve over time without surgical intervention.

Disc-related pain may result from the degenerated disc itself or from consequences of a herniated nucleus pulposus. Pain associated with a degenerated disc may be from damage to the innervated periphery of the posterior annulus fibrosus, posterior longitudinal ligament, or vertebral endplates. Perhaps more serious, however, is the pain and radiculopathy caused by the herniated disc compressing the neural tissues within the spinal canal (as seen in Fig. 9.60). In both scenarios, pain increases when the local tissues are swollen and inflamed.[135] If compressed, the inflamed nerves within the spinal canal or intervertebral foramina typically produce pain and altered sensations that are topographically associated with the dermatomes in the lower extremities. The symptoms are often referred to as "sciatica" because of the strong likelihood that the herniated disc affects nerve roots that ultimately form the sciatic nerve (L^4–S^3). Although pain may be a large component of a herniated nucleus pulposus, it is not a universal consequence of the pathology.[27]

Posterior disc herniation in the lumbar region typically involves two often interrelated mechanisms. The first involves a large, sudden compression or shear force delivered against an otherwise relatively healthy lumbar spine. This mechanism of injury may be associated with a single traumatic event, such as extremely strenuous coughing or vomiting[178] or the lifting or carrying of large loads.[196] A second and much more common mechanism involves a series of lower-magnitude forces delivered against the lumbar spine over the course of several years, most often involving preexisting disc degeneration.[73,254] A degenerated disc may possess radial clefts (or fissures) that serve as a path of least resistance for the migration of the nuclear material.

Repetitive or chronic flexion of the lumbar spine very likely increases the vulnerability of a posterior or posterior-lateral disc herniation. Flexion stretches and thins the posterior side of the annulus while the nuclear gel is forced posteriorly, often under high hydrostatic pressure. These pressures increase during strenuous lifting or bending activities that require strong activation of trunk muscles.[157,205] With sufficiently high hydrostatic pressure, the nuclear gel can create or find a preexisting fissure in the posterior annulus.

Lumbar flexion combined with a twisting motion (i.e., axial rotation combined with lateral flexion) further increases the vulnerability of a posterior or posterior-lateral disc herniation.[62,190] When the spine is rotated, only half the posterior fibers of the annulus are taut, reducing its resistance to the approaching nuclear gel. Computer modeling and cadaveric research have also shown that combined axial rotation and lateral flexion concentrate large circumferential tensions in the annular fibers located within the posterior-lateral quadrant of the disc.[205,234] Over time, this region is more prone to develop fissures or cracks, thereby providing little resistance to the encroaching nuclear material.

It has been argued that a severely degenerated (and dehydrated) disc seldom experiences the classic herniated nucleus pulposus.[30] Apparently, a dehydrated nucleus is too dry and not under sufficient hydrostatic pressure to flow through the annulus. Although exceptions certainly exist, the classic herniated nucleus pulposus tends to occur more frequently in persons younger than age 40 years, at a time when the nucleus is still able to retain a relatively large volume of water. Furthermore, the chance of experiencing a herniated disc tends to be greater in the morning, when the nucleus contains its greatest daily water content.[12,137]

MECHANICAL OR STRUCTURAL FACTORS THAT FAVOR A HERNIATED NUCLEUS PULPOSUS IN THE LUMBAR SPINE

1. Preexisting disc degeneration with radial fissures, cracks, or tears in the posterior annulus that allow a path for the flow of nuclear material
2. Sufficiently hydrated nucleus capable of exerting high intradiscal pressure
3. Inability of the posterior annulus to resist pressure from the migrating nucleus
4. Sustained or repetitive loading applied over a flexed and rotated (twisted) spine

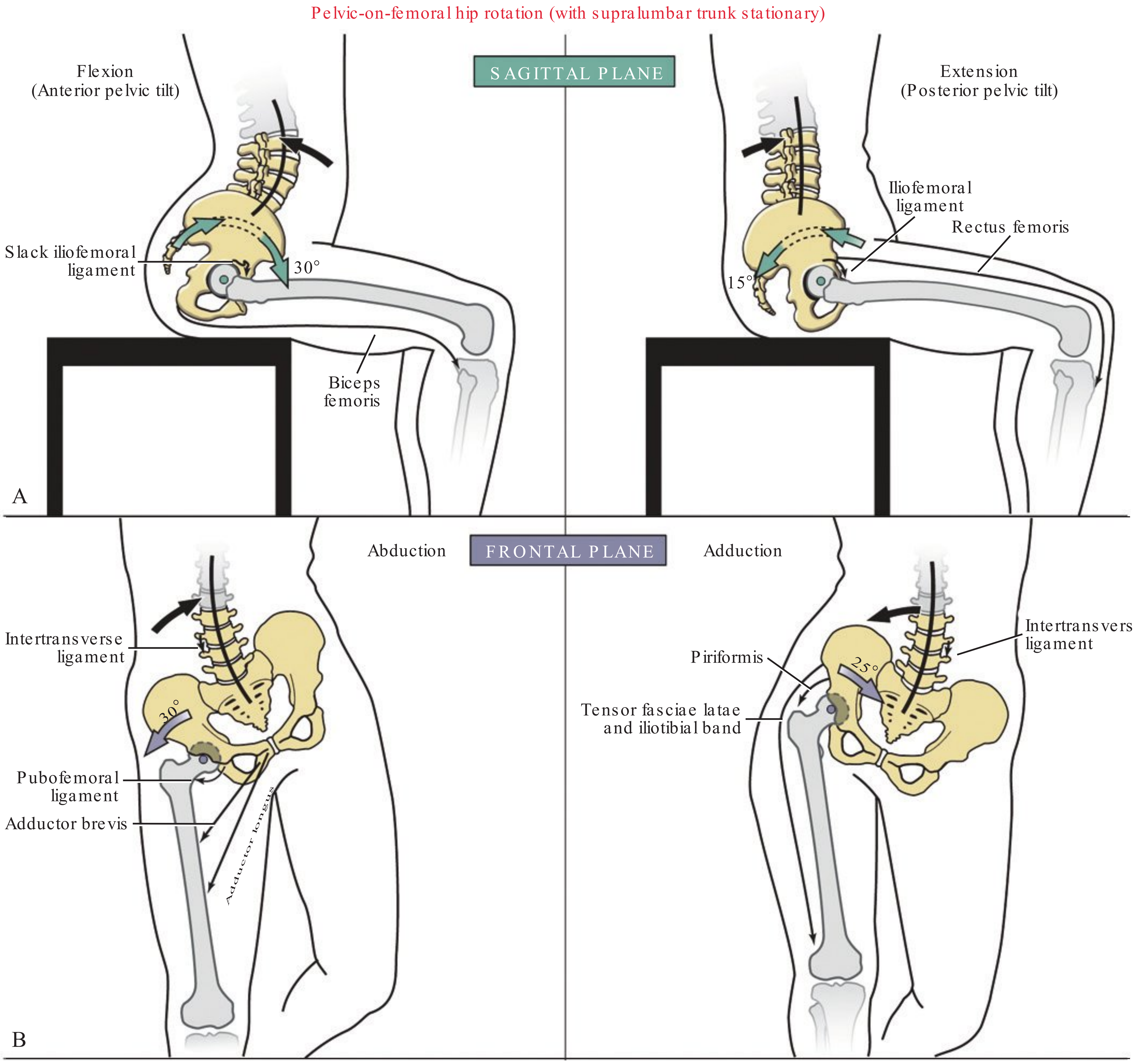


FIG. 12.22 The near maximal range of *pelvic-on-femoral* (hip) motion is shown in the sagittal plane (A) and frontal plane (B). The motion assumes that the supralumbar trunk remains nearly stationary during the hip motion (i.e., kinematics based on a *contradirectional* lumbopelvic rhythm). The large colored and black arrows depict pelvic rotation and the associated "offsetting" lumbar motion. Tissues that are elongated or pulled taut are indicated by thin, straight black arrows; tissue slackened is indicated by thin wavy black arrow.

Continued

Abduction of the support hip occurs by raising or "hiking" the iliac crest on the side of the nonsupport hip (see Fig. 12.22B). Assuming that the supralumbar trunk remains nearly stationary, the lumbar spine must bend in the direction opposite the rotating pelvis. The lumbar region thus forms a slight lateral convexity toward the side of the abducting hip.

Pelvic-on-femoral hip abduction is restricted to about 30 degrees, primarily because of the natural limits of lateral bending in the lumbar spine. Marked tightness in the ipsilateral adductor muscles or in the pubofemoral ligament can limit pelvic-on-femoral hip abduction. If a marked adductor contracture is present, the iliac crest on the side of the nonsupport hip may remain *lower* than the iliac crest of the support hip, which can interfere with walking.

Adduction of the support hip occurs by a *lowering* of the iliac crest on the side of the nonsupport hip. This motion produces a slight lateral concavity within the lumbar region toward the side of the adducted hip (see right side of Fig. 12.22B). A hypomobile or painful lumbar spine and/or reduced extensibility in the iliotibial band or hip abductor muscles, such as the gluteus medius, piriformis, or tensor fasciae latae, may restrict the extremes of this motion.

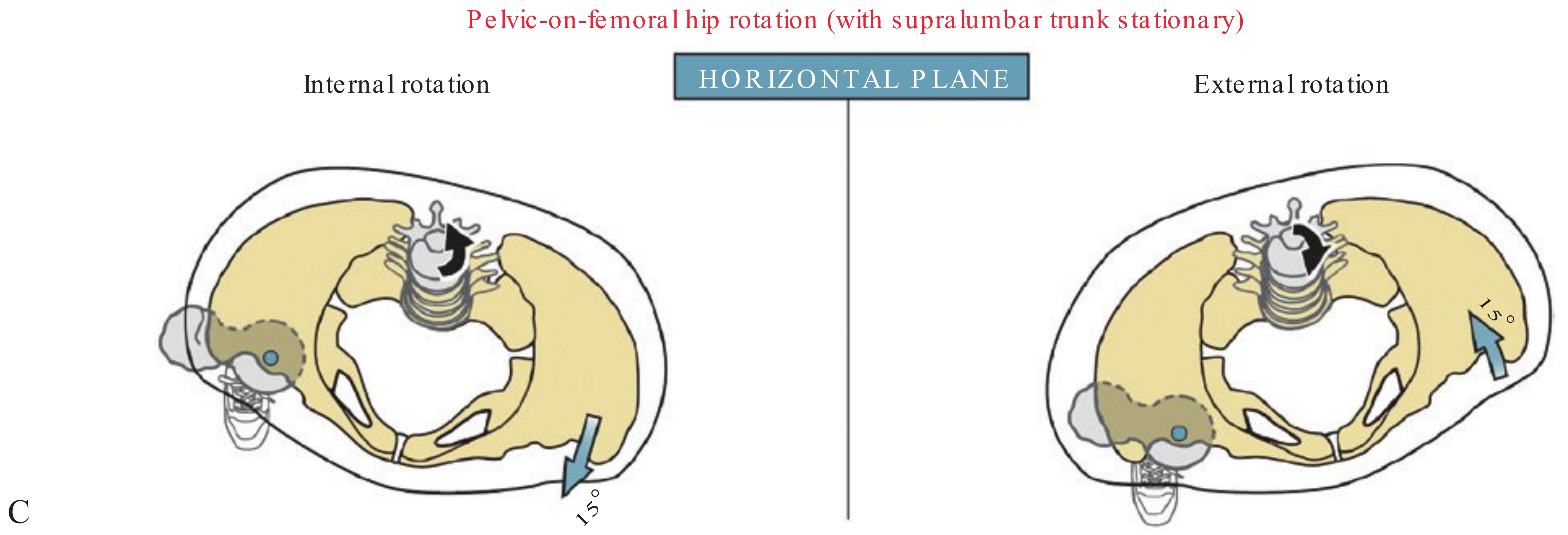


FIG. 12.22, cont'd. The near maximal range of *pelvic-on-femoral* (hip) internal and external is shown in the horizontal plane (C). The motion assumes that the supralumbar trunk remains nearly stationary during the hip motion (i.e., kinematics based on *contradirectional* lumbopelvic rhythm). The large colored and black arrows depict pelvic rotation and the associated "offsetting" lumbar motion.

SPECIAL FOCUS 12.3

Norms for Range of Motion: What About the Hip of the Child?

The normative range of motion of the hip (or any joint) is often determined by using a goniometer. Typically these normative measurements are made by experienced clinicians, using a relatively large sample of subjects, most often adults. These kinematic data serve many purposes, such as assessing an underlying pathology, determining the ability to perform self-care activities (such as reaching to don shoes), or designing medical equipment and prosthetic limbs. Although not as common, normative values are also available to describe pediatric hip range of motion. As in the case with adults, these norms for children can help determine underlying medical problems. For example, a child with an inflammatory arthropathy of the hip typically exhibits limited internal rotation. Likewise, a child with a slipped capital femoral epiphysis (SCFE) often will have reduced internal rotation and excessive external rotation because of the posterior-inferior slippage of the femoral epiphysis relative to the shaft of the femur.[135]

Table 12.2 lists average (passive) range of motion values measured from a sample of 252 young patients (2–17 years of age) who had no underlying pathology affecting their lower limbs.[198] Analysis of the data showed a decreasing trend in most ranges of hip motion as age advanced. The decline in range of motion was less apparent in girls. As a result, differences in range of motion by sex were more pronounced in the older children. For example, whereas no significant difference between boys and girls was detected in any range of motion among the 2–5 year olds, in the oldest group boys had less range of motion than girls for sagittal and frontal plane movements as well as for external rotation with the hip extended. These considerations are important for clinicians who treat children across a wide range of ages.

TABLE 12.2 **Average Passive Range of Motion of Pediatric Patients with No Pathology Affecting Their Lower Limbs***

	Males			Females		
	2–5 yr	**6–10 yr**	**11–17 yr**	**2–5 yr**	**6–10 yr**	**11–17 yr**
MOTION						
Flexion	118 (12)	118 (9)	113 (12)	121 (10)	122 (13)	120 (8)
Extension	21 (5)	19 (4)	15 (5)	21 (5)	21 (5)	22 (3)
Abduction	51 (11)	43 (12)	34 (10)	53 (15)	51 (12)	44 (14)
Adduction	17 (5)	15 (5)	14 (5)	18 (5)	18 (6)	17 (5)
Internal rotation (Fl)	45 (13)	40 (10)	35 (11)	47 (11)	41 (11)	35 (10)
Internal rotation (Ext)	47 (9)	42 (10)	36 (11)	51 (9)	47 (10)	42 (9)
External rotation (Fl)	51 (11)	44 (11)	40 (12)	49 (12)	48 (5)	46 (3)
External rotation (Ext)	47 (10)	42 (12)	39 (11)	50 (12)	45 (12)	44 (8)

Data from Sankar WN, Laird CT, Baldwin KD: Hip range of motion in children: what is the norm? J Pediatr Orthop 32(4):399–405, 2012.

*Average and standard deviations (in parentheses) are listed in degrees across three age groups for each sex (N= 163 males and 89 females). At the time of measurement, all patients were receiving fracture care of the upper extremity.

Ext, in extension; Fl, in flexion.

Additional Clinical Connections

CLINICAL CONNECTION 13.4

Synergy among Monoarticular and Biarticular Muscles of the Hip and Knee

TYPICAL MOVEMENT COMBINATIONS: HIP-AND-KNEE EXTENSION OR HIP-AND-KNEE FLEXION

Many movements performed by the lower extremities involve the cyclic actions of hip-and-knee extension or hip-and-knee flexion. These patterns of movement are fundamental components of walking, running, jumping, and climbing. Hip-and-knee extension propels the body forward or upward. Conversely, hip-and-knee flexion advances or swings the lower limb or is used to slowly lower the body toward the ground. These movements are controlled, in part, through a synergy among monoarticular and polyarticular muscles, many of which cross the hip and knee.

Fig. 13.43 shows an interaction of muscles during the hip-and-knee extension phase of running. The vastus group and gluteus maximus—two monoarticular muscles—are active synergistically, along with the biarticular semitendinosus and rectus femoris muscles. The vastus group of the quadriceps and the semitendinosus are both electrically active, yet their net torque at the knee favors extension. This occurs because the contracting vastus muscles overpower the contraction efforts of the semitendinosus. As a consequence, the tension stored in the forced lengthening of the semitendinosus across the knee is used to assist with active extension at the hip. In the combined movement of hip-and-knee extension, therefore, the semitendinosus muscle (when considered as a whole) extends the hip but actually contracts or shortens a relatively short distance. Because the contraction excursion is low, so is the contraction velocity when considered over a similar time span.

The action of the semitendinosus muscle as described favors relatively high force production per level of neural drive or effort. The physiologic basis for this efficient muscular action rests on the force-velocity and length-tension relationships of muscle (see Chapter 3). Consider first the effect of muscle velocity on muscle force production. Muscle force per level of effort increases sharply as the contraction velocity is reduced. As an example, a muscle contracting at 6.3% of its maximum shortening velocity produces a force of about 75% of its maximum. Slowing the contraction velocity to only 2.2% of maximal (i.e., very near isometric) raises force output to 90% of maximum.[190] In the movement of hip-and-knee extension, the vastus muscles, by extending the knee, indirectly augment hip extension force by reducing the contraction velocity of the semitendinosus.

Consider next the effect of muscle length on the passive force produced within a biarticular muscle. Based on a muscle's passive length-tension relationship, the internal resistance or force within a muscle, such as the semitendinosus, increases as it is stretched. The passive force created within the stretched semitendinosus across the extending knee, in this particular example, is "recycled" and used to help extend the hip. In this manner the semitendinosus—as well as all biarticular hamstrings—functions as a "transducer" by transferring force ultimately produced by the contracting vastus muscles to the extending hip.

During active hip-and-knee extension, the gluteus maximus and rectus femoris have a relationship similar to that described between the vastus muscles and the semitendinosus. In essence,

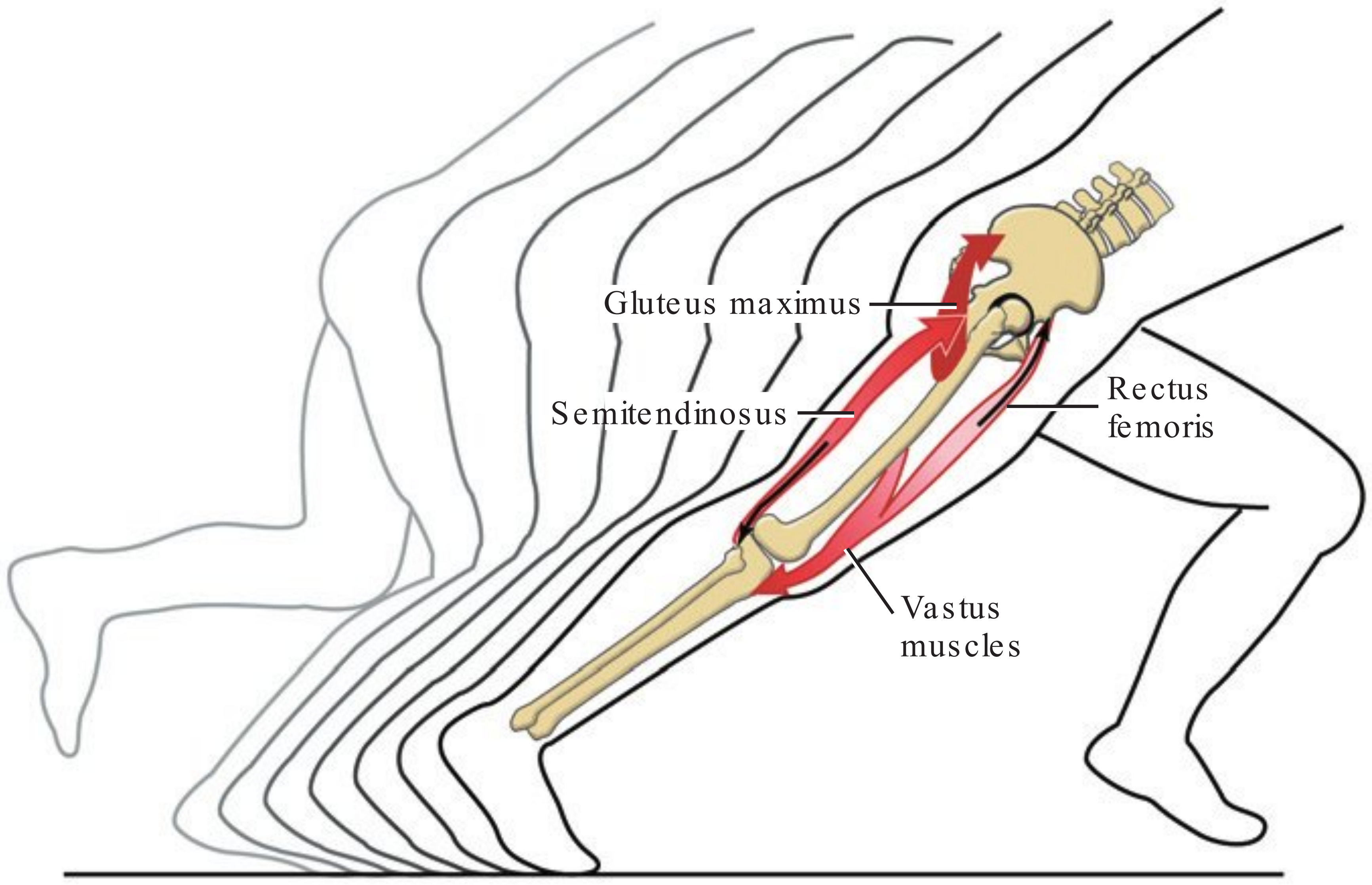


FIG. 13.43 The actions of several monoarticular and biarticular muscles are depicted during the hip-and-knee extension phase of running. Observe that the vastus muscles extend the knee, which then stretches the distal end of the semitendinosus. The gluteus maximus extends the hip, which stretches the proximal end of the rectus femoris. The stretched biarticular muscles are depicted by thin black arrows. The stretch placed on the active biarticular muscles reduces the rate and amount of their overall contraction. (See text for further details.)

Continued

Additional Clinical Connections

CLINICAL CONNECTION 13.4

Synergy among Monoarticular and Biarticular Muscles of the Hip and Knee—cont'd

the monoarticular gluteus maximus augments knee extension force by its dominating influence over hip extension. This dominance, in turn, stretches the activated rectus femoris. In this example the rectus femoris is the biarticular transducer, transferring force from the gluteus maximus to knee extension. Asummary of these and other muscular interactions used during hip-and-knee flexion is listed in Table 13.8.

The functional interdependence among the hip-and-knee extensor muscles and among the hip-and-knee flexor muscles should be considered in evaluation of functional activities that require these active movement combinations. Consider, for example, the combined movements of hip-and-knee extension required to stand from a seated position. Weakness of the vastus muscles could indirectly cause difficulty in extending the hip, whereas weakness of the gluteus maximus could indirectly cause difficulty in extending the knee. Strengthening programs may benefit by designing resistive challenges that incorporate this natural synergy between these muscles. Consider also someone with patellofemoral joint pain during active contraction of the quadriceps. Encouraging this person to activate his or her hip extensor muscles to assist with knee extension may reduce the active demands placed on the quadriceps, thereby potentially lowering the compression forces placed on the patellofemoral joint.

ATYPICAL MOVEMENT COMBINATIONS: HIP FLEXION AND KNEE EXTENSION, OR HIP EXTENSION AND KNEE FLEXION

Consider active movement patterns of the hip and knee that are "out of phase" with the more typical movement patterns described earlier. Hip flexion can occur with knee extension (Fig. 13.44A), or hip extension can occur with knee flexion (Fig. 13.44B). The physiologic consequences of these movements are very different from those described in Fig. 13.43. In Fig. 13.44A, the biarticular

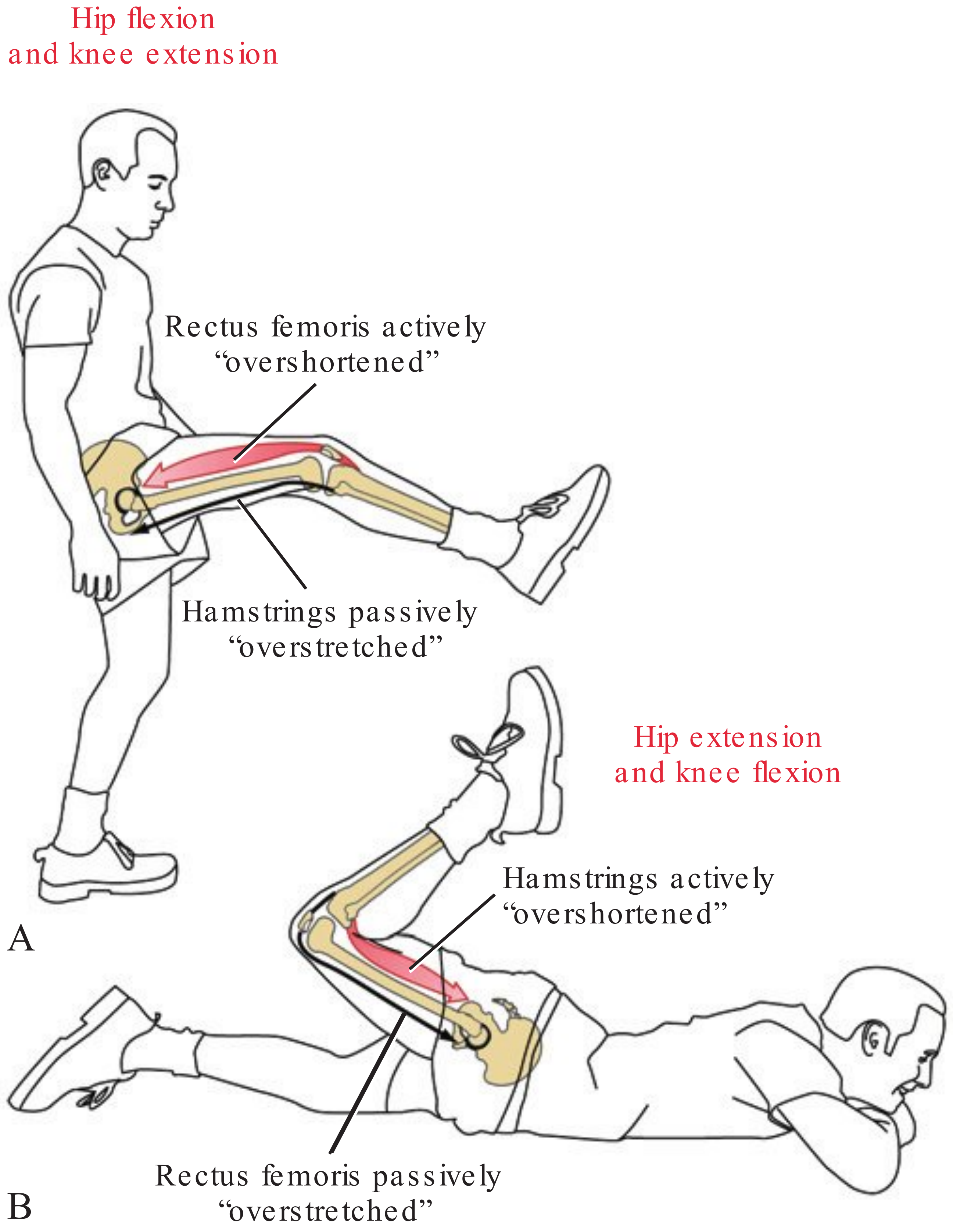


FIG. 13.44 The motions of (A) hip flexion and knee extension and (B) hip extension and knee flexion. For both movements the near-maximal contraction of the biarticular muscles *(red)* causes a near-maximal stretch in the biarticular antagonist muscles *(black arrows).*

TABLE 13.8 Examples of Muscle Synergies at the Hip and Knee

	Monoarticular Muscle(s)	Action	Biarticular Transducer(s)	Action Augmented
Active hip *and* knee *extension*	Vasti	Knee *extension*	Two-joint hamstrings	Hip *extension*
	Gluteus maximus	Hip *extension*	Rectus femoris	Knee *extension*
Active hip *and* knee *flexion*	Iliopsoas	Hip *flexion*	Two-joint hamstrings	Knee *flexion*
	Biceps femoris (short head), popliteus	Knee *flexion*	Rectus femoris	Hip *flexion*

Modified from Leiber RL: Skeletal muscle: structure and function, Baltimore, 1992, Williams & Wilkins.

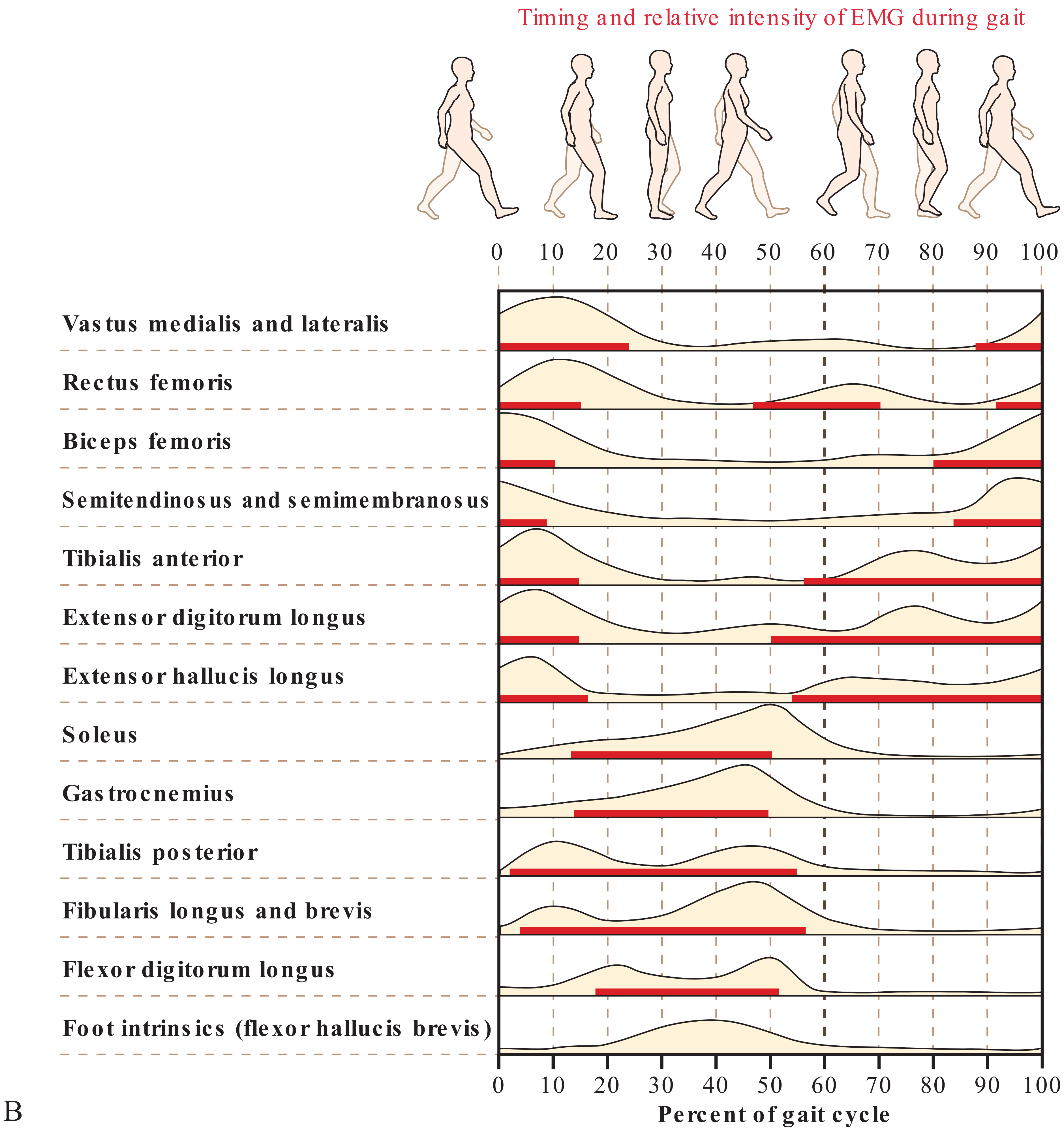


FIG. 15.29 cont'd.

knee extension in preparation for the placement of the foot on the ground. During the initial 10% of stance, the hamstrings are active to assist with hip extension and to provide stability to the knee through coactivation. The short head of the biceps femoris may also assist with knee flexion during the swing phase. Most of the knee flexion prior to toe off and during the swing phase of gait is performed passively as a result of the flexing hip and a small amount of gastrocnemius activation.[195,241]

Ankle and Foot

At the ankle and foot, several muscles play a crucial role in normal gait: the tibialis anterior, extensor digitorum, extensor hallucis longus, gastrocnemius, soleus, tibialis posterior, and fibularis longus and brevis.[32,55,146,224,228]

TIBIALIS ANTERIOR

The tibialis anterior has two periods of activity.[147] At heel contact, a strong eccentric activation is present to decelerate the passive plantar flexion of the ankle caused by the weight of the body being applied on the most posterior section of the calcaneus. If unopposed by the eccentric activation of the tibialis anterior and other ankle dorsiflexors, this large, passive plantar flexion torque results in the gait deviation referred to as "foot slap." This term is derived from the characteristic sound made by the foot slapping the ground just after heel contact. From heel contact to foot flat, the tibialis anterior may also assist with decelerating foot pronation, also through eccentric activation. The poor mechanical advantage of the muscle to invert the foot, however, raises some doubt with regard to the effectiveness of the tibialis anterior in strongly controlling foot pronation.

The second period of activation of the tibialis anterior occurs during the swing phase. The purpose of this activation is to produce sufficient dorsiflexion of the ankle to clear the toes from the ground. Extreme weakness of the tibialis anterior and the other ankle dorsiflexors typically results in a "drop foot" during the swing phase. As a mechanism of compensation, the individual typically excessively flexes the knee and hip during swing. Other compensatory maneuvers, such as vaulting, hip circumduction, and hip hiking (illustrated later in this chapter), may also be adopted to clear the toes from the ground. A common remedy for a drop-foot is a posterior ankle-foot orthosis that passively maintains ankle dorsiflexion during swing.

EXTENSOR DIGITORUM AND EXTENSOR HALLUCIS LONGUS

Similar to the tibialis anterior, the extensor digitorum longus and extensor hallucis longus decelerate plantar flexion of the ankle at heel contact. These muscles, however, lack the line of force to decelerate foot pronation during the early part of stance phase. During swing, the toe extensors assist with dorsiflexion of the ankle and extend the toes to ensure that the toes clear the ground. Minor activity of the extensor digitorum longus and extensor hallucis longus during push off may provide stability to the ankle through coactivation with the ankle plantar flexors.[241]

ANKLE PLANTAR FLEXORS

The soleus and gastrocnemius (triceps surae) are active throughout most of the stance phase, with the notable exception of the first 10% of the gait cycle. During this period, plantar flexion of the foot is controlled by an eccentric action of the ankle dorsiflexors. From about 10% of the gait cycle to heel off (approximately 30% to 40% of the gait cycle), the ankle plantar flexors are active eccentrically to control the forward movement of the tibia and fibula relative to the talus (i.e., ankle dorsiflexion). Excessive or uncontrolled forward movement of the leg results in exaggerated ankle dorsiflexion and possibly uncontrolled knee flexion.

The major burst of activity of the ankle plantar flexors occurs near heel off and decreases rapidly to near zero at toe off. During this brief period, shortening of the muscles creates an ankle plantar flexion torque that participates in the forward propulsion of the body. This action is referred to as *push off.*

The gastrocnemius also generates low-level muscular activity in early swing, presumably to help with knee flexion. Because the rectus femoris is also active during early swing, a small amount of coactivation of the knee flexors and extensors is taking place.[241]

The other plantar flexors of the ankle (tibialis posterior, flexor hallucis longus, flexor digitorum longus, and fibularis longus and brevis) assist the gastrocnemius-soleus group in the previously described actions. Some additional actions of these muscles are noteworthy.

SPECIAL FOCUS 15.7

Role of Triceps Surae

Work by Stewart and colleagues[208] provides some interesting additional insight into the functional role of the triceps surae in the stance phase of walking. In a healthy group of individuals, electrical stimulation of the soleus during the stance phase led to a reduced amount of knee flexion during this part of the gait cycle. In contrast, electrical stimulation of the biarticular gastrocnemius during the stance phase produced greater than normal knee flexion, as well as an increased ankle dorsiflexion. These findings suggest a complex biomechanical link between the sagittal plane control of the knee and ankle during the stance phase. Such a disruption in control of these two joints is often seen in individuals with certain neuromuscular diseases.

TIBIALIS POSTERIOR

The tibialis posterior, a potent supinator muscle of the foot, is active virtually throughout the entire stance phase. The tibialis posterior decelerates pronation of the foot from immediately after heel contact to about 35% of the gait cycle and supinates the foot from between 35% and 55% (mid stance to toe off) of the gait cycle.[145,147,148]

The tibialis posterior muscle acts on both the foot and the tibia throughout the stance phase. Based on its line of pull, shortening of this muscle could supinate the rearfoot (and raise the arch of the foot) as it simultaneously externally rotates the lower leg relative to the foot. Indeed, both of these coupled kinematics occur as the tibialis posterior is active. Although speculation, it is interesting to consider how dorsiflexion of the talocrural joint (which occurs through 50% of the gait cycle) may serve to stretch the tibialis posterior at a time when it may be overshortening during its coupled external rotation-supination action on the lower leg and foot. Maintaining adequate length (and tension) in this muscle at this time may assist in raising the medial longitudinal arch and adding the necessary rigidity to the foot to prepare for its impending push off. The near simultaneous and combined concentric and eccentric muscular activation within the tibialis posterior across multiple joints may partially explain its relative vulnerability to painful tendinopathy or degeneration.[229,239] Such a cause and effect relationship is strengthened considering the large load placed on the muscle, spring ligament, and medial longitudinal arch during the countless gait cycles in a lifetime.

There is evidence in the literature that individuals with excessively pronated (flat) feet exhibit greater activation of supinator muscles such as the tibialis posterior, tibialis anterior, and flexor hallucis longus.[146] Active individuals with overly pronated feet may develop overuse and subsequent strain of the supinator muscles as they attempt to control the excessive pronation bias of the foot during early stance.

The tibialis posterior receives special attention in the treatment of people with cerebral palsy. The often hyperactive tibialis posterior, along with the soleus muscle, may cause an equinovarus deformity of the foot and ankle, resulting in the individual's walking on a foot that is plantar flexed and supinated.

FIBULARIS MUSCLES

The fibularis (peroneus) brevis and longus are active from about 5% of the gait cycle to just before toe off.[147] In addition to their function as plantar flexors, these pronator (evertor) muscles help counteract the strong inversion effect caused by activation of the tibialis posterior and other deep posterior muscles. The fibularis longus also assists in the kinematics of the foot by holding the first ray rigidly to the ground, which provides a firm base of support for the action of the foot as a rigid lever during the second half of the stance phase of gait.

INTRINSIC MUSCLES OF THE FOOT

The intrinsic muscles of the foot are typically active from mid stance to toe off (30% to 60% of the gait cycle). These muscles stabilize the forefoot and raise the medial longitudinal arch, thereby providing a rigid lever for ankle plantar flexion during the second half of the stance phase. They also likely help with controlling toe extension between heel off and toe off.