C H A P T E R

8

The Biomechanics of the Human Lower Extremity

After completing this chapter, you will be able to:

Explain how anatomical structure affects movement capabilities of lower-extremity articulations.

Identify factors influencing the relative mobility and stability of lower-extremity articulations.

Explain the ways in which the lower extremity is adapted to its weight-bearing function.

Identify muscles that are active during specific lower-extremity movements.

Describe the biomechanical contributions to common injuries of the lower extremity.

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The lower extremity is well structured for its functions of weight bearing and locomotion.

• *The hip is inherently more stable than the shoulder because of bone structure and the number and strength of the muscles and ligaments crossing the joint.*

Although there are some similarities between the joints of the upper and the lower extremities, the upper extremity is more specialized for activities requiring large ranges of motion. In contrast, the lower extremity is well equipped for its functions of weight bearing and locomotion. Beyond these basic functions, activities such as kicking a field goal in football, performing a long jump or a high jump, and maintaining balance *en pointe* in ballet reveal some of the more specialized capabilities of the lower extremity. This chapter examines the joint and muscle functions that enable lower-extremity movements.

STRUCTURE OF THE HIP

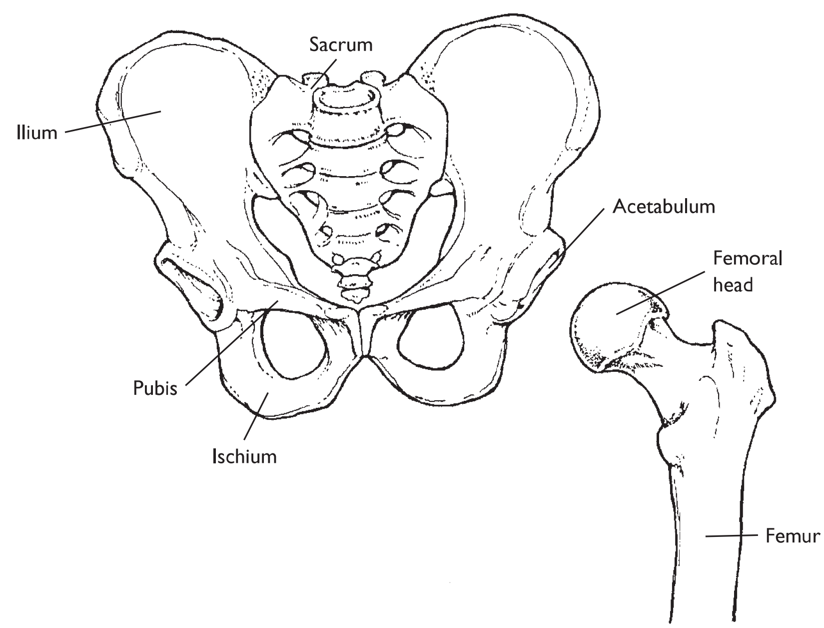
The hip is a ball-and-socket joint (Figure 8-1). The ball is the head of the femur, which forms approximately two-thirds of a sphere. The socket is the concave acetabulum, which is angled obliquely in an anterior, lateral, and inferior direction. Joint cartilage covers both articulating surfaces. The cartilage on the acetabulum is thicker around its periphery, where it merges with a rim, or labrum, of fibrocartilage that contributes to the stability of the joint. Hydrostatic pressure is greater within the labrum than outside of it, contributing to lubrication of the joint (31). The acetabulum provides a much deeper socket than the glenoid fossa of the shoulder joint, and the bony structure of the hip is therefore much more stable or less likely to dislocate than that of the shoulder.

Several large, strong ligaments also contribute to the stability of the hip (Figure 8-2). The extremely strong iliofemoral or Y ligament and the pubofemoral ligament strengthen the joint capsule anteriorly, with posterior reinforcement from the ischiofemoral ligament. Tension in these major ligaments acts to twist the head of the femur into the acetabulum during hip extension, as when a person moves from a sitting to a standing position. Inside the joint capsule, the ligamentum teres supplies a direct attachment from the rim of the acetabulum to the head of the femur.

As with the shoulder joint, several bursae are present in the surrounding tissues to assist with lubrication. The most prominent are the iliopsoas

FIGURE 8-1

The bony structure of the hip.



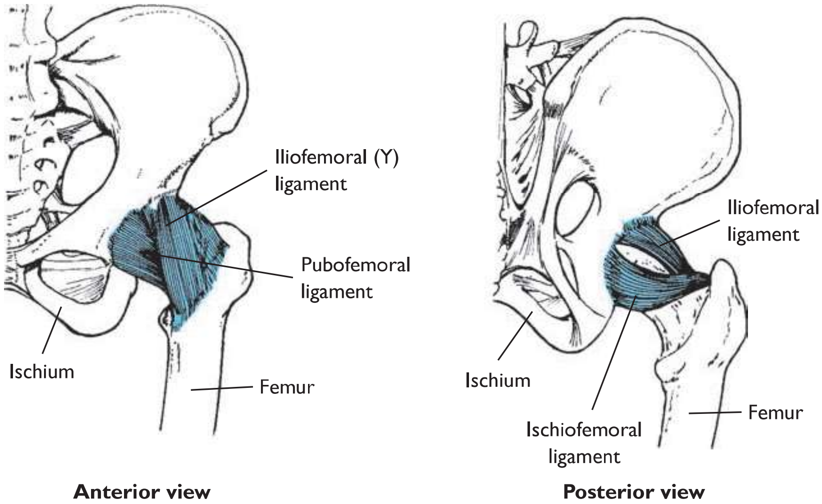


FIGURE 8-2

The ligaments of the hip.

bursa and the deep trochanteric bursa. The iliopsoas bursa is positioned between the iliopsoas and the articular capsule, serving to reduce the friction between these structures. The deep trochanteric bursa provides a cushion between the greater trochanter of the femur and the gluteus maximus at the site of its attachment to the iliotibial tract. The trochanteric bursae vary in number, position, and appearance among older individuals, suggesting that these bursae are formed to lessen friction between the greater trochanter and the gluteus maximus (24).

The femur is a major weight-bearing bone and is the longest, largest, and strongest bone in the body. Its weakest component is the femoral neck, which is smaller in diameter than the rest of the bone, and weak internally because it is primarily composed of trabecular bone. The femur angles medially downward from the hip during the support phase of walking and running, enabling single-leg support beneath the body's center of gravity.

MOVEMENTS AT THE HIP

Although movements of the femur are due primarily to rotation occurring at the hip joint, the pelvic girdle has a function similar to that of the shoulder girdle in positioning the hip joint for effective limb movement. Unlike the shoulder girdle, the pelvis is a single nonjointed structure, but it can rotate in all three planes of movement. The pelvis facilitates movement of the femur by rotating so that the acetabulum is positioned toward the direction of impending femoral movement. For example, posterior pelvic tilt, with the anterior superior iliac spine tilted backward with respect to the acetabulum, positions the head of the femur in front of the hipbone to enable ease of flexion. Likewise, anterior pelvic tilt promotes femoral extension, and lateral pelvic tilt toward the opposite side facilitates lateral movements of the femur. Movement of the pelvic girdle also coordinates with certain movements of the spine (see Chapter 9).

pelvic girdle
the two hip bones plus the sacrum, which can be rotated forward, backward, and laterally to optimize positioning of the hip joint

Muscles of the Hip

A number of large muscles cross the hip, further contributing to its stability. The locations and functions of the muscles of the hip are summarized in Table 8-1.

TABLE 8-1

Muscles of the Hip

MUSCLE	PROXIMAL ATTACHMENT	DISTAL ATTACHMENT	PRIMARY ACTION(S) ABOUT THE HIP	INNERVATION
Rectus femoris	Anterior inferior iliac spine (ASIS)	Patella	Flexion	Femoral (L_2–L_4)
Iliopsoas		Lesser trochanter of femur	Flexion	L_1 and femoral
(Iliacus)	Iliac fossa and adjacent sacrum			(L_2–L_4)
(Psoas)	12^{th} thoracic and all lumbar vertebrae and lumbar discs			(L_1–L_3)
Sartorius	Anterior superior iliac spine	Upper medial tibia	Assists with flexion, abduction, lateral rotation	Femoral (L_2, L_3)
Pectineus	Pectineal crest of pubic ramus	Medial, proximal femur	Flexion, adduction, medial rotation	Femoral (L_2, L_3)
Tensor fascia latae	Anterior crest of ilium and ASIS	Iliotibial band	Assists with flexion, abduction, medial rotation	Superior gluteal (L_4–S_1)
Gluteus maximus	Posterior ilium, iliac crest, sacrum, coccyx	Gluteal tuberosity of femur and iliotibial band	Extension, lateral rotation	Inferior gluteal (L_5–S_2)
Gluteus medius	Between posterior and anterior gluteal lines on posterior ilium	Superior, lateral greater trochanter	Abduction, medial rotation	Superior gluteal (L_4–S_1)
Gluteus minimus	Between anterior and inferior gluteal lines on posterior ilium	Anterior surface of greater trochanter	Abduction, medial rotation	Superior gluteal (L_4–S_1)
Gracilis	Anterior, inferior pubic symphysis	Medial, proximal tibia	Adduction	Obturator (L_3, L_4)
Adductor magnus	Inferior ramus of pubis and ischium	Entire linea aspera	Adduction, lateral rotation	Obturator (L_3, L_4)
Adductor longus	Anterior pubis	Middle linea aspera	Adduction, assists with flexion	Obturator (L_3, L_4)
Adductor brevis	Inferior ramus of the pubis	Upper linea aspera	Adduction, lateral rotation	Obturator (L_3, L_4)
Semitendinosus	Medial ischial tuberosity	Proximal, medial tibia	Extension	Tibial (L_5–S_1)
Semimembranosus	Lateral ischial tuberosity	Proximal, medial tibia	Extension	Tibial (L_5–S_1)
Biceps femoris (long head)	Lateral ischial tuberosity	Posterior lateral condyle of tibia, head of fibula	Extension	Tibial (L_5–S_2)
The six outward rotators	Sacrum, ilium, ischium	Posterior greater trochanter	Outward rotation	(L_5–S_2)

Flexion

iliopsoas
the psoas major and iliacus muscles with a common insertion on the lesser trochanter of the femur

The six muscles primarily responsible for flexion at the hip are those crossing the joint anteriorly: the iliacus, psoas major, pectineus, rectus femoris, sartorius, and tensor fascia latae. Of these, the large iliacus and psoas major—often referred to jointly as the iliopsoas because of their common attachment to the femur—are the major hip flexors (Figure 8-3). Other major hip flexors are shown in Figure 8-4. Because the rectus femoris is

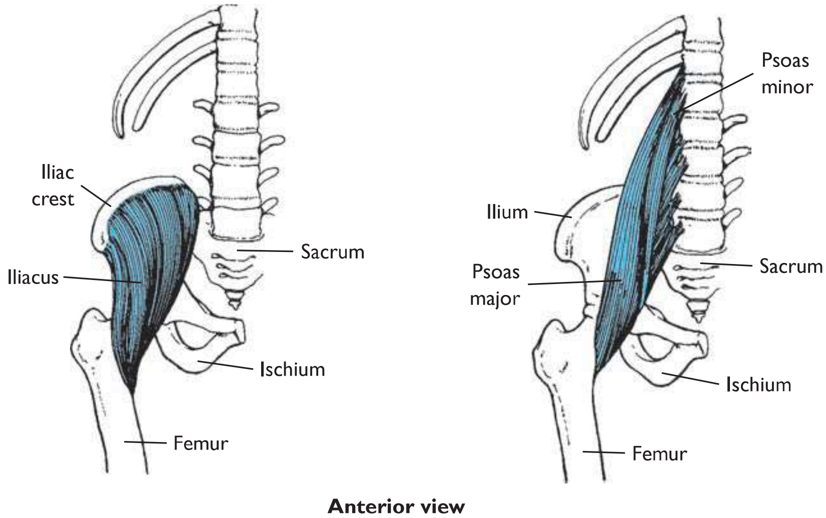


FIGURE 8-3

The iliopsoas complex is the major flexor of the hip.

a two-joint muscle active during both hip flexion and knee extension, it functions more effectively as a hip flexor when the knee is in flexion, as when a person kicks a ball. The thin, straplike sartorius, or *tailor's muscle*, is also a two-joint muscle. Crossing from the superior anterior iliac spine to the medial tibia just below the tuberosity, the sartorius is the longest muscle in the body.

Extension

The hip extensors are the gluteus maximus and the three hamstrings—the biceps femoris, semitendinosus, and semimembranosus (Figure 8-5). The gluteus maximus is a massive, powerful muscle that is usually active only when the hip is in flexion, as during stair climbing or cycling, or when extension at the hip is resisted (Figure 8-6). The hamstrings derive their name from their prominent tendons, which can readily be palpated on the posterior aspect of the knee. These two-joint muscles contribute to both extension at the hip and flexion at the knee, and are active during standing, walking, and running.

hamstrings
the biceps femoris, semimembranosus, and semitendinosus

● *Two-joint muscles function more effectively at one joint when the position of the other joint stretches the muscle slightly.*

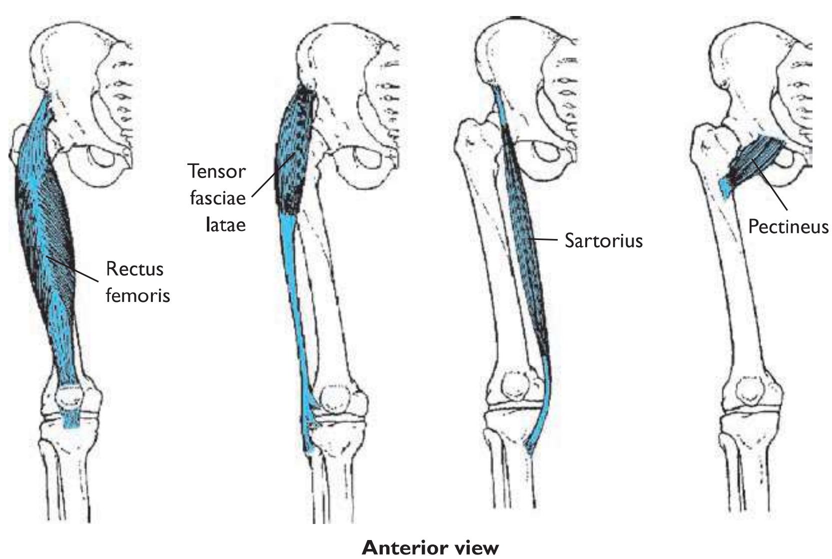
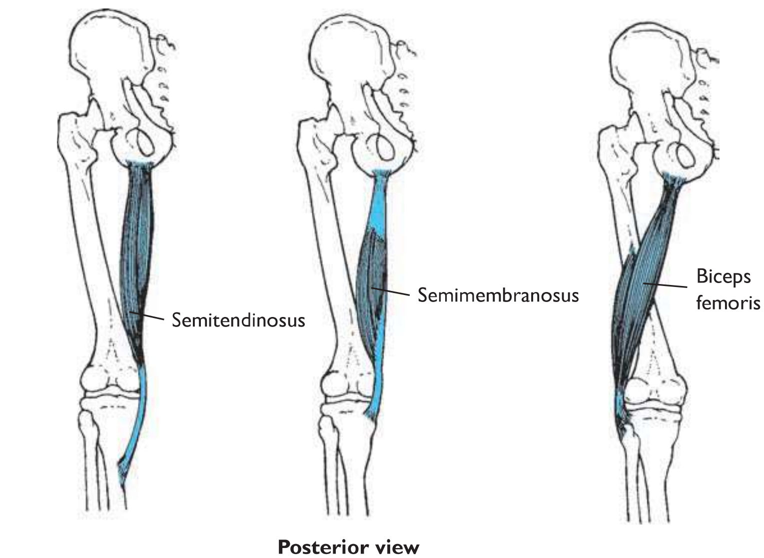


FIGURE 8-4

Assistant flexor muscles of the hip.

FIGURE 8-5

The hamstrings are major hip extensors and knee flexors.



Abduction

The gluteus medius is the major abductor acting at the hip, with the gluteus minimus assisting. These muscles stabilize the pelvis during the support phase of walking and running and when an individual stands on one leg. For example, when body weight is supported by the right foot during walking, the right hip abductors contract isometrically and eccentrically to prevent the left side of the pelvis from being pulled downward by the weight of the swinging left leg. This allows the left leg to move freely through the swing phase. If the hip abductors are too weak to perform this function, then lateral pelvic tilt and dragging of the swing foot occurs with every step during gait. The hip abductors are also active during the performance of dance movements such as the *grande ronde jambe*.

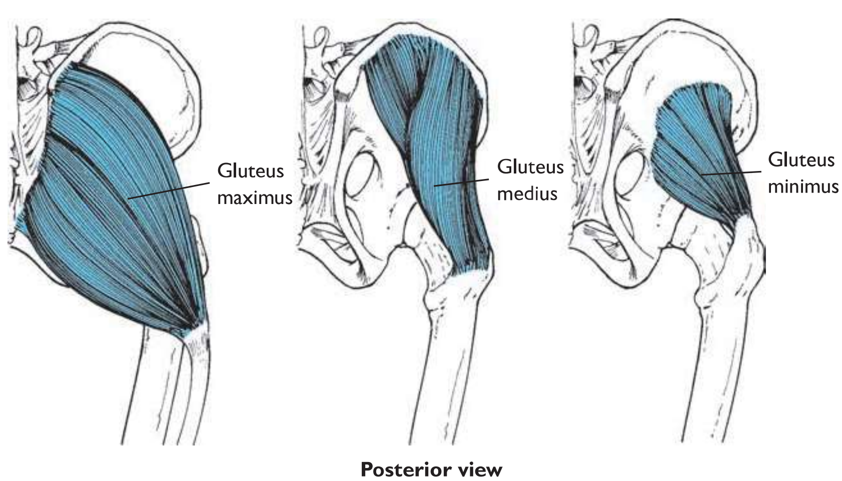
•*Contraction of the hip abductors is required during the swing phase of gait to prevent the swinging foot from dragging.*

Adduction

The hip adductors are those muscles that cross the joint medially and include the adductor longus, adductor brevis, adductor magnus, and gracilis (Figure 8-7). The hip adductors are regularly active during the swing phase of the gait cycle to bring the foot beneath the body's center of gravity for placement during the support phase. The gracilis is a long, relatively weak strap muscle that also contributes to flexion of the leg at the

FIGURE 8-6

The three gluteal muscles.



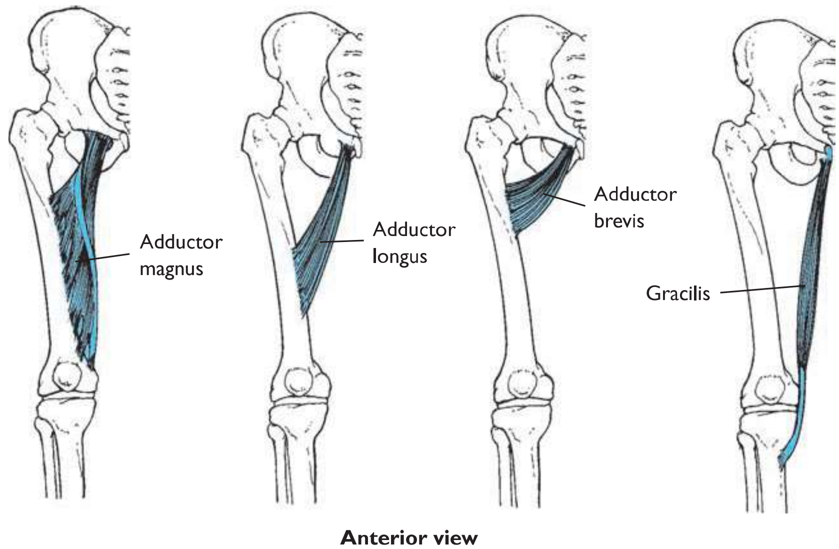


FIGURE 8-7

Adductor muscles of the hip.

knee. The other three adductor muscles also contribute to flexion and lateral rotation at the hip, particularly when the femur is medially rotated.

Medial and Lateral Rotation of the Femur

Although a number of muscles contribute to lateral rotation of the femur, six muscles function solely as lateral rotators. These are the piriformis, gemellus superior, gemellus inferior, obturator internus, obturator externus, and quadratus femoris (Figure 8-8). Although we tend to think of walking and running as involving strictly sagittal plane movement at the joints of the lower extremity, outward rotation of the femur also occurs with every step to accommodate the rotation of the pelvis.

•During the gait cycle, lateral and medial rotation of the femur occur in coordination with pelvic rotation.

The major medial rotator of the femur is the gluteus minimus, with assistance from the tensor fascia latae, semitendinosus, semimembranosus, and gluteus medius. Medial rotation of the femur is usually not a resisted motion requiring a substantial amount of muscular force. The medial rotators are weak in comparison to the lateral rotators, with the estimated strength of the medial rotators only approximately one-third that of the lateral rotators (57).

Horizontal Abduction and Adduction

Horizontal abduction and adduction of the femur occur when the hip is in 90° of flexion while the femur is either abducted or adducted. These actions require the simultaneous, coordinated actions of several muscles. Tension is required in the hip flexors for elevation of the femur. The hip abductors can then produce horizontal abduction and, from a horizontally abducted position, the hip adductors can produce horizontal adduction. The muscles located on the posterior aspect of the hip are more effective

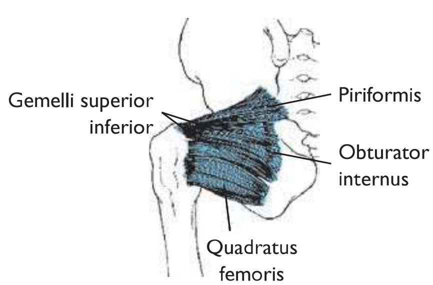


FIGURE 8-8

The lateral rotator muscles of the femur.

as horizontal abductors and adductors than the muscles on the anterior aspect, because the former are stretched when the femur is in 90° of flexion, whereas tension in the anterior muscles is usually reduced with the femur in this position.

LOADS ON THE HIP

The hip is a major weight-bearing joint that is never fully unloaded during daily activities (31). When body weight is evenly distributed across both legs during upright standing, the weight supported at each hip is one-half the weight of the body segments above the hip, or about one-third of total body weight. However, the total load on each hip in this situation is greater than the weight supported, because tension in the large, strong hip muscles further adds to compression at the joint (Figure 8-9).

•*During the support phase of walking, compression force at the hip reaches a magnitude of three to four times body weight.*

Because of muscle tension, compression on the hip is approximately the same as body weight during the swing phase of walking (85). Data from instrumented femoral implants show hip joint loading to range around 238% of body weight (BW) during the support phase of walking, with values of approximately 251% BW and 260% BW during climbing and descending stairs, respectively (9). Calculated hip contact forces for running at 3.5 m/s, Alpine skiing on a flat slope, Alpine skiing on a steep slope, cross-country skiing with classical technique, and cross-country skiing with skating technique, are around 520% BW, 410% BW, 780% BW, 400% BW, and 460% BW, respectively (113). During side diving by the goalkeeper in soccer, forces acting on the hip range from 4.2 to 8.6 times body weight (100). Hip loading increases with the wearing of hard-soled as compared to soft-soled shoes (8). Carrying a load such as a suitcase of 25% body weight on one side produces a 167% increase in loading on the contralateral hip as compared to the hip on the loaded side (7).

As gait speed increases, the load on the hip increases during both swing and support phases. Hip loads during jogging can be reduced with a smooth gait pattern and soft heel strikes (8). In summary, body weight, impact forces translated upward through the skeleton from the foot, and muscle tension all contribute to this large compressive load on the hip, as demonstrated in Sample Problem 8.1.

Fortunately, the hip joint is well designed to bear the large loads it habitually sustains. Because the diameter of the humeral head is

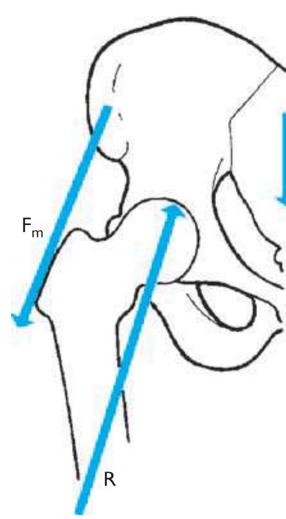


FIGURE 8-9

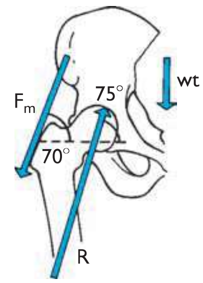
The major forces on the hip during static stance are the weight of the body segments above the hip (with one-half of the weight on each hip), tension in the hip abductor muscles (F_m), and the joint reaction force (R).

SAMPLE PROBLEM 8.1

How much compression acts on the hip during two-legged standing, given that the joint supports 250 N of body weight and the abductor muscles are producing 600 N of tension?

Known

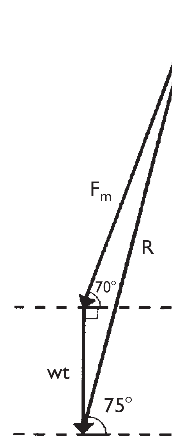
$$wt = 250\ N$$
$$F_m = 600\ N$$



Graphic Solution

Since the body is motionless, all vertical force components must sum to zero and all horizontal force components must sum to zero. Graphically, this means that all acting forces can be transposed to form a closed force polygon (in this case, a triangle). The forces from the diagram of the hip above can be reconfigured to form a triangle.

If the triangle is drawn to scale (perhaps 1 cm = 100 N), the amount of joint compression can be approximated by measuring the length of the joint reaction force (R).



$$R \approx 840\ N$$

Mathematical Solution

The law of cosines can be used with the same triangle to calculate the length of R.

$$R^2 = F_m{}^2 + wt^2 - 2(F_m)\,(wt)\cos 160°$$
$$R^2 = 600\ N^2 + 250\ N^2 - 2(600\ N)\,(250\ N)\cos 160°$$
$$R = 839.3\ N$$

somewhat larger than the articulating surface of the acetabulum, contact between the two bones during initiation of weight bearing begins around the periphery. As loading increases, the contact area at the joint also increases, such that stress levels remain approximately constant (83).

Use of a crutch or cane on the side opposite an injured or painful hip is beneficial in that it serves to more evenly distribute the load between the legs throughout the gait cycle. During stance, a support opposite the painful hip reduces the amount of tension required of the powerful abductor muscles, thereby reducing the load on the painful hip. This reduction in load on the painful hip, however, increases the stress on the opposite hip.

COMMON INJURIES OF THE HIP

Fractures

Although the pelvis and the femur are large, strong bones, the hip is subjected to high, repetitive loads ranging from four to seven times body weight during locomotion (57). Fractures of the femoral neck frequently occur during the support phase of walking among elderly individuals with osteoporosis, a

• *Fracture of the femoral neck (broken hip) is a seriously debilitating injury that occurs frequently among elderly individuals with osteoporosis.*

condition of reduced bone mineralization and strength (see Chapter 4). These femoral neck fractures often result in loss of balance and a fall. A common misconception is that the fall always causes the fracture rather than the reverse, which may also be true. Hip fractures in the elderly are a serious health issue, with increased risk of death increasing five- to eight-fold during the first three months following the fracture (41). A high percentage of cortical bone in the proximal femur is protective against hip fractures (17). When the hipbones have good health and mineralization, they can sustain tremendous loads, as illustrated during many weight-lifting events. Research demonstrates that regular physical activity helps protect against the risk of hip fracture (52).

Contusions

The muscles on the anterior aspect of the thigh are in a prime location for sustaining blows during participation in contact sports. The resulting internal hemorrhaging and appearance of bruises vary from mild to severe. A relatively uncommon but potentially serious complication secondary to thigh contusions is acute compartment syndrome, in which internal bleeding causes a build-up of pressure in the muscle compartment causing compression of nerves, blood vessels, and muscle (55). If not treated, this can lead to tissue death due to lack of oxygenation as the blood vessels are compressed by the raised pressure within the compartment.

Strains

Since most daily activities do not require simultaneous hip flexion and knee extension, the hamstrings are rarely stretched unless exercises are performed for that specific purpose. The resulting loss of extensibility makes the hamstrings particularly susceptible to strain. Strains to these muscles most commonly occur during sprinting, particularly if the individual is fatigued and neuromuscular coordination is impaired. Researchers believe that hamstring strains typically occur during the late stance or late swing phases of gait as a result of an eccentric contraction (99, 122). These injuries are troubling for athletes, given their high incidence rate and slowness of healing, and with a recurrence rate of nearly one-third during the first year following return to athletic participation (45). Strains to the groin area are also relatively common among athletes in sports in which forceful thigh abduction movements may overstretch the adductor muscles. A study of professional ice hockey players showed that players were 17 times more likely to sustain adduction sprains if adductor strength was less than 80% of abduction strength (112). This strongly suggests that strengthening of the hip adductors can reduce the likelihood of adduction sprains.

STRUCTURE OF THE KNEE

The structure of the knee permits the bearing of tremendous loads, as well as the mobility required for locomotor activities. The knee is a large synovial joint, including three articulations within the joint capsule. The weight-bearing joints are the two condylar articulations of the tibiofemoral joint, with the third articulation being the patellofemoral joint. Although not a part of the knee, the proximal tibiofibular joint has soft-tissue connections that also slightly influence knee motion.

tibiofemoral joint
dual condyloid articulations between the medial and lateral condyles of the tibia and the femur, composing the main hinge joint of the knee

patellofemoral joints
articulation between the patella and the femur

Tibiofemoral Joint

The medial and lateral condyles of the tibia and the femur articulate to form two side-by-side condyloid joints (Figure 8-10). These joints function

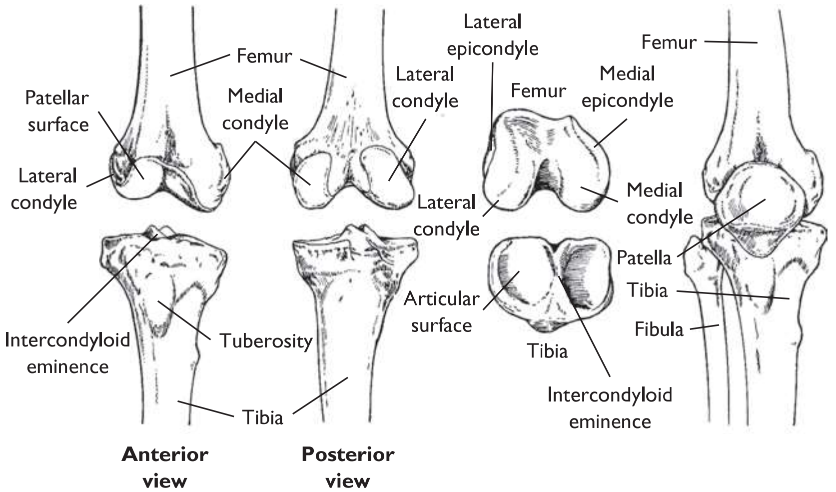


FIGURE 8-10

The bony structure of the tibiofemoral joint.

together primarily as a modified hinge joint because of the restricting ligaments, with some lateral and rotational motions allowed. The condyles of the tibia, known as the *tibial plateaus*, form slight depressions separated by a region known as the *intercondylar eminence.* Because the medial and lateral condyles of the femur differ somewhat in size, shape, and orientation, the tibia rotates laterally on the femur during the last few degrees of extension to produce "locking" of the knee. This phenomenon, known as the "screw-home" mechanism, brings the knee into the close-packed position of full extension. Because the curvatures of the tibial plateau are complex, asymmetric, and vary significantly from individual to individual, some knees are much more stable and resistant to injury than others (43).

•*The bony anatomy of the knee requires a small amount of lateral rotation of the tibia to accompany full extension.*

Menisci

The menisci, also known as semilunar cartilages after their half-moon shapes, are discs of fibrocartilage firmly attached to the superior plateaus of the tibia by the coronary ligaments and joint capsule (Figure 8-11). They are also joined to each other by the transverse ligament. The menisci are thickest at their peripheral borders, where fibers from the joint capsule solidly anchor them to the tibia (5). The medial semilunar disc is also directly attached to the medial collateral ligament. Medially, both menisci taper down to paper thinness, with the inner edges unattached to the bone.

menisci
cartilaginous discs located between the tibial and femoral condyles

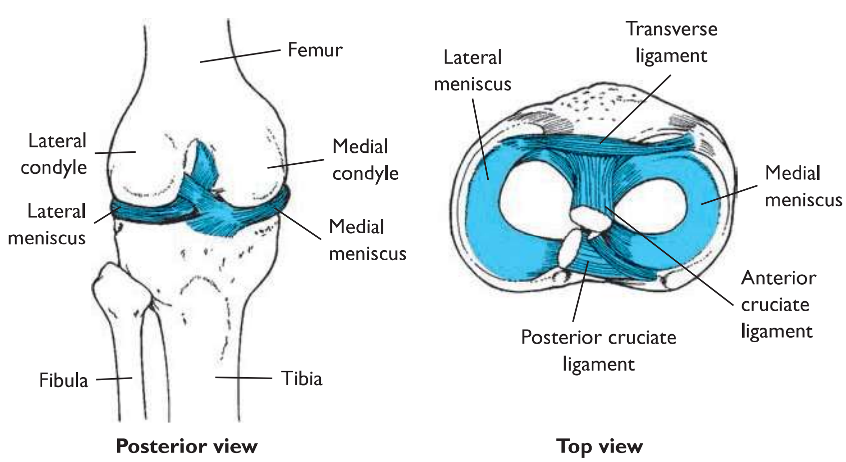


FIGURE 8-11

The menisci of the knee.

The menisci receive a rich supply of both blood vessels and nerves. The blood supply reaches the outer 10–33% of each meniscus, enabling inflammation, repair, and remodeling (39). The outer 66% of each meniscus is innervated, providing proprioceptive information regarding knee position, as well as the velocity and acceleration of knee movements (39).

•*The menisci distribute the load at the knee over a larger surface area and also help absorb shock.*

The menisci deepen the articulating depressions of the tibial plateaus and assist with load transmission and shock absorption at the knee. The internal structure of the medial two-thirds of each meniscus is particularly well suited to resisting compression (5). The stress on the tibiofemoral joint can be an estimated three times higher during load bearing if the menisci have been removed (101). Injured knees, in which part or all of the menisci have been removed, may still function adequately but undergo increased wear on the articulating surfaces, significantly increasing the likelihood of the development of degenerative conditions at the joint. Knee osteoarthritis is frequently accompanied by meniscal tears. Whereas a meniscal tear can lead to the development of osteoarthritis over time, having osteoarthritis can also cause a spontaneous meniscal tear (26).

Ligaments

Many ligaments cross the knee, significantly enhancing its stability (Figure 8-12). The location of each ligament determines the direction in which it is capable of resisting the dislocation of the knee.

collateral ligaments
major ligaments that cross the medial and lateral aspects of the knee

The medial and lateral collateral ligaments prevent lateral motion at the knee, as do the collateral ligaments at the elbow. They are also respectively referred to as the *tibial* and *fibular collateral ligaments,* after their distal attachments. Fibers of the medial collateral ligament complex merge with the joint capsule and the medial meniscus to connect the medial epicondyle of the femur to the medial tibia (92). The attachment is just below the pes anserinus, the common attachment of the semitendinosus, semimembranosus, and gracilis to the tibia, thereby positioning the ligament to resist medially directed shear (valgus) and rotational forces acting on the knee. The lateral collateral ligament courses from a few millimeters posterior to the ridge of the lateral epicondyle of the femur to the head of the fibula, contributing to lateral stability of the knee (73).

cruciate ligaments
major ligaments that cross each other in connecting the anterior and posterior aspects of the knee

The anterior and posterior cruciate ligaments limit the forward and backward sliding of the femur on the tibial plateaus during knee flexion

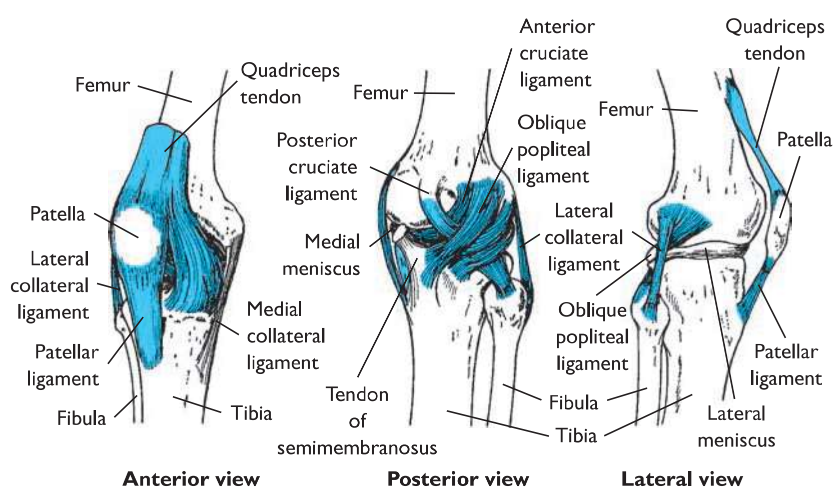


FIGURE 8-12
The ligaments of the knee.

and extension, and also limit knee hyperextension. The name *cruciate* is derived from the fact that these ligaments cross each other; *anterior* and *posterior* refer to their respective tibial attachments. The anterior cruciate ligament stretches from the anterior aspect of the intercondyloid fossa of the tibia just medial and posterior to the anterior tibial spine in a superior, posterior direction to the posterior medial surface of the lateral condyle of the femur. The shorter and stronger posterior cruciate ligament runs from the posterior aspect of the tibial intercondyloid fossa in a superior, anterior direction to the lateral anterior medial condyle of the femur. These ligaments restrict the anterior and posterior sliding of the femur on the tibial plateaus during knee flexion and extension, and limit knee hyperextension.

Several other ligaments contribute to the integrity of the knee. The oblique and arcuate popliteal ligaments cross the knee posteriorly, and the transverse ligament connects the two semilunar discs internally. Another restricting tissue is the iliotibial band or tract, a broad, thickened band of the fascia lata with attachments to the lateral condyle of the femur and the lateral tubercle of the tibia.

iliotibial band
thick, strong band of tissue connecting the tensor fascia lata to the lateral condyle of the femur and the lateral tuberosity of the tibia

Patellofemoral Joint

The patellofemoral joint consists of the articulation of the triangularly shaped patella, encased in the patellar tendon, with the trochlear groove between the femoral condyles. The posterior surface of the patella is covered with articular cartilage, which reduces the friction between the patella and the femur.

The patella serves several biomechanical functions. Most notably, it increases the angle of pull of the quadriceps tendon on the tibia, thereby improving the mechanical advantage of the quadriceps muscles for producing knee extension by as much as 50% (38). It also centralizes the divergent tension from the quadriceps muscles that is transmitted to the patellar tendon. The patella also increases the area of contact between the patellar tendon and the femur, thereby decreasing patellofemoral joint contact stress. Finally, it also provides some protection for the anterior aspect of the knee and helps protect the quadriceps tendon from friction against the adjacent bones.

• *The patella improves the mechanical advantage of the knee extensors by as much as 50%.*

Joint Capsule and Bursae

The thin articular capsule at the knee is large and lax, encompassing both the tibiofemoral and the patellofemoral joints. A number of bursae are located in and around the capsule to reduce friction during knee movements. The suprapatellar bursa, positioned between the femur and the quadriceps femoris tendon, is the largest bursa in the body. Other important bursae are the subpopliteal bursa, located between the lateral condyle of the femur and the popliteal muscle, and the semimembranosus bursa, situated between the medial head of the gastrocnemius and semimembranosus tendons.

Three other key bursae associated with the knee, but not contained in the joint capsule, are the prepatellar, superficial infrapatellar, and deep infrapatellar bursae. The prepatellar bursa is located between the skin and the anterior surface of the patella, allowing free movement of the skin over the patella during flexion and extension. The superficial infrapatellar bursa provides cushioning between the skin and the patellar tendon, and the deep infrapatellar bursa reduces friction between the tibial tuberosity and the patellar tendon.

MOVEMENTS AT THE KNEE

Muscles Crossing the Knee

Like the elbow, the knee is crossed by a number of two-joint muscles. The primary actions of the muscles crossing the knee are summarized in Table 8-2.

Flexion and Extension

popliteus
muscle known as the unlocker of the knee because its action is lateral rotation of the femur with respect to the tibia

Flexion and extension are the primary movements permitted at the tibiofemoral joint. For flexion to be initiated from a position of full extension, however, the knee must first be "unlocked." In full extension, the articulating surface of the medial condyle of the femur is longer than that of the lateral condyle, rendering motion almost impossible. The service of locksmith is provided by the popliteus, which acts to medially rotate the tibia with respect to the femur, enabling flexion to occur (Figure 8-13). As flexion proceeds, the femur must slide forward on the tibia to prevent rolling off the tibial plateaus. Likewise, the femur must slide backwards on the tibia during extension. Medial rotation of the tibia and anterior translation of the fibia on the tibial plateau have been shown to be coupled to

TABLE 8-2

Muscles of the Knee

MUSCLE	PROXIMAL ATTACHMENT	DISTAL ATTACHMENT	PRIMARY ACTION(S) ABOUT THE KNEE	INNERVATION
Rectus femoris	Anterior inferior iliac spine (ASIS)	Patella	Extension	Femoral (L_2–L_4)
Vastus lateralis	Greater trochanter and lateral linea aspera	Patella	Extension	Femoral (L_2–L_4)
Vastus intermedius	Anterior femur	Patella	Extension	Femoral (L_2–L_4)
Vastus medialis	Medial linea aspera	Patella	Extension	Femoral (L_2–L_4)
Semitendinosus	Medial ischial tuberosity	Proximal medial tibia at pes	Flexion, medial rotation	Sciatic (L_5–S_2)
Semimembranosus	Lateral ischial tuberosity	Proximal medial tibia	Flexion, medial rotation	Sciatic (L_5–S_2)
Biceps femoris		Posterior lateral condyle of tibia, head of fibula	Flexion, lateral rotation	Sciatic (L_5–S_2)
(Long head)	Ischial tuberosity			
(Short head)	Lateral linea aspera			
Sartorius	Anterior superior iliac spine	Proximal medial tibia at pes	Assists with flexion and lateral rotation of thigh	Femoral (L_2, L_3)
Gracilis	Anterior, inferior symphysis pubis	Proximal medial tibia at pes	Adduction of thigh, flexion of lower leg	Obturator (L_2, L_3)
Popliteus	Lateral condyle of the femur	Posterior medial tibia	Medial rotation, flexion	Tibial (L_4, L_5)
Gastrocnemius	Posterior medial and lateral femoral condyles	Tuberosity of calcaneus via Achilles tendon	Flexion	Tibial (S_1, S_2)
Plantaris	Distal posterior femur	Tuberosity of calcaneus	Flexion	Tibial (S_1, S_2)

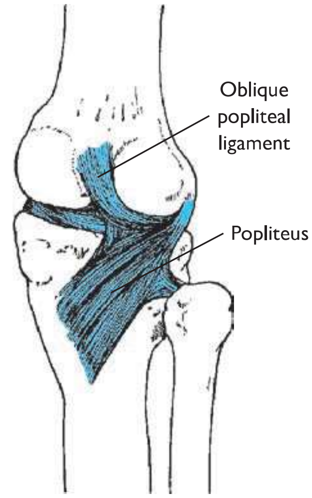


FIGURE 8-13

The popliteus muscle is the locksmith of the knee.

flexion at the knee, even when flexion is passive (22, 36, 56, 120). The exact nature of this coupling can vary between the knees of a given individual and is also influenced by loading at the knee (117). Both the ligaments of the knee and the shapes of the articular surfaces influence the patterns of these coupled motions at the knee (117).

The three hamstring muscles are the primary flexors acting at the knee. Muscles that assist with knee flexion are the gracilis, sartorius, popliteus, and gastrocnemius.

The quadriceps muscles, consisting of the rectus femoris, vastus lateralis, vastus medialis, and vastus intermedius, are the extensors of the knee (Figure 8-14). The rectus femoris is the only one of these muscles that also crosses the hip joint. All four muscles attach distally to the patellar tendon, which inserts on the tibia.

quadriceps
the rectus femoris, vastus lateralis, vastus medialis, and vastus intermedius

Rotation and Passive Abduction and Adduction

Rotation of the tibia relative to the femur is possible when the knee is in flexion and not bearing weight, with rotational capability greatest at approximately 90° of flexion. Tension development in the semimembranosus, semitendinosus, and popliteus produces medial rotation of the tibia,

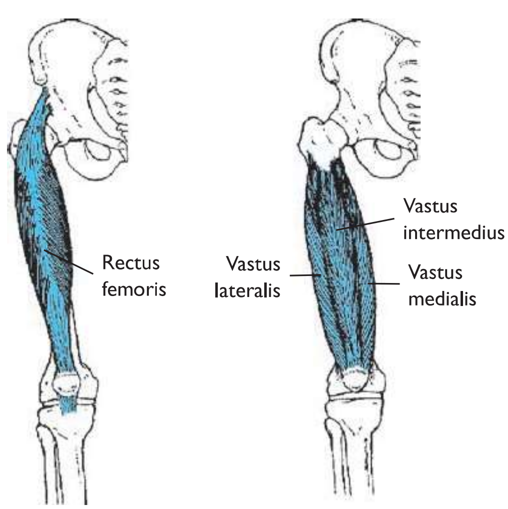


FIGURE 8-14

The quadriceps muscles extend the knee.

with the gracilis and sartorius assisting. The biceps femoris is solely responsible for lateral rotation of the tibia.

A few degrees of passive abduction and adduction are permitted at the knee. Abduction and adduction moments at the knee can also be actively generated by co-contraction of the muscles crossing the medial and lateral aspects of the knee to resist externally applied adduction and abduction moments (123). The primary contribution to these resistive moments comes from the co-contraction of the hamstrings and the quadriceps, with secondary contributions from the gracilis and the tensor fascia lata (67). The ability to resist abduction/adduction moments is relatively small, however, with only 11–14% of the experimentally applied moments resisted (67).

Patellofemoral Joint Motion

During flexion and extension at the tibiofemoral joint, the patella glides inferiorly and superiorly against the distal end of the femur with an excursion of approximately 7 cm. The path of the center of the patella is circular and uniplanar (51). Tracking of the patella against the femur is dependent on the direction of the net force produced by the attached quadriceps. The vastus lateralis tends to pull the patella laterally, while the vastus medialis oblique opposes the lateral pull of the vastus lateralis, keeping the patella centered in the patellofemoral groove. The medial and lateral quadriceps force components also tilt the patella in the sagittal and transverse planes (65). The iliotibial band also influences knee mechanics, and excessive tightness can cause maltracking of the patella (74).

LOADS ON THE KNEE

Because the knee is positioned between the body's two longest bony levers (the femur and the tibia), the potential for torque development at the joint is large. The knee is also a major weight-bearing joint.

Forces at the Tibiofemoral Joint

The tibiofemoral joint is loaded in both compression and shear during daily activities. Weight bearing and tension development in the muscles crossing the knee contribute to these forces, with compression dominating when the knee is fully extended.

Compressive force at the tibiofemoral joint has been reported to be slightly greater than three times body weight during the stance phase of gait, increasing up to approximately four times body weight during stair climbing (58). The medial tibial plateau bears most of this load during stance when the knee is extended, with the lateral tibial plateau bearing more of the much smaller loads imposed during the swing phase (121). Since the medial tibial plateau has a surface area roughly 60% larger than that of the lateral tibial plateau, the stress acting on the joint is less than if peak loads were distributed medially (58). The fact that the articular cartilage on the medial plateau is three times thicker than that on the lateral plateau also helps protect the joint from wear.

• The medial tibial plateau is well adapted for its weight-bearing function during stance, with greater surface area and thicker articular cartilage than the lateral plateau.

The menisci act to distribute loads at the tibiofemoral joint over a broader area, thus reducing the magnitude of joint stress. The menisci also directly assist with force absorption at the knee, bearing as much as an estimated 45% of the total load (104). Since the menisci help protect the articulating bone surfaces from wear, knees that have undergone meniscectomies are more likely to develop degenerative conditions.

Measurements of articular cartilage deformation on the tibial plateau during weight bearing show that stress at the joint is maximal from 180 to 120 degrees of flexion, with minimal stress at approximately 30 degrees of flexion (11). Comparison of front and back squat exercises shows no difference in overall muscle recruitment, but significantly less compressive force acting on the knee during the front squat (40). Among runners larger loads on the knee are related to reduced hamstring flexibility, greater body weight, greater weekly mileage, and greater muscular strength (75). Other general risk factors for development of knee osteoarthritis include a high body mass index and meniscal damage (93).

Forces at the Patellofemoral Joint

Compressive force at the patellofemoral joint has been found to be one-half of body weight during normal walking gait, increasing up to over three times body weight during stair climbing (89). As shown in Figure 8-15, patellofemoral compression increases with knee flexion during weight bearing. There are two reasons for this. First, the increase in knee flexion increases the compressive component of force acting at the joint. Second, as flexion increases, a larger amount of quadriceps tension is required to prevent the knee from buckling against gravity.

The squat exercise, known for being particularly stressful to the knee complex, produces a patellofemoral joint reaction force on the order of 7.6 times body weight (89). Patellofemoral joint reaction forces increase with the depth of the squat, although the variations in the magnitudes of these forces are not significantly different among shallow, medium, and deep squats (96). Training within the 0–50° knee flexion range is recommended for those who wish to minimize knee forces, however (28). The squat has been shown to be an effective exercise for use during rehabilitation following cruciate ligament or patellofemoral surgery (27). Sample Problem 8.2 illustrates the relationship between quadriceps force and patellofemoral joint compression.

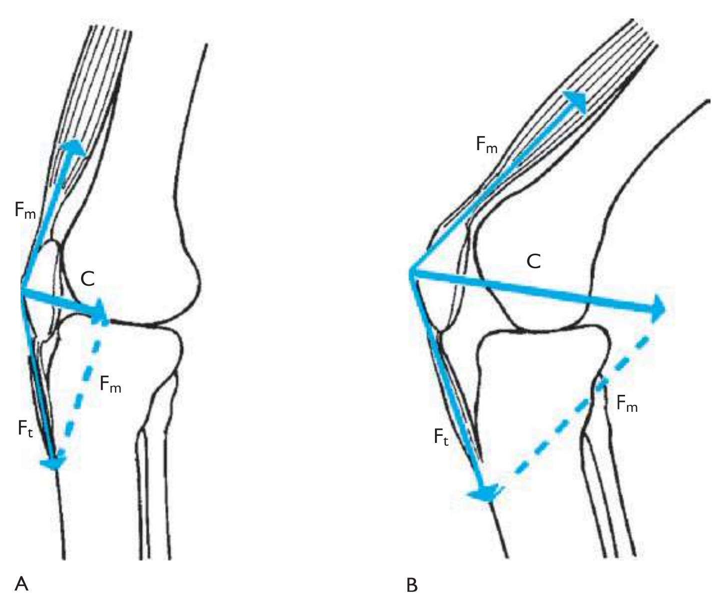


FIGURE 8-15

Compression at the patellofemoral joint is the vector sum of tension in the quadriceps and the patellar tendon. **A.** In extension, the compressive force is small because tension in the muscle group and tendon act nearly perpendicular to the joint. **B.** As flexion increases, compression increases because of changed orientation of the force vectors and increased tension requirement in the quadriceps to maintain body position.

SAMPLE PROBLEM 8.2

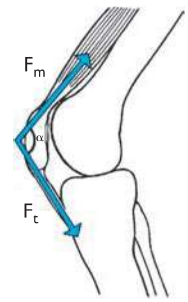
How much compression acts on the patellofemoral joint when the quadriceps exerts 300 N of tension and the angle between the quadriceps and the patellar tendon is (a) 160° and (b) 90°?

Known

$$F_m = 300 \text{ N}$$

Angle between F_m and F_t:

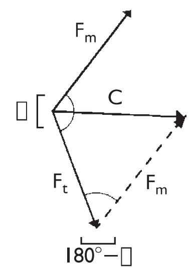
1. 160°
2. 90°



Graphic Solution

Vectors for F_m and F_t are drawn to scale (perhaps 1 cm: 100 N), with the angle between them first at 160° and then at 90°. The tip-to-tail method of vector composition is then used (see Chapter 3) to translate one of the vectors so that its tail is positioned on the tip of the other vector. The compression force is the resultant of F_m and F_t and is constructed with its tail on the tail of the original vector and its tip on the tip of the transposed vector.

The amount of joint compression can be approximated by measuring the length of vector C.



1. C ≈ 100 N
2. C ≈ 420 N

Mathematical Solution

The angle between F_t and transposed vector F_m is 180° minus the size of the angle between the two original vectors, or (a) 20° and (b) 90°. The law of cosines can be used to calculate the length of C.

1. $C^2 = F_m{}^2 + F_t{}^2 - 2(F_m)(F_t) \cos 20$

   $C^2 = 300 \text{ N}^2 + 300 \text{ N}^2 - 2(300 \text{ N})(300 \text{ N}) \cos 20$

   $C = 104 \text{ N}$

2. $C^2 = F_m{}^2 + F_t{}^2 - 2(F_m)(F_t) \cos 90$

   $C^2 = 300 \text{ N}^2 + 300 \text{ N}^2 - 2(300 \text{ N})(300 \text{ N}) \cos 90$

   $C = 424 \text{ N}$

Note: This problem illustrates the extent to which patellofemoral compression can increase due solely to changes in knee flexion.

Normally, there is also increased quadriceps force with increased knee flexion.

COMMON INJURIES OF THE KNEE AND LOWER LEG

The location of the knee between the long bones of the lower extremity, combined with its weight-bearing and locomotion functions, makes it susceptible to injury, particularly during participation in contact sports. A common injury mechanism involves the stretching or tearing of soft tissues on one side of the joint when a blow is sustained from the opposite side during weight bearing.

Anterior Cruciate Ligament Injuries

Injuries to the anterior cruciate ligament (ACL) are common in sports such as basketball and team handball, which involve pivoting and cutting, as well as in Alpine skiing, where a common mechanism involves catching a ski tip in the snow, with the skier simultaneously twisting and falling. Approximately 70% of ACL injuries are noncontact, with most of these being sustained when the femur is rotated on the planted leg with the knee close to full extension during cutting, landing, or stopping (13, 60). These kinds of activities involving sudden changes in direction combined with acceleration or deceleration of the body produce large rotational moments and varus/valgus forces at the knee, particularly when such movements are inadequately planned. The ACL is loaded when the net shear force at the knee is directed anteriorly (102). So, for ACL rupture to occur, there must be excess anterior translation or rotation of the femur on the tibia.

There is a striking gender disparity in the incidence of ACL injuries, with women sustaining significantly more than men. A number of hypotheses related to anatomical or neuromuscular factors have been advanced, but the reason for this disparity remains unknown. Research has shown that during running, cutting, and landing, women, as compared to men, tend to have less knee flexion, greater knee valgus angles, more hip abduction, greater quadriceps activation, less hamstring activation, and generally less variability in lower-extremity coordination patterns (32, 33, 49, 69, 72, 86). Some have advocated strengthening or stiffening of the hamstrings to protect the ACL, since female athletes tend to have greater quadriceps-to-hamstrings strength ratios than do male athletes (12). Research on the notion that tension in the hamstrings can reduce forces on the ACL has produced conflicting results, however (64, 105). Others have advocated strengthening the quadriceps to protect against ACL injuries, since the quadriceps provide the primary muscular restraint to anterior tibial translation during activities such as running and jumping (14). Yet other research has shown that women, as compared to men, have increased coactivation of the quadriceps during knee flexion, which may increase anterior tibial loads under dynamic conditions and increase the risk of ACL injury (116). Still others have encouraged training programs for female athletes focusing on landing and pivoting with increased knee flexion and not allowing medial or lateral sagging of the knees during cutting maneuvers to protect the ACL from excessive strain (25, 79). It has been demonstrated that sagittal plane knee forces cannot rupture the ACL during sidestep cutting, so during this maneuver, valgus loading is a more likely injury mechanism (71).

Following unrepaired ACL rupture, most individuals have difficulty with movements involving lateral or rotational loads at the knee, and 70–80% experience knee instability or “giving way” (103). There is also a notable lessening of flexion–extension range of motion at the knee during walking, which has been attributed to “quadriceps avoidance” (4). This does not appear to be related to a deficit in quadriceps strength, but instead may be attributed to the fact that quadriceps tension produces an anteriorly directed force on the tibia when the knee is near full extension. Individuals seem to adapt to the absence of the ACL by minimizing activation of the quadriceps when the knee is near full extension (4). There is also evidence of general impairment of neuromuscular control of the quadriceps, with the muscles remaining active during tasks not requiring quadriceps activation (119). Although some ACL-deficient individuals are able to stabilize their knees even during cutting and pivoting, for most, the absence of the ACL results in local instability of the knee, a change in the location of the center of rotation at the knee, a change in the area of tibiofemoral contact during gait, and altered joint kinetics, with subsequent onset of osteoarthritis (3, 22, 98, 107).

Surgical repair of ACL rupture involves reconstruction of the ligament using either the middle third of the patellar tendon, the semitendinosus, or the semitendinosus and gracilis (34). Problems that follow trauma to the knee, whether the trauma is injury- or surgery-induced, include notable weakness and loss of mass in the knee extensor muscles, dramatic reduction of joint range of motion, and impaired joint proprioception (109). The reasons for these changes are not understood; they may be neural or mechanical in origin or a product of deconditioning (46). One factor hypothesized to play a major role in precipitating these changes is muscle inhibition, or the inability to activate all motor units of a muscle during maximal voluntary contraction (108). It has been shown that muscle inhibition can persist for an extended time and may be responsible for long-term strength deficits that alter joint kinetics and lead to osteoarthritis (50, 106, 108).

muscle inhibition
the inability to activate all motor units of a muscle during maximal voluntary contraction

Posterior Cruciate Ligament Injuries

Posterior cruciate ligament (PCL) injuries most commonly result from sport participation or motor vehicle accidents (20, 54). When the PCL is ruptured in isolation, with no damage to the other ligaments or to the menisci, the mechanism is usually hyperflexion of the knee with the foot plantar flexed (54). Impact with the dashboard during motor vehicle accidents, on the other hand, with direct force on the proximal anterior tibia, results in combined ligamentous damage in 95% of cases (54). Isolated PCL injuries are usually treated nonoperatively.

Medial Collateral Ligament Injuries

Blows to the lateral side of the knee are much more common than blows to the medial side, because the opposite leg commonly protects the medial side of the joint. When the foot is planted and a lateral blow of sufficient force is sustained, the result is sprain or rupture of the medial collateral ligament (MCL). Modeling studies suggest that the muscles crossing the knee are able to resist approximately 17% of external medial and lateral loads on the knee, with the remaining 83% sustained by the ligaments and other soft tissues (66). However, direct measurements of strain to the knee ligaments indicate that external tibial torque is more dangerous than medially directed tibial force for the MCL (48). In contact sports such as football, the MCL is more frequently injured, while both medial and lateral collateral ligament sprains occur among wrestlers.

• *In contact sports, blows to the knee are most commonly sustained on the lateral side, with injury occurring to the stretched tissues on the medial side.*

Prophylactic Knee Bracing

To prevent knee ligament injuries, especially during contact sports, some athletes wear prophylactic knee braces. The wearing of such braces by healthy individuals has been a contentious issue since the American Academy of Orthopaedics issued a position statement against their use in 1987. Research on this topic has shown that knee braces can protect the ACL against anterior and torsional loads on the tibia by significantly reducing the strain present in the ligament under these conditions (10). Knee braces can also contribute 20–30% added resistance against lateral blows to the knee, with custom-fitted braces providing the best protection (1). A possible concern, however, is that knee braces act to change the pattern of lower-extremity muscle activity during gait, with less work performed at the knee and more at the hip (23). Other problems that appear to affect some athletes more than others and may be brace-specific include reduced sprinting speed and earlier onset of fatigue (1).

Meniscus Injuries

Because the medial collateral ligament attaches to the medial meniscus, stretching or tearing of the ligament can also result in damage to the meniscus. A torn meniscus is the most common knee injury, with damage to the medial meniscus occurring approximately 10 times as frequently as damage to the lateral meniscus. This is the case partly because the medial meniscus is more securely attached to the tibia, and therefore less mobile than the lateral meniscus. In knees that have undergone ACL rupture, the normal stress distribution is disrupted such that the force on the medial meniscus is doubled (84). In the absence of ACL reconstruction, this results in an increased incidence of medial meniscal tears, although loading of the meniscus returns to normal if the ACL is reconstructed (2, 47). A torn meniscus is problematic in that the unattached cartilage often slips from its normal position, interfering with normal joint mechanics. Symptoms include pain, which is sometimes accompanied by intermittent bouts of locking or buckling of the joint.

Iliotibial Band Friction Syndrome

The tensor fascia lata develops tension to assist with stabilization of the pelvis when the knee is in flexion during weight bearing. This can produce friction of the posterior edge of the iliotibial band (ITB) against the lateral condyle of the femur around the time of footstrike, primarily during foot contact with the ground (82). The result is inflammation of the distal portion of the ITB, as well as the knee joint capsule under the ITB, with accompanying symptoms of pain and tenderness over the lateral aspect of the knee (59). This condition is an overuse syndrome that affects approximately 2–12% of runners and can also affect cyclists (91). Both training errors and anatomical malalignments within the lower extremity increase the risk of ITB syndrome. Training factors in running include excessive running in the same direction on a track, greater-than-normal weekly mileage, and downhill running (35). Runners who had previously sustained iliotibial band syndrome displayed characteristic gait anomalies, including greater peak knee internal rotation and greater peak hip adduction compared to normal runners (30). Both of these kinematic differences place added stress on the iliotibial band. Improper seat height, as well as greater-than-normal weekly mileage, predisposes cyclists to the syndrome (29). Predisposing malalignments include excessive femoral anteversion, increased Q-angle (see below), lateral tibial torsion, tibial genu varum or valgum, subtalar varus, and excessive pronation (61).

Breaststroker's Knee

A condition of pain and tenderness localized on the medial aspect of the knee is often associated with performance of the whip kick, the kick

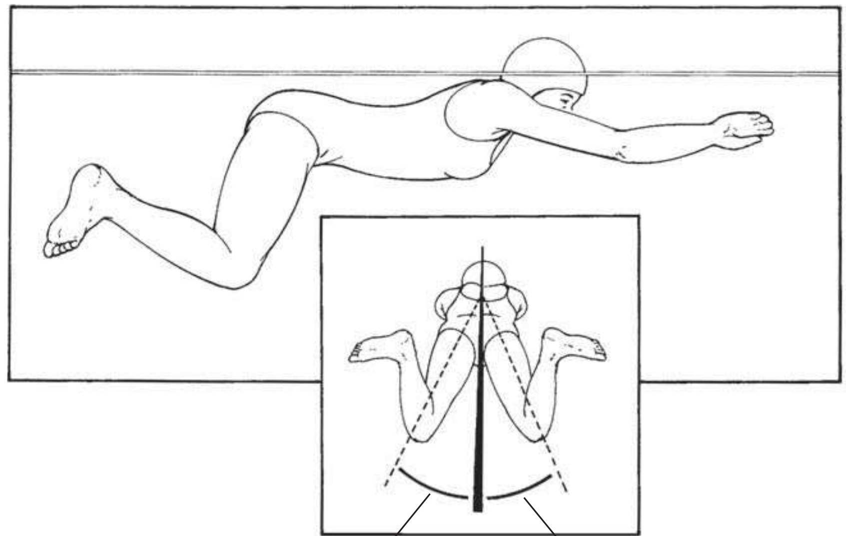


FIGURE 8-16

The likelihood of acquiring breaststroker's knee is much lower if the angle of hip abduction is between 37° and 42° at the beginning of the propulsive phase of the kick.

used with the breaststroke. The forceful whipping together of the lower legs that provides the propulsive thrust of the kick often forces the lower leg into slight abduction at the knee, with subsequent irritation to the medial collateral ligament and the medial border of the patellar tract. A survey of 391 competitive swimmers revealed incidences of knee pain among 73% of the breaststroke specialists and 48% of nonbreaststrokers (115). In a study of breaststroke kinematics, it was found that angles of hip abduction of less than 37° or greater than 42° at the initiation of the kick resulted in a dramatically increased incidence of knee pain (115) (Figure 8-16).

Patellofemoral Pain Syndrome

•Painful lateral deviation in patellar tracking could be caused by weakness of the vastus medialis oblique.

Painful patellofemoral joint motion involves anterior knee pain during and after physical activity, particularly activities requiring repeated flexion at the knee, such as running, ascending and descending stairs, and squatting. It is more common among females than among males. This syndrome has been attributed to a number of possible causes, including anatomical malalignment(s), imbalance between the VMO and the VL in strength or activation timing, decreased quadriceps and hamstring strength, increased hip external rotator strength, and overactivity (15, 68, 78, 86, 87, 93).

While the causes of this disorder are unknown, most research attention has focused on the relationship between the VMO and the VL. Weakness of the VMO relative to the VL has been shown to be associated with a lateral shift of the patella, particularly early in the range of knee flexion (87, 95). Research has also documented that individuals with patellofemoral pain display reduced patellofemoral joint loads with strengthening of the VMO (80). Such individuals also demonstrate onset of VL activation prior to VMO activation during stair stepping (21). An experiment in which the VMO and VL were electrically stimulated showed a respective increase and decrease in patellofemoral joint loading when VMO activation was delayed (80).

An anatomical factor hypothesized to contribute to lower-extremity malalignment that could trigger patellofemoral pain is an excessively large Q-angle, the angle formed between the anterior superior iliac spine, the center of the patella, and the tibial tuberosity (44). The Q-angle provides an approximation of the angle of pull of the quadriceps on the patella, and it has been hypothesized that a large Q-angle could lead to lateral patellar dislocation or increased lateral patellofemoral contact pressures (77). To date, however, research has not documented a relationship between Q-angle and incidence of patellofemoral pain. The one anatomical factor that has been found to be related to patellar maltracking is a shallow intercondylar groove (88).

Q-angle
angle formed between the anterior superior iliac spine, the center of the patella, and the tibial tuberosity

Shin Splints

Generalized pain along the anterolateral or posteromedial aspect of the lower leg is commonly known as *shin splints*. This is a loosely defined overuse injury, often associated with running or dancing, that may involve microdamage to muscle attachments on the tibia and/or inflammation of the periosteum. Common causes of the condition include running or dancing on a hard surface and running uphill. A change in workout conditions or rest usually alleviates shin splints.

•Shin splints *is a generic term often ascribed to any pain emanating from the anterior aspect of the lower leg.*

STRUCTURE OF THE ANKLE

The ankle region includes the distal tibiofibular, tibiotalar, and fibulotalar joints (Figure 8-17). The distal tibiofibular joint is a syndesmosis where dense fibrous tissue binds the bones together. The joint is supported by the anterior and posterior tibiofibular ligaments, as well as by the crural interosseous tibiofibular ligament. Most motion at the ankle occurs at the tibiotalar hinge joint, where the convex surface of the superior talus articulates with the concave surface of the distal tibia. All three articulations are enclosed in a joint capsule that is thickened on the medial side and extremely thin on the posterior side. Three ligaments—the anterior and posterior talofibular, and the calcaneofibular—reinforce the joint

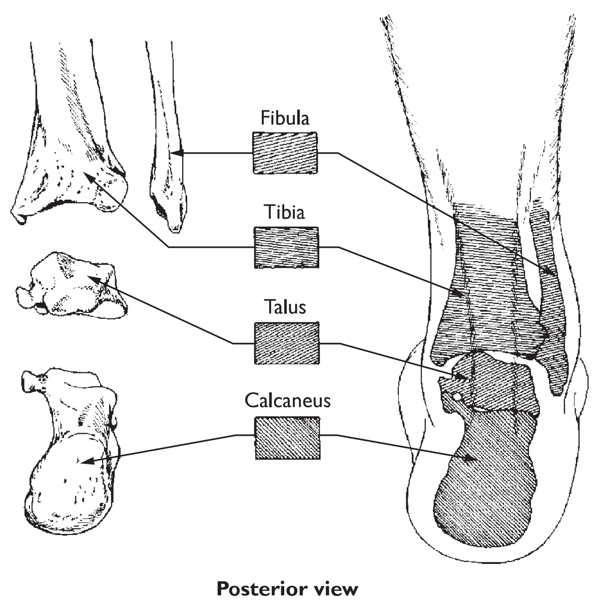


FIGURE 8-17

The bony structure of the ankle.

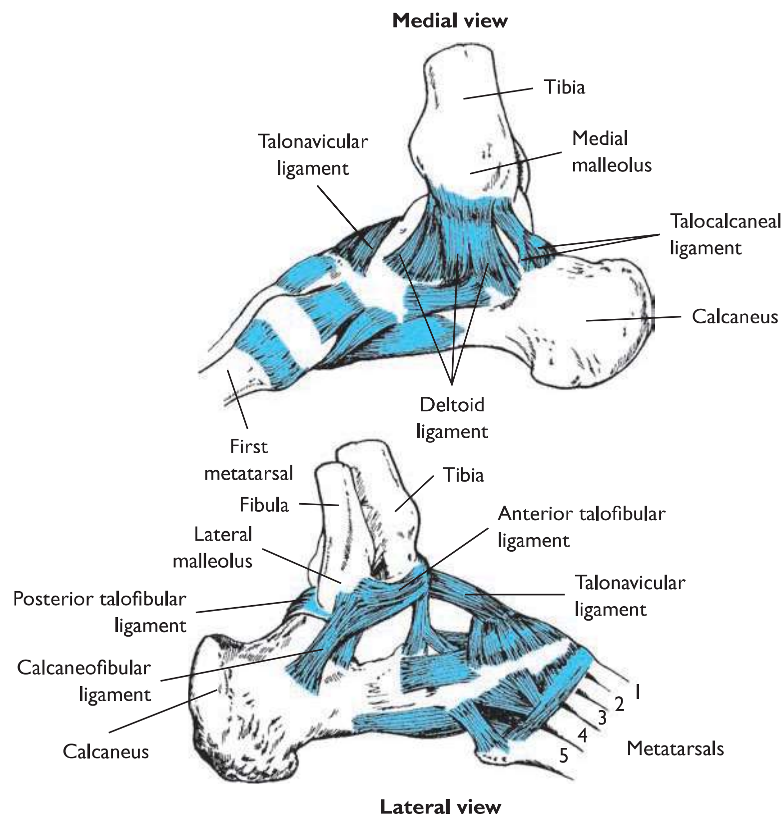


FIGURE 8-18

The ligaments of the ankle.

capsule laterally. The four bands of the deltoid ligament contribute to joint stability on the medial side. The ligamentous structure of the ankle is displayed in Figure 8-18.

MOVEMENTS AT THE ANKLE

• *The malleoli serve as pulleys to channel muscle tendons anterior or posterior to the axis of rotation at the ankle; those anterior to the malleoli are dorsiflexors and those posterior to the malleoli serve as plantar flexors.*

The axis of rotation at the ankle is essentially frontal, although it is slightly oblique and its orientation changes somewhat as rotation occurs at the joint. Motion at the ankle occurs primarily in the sagittal plane, with the ankle functioning as a hinge joint with a moving axis of rotation during the stance phase of gait (63). Ankle flexion and extension are termed *dorsiflexion* and *plantar flexion*, respectively (see Chapter 2). During passive motion, the articular surfaces and ligaments govern joint kinematics, with the articular surfaces sliding upon each other without appreciable tissue deformation (63).

The medial and lateral malleoli serve as pulleys to channel the tendons of muscles crossing the ankle either posterior or anterior to the axis of rotation, thereby enabling their contributions to either dorsiflexion or plantar flexion.

The tibialis anterior, extensor digitorum longus, and peroneus tertius are the prime dorsiflexors of the foot. The extensor hallucis longus assists in dorsiflexion (Figure 8-19).

The major plantar flexors are the two heads of the powerful two-joint gastrocnemius and the soleus, which lies beneath the gastrocnemius (Figure 8-20). Assistant plantar flexors include the tibialis posterior,

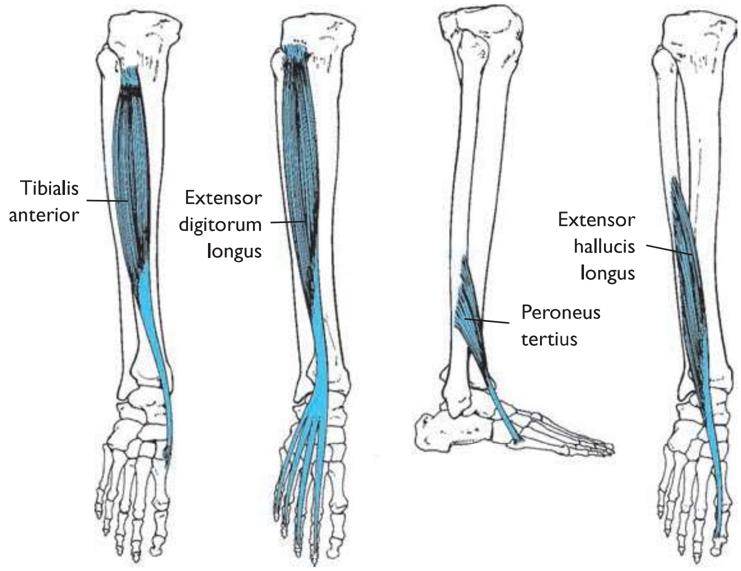


FIGURE 8-19

The dorsiflexors of the ankle.

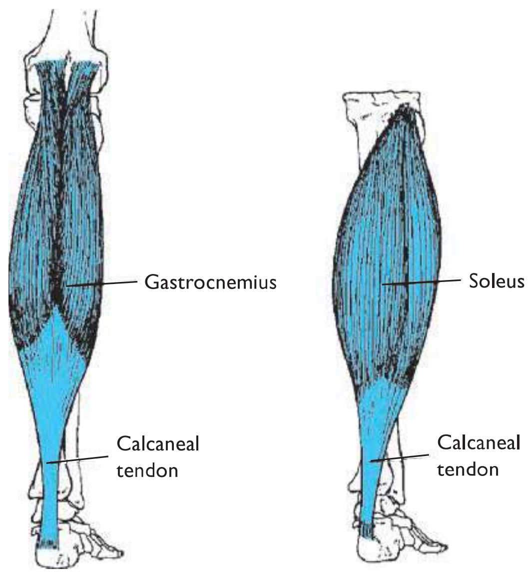


FIGURE 8-20

The major plantar flexors of the ankle.

peroneus longus, peroneus brevis, plantaris, flexor hallucis longus, and flexor digitorum longus (Figure 8-21).

STRUCTURE OF THE FOOT

Like the hand, the foot is a multibone structure. It contains a total of 26 bones with numerous articulations (Figure 8-22). Included are the subtalar and midtarsal joints and several tarsometatarsal, intermetatarsal, metatarsophalangeal, and interphalangeal joints. Together, the bones and joints of the foot provide a foundation of support for the upright body and help it adapt to uneven terrain and absorb shock.

Subtalar Joint

As the name suggests, the subtalar joint lies beneath the talus, where anterior and posterior facets of the talus articulate with the sustentaculum tali on the superior calcaneus. Four talocalcaneal ligaments join the

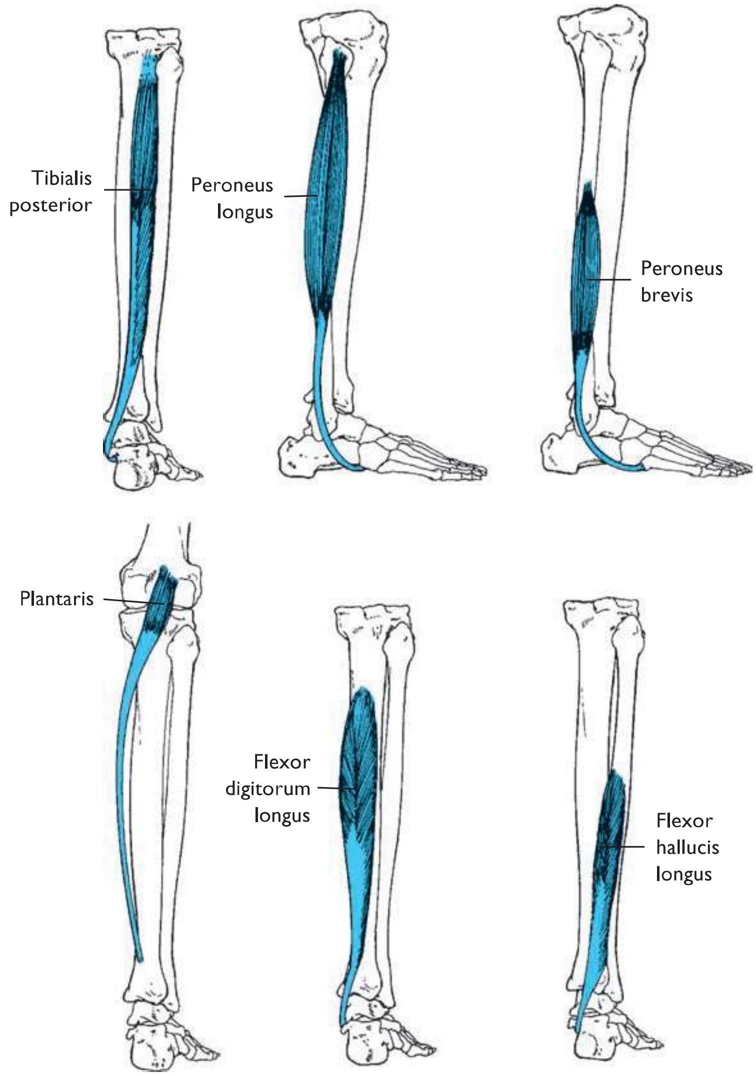


FIGURE 8-21

Muscles with tendons passing posterior to the malleoli assist with plantar flexion of the ankle.

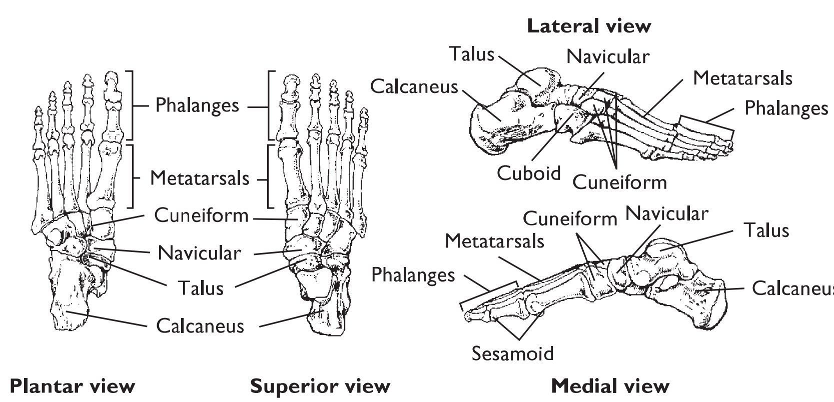


FIGURE 8-22

The foot is composed of numerous articulating bones.

talus and the calcaneus. The joint is essentially uniaxial, with an alignment slightly oblique to the conventional descriptive planes of motion.

Tarsometatarsal and Intermetatarsal Joints

Both the tarsometatarsal and the intermetatarsal joints are nonaxial, with the bone shapes and the restricting ligaments permitting only gliding movements. These joints enable the foot to function as a semirigid unit or to adapt flexibly to uneven surfaces during weight bearing.

Metatarsophalangeal and Interphalangeal Joints

The metatarsophalangeal and interphalangeal joints are similar to their counterparts in the hand, with the former being condyloid joints and the latter being hinge joints. Numerous ligaments provide reinforcement for these joints. The toes function to smooth the weight shift to the opposite foot during walking and help maintain stability during weight bearing by pressing against the ground when necessary. The first digit is referred to as the *hallux,* or "great toe."

Plantar Arches

The tarsal and metatarsal bones of the foot form three arches. The medial and lateral longitudinal arches stretch from the calcaneus to the metatarsals and tarsals. The transverse arch is formed by the bases of the metatarsal bones.

Several ligaments and the plantar fascia support the plantar arches. The spring ligament is the primary supporter of the medial longitudinal arch, stretching from the sustentaculum tali on the calcaneus to the inferior navicular. The long plantar ligament provides the major support for the lateral longitudinal arch, with assistance from the short plantar ligament. Thick, fibrous, interconnected bands of connective tissue known as the plantar fascia extend over the plantar surface of the foot, assisting with support of the longitudinal arch (Figure 8-23). When muscle tension is present, the muscles of the foot, particularly the tibialis posterior, also contribute support to the arches and joints as they cross them.

As the arches deform during weight bearing, mechanical energy is stored in the stretched tendons, ligaments, and plantar fascia. Additional energy is stored in the gastrocnemius and soleus as they develop eccentric tension. During the push-off phase, the stored energy in all of these elastic structures is released, contributing to the force of push-off and actually reducing the metabolic energy cost of walking or running.

plantar fascia
thick bands of fascia that cover the plantar aspect of the foot

• *During weight bearing, mechanical energy is stored in the stretched ligaments, tendons, and plantar fascia of the arches of the foot, as well as in eccentrically contracting muscles. This stored energy is released to assist with push-off of the foot from the surface.*

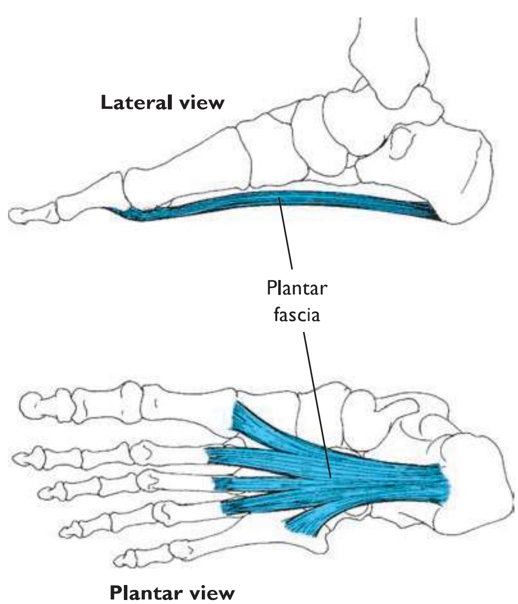


FIGURE 8-23

The plantar fascia.

MOVEMENTS OF THE FOOT

Muscles of the Foot

The locations and primary actions of the major muscles of the ankle and foot are summarized in Table 8-3. As with the muscles of the hand, extrinsic muscles are those crossing the ankle, and intrinsic muscles have both attachments within the foot.

Toe Flexion and Extension

Flexion involves the curling under of the toes. Flexors of the toes include the flexor digitorum longus, flexor digitorum brevis, quadratus plantae, lumbricals, and interossei. The flexor hallucis longus and brevis produce flexion of the hallux. Conversely, the extensor hallucis longus, extensor digitorum longus, and extensor digitorum brevis are responsible for extension of the toes.

TABLE 8-3

Muscles of the Ankle and Foot

MUSCLE	PROXIMAL ATTACHMENT	DISTAL ATTACHMENT	PRIMARY ACTION(S)	INNERVATION
Tibialis anterior	Upper two-thirds of lateral tibia	Medial surface of first cuneiform and first metatarsal	Dorsiflexion, inversion	Deep peroneal (L_4–S_1)
Extensor digitorum longus	Lateral condyle of tibia, head of fibula, upper two-thirds of anterior fibula	Second and third phalanges of four lesser toes	Toe extension, dorsiflexion, eversion	Deep peroneal (L_4–S_1)
Peroneus tertius	Lower third anterior fibula	Dorsal surface of fifth metatarsal	Dorsiflexion, eversion	Deep peroneal (L_4–S_1)
Extensor hallucis longus	Middle two-thirds of medial anterior fibula	Dorsal surface of distal phalanx of great toe	Dorsiflexion, inversion, hallux extension	Deep peroneal (L_4–S_1)
Gastrocnemius	Posterior medial and lateral condyles of femur	Tuberosity of calcaneus via Achilles tendon	Plantar flexion	Tibial (S_1–S_2)
Plantaris	Distal, posterior femur	Tuberosity of calcaneus via Achilles tendon	Assists with plantar flexion	Tibial (S_1–S_2)
Soleus	Posterior proximal fibula and proximal two-thirds of posterior tibia	Tuberosity of calcaneus via Achilles tendon	Plantar flexion	Tibial (S_1–S_2)
Peroneus longus	Head and upper two-thirds of lateral fibula	Lateral surface of first cuneiform and first metatarsal	Plantar flexion, eversion	Superficial peroneal (L_4–S_1)
Peroneus brevis	Distal two-thirds lateral	Tuberosity of fifth fibula	Plantar flexion, eversion metatarsal	Superficial peroneal (L_4–S_1)
Flexor digitorum longus	Middle third of posterior tibia	Distal phalanx of four lesser toes	Plantar flexion, inversion, toe flexion	Tibial (L_5–S_1)
Flexor hallucis longus	Middle two-thirds of posterior fibula	Distal phalanx of great toe	Plantar flexion, inversion, toe flexion	Tibial (L_4–S_2)
Tibialis posterior	Posterior upper two-thirds tibia and fibula and interosseous membrane	Cuboid, navicular, and second to fifth metatarsals	Plantar flexion, inversion	Tibial (L_5–S_1)

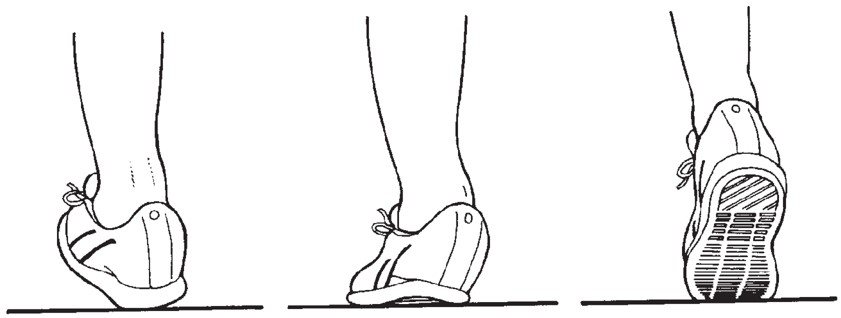


FIGURE 8-24

Rearfoot movement during running. Adapted from Nigg BM et al: Factors influencing kinetic and kinematic variables in running, in BM Nigg (ed): *Biomechanics of running shoes,* Champaign, 1986, Human Kinetics Publishers.

Inversion and Eversion

Rotational movements of the foot in medial and lateral directions are termed *inversion* and *eversion,* respectively (see Chapter 2). These movements occur largely at the subtalar joint, although gliding actions among the intertarsal and tarsometatarsal joints also contribute. Inversion results in the sole of the foot turning inward toward the midline of the body. The tibialis posterior and tibialis anterior are the main muscles involved. Turning the sole of the foot outward is termed *eversion.* The muscles primarily responsible for eversion are the peroneus longus and the peroneus brevis, both with long tendons coursing around the lateral malleolus. The peroneus tertius assists.

Pronation and Supination

During walking and running, the foot and ankle undergo a cyclical sequence of movements (Figure 8-24). As the heel contacts the ground, the rear portion of the foot typically inverts to some extent. When the foot rolls forward and the forefoot contacts the ground, plantar flexion occurs (114). The combination of inversion, plantar flexion, and adduction of the foot is known as supination (see Chapter 2). While the foot supports the weight of the body during midstance, there is a tendency for eversion and abduction to occur as the foot moves into dorsiflexion. These movements are known collectively as pronation. Pronation serves to reduce the magnitude of the ground reaction force sustained during gait by increasing the time interval over which the force is sustained (18).

supination
combined conditions of plantar flexion, inversion, and adduction

pronation
combined conditions of dorsiflexion, eversion, and abduction

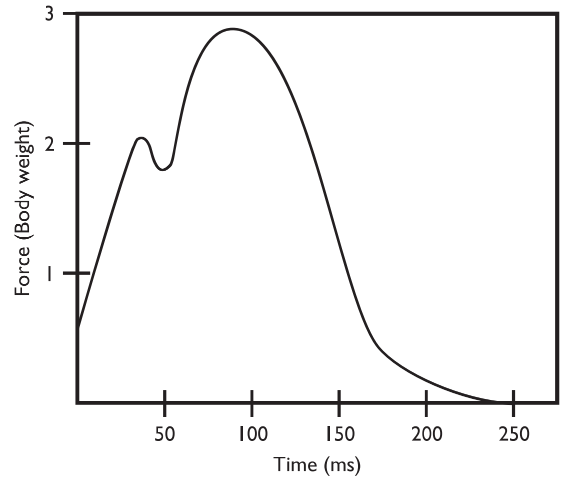
LOADS ON THE FOOT

Impact forces sustained during gait increase with body weight and with gait speed in accordance with Newton's third law of motion (see Chapter 3). The vertical ground reaction force applied to the foot during running is bimodal, with an initial impact peak followed almost immediately by a propulsive peak, as the foot pushes off against the ground (Figure 8-25). As running speed increases from 3.0 m/s (8:56 minutes per mile) to 5.0 m/s (5:22 minutes per mile), impact forces range from 1.6 to 2.3 times body weight and propulsive forces range from 2.5 to 2.8 times body weight (78).

The structures of the foot are anatomically linked such that the load is evenly distributed over the foot during weight bearing. Approximately 50% of body weight is distributed through the subtalar joint to the calcaneus, with the remaining 50% transmitted across the metatarsal heads (97). The head of the first metatarsal sustains twice the load borne by each of the other metatarsal heads (97). A factor that influences this loading pattern,

FIGURE 8-25

Vertical ground reaction force during running with an initial impact peak followed almost immediately by a propulsive peak.



however, is the architecture of the foot. A pes planus (relatively flat arch) condition tends to reduce the load on the forefoot, with pes cavus (relatively high arch) significantly increasing the load on the forefoot (117, 118).

COMMON INJURIES OF THE ANKLE AND FOOT

Because of the crucial roles played by the ankle and foot during locomotion, injuries to this region can greatly limit mobility. Injuries of the lower extremity, especially those of the foot and ankle, may result in weeks or even months of lost training time for athletes, particularly runners. Among dancers, the foot and the ankle are the most common sites of both chronic and acute injuries.

Ankle Injuries

• *Ankle sprains usually occur on the lateral side because of weaker ligamentous support than is present on the medial side.*

Ankle sprains are the most common of all sport- and dance-related injuries (94). Because the joint capsule and ligaments are stronger on the medial side of the ankle, inversion sprains involving stretching or rupturing of the lateral ligaments are much more common than eversion sprains of the medial ligaments (16). In fact, the bands of the deltoid ligament are so strong that excessive eversion is more likely to result in a fracture of the distal fibula than in rupturing of the deltoid ligament. The ligaments most commonly injured are the anterior and posterior talofibular ligaments and the calcaneofibular ligament. Because of the protection by the opposite limb on the medial side, fractures in the ankle region also occur more often on the lateral than on the medial side. Repeated ankle sprains can result in functional ankle instability, which is characterized by significantly altered patterns of ankle and knee movement. Researchers hypothesize that this is related to altered motor control of the foot/ankle complex, which unfortunately predisposes the ankle to further injury (18).

Bracing and taping are two prophylactic measures often used to protect ankles from sprain during sport participation. Ankle braces are designed to preload the ankle and maintain it in a neutral position, thereby counteracting inversionally directed rotation (111). There are contradictory reports in the scientific literature regarding the efficacy of both bracing and taping of the ankle. One reported disadvantage of both bracing and taping of the ankle is a reduction in postural control, causing less stability and more touching down on the foot of the supported ankle (6).

Overuse Injuries

Achilles tendinitis involves inflammation and sometimes microrupturing of tissues in the Achilles tendon, typically accompanied by swelling. Two possible mechanisms for tendinitis have been proposed (90). The first is that repeated tension development results in fatigue and decreased flexibility in the muscle, increasing tensile load on the tendon even during relaxation of the muscle. The second theory is that repeated loading actually leads to failure or rupturing of the collagen threads in the tendon. Achilles tendinitis is usually associated with running and jumping activities and is extremely common among theatrical dancers. It has also been reported in skiers. Complete rupturing of the Achilles tendon occurs almost exclusively in male skiers, although incidence of the injury has decreased with the advent of high, rigid ski boots and effective release bindings (81).

Repetitive stretching of the plantar fascia can result in plantar fascitis, a condition characterized by microtears and inflammation of the plantar fascia near its attachment to the calcaneus. The symptoms are pain in the heel and/or arch of the foot. The condition is the fourth most common cause of pain among runners, and also occurs with some frequency among basketball players, tennis players, gymnasts, and dancers (62). Anatomical factors believed to contribute to the development of plantar fascitis include pes planus (flat foot), a rigid cavus (high-arch) foot, and a tight Achilles tendon, all of which reduce the foot's shock-absorbing capability (110).

Another factor linked to overuse injuries of the lower extremity is excessive pronation (19). Although walking normally involves approximately 6–8° of subtalar pronation, individuals with pes planus undergo 10–12° of pronation (90). Because pronation also causes a compensatory inward rotation of the tibia, excessive pronation can result in increased stress within the plantar fascia and Achilles tendon. Excessive pronation has been associated with running injuries, including shin splints, chondromalacia, plantar fascitis, and Achilles tendinitis. Excessive pronation has been documented among 60% of one group of injured runners (53).

Stress fractures (see Chapter 4) occur relatively frequently in the bones of the lower extremity. Among a group of 320 athletes with bone-scan-positive stress fractures, the bone most frequently injured was the tibia (49.1%), followed by the tarsals (25.3%), metatarsals (8.8%), femur (7.2%), fibula (6.6%), and pelvis (1.6%) (70). The sites most frequently injured in the older athletes in the group were the femur and the tarsals, with the fibula and tibia most often injured among the younger athletes. Among runners, factors associated with stress fractures include training errors, forefoot striking (toe–heel gait), running on hard surfaces such as concrete, improper footwear, and alignment anomalies of the trunk and/or lower extremity (37). Female runners with a history of tibial stress fracture displayed greater peak hip adduction and peak rear foot eversion angles as compared to other runners, suggesting that this kinematic pattern may be predisposing for the injury (76). Stress fractures among dancers occur most frequently to the second and third metatarsals, and appear to be related to dancing on overly hard surfaces (42). Dancing *en pointe* is particularly stressful to the second metatarsal, because tension in the peroneus longus and tibialis posterior needed for maintaining the *en pointe* position places the stressed second metatarsal in traction (42). Stress fractures among women runners, dancers, and gymnasts may be related to decreased bone mineral density secondary to oligomenorrhea (see Chapter 4).

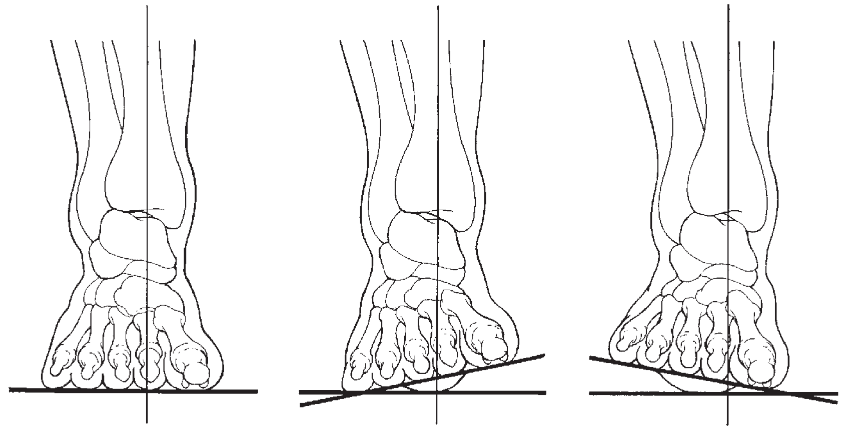


FIGURE 8-26

Varus and valgus conditions of the forefoot.

Alignment Anomalies of the Foot

varus
condition of inward deviation in alignment from the proximal to the distal end of a body segment

valgus
condition of outward deviation in alignment from the proximal to the distal end of a body segment

Varus and valgus conditions (inward and outward lateral deviation, respectively, of a body segment) can occur in all of the major links of the lower extremity. These may be congenital or may arise from an imbalance in muscular strength.

In the foot, varus and valgus conditions can affect the forefoot, the rearfoot, and the toes. Forefoot varus and forefoot valgus refer to inversion and eversion misalignments of the metatarsals, and rearfoot varus and valgus involve inversion and eversion misalignments at the subtalar joint (Figure 8-26). Hallux valgus is a lateral deviation of the big toe often caused by wearing women's shoes with pointed toes (Figure 8-27).

Varus and valgus conditions in the tibia and the femur can alter the kinematics and kinetics of joint motion, because they cause added tensile stress on the stretched side of the affected joint. For example, a combination of femoral varus and tibial valgus (a knock-knee condition) places added tension on the medial aspect of the knee (Figure 8-28). In contrast, the bow-legged condition of femoral valgus and tibial varus stresses the lateral aspect of the knee and is therefore a predisposing factor for iliotibial band friction syndrome. Unfortunately, lateral misalignments at one joint of the lower extremity are typically accompanied by compensatory

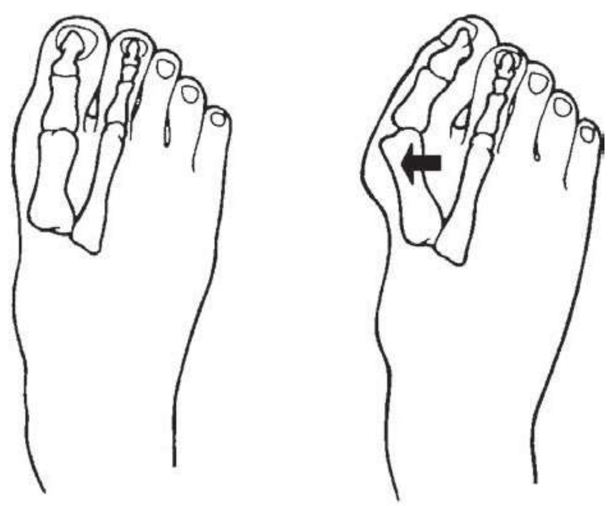


FIGURE 8-27

Wearing shoes with pointed toes can cause hallux valgus.

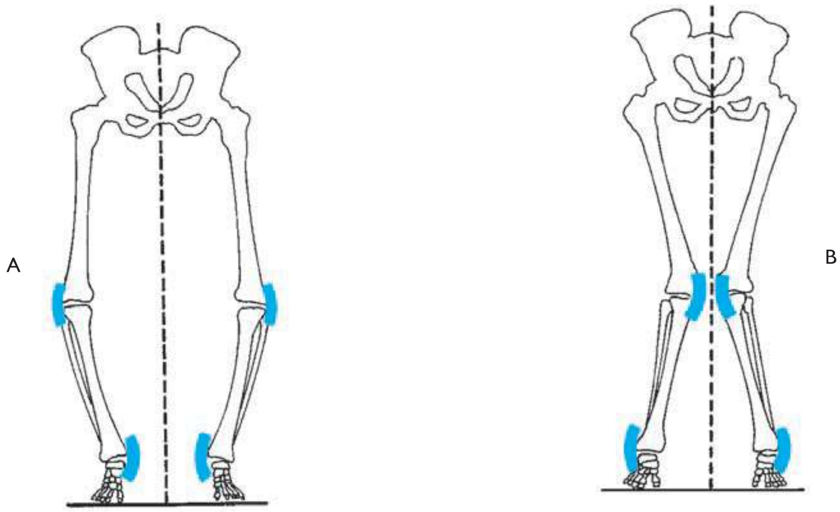


FIGURE 8-28

Areas of strain are highlighted. **A.** Femoral valgus and tibial varus. **B.** Femoral varus and tibial valgus.

misalignments at other lower-extremity joints because of the nature of joint loading during weight bearing.

Depending on the cause of the misalignment problem, correctional procedures may involve exercises to strengthen or stretch specific muscles and ligaments of the lower extremity, as well as the use of orthotics, specially designed inserts worn inside the shoe to provide added support for a portion of the foot.

• *Misalignment at a lower extremity joint typically results in compensatory misalignments at one or more other joints because of the lower extremity's weightbearing function.*

Injuries Related to High and Low Arch Structures

Arches that are higher or lower than the normal range have been found to influence lower-extremity kinematics and kinetics, with implications for injury. Specifically, as compared to those with normal arches, high-arched runners have been found to exhibit increased vertical loading rate, with related higher incidences of ankle sprains, plantar fascitis, iliotibial band friction syndrome, and fifth metatarsal stress fractures (115, 116). Low-arched runners, as compared to those with normal arches, have been found to exhibit increased range of motion and velocity in rearfoot eversion, as well as an increased ratio of eversion to tibial internal rotation (116). These kinematic alterations were found to result in increased incidences of general knee pain, patellar tendinitis, and patellar fascitis (115).

SUMMARY

The lower extremity is well adapted to its functions of weight bearing and locomotion. This is particularly evident at the hip, where the bony structure and several large, strong ligaments provide considerable joint stability. The hip is a typical ball-and-socket joint, with flexion, extension, abduction, adduction, horizontal abduction, horizontal adduction, medial and lateral rotation, and circumduction of the femur permitted.

The knee is a large, complex joint composed of two side-by-side condyloid articulations. Medial and lateral menisci improve the fit between the articulating bone surfaces and assist in absorbing forces transmitted across the joint. Because of differences in the sizes, shapes, and orientations of the medial and lateral articulations, medial rotation of the tibia accompanies full knee extension. A number of ligaments cross the knee and restrain its mobility. The primary movements allowed at the knee are flexion and extension, although some rotation of the tibia is also possible when the knee is in flexion and not bearing weight.