The human foot is an intricate mechanism that functions interdependently with other components of the locomotor system. Failure of the functioning of a single part, whether by disease, external forces, or surgical manipulation, will alter the functions of the remaining parts. To further complicate things, wide variations occur in the normal component parts of the foot and ankle, and these variations affect the degree of contribution of each part to the function of the entire foot. Depending on the contributions of an individual component, the loss or functional modification of that component by surgical intervention may result in minor or major alterations in the function of adjacent components. This variation helps to explain why the same procedure performed on the foot of one person produces a satisfactory result, whereas in another person the result is unsatisfactory.

Yet the surgeon is called on constantly to change the anatomic and structural components of the foot. When so doing, awareness of the consequences of these changes is fundamental to achieving desired results. Put another way, an understanding of interrelationships between foot and ankle components and how they interact with the greater locomotor system is critical to achieving predictable outcomes when altering these components surgically.

Understanding the biomechanics of the foot and ankle also contributes to sound surgical decision making and adds to the success of postoperative treatment. Appreciating the mechanical behavior of the foot allows the physician to differentiate foot disabilities that may be successfully treated by nonsurgical procedures rather than approached surgically. Furthermore, some operative procedures that fail to completely achieve the desired result can be improved by minor alterations in the behavior of adjacent components through shoe modification or the use of orthotic inserts or braces.
With increased attention being given to athletics, the physician must have a basic knowledge of the mechanics that occur during running. Many of the same basic mechanisms that will be described for the biomechanics of the foot and ankle are not significantly altered during running. The same stabilization mechanism within the foot occurs during running as during walking. The major differences observed during running are that the gait cycle is altered considerably, the amount of force generated (as measured by force plate data) is markedly increased, the range of motion of the joints of the lower extremities is increased, and the phasic activity of the muscles of the lower extremities is altered. Differences between walking and running will be highlighted in the following sections.

Starting this textbook with a chapter focused on foot and ankle biomechanics is meant to provide a foundation for the reader upon which the remaining chapters are built. It has been assumed that the orthopaedic surgeon possesses an accurate knowledge of the anatomy of the foot and ankle. If this knowledge is lacking, textbooks of anatomy are available that depict in detail the precise anatomic structures constituting this part of the human body. In this chapter, the gait cycle is reviewed, kinematic and kinetic aspects of gait are explored, and specific anatomic interrelationships of the foot and ankle are emphasized. Throughout this discussion, mechanics that differentiate running from walking are described. Finally, clinical examples are explored, and methods for functional evaluation of the foot are presented as practical demonstrations of the concepts within.

**GAIT CYCLE**

**Walking Cycle**

Human gait is a rhythmic, cyclic forward progression involving motion of all body segments. A single cycle is often defined as the motion between the heel strike of one step and the heel strike of the same foot on the subsequent step. Gait parameters, such as stride length, velocity, and cadence, are easy to measure based on this definition.

A single cycle can be divided further. The walking cycle for one limb is broken into a stance phase and a swing phase. The stance phase typically constitutes 62% of the cycle and the swing phase 38%. The stance phase is further divided into a period of double limb support (from 0% to 12%), in which both feet are on the ground, followed by a period of single limb support (from 12% to 50%) and a second period of double limb support (from 50% to 62%), after which the swing phase begins (Fig. 1-1).

The opposite leg also goes through a predictable sequence during a gait cycle. The position and activities of this contralateral leg can be seen at predictable times. For instance, contralateral toe-off is typically at 12% of the gait cycle, occurring after the ipsilateral foot has reached a foot-flat position. Ipsilateral heel rise begins at 34% as the contralateral leg swings through and passes the stance foot. Finally, contralateral heel strike occurs at 50% of the gait cycle.

In a patient with spasticity, the initial heel strike may be toe contact, and foot flat may not occur by 7% of the cycle. Heel rise may be premature if spasticity or an equinus contracture is present or delayed in the case of weakness of the gastrocnemius–soleus muscle group. Weakness of anterior compartment leg musculature resulting in a footdrop may lead to accentuated hip and knee flexion during swing-through and alteration in attaining a foot-flat position.

The walking cycle being one of continuous motion is difficult to appreciate in its entirety because so many events occur simultaneously. To help appreciate the different activities and functions of the components of the foot and ankle during gait, the stance phase can be divided into three intervals: the first interval, extending from initial heel strike to the foot laying flat on the floor; the second interval, occurring during the period of foot flat as the body passes over the foot; and the third interval, extending from the beginning of ankle joint plantar flexion as the heel rises from the floor to when the toes lift from the floor.

**First Interval**

The first interval occurs during approximately the first 15% of the walking cycle and is defined from the moment of initial heel strike to when the foot becomes flat on the floor. Typically, the opposite heel has lifted from the floor, but weight remains on the forefoot. During the first interval, the foot helps to absorb and dissipate the forces generated by the foot striking the ground.
and ligamentous support. No significant muscle function of the articulating surfaces, their capsular attachments, motion appears to depend entirely on the configuration of the articulating surfaces, their capsular attachments, and ligamentous support. No significant muscle function appears to play a role in restricting this motion at initial ground contact.

The subtalar joint links rotation of the hindfoot to rotation of the leg. During the first interval, eversion of the calcaneus is translated by the subtalar joint into inward rotation that is transmitted proximally across the ankle joint into the lower extremity (Fig. 1-2E). Distally, this hindfoot eversion unlocks the transverse tarsal joint (Fig. 1-2D), allowing the midfoot joints to become supple. This allows the flattening of the longitudinal arch that contributes to energy dissipation during this phase.

At heel strike, the center of gravity of the body is decelerated by ground contact, then immediately accelerated upward to carry it over the extending lower extremity. The heel’s impact and body’s center of gravity shift accounts for a vertical floor reaction that exceeds body weight by 15% to 25% (Fig. 1-2A).

Eccentric contraction of the anterior compartment leg muscles slows the rapid ankle plantar flexion during this phase from heel strike until a foot-flat position is reached. The posterior calf muscles all are electrically quiet, as are the intrinsic muscles in the sole of the foot (Fig. 1-2C). There is no muscular response in those muscles usually considered important in supporting the longitudinal arch of the foot. Weakness of the anterior compartment muscles leads to a loss of this deceleration and a characteristic slap foot gait.

Second Interval
The second interval extends from 15% to 40% of the walking cycle. During this interval, the body’s center of gravity passes from behind to in front of the weight-bearing leg. It reaches a maximum height as it passes over the leg at about 35% of the cycle, after which it commences to fall. During this interval, the foot transitions from a flexible, energy-absorbing structure to a more rigid one, capable of bearing the body’s weight.

The ankle joint undergoes progressive dorsiflexion during the second interval, reaching its peak at 40% of the walking cycle. This is when the force across the ankle joint has reached a maximum of 4.5 times body weight. Heel rise begins at 34% of the cycle as the contralateral leg passes by the stance foot and precedes the onset of plantar flexion, which begins at 40% (Fig. 1-3B).

During the second interval, the subtalar joint progressively inverts. This starts at about 30% of the cycle in a normal foot and at about 15% of the cycle in a flatfoot (Fig. 1-3D). Multiple factors contribute to this inversion, but precisely which plays the greatest role is unclear. Above the subtalar joint, the swinging contralateral limb externally rotates the stance limb. This external rotation torque is translated by the subtalar joint into hindfoot inversion. The oblique nature of the ankle joint axis, the oblique setting of the metatarsal break, and the function of the plantar aponeurosis also contribute to hindfoot inversion. Inversion of the subtalar joint is passed distally into the midfoot, increasing the stability of the transverse

![Figure 1-2](http://www.us.elsevierhealth.com/orthopaedics/mann-s-surgery-of-the-foot-and-ankle-2-volume-set-expert-consult/9780323072427)
Part I ■ General Considerations

The third interval constitutes the last of the stance phase and extends from 40% to 62% of the walking cycle. The ankle joint demonstrates rapid plantar flexion during this interval as the foot essentially extends the stance, effective length. The subtalar joint continues to invert during this interval, reaching its maximum at toe-off (Fig. 1-4D). This completes the conversion of the forefoot from the flexible structure observed in the first interval at the time of weight acceptance to a rigid structure at the end of the third interval in preparation for toe-off. The inversion is a continuation of the processes that began in the second interval. These include external rotation of limb above the foot passing across the ankle tarsal articulation and transforming the flexible midfoot into a rigid structure.

During this interval, full body weight is not borne on the foot, smoothing the transition to single limb support. Force plate recordings show that the load on the foot may be as low as 70% to 80% of actual body weight (Fig. 1-3A).

During the second interval, important functional changes occur in both the foot and leg, which are the result of muscular action. The posterior and lateral compartment leg muscles (triceps surae, peroneals, tibialis posterior, long toe flexors) and intrinsic muscles in the sole of the foot demonstrate electrical activity (Fig. 1-3C). Intrinsic muscle activity of the normal foot begins at 30% of the cycle, whereas in flatfoot, activity begins at 15% of the cycle. The posterior calf musculature slows the forward movement of the tibia over the fixed foot, which permits the contralateral limb to increase its step length. Weakness of the posterior compartment muscles may lead to premature contralateral heel strike and shortened stride length.

**Figure 1-3** Composite of events of second interval of walking, or period of foot flat. EMG, electromyograph.

**Figure 1-4** Composite of all events of third interval of walking, or period extending from foot flat to toe-off. EMG, electromyograph.

**Third Interval**

The third interval constitutes the last of the stance phase and extends from 40% to 62% of the walking cycle. The ankle joint demonstrates rapid plantar flexion during this interval as the foot essentially extends the stance, effective length. The subtalar joint continues to invert during this interval, reaching its maximum at toe-off (Fig. 1-4D). This completes the conversion of the forefoot from the flexible structure observed in the first interval at the time of weight acceptance to a rigid structure at the end of the third interval in preparation for toe-off. The inversion is a continuation of the processes that began in the second interval. These include external rotation of limb above the foot passing across the ankle.
and subtalar joints as well as mechanisms in the foot such as the obliquity of the ankle joint, the function of the plantar aponeurosis, and obliquity of the metatarsal break. Distally, the transverse tarsal joint is converted from a flexible structure into a rigid one by the progressive inversion of the calcaneus. The talonavicular joint also is stabilized during this period by the pressure placed across the joint by both body weight and the intrinsic force created by the plantar aponeurosis.

At the beginning of the third interval, force plate recordings demonstrate an increase in the percentage of body weight borne by the foot resulting from the center of gravity falling. The load on the foot exceeds body weight by approximately 20%. Later in the interval, the vertical floor reaction force falls to zero as the body's weight is transferred to the opposite foot (Fig. 1-4A).

Ankle plantar flexion during the third interval is caused primarily by the concentric contraction of the posterior calf musculature, in particular the triceps surae (Fig. 1-4B). The plantar flexion leads to relative elongation of the extremity. Although full plantar flexion at the ankle joint occurs during this interval, electrical activity is observed only until 50% of the cycle, after which there is no longer electrical activity in the extrinsic muscles (Fig. 1-4C). The remainder of ankle plantar flexion occurs because of the transfer of weight from the stance leg to the contralateral limb. The intrinsic muscles of the foot are active until toe-off. Although the intrinsic muscles help to stabilize the longitudinal arch, the main stabilizer is the plantar aponeurosis, which is functioning maximally during this period as the toes are brought into dorsiflexion and the plantar aponeurosis is wrapped around the metatarsal heads, forcing them into plantar flexion and elevating the longitudinal arch. The anterior compartment muscles become active in the last 5% of this interval, probably to initiate dorsiflexion of the ankle joint immediately after toe-off.

**Running Cycle**

The changes that occur in the gait cycle during running relative to walking are illustrated in Figure 1-5. During walking, one foot is always in contact with the ground; as the speed of gait increases, a transition occurs wherein a float phase is incorporated, during which time both feet are off the ground. Rather than a period of double limb support as occurs during walking, there is a period of no limb support. As the speed of gait continues to increase, the time the foot spends on the ground, both in real time and in percentage of cycle, decreases considerably. The speed at which one transitions from walking to running is greater than the speed at which one transitions back from running to walking.

**KINEMATICS OF HUMAN LOCOMOTION**

Humans use a unique and characteristic orthograde bipedal mode of locomotion. But walking is more than merely placing one foot in front of the other. During walking, all major segments of the body are in motion. Displacements of the body segments occur in a well-preserved fashion and can be accurately described. Kinematics is the study of the motion of these body segments.

Human locomotion is a learned process; it does not develop as the result of an inborn reflex. The first few steps of an infant holding onto his or her parent’s hand exemplify the learning process necessary to achieve orthograde progression. The result of this learning process is the integration of the neuromusculoskeletal mechanisms, with their gross similarities and individual variations, into an adequately functioning system of locomotion. Once a person has learned to walk, the mechanisms of ambulation are adaptable and work whether the person is an amputee learning to use a prosthesis, a long-distance runner, or a high-heeled shoe wearer.

A smoothly performing locomotor system results from the harmonious integration of many components. Because human locomotion involves all major segments of the body, certain suprapedal movements demand specific functions from the foot, and the manner in which the foot functions or fails to function may be reflected in patterns of movement in the other segments of the body. Similarly, alterations in movements above, such as a stiff knee or hip from arthritis or knee hyperextension from postpolio quadriceps weakness, may be reflected below by changes in the behavior of the foot.

Although bipedal locomotion imposes gross similarities in the manner in which all of us walk, each of us exhibits minor individual differences that allow us to be recognized by a friend or acquaintance, even from a distance. The causes of these individual characteristics of
locomotion are many. Each of us differs somewhat in the length and distribution of mass of the various segments of the body, segments that must be moved by muscles of varying fiber length. Furthermore, individual differences occur in the position of axes of movement of the joints, with concomitant variations in effective lever arms. These and many more such factors combine to establish in each of us a final idiosyncratic manner of locomotion.

Just as no two people walk exactly alike, gait kinematics will not always be identical even within the same individual. The contribution of a single component varies under different circumstances. Type of shoe, amount of fatigue, weight of load carried, and other such variables can cause diminished functioning of some components, with compensatory increased functioning of others. An enormous number of variations in the behavior of individual components are possible; however, the diversely functioning components, when integrated, are complementary and will produce smooth forward progression.

Average values of single anthropometric observations of gait kinematic parameters are alone of little value. The surgeon should be alert to the anthropometric variations that occur within the population, but it is more important to understand the functional interrelationships among the various components. This is particularly true in the case of the foot, where anatomic variations are extensive. If average values are the only bases of comparison, it becomes difficult to explain why some feet function adequately and asymptotically, although their measurements deviate from the average, whereas others function symptomatically, even though their measurements approximate the average. Therefore, in this chapter, emphasis is placed on functional interrelationships and not on lists of kinematic measurements.

**Vertical Body Displacements**

The rhythmic upward and downward displacement of the body during walking is familiar to everyone, and is particularly noticeable when someone is out of step in a parade. These displacements in the vertical plane are a necessary concomitant of bipedal locomotion. When the legs are separated, as during transmission of the body weight from one leg to the other (double weight bearing), the distance between the trunk and the floor must be less than when it passes over a relatively extended leg, as during midstance.

Smoothing and minimizing vertical oscillations of the body’s center of gravity minimizes energy expenditure. Physics principles tell us that much more energy is needed to lift the body against gravity and slow its descent (vertical displacement) than to move perpendicular to gravity’s pull (fore–aft or lateral displacement). Because the nature of bipedal locomotion demands such vertical oscillations of the body, they should occur in a smooth manner. The center of gravity of the body does displace in a smooth sinusoidal path; the amplitude of displacement is approximately 4 to 5 cm (Fig. 1-6).

![Figure 1-6](http://www.us.elsevierhealth.com/orthopaedics/mann-s-surgery-of-the-foot-and-ankle-2-volume-set-expert-consult/9780323072427)

Figure 1-6 Displacement of center of gravity of body in smooth sinusoidal path. (From Saunders JB, Inman VT, Eberhart HD: The major determinants in normal and pathological gait. *J Bone Joint Surg Am* 35A:543-558, 1953.)
is achieved by pronation of the foot to a degree permitted by the ligamentous structures within.

So, to reemphasize, hindfoot pronation constitutes an important additional factor to that of knee flexion and ankle plantar flexion needed to smoothly decelerate and finally to stop the downward path of the body. If one were forced to walk stiff-kneed or without a mobile foot and ankle, the downward deceleration of the center of gravity at heel strike would be instantaneous. The body would be subjected to a severe jarring force, and the locomotor system would lose kinetic energy.

After reaching its nadir, the center of gravity moves upward to propel it over the stance leg. The leg functionally elongates by transitory extension of the knee, further plantar flexion of the ankle as the heel elevates, and supination of the foot. Elevation of the heel is the major component contributing to upward acceleration of the center of gravity at this time.

**Lateral Body Displacements**

When a person is walking, the body does not remain precisely in the plane of progression but oscillates slightly from side to side to keep the center of gravity approximately over the weight-bearing foot. Watching someone walk from behind highlights this subtle side-to-side shift of their center of gravity toward the stance limb. When walking side by side with a companion, if one gets out of step with the other, their bodies may bump from this side-to-side sway.

The body is shifted slightly over the weight-bearing leg, with each step creating a sinusoidal lateral displacement of the center of gravity of approximately 4 to 5 cm with each complete stride. This lateral displacement can be increased by walking with the feet more widely separated and decreased by keeping the feet close to the plan of progression (Fig. 1-7). Normally, the slight valgus of the tibiofemoral angle (physiologic genu valgum) permits the tibia to remain essentially vertical and the feet close together while the femurs diverge to articulate with the pelvis, minimizing the lateral displacement.

**Horizontal Limb Rotation**

In addition to vertical and lateral displacements of the body, a series of axial rotatory movements occur that can be measured in the horizontal (transverse) plane. Rotations of the pelvis and the shoulder girdle are easy to see.
when watching someone walk. Similar horizontal rotations occur in the femoral and tibial segments of the extremities. The tibias rotate about their long axes, internally during swing phase and into the first interval of stance phase and externally during the latter phases of stance. The degree of these rotations is subject to marked individual variations. In a series of 12 male subjects, the recorded average horizontal rotation of the tibia was 19 degrees during a gait cycle but varied between 13 and 25 degrees.\(^\text{48}\)

At heel strike, progressive inward rotation occurs in the lower extremity, which consists of the pelvis, femur, and tibia, and this inward rotation reaches a maximum at the time of foot flat. The internal rotation at heel strike is initiated by the collapse of the subtalar joint into valgus, and its magnitude is determined by the flexibility of the foot and its ligamentous support. After contralateral toe-off, at about 12% of the cycle, progressive outward rotation occurs, which reaches a maximum at the time of toe-off, when inward rotation resumes (Fig. 1-8). Once the foot is on the ground, progressive external rotation is probably initiated by the contralateral swinging limb, which rotates the pelvis forward, imparting a certain degree of external rotation to the stance limb. This external rotation subsequently is passed from the pelvis distally to the femur and tibia, across the ankle joint, and is translated by the subtalar joint into inversion, which reaches its maximum at toe-off. The external rotation is enhanced by the external rotation of the ankle joint axis, the oblique metatarsal break, and the plantar aponeurosis after heel rise begins.


Figure 1-8 Transverse rotation occurring in the lower extremity during walking. Internal rotation occurs until approximately 15% of cycle, at which time progressive external rotation occurs until toe-off, when internal rotation begins again.

**KINETICS OF HUMAN LOCOMOTION**

To begin a review of gait kinetics, one must recognize that the ambulating human is both a physical machine and a biologic organism subject to physical laws and beholden to muscular action. Gait kinematics and lower-extremity anatomic interrelationships strive to achieve a system that takes us from one spot to another with the least expenditure of energy.\(^\text{60}\) Said another way, human locomotion is a blending of physical and biologic forces that combine to achieve maximum efficiency at minimum cost. Kinetics is the study of these energy expenditures.

All characteristics of muscular behavior are exploited in locomotion. Muscle groups may accelerate or decelerate body segments at different points in the gait cycle. They may contract concentrically (as they shorten) or eccentrically (as they lengthen). Part of energy conservation during the gait cycle involves having muscles work near their peak efficiency, which tends to be at or longer than their resting length.\(^\text{14,17,65}\) When motion in the skeletal segments is decelerated or when external forces work on the body, activated muscles become efficient. Activated muscles, in fact, are approximately six times as efficient when resisting elongation (eccentric contraction) as when shortening to perform external work.\(^\text{1,5,6}\) In addition, noncontractile elements in muscles and specific connective tissue structures assist muscular action by providing an elastic component that stores and later releases kinetic energy.

Assessment of the forces and torques imparted by the ground on the lower extremity has illuminated the biomechanical processes at work during gait. Investigation of the pressures experienced by the various regions of the plantar foot has provided insight into the pathogenesis and treatment of many foot and ankle disorders. A number of tools have evolved to study gait kinetics. These are described in detail in the next section, followed by an analysis of kinetics during gait.

**Measuring Whole Body Kinetics and Plantar Pressure**

Studying the foot’s interaction with the ground has a long history, ranging from examining footprints in soil to real-time mapping of plantar pressure under natural conditions. Plantar pressure and ground reaction force measurements are well established in the research realm and have been instrumental in refining our understanding of foot and ankle biomechanics. In conjunction with other technology, including high-speed cameras, video motion-sensing equipment, electrogoniometers, and electromyograph (EMG) devices, the study of the ground-foot interaction has aided the understanding of gait kinetics and kinematics.

Despite improvements in available measurement methods, however, practical collection of clinically novel information remains difficult. The wide variability of normal measures makes clinical comparisons difficult.
The large number of measurement systems and equally large number of data analysis techniques make it difficult to generalize results.

Although confirmation of areas of excess pressure and monitoring the effects of treatment may prove useful, there is little specificity between plantar pressure patterns and clinical syndromes.

**Types of Studies**

A variety of measurement techniques have been used to study the interaction of the foot with the ground. Indirect techniques rely on correlating other measurable gait parameters to plantar characteristics and offer the advantage of not relying on expensive and often bulky equipment. For example, an estimation of ground reaction force can be made based on a simple-to-measure temporal variable, foot–ground contact time.\(^{13}\)

Direct measurement techniques rely on physical properties or electronic transducers to translate the interaction between the foot and the ground into a measurable quantity. Multiple direct measurement systems are available that use a variety of strategies to record plantar pressure or ground reaction force. Unfortunately, results obtained with different systems under similar conditions are not always similar, and even qualitative comparisons may not be appropriate.\(^{38}\) Spatial resolution and sample rate affect the ability of a system to record true peak plantar pressures and to isolate particular areas under the foot.

The earliest direct measurement methods relied on physical properties of a material to capture the interaction of the foot with the ground. Casts of the foot in clay, plaster, or soil were used with the assumption that areas of deeper penetration represented areas of highest pressure.\(^{10,21}\) Rubber mats incorporating longitudinal ridges,\(^{54}\) pyramidal projections,\(^{21}\) or a multilevel grid (such as the Harris-Beath mat),\(^{67,78}\) use the elastic property of rubber which, when stood or walked on, distorts in proportion to the pressure applied (Fig. 1-9). Although fast, inexpensive, and portable, these methods have low measurement resolution and lack temporal discrimination.\(^{67}\)

Optically based systems rely on visualizing the plantar aspect of the foot during stance or gait. The simplest allows observation or photographic recording of the plantar foot through a clear platform (Fig. 1-10). This provides an accurate, dynamic, qualitative representation of foot morphology. Addition of a physical transduction device between the foot and glass plate allows quantification of regionalized plantar pressures and adds the temporal component missed using a physical transduction system alone.\(^{21}\) The pedobarograph places a thin plastic sheet over the clear plate.\(^{4}\) The sheet is illuminated at the edges, and pressure on the plastic distorts the light in

---

**Figure 1-9** Pressure distribution on plantar aspect of foot as demonstrated by use of barograph. As dots get larger and denser, pressure distribution is greater. (From Elftman H: A cinematic study of the distribution of pressure in the human foot. *Anat Rec* 59:481-491, 1934.)
proportion to the pressure applied. The images can be recorded and calibrated to provide a spatial resolution and temporal responsiveness not found with the Harris-Beath mat. However, slow responsiveness at high forces may bias results.36

A force plate measures the ground reaction force, that is, the force exerted by the ground on the foot, in three degrees of freedom (vertical force, forward shear, side shear), and allows calculation of the torques around the foot and ankle (axial torque, sagittal torque, coronal torque). Force transducers are configured in orthogonal planes at the corners of a section of floor. The resulting data provide a representation of the average forces experienced by the foot over the gait cycle (Fig. 1-11). One advantage of this type of system is that shear forces and torques can be measured in addition to vertical force. The limitations include the lack of ability to map specific regions of plantar pressure. This limitation can be circumvented with the addition of an optical diffraction system, as described above, or with a series of smaller force plates placed in tandem.71

Figure 1-10 Feet and legs of person standing on barograph. A, Weight bearing with muscles relaxed. B, Rising on toes.


reporting results as force versus pressure, peak values versus sum of values over time, and strategies of regionalizing the foot’s plantar surface. Increasing pressure transducer density provides better spatial representation of plantar pressure, whereas systems with relatively lower transducer density may underestimate measurements, such as peak pressure, because the true peak may be missed. Some transducers may have a nonlinear response at the extremes of their measurable range or have a low-level cutoff. The maximum sample rate affects contact time measurements, and low sample rates may underestimate peak pressure measurements because the true peak pressure may be missed.

Data Representations

Output from the different measurement systems reflects the nature of their measurement mechanisms. The Harris mat reports pedal pressure but does not vary with time. The force plate reports a true ground reaction force but in not spatially discriminative. The optical systems and the transduction arrays each report pedal pressure that varies with time. The data measured by these systems is subject to sensor density, resolution, and sample rate limitations discussed above. To simplify the information and allow comparisons between subjects or after treatments, a variety of derivative parameters have been

Figure 1-12  Pressure distribution under bare foot during walking. Height of display above ground is proportional to pressure. (From Clarke TE: The pressure distribution under the foot during barefoot walking [doctoral dissertation], University Park, Pa, 1980, Pennsylvania State University.)

Figure 1-13  Peak plantar pressure map using an in-shoe thin-film pressure transducer. Red represents areas of relatively high pressure, and violet, areas of low pressure. (Courtesy Ken Hunt, MD.)
The ground reaction force is a vector quantity varying temporally and spatially over the gait cycle that represents the average reciprocal force exerted by the floor in response to the foot. It has a magnitude and direction, and the starting point may be projected onto a representation of the plantar foot at the point of average maximum vertical force (Fig. 1-14). The ground reaction force can be deconstructed into vertical force, anterior–posterior shear, and medial–lateral shear. The vertical ground reaction force represents the force of the ground pushing upward on the foot, and can be calculated from systems that measure plantar pressure for the whole foot or for defined regions. Peak pressure and magnitude on a diagram of the foot. Peak force can be calculated from peak pressure because the size of the pressure transducers is known. Calculated joint moments represent the torque applied by muscles to counteract the measured ground reaction force, and joint power is calculated from the joint moment and angular velocity (Fig. 1-15).

Timing measurements can also be made. The time intervals from heel strike to metatarsal strike, toe strike, heel-off, metatarsal-off, and toe-off can be calculated. The pressure · time integral, or impulse, for the whole foot or defined regions can be calculated. This may be standardized for each region as a percentage of the total impulse for a given foot. The impulse may characterize plantar loading better than peak pressure by taking both pressure and time into consideration.

Finally, the pattern of plantar loading can be categorized based on the pressure measurements. Patients may tend to load the medial ray, the medial and central rays, the central rays, or the central and lateral rays. Put another way, there is an inverse relationship between peak pressure under the first metatarsal head and toe relative to the lesser metatarsal heads. As walking speed increases, a medialization of forefoot pressure occurs such that peak pressure under the first metatarsal head decreases and that under the lesser metatarsal heads increases.

Measurement Variability

Many sources of variability affect the results of these measurements. Separating important clinical or research findings from differences based on testing apparatus, measurement methodology, patient demographic factors, or analysis methodology requires an understanding of how these factors affect the measured results. Differences between the different testing apparatus have been described above. Other sources of variability can be divided into methodology, analysis, and patient-specific factors.

Walking speed affects the magnitude of plantar pressures during gait. Velocity is linearly related to peak vertical and fore–aft ground reaction forces, and inversely
related to the pressure · time integral. As velocity increases, peak pressures on the heel, medial metatarsal heads, and the first toe increase while peak pressure in the fifth metatarsal head decreases. This medialization may be related to increased magnitude and velocity of hindfoot eversion and medial shear force at heel strike. Timing measurements also change with increasing speed. The normalized time to peak pressure is decreased on the heel but unchanged in the midfoot and forefoot, suggesting the rollover process is mainly accelerated by reducing the time from heel strike to foot flat. To minimize variability introduced because of walking speed, subjects may walk at a fixed rate or at their natural pace.

Deviations from a normal gait pattern can occur if the subject has to take a long or short stride in an effort to place the foot on the appropriate measurement area of floor-based systems. To minimize this effect, the measurement platform is placed flush with the floor and hidden from the subject with a thin, uniform floor covering. The traditional midgait method uses a short lead-up walk before the foot strikes the measurement platform. A three-step or two-step lead-up is as reproducible, but a one-step lead-up is not adequate.

Variability of the measurements is also dependent on the type of gait. For example, plantar pressures measured when standing differ from pressures measured during gait. Variations in walking patterns, such as a shuffling-type gait, alter the peak forces on the foot. Gait pattern alteration can be seen in certain conditions, such as after ankle fracture fixation or with concurrent knee pathology.

Drift and calibration of the measurement systems affect the variability of measurements. Plantar pressure measurement systems need to be calibrated to allow comparisons between systems. Transducer output varies between different transducers, with temperature, when an in-shoe system is removed and reinserted, and with the number of trials performed. Pressure can vary by as much as 20% with repeated measurements on the same insert. There may be an offset that drifts with time. The measurements may be adequate for relative ranking purposes but need repeated calibration with a fixed system if accurate values are needed.

Variability is also introduced in the methods by which the acquired data are analyzed. For example, peak pressure can be reported for the whole surface of the foot during a gait cycle, but the clinical utility of this is limited because different regions of the foot experience different plantar pressures during the gait cycle. Subdividing the regions of the plantar foot and recording peak pressures in each of these areas over the gait cycle provides more meaningful data. The heel is often represented as a single region, and in adults may be the fourth metatarsal head, and in children may be the fourth metatarsal head or the midfoot.

Individuals load the foot with different spatial patterns as well. After heel strike, the forefoot may be loaded more medially or laterally across the metatarsal heads and may load the metatarsals and toes simultaneously or in turn. A variety of classification systems have been proposed to group these types of loading, and biomechanical theories have been proposed to explain the different loading patterns. Finally, there is an inherent variability in an individual’s gait from step to step that ranges from less than 1% for vertical ground reaction force to much higher for timing-dependent variables and values calculated as a product of measures. Measured values may vary by more than 10% under identical testing conditions. Averaging data from as few as three trials improves the reliability of the measurement.

**Kinetics of Walking**

Force plates measure the force felt by the floor produced by displacement of the body’s center of gravity. By Newton’s law of equal and opposite forces, this is the same force experienced by the foot and represents the effect of gravitational forces on the whole body while walking. The principle of the force plate is seen when one stands on a bathroom scale and flexes and extends the knees to
raise and lower the body. The indicator on the dial moves abruptly as vertical floor reaction is registered.

**Whole Body Kinetics**

The only forces that can produce motion in the human body are those created by gravity, by muscular activity, and, in a few instances, by the elasticity of specific connective tissue structures. A force plate instantaneously records the forces imposed by the body through the foot onto the floor. These measurements include vertical floor reactions, fore and aft shears, medial and lateral shears, and horizontal torques. During the stance phase of walking, the floor reactions in all four categories are continuously changing. Figure 1-11 demonstrates the force plate data obtained during normal walking. The slower an individual walks, the less the center of gravity moves, and the resultant forces are less. Conversely, the faster the gait, the greater the movement of the center of gravity, and hence a larger force is experienced. When shoes are donned, these forces are transmitted through the interface between the sole of the shoe and the walking surface. This can attenuate rapid spikes, such as the heel striking the ground, and distribute the force over a larger area of the foot, diminishing peak plantar pressures.

The vertical element of ground reaction force is the largest of the component vectors and represents the force required to oppose the pull of gravity. It demonstrates an initial spike and rapid decline as the heel contacts the ground. Shoe material can alter the magnitude of the spike: a softer heel will result in a smaller initial spike, and a harder heel in a larger spike. The vertical ground reaction force curve then has two peaks during the stance phase. The first whole body vertical force peak is 10% to 15% greater than body weight and is caused by the upward acceleration of the body's center of gravity. This is followed by a dip to approximately 20% less than body weight as the center of gravity reaches the top of its trajectory and begins to fall. A second peak of 10% to 15% greater than body weight results from resisting the falling of the center of gravity as the body moves over the stance leg. After this, the force rapidly declines to zero at toe-off as weight transfers to the opposite limb (see Fig. 1-11A).

We see from the lack of a vertical ground reaction peak at 5% of body weight (see Fig. 1-11C).

The movement of the ground reaction force vector along the bottom of a normal foot follows a consistent pattern (Fig. 1-16). After heel strike, it moves rapidly forward until it reaches the metatarsal area, where it dwells for about half of the stance phase, then passes distally to the great toe. In a patient with a rheumatoid arthritis–related hallux valgus deformity and significant metatarsalgia, the center of pressure remains in the posterior aspect of the foot, avoiding the painful metatarsal area, then rapidly passes over the metatarsal heads along the middle of the foot (Fig. 1-17). In patients with amputation of the great toe, the center of pressure passes in a more lateral direction (Fig. 1-18).
Plantar Pressure Kinetics

Research on plantar pressure during gait has proved useful in a number of clinically relevant areas, including forefoot pressure involving a number of clinical syndromes. Increased forefoot pressures may lead to metatarsalgia or neuropathic ulceration and is mitigated by simple insole modifications. Diabetic and neuropathic foot ulceration correlate with areas of increased vertical and shear forces. The weight-bearing pattern in these patients tends to shift from the medial to the lateral border of the forefoot, and the load taken by the toes is reduced. The rheumatoid foot demonstrates similar findings. A soft pad placed proximal to the metatarsal heads decreases metatarsal head pressure from 12 to 60%. Placement of a ½-inch lateral heel wedge decreased pressure under the third through fifth metatarsal heads by 24% and increased pressure under first and second metatarsal heads by 21%. A ½-inch medial heel wedge decreased the pressure under the first and second metatarsal heads by 28% and under the first toe by 31%.

Patients with hallux valgus may develop transfer metatarsalgia as plantar pressure increases under the lesser metatarsal heads and decreases under the first toe in relation to the size of the deformity. Those patients with hallux valgus and lesser toe metatarsalgia have greater peak pressure and peak pressure · time integral under the second through fifth metatarsal heads than those without metatarsalgia. Measurement of plantar pressure may be predictive because no patients with less than 20 N · cm⁻²...
peak pressure had metatarsalgia, and all patients with more than 70 N · cm$^{-2}$ peak pressure had metatarsalgia. Hallux valgus correction with proximal first metatarsal osteotomy and distal soft tissue procedure decreases peak pressure under the second and third metatarsal heads.\textsuperscript{80} After a distal chevron osteotomy for mild-to-moderate hallux valgus, the degree of plantar displacement of the distal first metatarsal osteotomy correlates with increased pressure under the first metatarsal head and to a decrease in clinical metatarsalgia.\textsuperscript{75} Procedures that destabilize the first metatarsophalangeal joint, such as Keller resection arthroplasty and silicone (Silastic) implant arthroplasty, increase pressure on the lesser metatarsal heads (Fig. 1-19).\textsuperscript{20,28,40,70}

The Achilles tendon and plantar fascia also influence plantar pressure and gait biomechanics.\textsuperscript{33} The Achilles tendon contributes to heel rise, leading to a reduction in the vertical displacement of the center of gravity and minimizing energy expenditure.\textsuperscript{47} During the stance phase, energy is stored in the gastrocnemius–soleus complex as the ankle dorsiflexes, and the tendon is elastically stretched and is returned after heel rise as the ankle plantar flexes. This elastic recoil facilitates shortening of the gastrocnemius–soleus complex at rates well above those possible by maximal muscle contraction and allows the muscles to act at a rate and length of maximum efficiency over the gait cycle.\textsuperscript{31,32} Gastrocnemius–soleus work increases with step length, effectively lengthening the limb by plantar flexing the ankle.\textsuperscript{32} A chronically elongated or ruptured tendon leads to a paradoxically rigid ankle by recruiting other ankle stabilizers.\textsuperscript{12} The time to initial peak vertical force is shortened, highlighting a loss of shock absorption, but the second peak vertical force, representing metatarsal head pressure, is not diminished.\textsuperscript{72} In diabetic patients with plantar ulceration, adding Achilles tendon lengthening to total contact casting leads to increased rate of healing and decreased recurrence of neuropathic ulcers.\textsuperscript{55} Ankle dorsiflexion is increased, and both plantar-flexion torque and peak plantar pressure are reduced after Achilles tendon lengthening initially, but plantar-flexor torque and peak pressure return by 7 months even though accentuated dorsiflexion remains.\textsuperscript{55} This suggests that the decrease in peak plantar pressure may be related to a weakening of ankle plantar flexors rather than to an increase in ankle dorsiflexion.

**Kinetics of Running**

The forces involved during running are considerable, reaching 2.5 to 3 times body weight (Fig. 1-20). The larger forces generated are related to increased displacement of the center of gravity as the speed of gait increases. At initial ground contact, increasing the range of motion at the ankle, knee, and hip joints helps absorb these larger forces. As the speed of gait further increases, the degree of motion in these joints also increases to help absorb the added impact. Muscles are active over a greater percentage of the gait cycle during running. The gastrocnemius–soleus contribution to forward propulsion is minimal during normal walking but plays a larger role as walking speed increases.\textsuperscript{23}
The human foot too often is viewed as a semirigid base whose principal function is to provide a stable support for the superincumbent body. Instead, it has evolved as a dynamic mechanism functioning as an integral part of the locomotor system. From the moment of heel strike to the instant of toe-off, floor reactions, joint motions, and muscular activity are changing constantly. Floor reactions and pedal pressure measurements demonstrate the forces transmitted through the foot, continuous geometric measurements record joint motion, and electromyographic studies show the phasic activity of the intrinsic and extrinsic muscles during gait. To make it easier to understand the various events that occur during a step, a discussion of the biomechanics of the various articulations and muscles that control their function is presented. The discussion divides the gait cycle into two separate themes. The first discusses mechanisms by which the foot and ankle contribute to energy absorption during the early phases of stance, followed by a section discussing mechanisms by which the foot converts from a supple to a rigid platform allowing heel rise and toe-off. Swing phase is discussed, and finally, distinctions between walking and running gait are highlighted.

**Heel Strike to Foot Flat: Supple for Impact Absorption**

**Ankle Joint**

At heel strike, the ankle is initially dorsiflexed from swing-through and rapidly plantar flexes, reaching a maximum of 10 degrees at 7% of the cycle once foot flat has occurred (see Fig 1-2). After heel strike, the anterior compartment leg muscles function as a group to slow the rapid ankle plantar flexion rotation. This activity continues until plantar flexion is complete. During this time, the muscle undergoes an eccentric (lengthening) contraction that helps absorb the energy of heel strike and transfer of weight from the opposite leg. Clinically, if the anterior tibial muscle group is not functioning, a foot slap is noted after heel strike, resulting from lack of control of initial ankle plantar flexion.

The direction of the ankle axis in the transverse plane of the leg dictates the vertical plane in which the foot will flex and extend. In the clinical literature, this plane of ankle motion in relation to the sagittal plane of the leg is referred to as the degree of tibial torsion. Rotation of the ankle axis in the horizontal plane can affect only the amount of toeing-out or toeing-in of the foot. Although it is common knowledge that the ankle axis is directed laterally as projected on the transverse plane of the leg, it is not widely appreciated that the ankle axis is also directed laterally and downward, as seen in the coronal plane. Inman, in anthropometric studies, found that, in the coronal plane, the axis of the ankle may deviate 88 to 100 degrees from the vertical axis of the leg (Fig. 1-21A). The axis of the ankle passes just distal to the tip of each malleolus, allowing the examiner to obtain a reasonably accurate estimate of the position of the empiric axis by placing the tips of the index fingers at the most distal bony tips of the malleoli (Figs. 1-21B and 1-22).

Because the ankle joint axis is obliquely oriented, an apparent rotation of the foot relative to the horizontal plane of the leg occurs with movements of the ankle. With the foot free and the leg fixed, the oblique ankle joint axis causes the foot to deviate outward on dorsiflexion and...
inward on plantar flexion, as seen by the projection of the foot onto the transverse plane (Fig. 1-23). The amount of this rotation will vary with the obliquity of the ankle axis and the amount of dorsiflexion and plantar flexion. Conversely, with the foot fixed to the floor, the oblique ankle axis causes the tibia to rotate internally with dorsiflexion and externally with plantar flexion.

Rotations of the leg and movements of the foot caused by an oblique ankle axis, when observed independently, are qualitatively and temporarily in agreement. However, when the magnitudes of the various displacements are studied, it becomes clear that rotation of the leg attributable to ankle axis obliquity is much smaller than the degree of horizontal rotation of the leg that actually occurs. In normal locomotion, ankle motion ranges from 20 to 36 degrees, with an average of 24 degrees. The obliquity of the ankle axis ranges from 88 to 100 degrees, with an average of 93 degrees from the vertical.

Even in the most oblique axis and movement of the ankle through the maximum range of 36 degrees, only 11 degrees of rotation of the leg around a vertical axis will occur.

**Subtalar Joint**

The subtalar joint works in cooperation with the ankle to account for the additional leg rotation not explained by the obliquity of the ankle joint axis. The subtalar joint is a sliding single-axis joint that acts like a mitered hinge connecting the talus and the calcaneus. The axis of the subtalar joint passes from medial to lateral at an angle of approximately 16 degrees and from the horizontal plane approximately 42 degrees (Fig. 1-24). Individual variations are extensive and impart variability to the behavior of this joint during locomotion. Furthermore, the subtalar joint appears to be a determinative joint of the foot.

![Figure 1-22](http://www.us.elsevierhealth.com/orthopaedics/mann-s-surgery-of-the-foot-and-ankle-2-volume-set-expert-consult/9780323072427)

**Figure 1-22** Estimation of obliquity of empirical ankle axis by palpating tips of malleoli.

![Figure 1-24](http://www.us.elsevierhealth.com/orthopaedics/mann-s-surgery-of-the-foot-and-ankle-2-volume-set-expert-consult/9780323072427)

**Figure 1-24** Variations in subtalar joint axes. A, In transverse plane, subtalar axis deviates approximately 23 degrees medial to long axis of foot, with range of 4 to 47 degrees. B, In horizontal plane, axis approximates 41 degrees, with range of 21 to 69 degrees. \( \bar{x} \), arithmetic mean. (Modified from Isman RE, Inman VT: Anthropometric studies of the human foot and ankle. *Bull Prosthet Res* 10:97, 1969.)

![Figure 1-23](http://www.us.elsevierhealth.com/orthopaedics/mann-s-surgery-of-the-foot-and-ankle-2-volume-set-expert-consult/9780323072427)

**Figure 1-23** Effect of obliquely placed ankle axis on rotation of foot in horizontal plane during plantar flexion and dorsiflexion, with foot free. Displacement is reflected in shadows of foot.
influencing the performance of the more distal articulations and modifying the forces imposed on the skeletal and soft tissues.

Based on its inclined axis, the subtalar joint functions essentially like a hinge connecting the talus and the calcaneus. The functional relationships that result from such a mechanical arrangement are illustrated in Figure 1-25A, which shows two boards jointed by a hinge. The vertical board represents the tibia and the horizontal board the foot. If the axis of the hinge is at 45 degrees, a simple torque converter has been created. Rotation of the vertical member causes equal rotation of the horizontal member. Changing the angle of the hinge alters this one-to-one relationship such that a more horizontally placed hinge causes a greater rotation of the horizontal member for each degree of rotation of the vertical member; the reverse holds true if the hinge is placed more vertically.

The model can be refined further (Fig. 1-25B) by dividing the horizontal “foot” segment into a short proximal and a long distal segment, with a pivot between the two segments. This pivot represents the transverse tarsal joint complex, which consists of the talonavicular and calcaneocuboid joints. The longer distal segment remains fixed to the floor in this model, and rotation at the transverse tarsal joint complex accommodates hindfoot inversion and eversion during stance phase. Thus the distal segment remains stationary, and only the short segment adjacent to the hinge rotates. The specific mechanics of this joint complex are discussed in the following section.

The interrelated rotation described by these models helps to demonstrate motion of the subtalar joint during walking. At the time of heel strike, the subtalar joint is slightly inverted and rapidly everts, reaching a maximum at foot flat, after which progressive inversion occurs until the time of toe-off. In the normal foot, approximately 6 degrees of rotation occurs. Although quantification of subtalar joint motion remains elusive because of the complexity of the movement, subsequent studies have confirmed qualitatively the direction of movement, namely, eversion after heel strike until foot flat, then inversion until toe-off (Fig. 1-26). Eversion of the hindfoot at heel strike occurs passively, dictated by the lateral

![Figure 1-25](http://www.us.elsevierhealth.com/orthopaedics/mann-s-surgery-of-the-foot-and-ankle-2-volume-set-expert-consult/9780323072427)

Figure 1-25 Simple mechanism demonstrating functional relationships. A, Action of mitered hinge. B, Addition of pivot between two segments of mechanism.

![Figure 1-26](http://www.us.elsevierhealth.com/orthopaedics/mann-s-surgery-of-the-foot-and-ankle-2-volume-set-expert-consult/9780323072427)

Figure 1-26 Subtalar joint motion in normal foot and flatfoot. Shaded areas indicate period of activity of intrinsic muscles in normal foot and flatfoot.
Transverse Tarsal Joint Complex

The calcaneocuboid and talonavicular articulations together often are considered to make up the transverse tarsal joint complex. Each possesses some independent motion and has been subjected to intensive study. Elftman demonstrated that the axes of these two joints are parallel when the calcaneus is in an everted position and are nonparallel when the calcaneus is in an inverted position. The importance of this is that, when the axes are parallel, there is flexibility within the transverse tarsal joint, whereas when the axes are nonparallel, there is rigidity at the transverse tarsal joint (Fig. 1-28). Imagine a door where the hinges all line up and will open and close easily, whereas if the hinges of a door diverge, the door will be stuck in one position.

The transverse tarsal joint transmits the motion that occurs in the hindfoot distally into the forefoot, which is fixed to the ground. To approach the true anatomic situation of the human foot even more closely, the wooden foot model described above is modified to split the distal portion of the horizontal member into two structures (Fig. 1-29A and B). The medial one represents the three medial rays of the foot that articulate through the navicular and cuneiform bones to the talus; the lateral one represents the two lateral rays that articulate through the cuboid to the calcaneus. In Figure 1-29C and D, the entire mechanism has been placed into the leg and foot to demonstrate the mechanical linkages resulting in specific

placement of the subtalar axis relative to the weight-bearing axis through the tibia (Fig. 1-27). Energy is passively absorbed by the stretch of the surrounding ligaments that control subtalar eversion.

At heel strike, there is also progressive inward rotation in the lower extremity, reaching a maximum at the time of foot flat. The internal rotation at heel strike is initiated by the collapse of the subtalar joint into eversion through the obliquity of the subtalar joint axis. The flexibility of the foot and its surrounding ligamentous support determines the magnitude of this rotation. The recording of torques imposed on a force plate substantiates these rotations. Magnitudes vary but range from 7 to 8 newton-meters. Because the foot does not typically rotate on the floor, this torque is absorbed by the joint complexes and surrounding ligaments, further contributing to energy absorption during this part of stance phase.

Of interest, in persons with flatfeet, the axis of the subtalar joint is more horizontal than in persons with “normal” feet; therefore the same amount of rotation of the leg imposes greater supinatory and pronatory effects on the foot. Furthermore, people with asymptomatic flatfeet usually show a greater range of subtalar motion than do persons with more neutrally aligned hindfeet. In the neutral foot, approximately 6 degrees of rotation occurs, and in flatfoot, about 12 degrees (see Fig. 1-26). The reverse holds true for people with pes cavus, in whom the generalized rigidity of the foot, more vertical subtalar axis, and limited motion in the subtalar joint often are observed.

Transverse Tarsal Joint Complex

The calcaneocuboid and talonavicular articulations together often are considered to make up the transverse tarsal joint complex. Each possesses some independent motion and has been subjected to intensive study. Elftman demonstrated that the axes of these two joints are parallel when the calcaneus is in an everted position and are nonparallel when the calcaneus is in an inverted position. The importance of this is that, when the axes are parallel, there is flexibility within the transverse tarsal joint, whereas when the axes are nonparallel, there is rigidity at the transverse tarsal joint (Fig. 1-28). Imagine a door where the hinges all line up and will open and close easily, whereas if the hinges of a door diverge, the door will be stuck in one position.

The transverse tarsal joint transmits the motion that occurs in the hindfoot distally into the forefoot, which is fixed to the ground. To approach the true anatomic situation of the human foot even more closely, the wooden foot model described above is modified to split the distal portion of the horizontal member into two structures (Fig. 1-29A and B). The medial one represents the three medial rays of the foot that articulate through the navicular and cuneiform bones to the talus; the lateral one represents the two lateral rays that articulate through the cuboid to the calcaneus. In Figure 1-29C and D, the entire mechanism has been placed into the leg and foot to demonstrate the mechanical linkages resulting in specific
At the time of heel strike, as the calcaneus moves into eversion, the joints of the transverse tarsal joint complex become parallel, and the midfoot becomes flexible. Although quantification of motion in this joint has not been achieved, Figure 1-30 visually demonstrates the degree of motion that occurs in the transverse tarsal joint when the hindfoot is everted, contrasted to when it is inverted. The suppleness of the midfoot and stretch of surrounding ligaments further contributes to energy absorption during the period from heel strike to foot flat. From a clinical standpoint, the importance of this joint is observed if a subtalar arthrodesis is placed into too much inversion, resulting in stiffness of the midfoot region and causing excessive weight on the lateral border of the foot and a tendency to vault over the rigid midfoot.

**Foot Flat to Toe-Off: Progression to a Rigid Platform**

All of the essential mechanisms discussed in this section are pictorially summarized in Figure 1-10. The two lower photographs, taken with the subject standing on a barograph, reveal the distribution of pressure between the foot and the weight-bearing surface. (A barograph records reflected light through a transparent plastic platform; the intensity of the light is roughly proportionate to the pressure the foot imposes on the plate.) In Figure 1-10A, the subject was asked to stand with muscles relaxed. Note
that the leg is moderately rotated internally and the heel is slightly everted (in valgus position). The body weight is placed on the heel, the outer side of the foot, and the metatarsal heads. In Figure 1-10B, the subject was asked to rise on his toes. Note that the leg is now externally rotated, the heel is inverted (in varus position), and the longitudinal arch is elevated. The weight is concentrated on the metatarsal heads and is shared equally by the metatarsal heads and the toes. Contraction of the intrinsic and extrinsic muscles contributes to stability of the foot and ankle as the body weight is transferred to the forefoot and the heel is raised. Dorsiflexion of the toes tightens the plantar aponeurosis and assists in inversion of the heel. The supinatory twist activates the “locking” mechanism in the transverse tarsal articulation and talonavicular joint, thus converting a flexible foot into a rigid lever. The following sections describe these changes in detail.

**Ankle Joint**

With the foot fixed on the ground during midstance, the body passing over the foot produces dorsiflexion of the ankle (see Fig. 1-3). The ankle undergoes progressive dorsiflexion until approximately 40% of the gait cycle, at which time plantar flexion once again begins, reaching a maximum at the time of toe-off (see Fig 1-4). The oblique ankle axis initially imposes an internal rotation on the leg, the degree of which depends on the amount of dorsiflexion and the obliquity of the ankle axis (Fig. 1-31). During midstance, as the ankle dorsiflexes, a resulting internal rotational torque to the leg occurs. As the heel rises in preparation for lift-off, the ankle is plantar flexed.

This, in turn, reverses the horizontal rotation, causing the leg to rotate externally.

The posterior calf muscles basically function as a group, although the tibialis posterior and peroneus longus muscles usually begin functioning by about 10% of the stance phase, whereas the other posterior calf muscles tend to become functional at about 20% of the stance phase. As the ankle joint undergoes progressive dorsiflexion from foot flat until heel rise at 40% of the cycle, these muscles contract eccentrically. After heel rise, as ankle plantar flexion begins, they continue to contract, but now via a concentric contraction. It is interesting to note, however, that by 50% of the cycle, the electrical activity in these muscles ceases, and the remainder of the plantar flexion of the ankle joint is a passive event. High-speed motion pictures have demonstrated that during steady-state walking, at the time of toe-off, the foot is lifted from the ground, and the toes do not actively push off.

The function of the posterior calf group during stance phase is to control the forward movement of the tibia on the fixed foot. Control of the forward movement of the stance leg tibia is critical to normal gait because it permits the contralateral leg to take a longer step, increasing stride length and improving walking efficiency. In pathologic states in which the calf muscle is weak, the stride length shortens, and dorsiflexion occurs at the ankle joint after heel strike because it is a position of stability. Paradoxically, the ankle is held more rigidly by secondary stabilizers to make up for the inability to control ankle dorsiflexion.

Forces across the ankle joint reach a peak at approximately 40% of the cycle, which is when the transition from dorsiflexion to plantar flexion occurs (Fig. 1-32). The force across the ankle joint reaches approximately 4.5 times body weight at 60% to 70% of stance phase. This corresponds to 40% of walking cycle when ankle plantar flexion is beginning. (From Stauffer RN, Chao EY, Brewster RC: Force and motion analysis of the normal, diseased, and prosthetic ankle joint. *Clin Orthop* 127:189-196, 1977.)
motion achievable by the transverse tarsal articulation with the forefoot fixed depends on the position of the heel. This phenomenon can be seen when examining the foot. If the examiner holds the hindfoot in an everted position, it seems the midfoot becomes “unlocked” and that maximum motion is possible in the transverse tarsal articulation. However, if the hindfoot is inverted and held firmly in one hand, the transverse tarsal articulation appears to become “locked.” The previously elicited motions all become suppressed, and the midfoot becomes rigid (Fig. 1-33). The phenomenon is explained by convergence and divergence of the transverse tarsal joint axes (see Fig. 1-30).

The same relationship between hindfoot position and midfoot suppleness holds during the stance phase of gait. At the time of heel strike, as the calcaneus moves into eversion, there is flexibility in the transverse tarsal joint, and at the time of toe-off, the calcaneus is in an inverted position, resulting in stability of the transverse tarsal joint and hence the longitudinal arch of the foot. This relationship contributes to longitudinal arch stability as the heel rises from the floor, allowing the foot to act as an extension of the leg and improving stride length.

Plantar Aponeurosis
The plantar aponeurosis is a band of fibrous tissue arising from the tubercle of the calcaneus and passing distally to insert into the base of the proximal phalanx. As the plantar aponeurosis passes the plantar aspect of the metatarsophalangeal joints, it combines with the joint capsule to form the plantar plate. The function of the plantar aponeurosis has been likened to a windlass mechanism (Fig. 1-34). The plantar aponeurosis is the most significant stabilizer of the longitudinal arch between heel rise and toe-off. As the body moves over the fixed foot and the heel begins to rise, the proximal phalanges dorsiflex, pulling the plantar aponeurosis over the metatarsal heads. This tightens the plantar fascia, resulting in a depression of the times body weight. This much force confined to a small surface area probably is one reason the components of total ankle joints may loosen and why malreduced ankle fractures rapidly progress to arthritis.

Subtalar Joint
After the hindfoot reaches maximal eversion during the initial phase of stance, it progressively inverts from the foot-flat phase through toe-off for a total arc of 6 degrees in a normal foot (see Fig. 1-26). Both passive and active mechanisms lead to this progressive inversion of the hindfoot. Hindfoot inversion stabilizes the midfoot during the later stages of stance phase by producing a rigid transverse tarsal articulation.

Muscle activity in the deep posterior compartment contributes to hindfoot inversion (see Fig. 1-3). As the posterior tibial muscle–tendon complex contracts, the hindfoot is pulled into inversion. Activity of the intrinsic muscles of the foot also contributes to midfoot stability and correlates fairly closely with the degree of subtalar joint rotation. In the normal foot, the intrinsic muscles become active at about 30% of the walking cycle, whereas in flatfoot, they become active during the first 15% of the walking cycle (see Fig. 1-26).

Passive mechanisms contributing to hindfoot inversion and midfoot stabilization include the plantar aponeurosis and metatarsophalangeal break, which will be described below. Linkage of leg rotation to hindfoot motion also contributes to hindfoot inversion during the later stages of stance. The pelvis, thigh, and leg rotate externally during the last two thirds of stance. This external rotation is converted to hindfoot inversion through the oblique axis subtalar joint.

Transverse Tarsal Articulation
The importance of the transverse tarsal articulation lies not in its axes of motion while non–weight bearing but in how it functions during the stance phase when the foot is required to support the body’s weight. The amount of

Figure 1-33  Rearrangement of skeletal components of foot. A, Supination of forefoot and eversion of heel permitting maximal motion in all components of foot. B, Pronation of forefoot and inversion of heel resulting in locking of all components of foot and producing rigid structure.
supported by the two sesamoid bones), it often functionally approximates the length of the second. When the heel is elevated during standing or at the time of toe lift-off, all the metatarsal heads normally share the weight of the body. To achieve this fair division, the foot must supinate slightly and deviate laterally. After metatarsal heads and an elevation of the longitudinal arch (Fig. 1-35). This mechanism is passive in that no muscle function per se brings about this stabilization.

The plantar aponeurosis is most functional on the medial side of the foot and becomes less functional as one moves laterally toward the fifth metatarsophalangeal articulation. Based on its medial attachment to the calcaneus, plantar fascia tightening also contributes to hindfoot inversion, tibial external rotation, and transverse tarsal joint stabilization. These changes stabilize the midfoot and allow the foot to act as a rigid lever during the toe-off phase of gait.

The mechanics of the windlass mechanism can be demonstrated clinically by having an individual stand and forcing the great toe into dorsiflexion. As this occurs, one observes elevation of the longitudinal arch by the depression of the first metatarsal by the proximal phalanx, and, at the same time, inversion of the calcaneus. Careful observation of the tibia demonstrates that it externally rotates in response to this calcaneal inversion.

**Metatarsophalangeal Break**

The metatarsophalangeal break refers to the axis formed by the unequal forward extension of the metatarsals. The head of the second metatarsal is the most distal head; that of the fifth metatarsal is the most proximal. Although the first metatarsal usually is shorter than the second (because the first metatarsal head is slightly elevated and is supported by the two sesamoid bones), it often functionally approximates the length of the second.

When the heel is elevated during standing or at the time of toe lift-off, all the metatarsal heads normally share the weight of the body. To achieve this fair division, the foot must supinate slightly and deviate laterally. After
Swing Phase

During swing phase, dorsiflexion occurs at the ankle joint. Beginning at about 55% of the cycle and throughout swing phase, the anterior compartment muscles contract concentrically to dorsiflex the ankle. The medial insertion of the tibialis anterior tendon pulls the hindfoot into slight inversion during swing phase such that the calcaneus is slightly inverted at initial heel strike. This is why most people will wear down the outer edge of the heel in their shoes asymmetrically. Anterior compartment musculature weakness results in a footdrop gait, characterized by an inability to dorsiflex the ankle, resulting in a decreased range of motion and potential for increased plantarflexion during the stance phase. This can lead to a variety of gait disturbances, including a shortened step length, increased knee flexion, and a decreased ability to maintain balance.

Figure 1-36  Variations in metatarsal break in relation to longitudinal axis of foot. (From Isman RE, Inman VT: Anthropometric studies of the human foot and ankle. Bull Prosthet Res 10:97, 1969.)

wearing a new pair of shoes for a while, one notices the appearance of an oblique crease in the area overlying the metatarsophalangeal articulation (Fig. 1-36). This oblique crease demonstrates the metatarsophalangeal break. The angle between the metatarsophalangeal break and the long axis of the foot may vary from 50 to 70 degrees.44 The more oblique the metatarsophalangeal break, the more the foot must supinate and deviate laterally after heel rise.

If the leg and foot acted as a single rigid member without ankle, subtalar, or transverse tarsal articulations, the metatarsophalangeal break would cause lateral inclination and external rotation of the leg (Fig. 1-37A). However, the subtalar joint accommodates this supination and permits the leg to remain in a vertical plane during walking (Fig. 1-37B and C).

Talonavicular Joint

The talonavicular joint morphology adds additional stability to the longitudinal arch when force is applied across it during the last half of the stance phase. The joint surface has different curvature of radius in the anteroposterior and lateral projections (Fig. 1-38). When force is applied across a joint of this shape, stability is enhanced. This occurs at toe-off, when the plantar aponeurosis has stabilized the longitudinal arch and most of the body weight is being borne by the forefoot and medial longitudinal arch.

Figure 1-37  Supination and lateral deviation of foot during raising of heel caused by oblique metatarsophalangeal break. A, Wooden mechanism without articulation. If no articulation is present, leg deviates laterally. B, Wooden mechanism with articulation. Leg remains vertical; hence some type of articulation must exist between foot and leg. C, Articulation similar to that of subtalar joint. In addition to its other complex functions, subtalar joint also functions to permit leg to remain vertical.

Figure 1-38  Talonavicular joint. Left, Anterior view. Right, Lateral view. Relationship of head of talus to navicular bone shows differing diameters of head of talus. (From Mann RA: Intractable Plantar Keratoses. In Nicholas JA, Hershman EB, editors: The lower extremity and spine in sports medicine, ed 2, St Louis, 1995, Mosby.)
by accentuated hip flexion or circumduction of the hip during swing phase to avoid the toes of the dropped foot hitting the floor during swing-through.

**Component Mechanics of Running**

During running, the stance phase is diminished from approximately 0.6 second while walking to 0.2 second while sprinting (Fig. 1-39). During this brief period of stance phase, the forces involved in the vertical plane are increased to 2.5 to 3 times body weight. The range of motion of the joints is increased approximately 50%, and the muscles in the lower extremity must control these motions over a short time when measured in real time but over a considerable period when expressed as percentage of the gait cycle. It is probably because of the increased forces and muscle action required over a shorter period of time, and the repetitive nature of sport, that overuse injuries occur during running.

Considerable alterations occur around the ankle joint when comparing jogging or running with walking. The gait cycle time progressively decreases from 1 second to 0.6 second. The ankle’s total arc of motion increases from 30 degrees during walking to 45 degrees during running. This motion occurs during 0.6 second for walking and 0.2 second for running. The direction of motion also changes: during walking, plantar flexion occurs at heel strike, whereas during jogging and running, there is progressive dorsiflexion. Rapid plantar flexion occurs at toe-off during all speeds of gait.

Along with this increase in the range of motion and in the forces generated during running, the muscle function in the lower extremity also is altered. In real time, the phasic activity of most muscles decreases; however, when considered as a percentage of the gait cycle, the period of activity of these muscles increases considerably. Generally speaking, at initial ground contact, the majority of the muscles about the hip, knee, and ankle joints are active, and their period of activity, which begins during the late float phase, increases as the speed of gait increases. This is probably related to the rapid motion required by these joints in preparation for the impact of ground contact. During walking, there is adequate time for most of the preparation for ground contact to be carried out rather passively, but with the markedly increased range and speed of motion of these joints during running, muscle function plays a more active role. As the speed of gait increases, the muscle function in the posterior calf group changes significantly. During walking, the posterior calf group functions in stance phase, and during jogging and running, it performs in late swing phase; its activity is ongoing from the time of initial ground contact through most of the stance phase. The muscle group controls the ankle dorsiflexion that occurs after initial ground contact, the forward movement of the tibia, and brings about plantar flexion of the ankle joint. Similar changes in both the magnitude of motion and muscle function occur about the hip and knee joints as well. During running and changing direction, as well as acceleration and deceleration, the toes play an active role in push-off, whereas push-off is minimal during steady-state walking.

**Figure 1-39** Ankle joint dorsiflexion–plantar flexion during running, jogging, and walking. Note that time of walking cycle decreases from 1 second for walking to approximately 0.6 second for running. Stance-phase time decreases significantly, as well. Muscle function is characterized by gastrocnemius–soleus muscle group and anterior tibial muscle. Note that gastrocnemius–soleus muscle group becomes active in late swing phase for jogging and running, compared with stance-phase muscle for walking. (From Mann RA: Intractable Plantar Keratoses. In Nicholas JA, Hershmann EB, editors: The lower extremity and spine in sports medicine, ed 2, St Louis, 1995, Mosby.)

**Surgical Implications of Biomechanics of the Foot and Ankle**

The purpose of this section is to correlate the biomechanical principles discussed thus far with some of the surgical procedures carried out about the foot and ankle. The decisions made by the orthopaedic surgeon when planning...
and undertaking a surgical procedure depend on a thorough understanding of biomechanical principles.

**Biomechanical Considerations in Ankle Arthrodesis**

Because the subtalar and ankle joints work together during gait, it is important that certain anatomic facts be kept in mind when carrying out an ankle arthrodesis. An arthrodesis of the ankle joint places increased stress on the subtalar joint below and the knee joint above. The degree of internal or external tibial torsion, genu varum or genu valgum, proximal muscle weakness, and configuration of the longitudinal arch should be considered.

When an ankle arthrodesis is carried out, the degree of transverse rotation placed in the ankle mortise must be carefully considered so that increased stress is not caused within the foot. If the ankle is placed into excessive internal rotation, the patient experiences difficulty when the center of gravity passes over the foot. The position of internal rotation places increased stress on the subtalar and midtarsal joint region, which may become painful as a result of increased stress. Knee pain, and possibly hip pain, also may develop secondarily as a result of attempts to externally rotate the lower limb to help compensate for the abnormal position of the foot. If the ankle is placed into too much external rotation, the patient tends to roll over the medial border of the foot. This position permits the patient to easily roll over the foot, but in turn, it places increased stress on the medial side of the knee joint.

The degree of varus or valgus tilt of the ankle joint must be carefully considered and should be related to the degree of subtalar joint motion and the overall alignment of the knee and tibia. If the subtalar joint is stiff and unable to compensate for any malalignment, it is imperative to place the ankle joint into sufficient valgus position to obtain a plantigrade foot. If the ankle joint is placed into varus position, the patient will walk on the lateral border of the foot. This not only causes the patient discomfort because of localized weight bearing in a relatively small area, but the persistent varus position of the subtalar joint keeps the transverse tarsal joint in a semirigid state, resulting in a rather immobile forefoot that is difficult for the body to pass over during the stance phase.

The degree of dorsiflexion and plantar flexion of the ankle joint must also be carefully considered when carrying out an ankle arthrodesis. If there is a short lower extremity or an unstable knee joint as a result of weakness or loss of quadriceps function, the ankle joint should be placed into plantar flexion (10 to 15 degrees) to help give stability to the knee joint. If the pathologic process involves only the ankle joint, a neutral position is considered the position of choice. If the ankle joint is placed into excessive plantar flexion, the involved limb is lengthened, which, in turn, causes a back-knee thrust on the midfoot. If the ankle is placed into too much dorsiflexion, the impact of ground contact is concentrated in one small area of the heel, which may result in chronic pain. After an ankle arthrodesis, patients usually develop increased motion in the sagittal plane, which helps to compensate for loss of ankle motion. In our study of 81 ankle fusions, the sagittal arc of motion of the talocalcaneal joint averaged 24 degrees (9 to 43 degrees), at the talonavicular joint 14 ± 6 degrees (Fig. 1-40).²

**Hindfoot Alignment**

Rotation occurs in the transverse plane during normal walking. This transverse rotation increases as we proceed from the pelvis to the ankle. Internal rotation occurs at initial ground contact, followed by external rotation until toe-off, when internal rotation begins again (see Fig. 1-8). This transverse rotation passes across the ankle joint and is translated by the subtalar joint to the calcaneus and foot. The loss of subtalar joint motion may result from trauma, arthritis, surgery, or congenital abnormality. This loss of rotation causes increased stress to be placed on the
Joint above (ankle) and below (transverse tarsal) the immobile joint. These changes brought on by lack of subtalar joint function may lead to chronic pain. The increased stress may cause secondary changes to occur in some individuals, which may take the form of a ball-and-socket ankle joint (Fig. 1-41). At other times, beaking may occur in the talonavicular joint in a patient with a subtalar coalition (Fig. 1-42).

When a subtalar joint is fused, the transverse rotation that occurs in the lower extremity is partially absorbed in the ankle joint because it no longer can pass through the subtalar joint into the foot. The varus or valgus alignment of the subtalar joint will affect the position of the forefoot, so accurate alignment is essential. If the subtalar joint is placed into too much varus, the forefoot is rotated into supination, and the weight-bearing line of the extremity then passes laterally to the calcaneus and fifth metatarsal. This results in increased stress on the lateral collateral ligament structure and abnormal weight bearing along the lateral aspect of the foot. This position also holds the forefoot in a semirigid position, so the patient must either vault over it or place the foot in external rotation to roll over the medial aspect.

The position of choice is a valgus tilt of about 5 degrees in the subtalar joint because this permits satisfactory stability of the ankle joint, and the weight-bearing line of the body will pass medial to the calcaneus; therefore no stress will be placed on the lateral collateral ligament structure. This position results in slight pronation of the forefoot, which permits even distribution of weight on the plantar aspect of the foot. The slight valgus position also allows the forefoot to remain flexible so that the body can more easily pass over it.

Midfoot Alignment

When surgical stabilization of the talonavicular or transverse tarsal joint is carried out, motion in the subtalar joint is largely eliminated. For motion to occur in the subtalar joint, rotation of the navicular over the head of the talus must occur. If it cannot, there is essentially no subtalar joint motion. An isolated fusion of the calcaneocuboid joint results in about a 30% loss of subtalar joint motion. Motion of the subtalar joint directly affects the stability of the foot through its control of the transverse tarsal joint. When the subtalar joint is in valgus position, the transverse tarsal joint is unlocked and the forefoot is flexible. Conversely, when the subtalar joint is inverted, the transverse tarsal joint is locked and the forefoot is fairly rigid. Because of the role the transverse tarsal joint plays in controlling the forefoot, it is essential that the foot be placed in a plantigrade position when the joints are stabilized. If the foot is placed into too much supination, the medial border of the foot is elevated, and undue stress is placed on the lateral aspect of the foot. It also

---

Figure 1-41  Etiology of a ball-and-socket ankle joint in adults. A, As a result of a congenital abnormality of the subtalar joint that eliminated subtalar motion, the ankle joint absorbed transverse rotation that normally occurs in subtalar joint. B, A congenital talonavicular fusion, which results in loss of subtalar joint motion, causes the ankle to absorb transverse rotation, resulting in a ball-and-socket ankle joint.

Figure 1-42  Talar beaking after increased stress as result of subtalar coalition.
creates a rigid forefoot. The position of choice is neutral rotation or slight pronation, which ensures a flexible plantigrade foot.

When a triple arthrodesis is carried out, the position of choice is 5 degrees of valgus for the subtalar joint and neutral rotation of the transverse tarsal joint. It should be emphasized, however, that it is better to err on the side of too much valgus and pronation to keep the weight-bearing line medial to the calcaneus because that produces a more flexible plantigrade foot. When carrying out a pantalar arthrodesis, the same basic principles apply.

Surgical stabilization of the intertarsal and medial three tarsometatarsal joints can be carried out with minimum loss of function or increased stress on the other joints in the foot. The intertarsal joints, which are distal to the transverse tarsal joint and proximal to the metatarsophalangeal joints, have little or no motion between them. The lateral two tarsometatarsal joints are more flexible, and surgically, strategies that maintain flexibility are favored to fusion.

Forefoot Principles

Removal of the base of the proximal phalanx of the great toe causes instability of the medial longitudinal arch as a result of disruption of the plantar aponeurosis and the windlass mechanism. This leads to decreased weight bearing of the first metatarsal head, which results in weight being transferred to the lesser metatarsal heads. Surgical techniques that remove the proximal phalanx base but preserve the plantar plate may lessen this effect. If the base of the proximal phalanx of one of the lesser toes is removed, a similar problem of instability occurs, but to a much lesser degree, particularly moving laterally across the foot. Conversely, resection of the metatarsal head, except in severe disease states such as rheumatoid arthritis or diabetes, results in a similar problem because the windlass mechanism is destroyed as a result of the relative shortening of the ray. This also causes increased stress and callus formation beneath the adjacent metatarsal head, which is subjected to increased weight bearing.

When carrying out an arthrodesis of the first metatarsophalangeal joint for such conditions as hallux rigidus, recurrent hallux valgus, or degenerative arthritis, the alignment of the arthrodesis site is critical. The metatarsophalangeal joint should be placed into approximately 10 to 15 degrees of valgus and 15 to 25 degrees of dorsiflexion in relation to the first metatarsal shaft. The degree of dorsiflexion depends to a certain extent on the heel height of the shoe that the patient desires to wear. An arthrodesis of the first metatarsophalangeal joint has a minimum effect on gait. The arthrodesis places increased stress on the interphalangeal joint of the hallux. This increased stress may result in degenerative changes over time, but these rarely become symptomatic. From a theoretic standpoint, increased stress is placed on the first metatarsocuneiform joint after arthrodesis of the metatarsophalangeal joint, but it is unusual to see any form of degenerative change.

An isolated arthrodesis of the interphalangeal joint of the great toe does not seem to have any significant effect on the biomechanics of gait, nor does an arthrodesis of the proximal and distal interphalangeal joints of the lesser toes.

Resection of a single sesamoid bone because of a pathologic condition, such as a fracture, avascular necrosis, or intractable plantar keratosis, may be done with relative impunity. If, however, one sesamoid already has been removed, the second sesamoid probably should not be removed because of risk of a cock-up deformity of the metatarsophalangeal joint. This occurs because the intrinsic muscle insertion into the proximal phalanx of the great toe encompasses the sesamoids, and when the sesamoid is removed, this insertion is impaired to a varying degree. If adequate intrinsic function is not present, flexion of the proximal phalanx cannot be brought about, and a cock-up deformity results.

Tendon Transfers

When evaluating muscle weakness or loss about the foot and ankle, the diagram in Figure 1-43 can be useful. It demonstrates the motion that occurs around each joint axis and the location of the muscles in relation to the axes. By considering the muscles in relation to the axes, it is possible to carefully note which muscles are functioning and thereby determine which muscles might be transferred to rebalance the foot and ankle. Generally speaking, if inadequate strength is present to balance the foot adequately, it is important to establish adequate plantar flexion function over that of dorsiflexion; an equinus gait is not as disabling as a calcaneal-type gait. Also keep in mind that it is much more difficult to retrain a muscle that has been a stance-phase muscle to become a swing-phase muscle than to retrain a swing-phase muscle to become a stance-phase muscle. Therefore, if possible, an in-phase muscle transfer will produce a more satisfactory result because no phase conversion is necessary.

Ligaments of the Ankle Joint

The configuration and alignment of the ligamentous structures of the ankle are such that they permit free movement of the ankle and subtalar joints to occur simultaneously. Because the configuration of the trochlear surface of the talus is curved to produce a cone-shaped articulation whose apex is directed medially, the single fan-shaped deltoid ligament is adequate to provide stability to the medial side of the ankle joint (Fig. 1-44). On the lateral aspect of the ankle joint, however, where there is a larger area to be covered by a ligamentous structure, the ligament is divided into three bands: the anterior and posterior talofibular ligaments and the calcaneofibular ligament. The relationship of these ligaments to each other and to the axes of the subtalar and ankle joints must
always be considered carefully when these joints are examined or ligamentous surgery is contemplated.

Figure 1-45 demonstrates the anterior talofibular and calcaneofibular ligaments in relation to the subtalar joint axis. The calcaneofibular ligament is parallel to the subtalar joint axis in the sagittal plane. As the ankle joint is dorsiflexed and plantar flexed, this relationship between the calcaneofibular ligament and the subtalar joint axis does not change. Furthermore, the calcaneofibular ligament crosses both the ankle and the subtalar joint. This ligament is constructed to permit motion to occur in both of these joints simultaneously. It is important to appreciate that, when the ankle joint is in neutral position, the calcaneofibular ligament is angulated posteriorly, but as the ankle joint is brought into more dorsiflexion, the calcaneofibular ligament is brought into line with the fibula, thereby becoming a true collateral ligament. Conversely, as the ankle joint is brought into plantar flexion, the calcaneofibular ligament becomes horizontal to the ground. In this position, it provides little or no stability for resisting inversion stress. The anterior talofibular ligament, on the other hand, is brought into line with plantar flexion, the calcaneofibular ligament becomes horizontal to the ground. In this position, it provides little or no stability for resisting inversion stress. The anterior talofibular ligament, on the other hand, is brought into line with plantar flexion, thereby acting as a collateral ligament. When the ankle joint is brought up into dorsiflexion, the anterior talofibular ligament becomes sufficiently horizontal so that it does not function as a collateral ligament. It can thus be appreciated that, depending on the position of the ankle joint, either the calcaneofibular or the anterior talofibular ligament will be a true collateral ligament with regard to providing stability to the lateral side of the ankle joint.

The relationship between these two ligaments has been quantified and is presented in Figure 1-46. This demonstrates the relationship of the angle produced by the calcaneofibular and the anterior talofibular ligaments to one another. The average angle in the sagittal plane is approximately 105 degrees, although there is considerable variation, from 70 to 140 degrees. This is important because, from a clinical standpoint, it partially explains why some persons have lax collateral ligaments. If we assume that when the ankle is in full dorsiflexion the calcaneofibular ligament provides most of the stability...
and that in full plantar flexion the anterior talofibular ligament provides stability, then as we pass from dorsiflexion to plantar flexion and back there will be a certain period in which neither ligament is functioning as a true collateral ligament. If we assume there is an average angle of approximately 105 degrees between these ligaments, then generally speaking, an area in which an insufficient lateral collateral ligament is present is unusual; however, if we have angulation of 130 to 140 degrees between these two ligaments, there is a significant interval while the ankle is passing from dorsiflexion to plantar flexion and back in which neither ligament is functioning as a collateral ligament. This may explain why some persons are susceptible to chronic ankle sprains. Some patients who are thought to have ligamentous laxity may, in reality, possess this anatomic configuration of lateral collateral ligaments.

The other factor that needs to be considered is the relationship of the calcaneofibular ligament to subtalar joint motion. The primary stabilizers of the subtalar joint are the interosseus talocalcaneal ligaments that reside within the sinus tarsi, not the calcaneofibular ligament. Because motion in the subtalar joint occurs about an axis that deviates from dorsal-medial to plantar-lateral (see Fig. 1-24), and the calcaneal attachment of the calcaneofibular ligament lies on the subtalar joint axis, motion of the subtalar joint around this axis occurs with minimal change in calcaneofibular length. Instead, as the subtalar joint moves, the calcaneofibular ligament moves along a path approximating the surface of a cone whose apex is the intersection of the ligament and the subtalar joint axis. This relationship of the calcaneofibular ligament to the ankle and subtalar joint axes is critical when contemplating ligamentous reconstruction because any ligament reconstruction that fails to take this normal

Figure 1-45 Calcaneal fibular ligament and anterior talofibular ligament. A, In neutral position of ankle joint, both anterior talofibular and calcaneofibular ligaments provide support to joint. B, In plantar flexion, anterior talofibular ligament is in line with fibula and provides most of support to lateral aspect of ankle joint. C, In dorsiflexion, calcaneofibular ligament is in line with the fibula and provides support to the lateral aspect of ankle joint. (From Inman VT: The joints of the ankle, Baltimore, 1976, Williams & Wilkins.)

Figure 1-46 Average angle between calcaneofibular and talofibular ligaments in sagittal plane. Although the average angle is 105 degrees, there is considerable variation, from 70 to 140 degrees. (From Inman VT: The joints of the ankle, Baltimore, 1976, Williams & Wilkins.)
Part I ■ General Considerations

Anatomic configuration into consideration results in a situation in which motion in one or both of these joints is restricted.

From a clinical standpoint, when one is evaluating the stability of the lateral collateral ligament structure, the ankle joint should be tested in dorsiflexion to demonstrate the competency of the calcaneofibular ligament and in plantar flexion to test the competency of the anterior talofibular ligament. If both ligaments are completely disrupted, there will be no stability in either position. Furthermore, to test for stability of the anterior talofibular ligament, the anterior drawer sign should be

Figure 1-47  A, Stress radiographs of ankle in dorsiflexion (DF) demonstrate no instability in calcaneofibular ligament. Same ankle stressed in plantar flexion (PF) demonstrates loss of stability caused by disruption of anterior talofibular ligament. Note anterior subluxation present when this ligament (L) is torn (anterior drawer sign). B, Stress radiograph of ankle in plantar flexion demonstrates no ligamentous instability. Same ankle stressed in dorsiflexion demonstrates laxity of calcaneofibular ligament. C, Stress radiograph of ankle joint in dorsiflexion, plantar flexion, and anteriorly all demonstrate evidence of ligamentous disruption. This indicates complete tear of lateral collateral ligament structure.
elicited, with the ankle joint in neutral position, when the anterior talofibular ligament is in a position to resist anterior displacement of the talus from the ankle mortise (Fig. 1-47).

REFERENCES