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The Role of Foot Biomechanics in Lower Extremity Pathologies

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THE ROLE OF FOOT BIOMECHANICS
IN LOWER EXTREMITY PATHOLOGIES

by

Don Martin
Bachelor of Science in Physical Therapy
University of North Dakota, 1994

An Independent Study
Submitted to the Graduate Faculty of the
Department of Physical Therapy
School of Medicine
University of North Dakota
in partial fulfillment of the requirements
for the degree of
Master of Physical Therapy

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1995
This Independent Study, submitted by Don Martin in partial fulfillment of the requirements for the Degree of Master of Physical Therapy from the University of North Dakota, has been read by the Faculty Preceptor, Advisor, and Chairperson of Physical Therapy under whom the work has been done and is hereby approved.

(Faculty Preceptor)

(Graduate School Advisor)

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Title The Role of Foot Biomechanics in Lower Extremity Pathologies

Department Physical Therapy

Degree Masters of Physical Therapy

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ABSTRACT

Lower extremity pathologies caused by abnormal biomechanics of the subtalar joint are commonly seen in the health care setting. Certain foot types will predispose an individual to excessive amounts of subtalar joint pronation or supination during gait. Subtalar joint movement is transmitted proximally to the lower extremity during gait and excessive amounts of pronation or supination can lead to altered biomechanics in the lower extremity with development of various lower extremity injuries. The purpose of this study is to analyze the biomechanical events of the subtalar joint of the foot during gait in order to show how abnormalities in these events can be responsible for lower extremity injuries. This information will enable clinicians to conduct a more accurate and comprehensive assessment of the cause of lower extremity injuries. By assessing the cause of lower extremity injury, a rapid recovery can be anticipated and recurrence of the injury can be prevented.
The foot, as the structure that connects the body to the ground, is an important joint functionally. It must enable the body to easily stand on the ground while a myriad of other activities are performed by the trunk and extremities. An important activity in which the foot is involved is walking. During the normal walking cycle the foot goes through a complex set of movements at each of its joints. These movements are necessary to allow the foot to play two key roles. First, the foot must function as a mobile adaptor to accept uneven terrain and provide shock absorption for the lower extremity. Second, the bones of the foot must become stable enough to allow the foot to function as a rigid lever to propel the body forward during gait.

In addition to functioning as a mobile adaptor and rigid lever, the foot must also enable the lower extremity to rotate in the transverse plane during gait. The pelvis moves anteriorly and posteriorly during gait due to the movements of the trunk and lower extremity. The pelvis of the reference leg moves anteriorly from the beginning of swing phase to shortly after the foot strikes the ground, causing the ipsilateral lower extremity to internally rotate. The pelvis then moves posteriorly until swing begins again, causing the ipsilateral lower extremity to externally rotate. If the foot followed the transverse plane rotations of the lower extremity, the foot would rotate from side to side on the ground and prevent smooth, continuous forward movement of the body.
during gait, as well as interrupt the stable foot-to-ground relationship. In actuality the transverse plane motions of the lower extremity during gait are converted by the foot to motions which will allow the foot to maintain firm contact on the ground without rotating side to side.

The key to the foot being able to accomplish the roles just described lies in the biomechanics of the subtalar joint. In early stance phase the subtalar joint pronates as the heel strikes the ground. With pronation of the subtalar joint, the joints of the foot become less rigid and the foot is able to function as a mobile adaptor, providing solid foot contact on uneven terrain. Also, subtalar joint pronation in the closed kinetic chain is accompanied by tibial internal rotation and therefore allows the lower extremity internal rotation transmitted inferiorly by the pelvis in early stance phase to be absorbed without changing the foot to ground relationship.

In later stance phase external rotation of the ipsilateral pelvis is occurring, with this rotation being transmitted to the femur and tibia. In the closed kinetic chain subtalar joint supination occurs together with tibial external rotation; thus, the subtalar joint is able to accommodate the external rotation of the lower extremity in late stance phase by supinating. In addition to allowing for tibial external rotation, subtalar joint supination will cause the joints of the foot to become less supple, making the foot a rigid lever which can efficiently propel the body forward at the end of stance phase. It becomes evident that the biomechanics of the foot play a critical role in stance phase to allow the foot to complete its necessary functions during gait.

In gait the motions of the subtalar joint and the other joints of the foot are controlled by muscle activity, ground reaction forces, and transverse plane
rotations of the lower extremity transmitted to the foot through the tibia. Of these forces affecting foot motion, ground reaction forces are the primary determinant of foot joint position and movement. The body's weight creates ground reaction forces which cause the foot to assume a position in which it is as close to being flat on the ground as possible. If there is a structural deformity in the foot, the foot may be forced to assume an abnormal position to allow itself to rest evenly on the ground. In this instance, motion in the joints of the foot will not occur in a biomechanically correct manner and lower extremity pathology may result.

For example, if either the calcaneus or the plane of the metatarsal heads is inverted excessively, the foot may be forced to pronate excessively at the subtalar joint in order to remain flat on the ground during gait. This excessive pronation can strain the soft tissues responsible for controlling the amount of pronation which takes place during gait.\(^1\) Also, with a foot that pronates too long during the stance phase of gait, pathology may occur as a result of the foot remaining flexible and mobile at a time when rigidity is needed for gait propulsion. The soft tissues of the foot may then be overloaded as they are called upon to support the foot during single limb pushoff in gait.\(^2\) Prolonged pronation of the foot during stance phase may also cause internal rotation forces to be transmitted superiorly along the lower extremity at the same time the pelvis is transmitting external rotation forces inferiorly, thus causing soft tissue stresses where these forces meet.\(^3\)

Structural deformities which cause the subtalar joint to remain supinated throughout the gait cycle can also lead to lower extremity pathology. With a foot that remains supinated during the early part of stance phase, the shock of the ground reaction forces at heelstrike will not be properly absorbed.\(^4\) This leads
to excessive stress to certain soft tissue and bony structures of the lower extremity.

It becomes apparent that structural deformities in the foot may compromise the normal biomechanics of the foot, hindering the foot’s ability to function in the gait cycle as a mobile adaptor, rigid lever, and buffer to transverse plane rotations of the lower extremity. When the foot is not able to carry out its necessary functions in gait, different anatomical structures in the lower extremity are stressed excessively, leading to a variety of lower extremity pathologies. These pathologies may include plantar fascitis, Achilles tendonitis, tibialis posterior tendonitis, shin splints, stress fractures, iliotibial band syndrome, patellofemoral pain syndrome, hip rotator strain, and sacroiliac dysfunction.\(^1,2,5,6\) The purpose of this paper is to discuss normal and abnormal foot biomechanics in order to describe the means by which abnormal foot biomechanics produce these and other lower extremity pathologies, with the intent to provide present and future clinicians with the knowledge to better evaluate and treat lower extremity injuries.
STRUCTURAL ANATOMY

As a foundation for understanding the normal and abnormal function of the foot, a thorough grasp of the structural anatomy of the foot is essential. The foot is made of many bones, all arranged to allow the foot to be both a mobile adaptor to ground reaction forces and a rigid lever for propulsion in gait. The bones of the foot complex include the tibia, fibula, talus, calcaneus, navicular, cuboid, cuneiforms, metatarsals, and phalanges. These bones make up many joints in the foot, with the major functional joints of the foot being the subtalar, talocrural, midtarsal, and tarsometatarsal joints.

Subtalar Joint

The calcaneus is the largest bone in the foot and plays a controlling role in the movement that occurs in the functional joints of the foot. The superoanterior portion of the calcaneus is concave and articulates with the convex inferior portion of the talus, forming the subtalar joint. This joint has been found to be a ginglymus joint, with motion occurring about one axis; however, the motion does not occur in one pure cardinal plane and is best described as triplanar motion. The axis of motion for the subtalar joint lies 23 degrees medially rotated from the sagittal midline of the foot, directed posterolateral to anteromedial. This same axis rises 42 degrees from the horizontal in a posterior to anterior direction. Thus, motion that occurs in the
subtalar joint is either a combination of inversion, plantarflexion, and adduction of the calcaneus, (termed supination), or a combination of eversion, dorsiflexion, and abduction of the calcaneus, (termed pronation). With supination the most measurable movement occurring is calcaneal inversion, and with pronation the most measurable motion occurring is calcaneal eversion. Thus calcaneal inversion and eversion are often used as clinical measures of subtalar joint supination and pronation.

The talocalcaneal (interosseous) ligament divides the subtalar joint surfaces into an anterior half and a posterior half and serves to hold the calcaneus and talus together, becoming taught in supination and slack in pronation. The ligament is located within a tunnel in the subtalar joint, the sinus tarsi, which protects the ligament from weightbearing forces between the calcaneus and talus.

Talocrural Joint

Above the talus the distal tibia and fibula come together to form a concave socket into which fits the convex superior portion of the talus. This joint, the talocrural or ankle joint, is also a ginglymus joint. The axis of motion for the ankle joint lies 23 degrees externally rotated from the coronal midline of the joint in the transverse plane, while rising 8 degrees in the transverse plane from the lateral malleolus to the medial malleolus. Because the joint axis does not lie in one cardinal plane, the motions at the talocrural joint are also triplanar. Talocrural supination combines ankle plantarflexion with adduction and inversion, while talocrural pronation combines ankle dorsiflexion with abduction and eversion. The orientation of the talocrural joint axis does make
plantarflexion and dorsiflexion the primary movements which occur with supination and pronation. For this reason, talocrural joint movement is most often referred to as plantarflexion and dorsiflexion rather than supination and pronation.

Medial to the talocrural joint lies the deltoid ligament. This ligament is very broad and strong, connecting the talus, tibia, calcaneus, and navicular to limit valgus stress to the talocrural joint and pronation of the subtalar joint. Lateral to the ankle three ligaments exist to limit varus stress to the talocrural joint and supination of the subtalar joint. These are the anterior talofibular ligament, running from the anterolateral talus to the lateral side of the fibula, the posterior talofibular ligament, running from the posterolateral talus to the lateral side of the fibula, and the calcaneofibular ligament, running from the lateral calcaneus to the lateral fibula.

Midtarsal Joint

Anterior to the talus and calcaneus lies the midtarsal joint, which divides the forefoot from the rearfoot. This joint separates the talus and calcaneus from the navicular and cuboid and allows gliding in conjunction with rotation. Although it is easiest to visualize this joint as a single articulation dividing the talus and calcaneus from the navicular and cuboid, it is actually two separate articulations, one between the talus and navicular and one between the calcaneus and cuboid. Due to the congruency of the tarsal bones and the abundance of connective tissue in the midfoot, only a small amount of movement is normally available between the navicular and cuboid, causing this joint to move functionally as one articulation.
There are two different axes of motion in the midtarsal joint and they allow two different types of motion. First, there is rotary motion around an axis running nine degrees from the sagittal midline of the foot in the anteromedial direction and rising 15 degrees from the transverse plane in the anterodorsal direction. The rotary motion occurring about this axis is termed inversion and eversion, inversion being equated with raising the medial longitudinal arch of the foot and eversion being equated with lowering the arch. The second motion available at the midtarsal joint is commonly termed flexion and extension, although adduction occurs with flexion of the midtarsal joint and abduction occurs with extension. Flexion and extension of the midtarsal joint can be represented by a single axis which runs 57 degrees anteromedially from the sagittal midline of the foot and 52 degrees anterodorsally from the transverse plane. The flexion and extension axis of the midtarsal joint may be thought of as a “little ankle” axis as it approximately parallels the ankle axis and allows similar motion to that of the ankle.

Tarsometatarsal Joint

The tarsometatarsal joint divides the cuneiforms and cuboid from the metatarsals. This joint allows flexion and extension of the metatarsal bones and a small amount of supination and pronation of the first and fifth rays. These motions occur together and result in a supination or pronation twist of the forefoot, thus establishing the forefoot as a separate functional part of the foot.

A supination twist of the forefoot is a result of first ray extension and fifth ray flexion, with the second through fourth rays extending or flexing to various degrees so that the metatarsal heads may remain in the same plane.
Tarsometatarsal supination causes flattening of the arch of the foot. A pronation twist of the forefoot is a result of first ray flexion and fifth ray extension, with the second through fourth metatarsal heads again extending and flexing to various degrees to enable the metatarsal heads to remain in the same plane. Pronation of the tarsometatarsal joint creates a high medial arch.

In the midfoot, including the midtarsal and tarsometatarsal joints, there are many ligaments which serve to limit range of motion. Movement in the midfoot is also limited by the tight fit of the bones in this area of the foot. For this reason trauma to specific ligaments of the midfoot is rare and details about how specific motions of the midtarsal and tarsometatarsal joints are limited by specific ligaments is not of major concern.

The ligaments of the midfoot should, however, be discussed along with the plantar aponeurosis in respect to the their role in maintaining the arches of the foot. The arches of the foot provide structural form for the foot and ensure proper biomechanical and weightbearing patterns for gait and other closed chain activities of the foot.

There are three arches of the foot whose primary purpose is to prevent the collapse of the foot while supporting the body during weightbearing activities. The individual arches of the foot are the medial longitudinal arch, the lateral longitudinal arch, and the transverse arch. Connective tissue running along the base of each arch ties the front of the arch to the rear of the arch and locks the bones it traverses into a truss-like structure which will support the body's weight without collapse. This mechanism is the means by which the arches of the foot derive their primary support. In addition, limited support for
the arch is also given by the way the bones of the arch fit together and by muscular suspension from above.  

Medial Longitudinal Arch

The bones of the medial longitudinal arch are the calcaneus, talus, navicular, the three cuneiforms, and the first three metatarsals. A primary purpose of the medial longitudinal arch is support of the talus, which bears the full weight of the body at times during the gait cycle. The plantar fascia or plantar aponeurosis provides primary support of the medial longitudinal arch and talus. The plantar fascia is a strong, thick band of longitudinally arranged collagen fibers designed to resist tensile forces. It originates predominantly from the medial aspect of the calcaneus and runs to the root of the toes where it blends with the flexor tendons and sheaths of each toe. The plantar fascia provides strong support for the whole of the medial arch by connecting the calcaneus and metatarsals, thus locking the bones between the calcaneus and metatarsals in their arched shape.

Support of the talus is also accomplished in other ways. For one, the sustenaculum tali of the calcaneus supports the talus from below. Also, the navicular and calcaneus form a concavity in which the talus fits, providing a somewhat stable position for the talus. This concavity is maintained by the plantar fascia and the strong plantar calcaneonavicular ligament, which runs from the anterior margin of the sustenaculum tali to the posterior border of the navicular tuberosity.

Muscles acting on the foot may also aid in support of the arches. The tendonous extensions of the tibialis posterior, which insert into the navicular,
Cuneiforms, cuboid, and bases of the second, third, and fourth metatarsals, help to link the bones of the medial longitudinal arch together. Within the foot, the flexor digitorum brevis, abductor hallucis, flexor hallucis longus, medial flexor digitorum longus, and flexor hallucis brevis all serve to help tie the front and back of the medial longitudinal arch together to assist in maintaining the arch in a locked, truss-like position. In addition, the tibialis anterior and tibialis posterior help to suspend the arch from above.

Lateral Longitudinal Arch

The lateral longitudinal arch consists of the calcaneus, cuboid, and the fourth and fifth metatarsal bones. This arch is more stable and less adjustable than the medial longitudinal arch. The long and short plantar ligaments help maintain this arch by connecting the inferior surfaces of the bones of the arch. The long plantar ligament runs from the undersurface of the calcaneus to the undersurface of the cuboid and third, fourth, and fifth metatarsals. The short plantar ligament is a wide, strong ligament that connects the cuboid to the anterior tubercle on the underside of the calcaneus. The plantar aponeurosis also helps maintain the arch by linking the ends of the arch together to form a truss-like structure.

Muscles of the foot, including the abductor digitii minimi, flexor digitorum longus, and flexor digitorum brevis aid minimally in supporting the lateral longitudinal arch by connecting the ends of the arch. The peroneus longus, peroneus tertius, and peroneus brevis serve to support the arch from above.
Transverse Arch

The transverse arch is made up of the navicular, cuneiforms, cuboid, and metatarsals. The transverse arch is given support by the wedging of the cuneiforms and metatarsal bases as well as the deep tarsal, metatarsal, and plantar ligaments which tie the arch into a truss-like structure. The arch is suspended minimally from above by the peroneus longus which also supplies truss-like support by connecting the ends of the arch. The intrinsic muscles of the foot play a minimal role in support of the transverse arch.

In summary, the arches of the foot are maintained by strong ligaments and the plantar fascia, the shape of the bones, and muscle tone. Basmajian and Stecko\textsuperscript{9} found through electromyographic studies that the muscles of the foot play no significant role in maintaining the arches of the foot when the foot is in a static weightbearing position. However, some limited support for the arches may be provided by the muscles of the foot during dynamic activities such as walking and running.\textsuperscript{8} Regardless of whether the feet are active or static, the plantar fascia and ligaments of the foot are chiefly responsible for maintaining the arches of the foot.\textsuperscript{9-12} The plantar fascia is particularly important as it is a major support for all three arches of the foot.
CLOSED CHAIN BIOMECHANICS

The open chain movements of the joints of the foot described above are helpful in understanding how the foot functions in gait. However, the functional biomechanics of the joints of the foot occur primarily in the closed kinetic chain, and for this reason it is necessary to discuss foot motion as it occurs during support of the body’s weight. The closed chain biomechanics of the subtalar joint are particularly important as this joint is the first joint of the foot subject to ground reaction forces during gait. The motions occurring in this joint serve to drive the motions that will occur throughout the rest of the foot and lower extremity.

Subtalar Joint

Closed kinetic chain subtalar joint motion results in movement of both the calcaneus and talus, different from the open chain motion of the subtalar joint in which the calcaneus moves on a stable talus. In the closed kinetic chain, the calcaneus moves in the frontal plane in either eversion or inversion during subtalar joint motion. Correspondingly, the talus moves in the transverse and sagittal planes, with talar abduction and dorsiflexion occurring during calcaneal inversion, and talar adduction and plantarflexion occurring with calcaneal eversion. The leg follows the transverse plane motion of the talus, externally rotating as the talus abducts, and internally rotating as the talus adducts. The
leg will also follow the sagittal plane motions of the talus, with knee extension occurring along with talar dorsiflexion, and knee flexion occurring along with talar plantarflexion.  

Summarizing subtalar joint motion and its effects along the kinetic chain superiorly; supination is a combination of calcaneal inversion and talar abduction and dorsiflexion, producing tibial external rotation and some knee extension in the closed chain. Closed chain pronation is a combination of calcaneal eversion and talar adduction and plantarflexion, with tibial internal rotation and some knee flexion resulting.

Subtalar joint motion may also be initiated by movement of the tibia in the transverse plane. In the closed kinetic chain, internal rotation of the tibia causes the talus to adduct and plantarflex while the calcaneus everts, producing subtalar joint pronation. Likewise, tibial external rotation in the closed kinetic chain produces subtalar joint supination.

During gait, the tibia rotates an average of 19 degrees in the transverse plane.  

The foot must be able to accommodate this motion without rotating on the ground. Both the subtalar and talocrural joints are able to accommodate transverse plane rotations of the tibia by virtue of their triplanar axes. However, the talocrural joint can accommodate only 11 degrees of tibial rotation at the most, while the subtalar joint can accommodate an amount of tibial rotation equal to the amount of calcaneal motion in the frontal plane if the subtalar joint axis is inclined 45 degrees from the transverse plane. Since the average subtalar joint axis is inclined 42 degrees from the transverse plane and the average range of motion for the calcaneas in the frontal plane is 30 degrees, (20 degrees of inversion and 10 degrees of eversion), the subtalar joint is much
more capable of absorbing and causing transverse plane rotations of the tibia than the talocrural joint is. Because the subtalar joint responds to tibial rotation by pronating or supinating, the foot is able to absorb the transverse plane motion of the tibia without rotating on the ground. Instead, the calcaneus simply inverts or everts, depending on the movement which the tibia transmits to the talus.

The subtalar joint, in addition to influencing the biomechanics of the lower extremity proximal to the foot, also plays a role in the biomechanics of the remaining foot joints. Since the calcaneus and talus of the subtalar joint are also part of the midtarsal joint, subtalar joint motion plays a particularly important role in the biomechanics of the midtarsal joint.

As mentioned earlier, the midtarsal joint is actually made up of two separate articulations, one between the talus and navicular and one between the calcaneus and cuboid. Since there is little movement between the cuboid and navicular, any motion in the midtarsal joint must occur together at both the calcaneocuboid and talonavicular articulations. When the subtalar joint is in a neutral or supinated position, the axis of motion for the talonavicular joint is not aligned in a parallel fashion with the axis of motion for the calcaneocuboid joint; thus, the calcaneocuboid and talonavicular articulations cannot move together in a neutral or supinated foot and motion of the midtarsal joint is limited (Figure 1).

As subtalar joint supination increases, the talonavicular and calcaneocuboid axes of motion become less parallel and midtarsal joint motion becomes more restricted. However, when the subtalar joint moves toward pronation, the axes of motion for the calcaneocuboid and talonavicular joints
Figure 1. Direction of the axes of the midtarsal joint during subtalar joint supination.
become more parallel (Figure 2). This allows for more movement in the midtarsal joint, as the talonavicular and calcaneocuboid joints are able to move in unison.4,18,19

Although the biomechanical relationship between the subtalar joint and the midtarsal joint is complex, it does help to easily explain how the foot is able to function as both a mobile adaptor and a rigid lever. When the subtalar joint pronates, the axes of motion for the calcaneocuboid and talonavicular joints become parallel and the movements of the calcaneocuboid and talonavicular joints occur in unison, thus minimizing the bony and connective tissue restrictions of the tarsal bones and allowing greater range of motion. When the subtalar joint supinates, the axes of motion for the talonavicular and calcaneocuboid joints converge and the bony and connective tissue limitations in the midfoot and forefoot increase.

In summary, subtalar joint pronation unlocks the midtarsal joint, allowing the midfoot and forefoot to become a “loose bag of bones” which can easily adapt to the terrain. Subtalar joint supination causes the midtarsal joint to lock and the midfoot and forefoot become more stable, allowing the foot the function as a rigid lever for gait propulsion.

Midtarsal Joint

It was previously stated that the midtarsal joint allows inversion and eversion about one axis and dorsiflexion with abduction or plantarflexion with adduction about another axis. In the closed kinetic chain, motion occurs together on both axes of the midtarsal joint and is termed either pronation or supination. Midtarsal joint pronation occurs as the subtalar joint pronates and
Figure 2. Direction of the axes of the midtarsal joint during subtalar joint pronation.
allows the midtarsal joint to become more supple. With weightbearing, midtarsal joint pronation causes the medial longitudinal arch of the foot to fall as the midtarsal joint dorsiflexes, abducts, and everts in response to supporting the body's weight. The opposite movement, midtarsal joint supination, is a closed kinetic chain combination of inversion, plantarflexion, and adduction. Midtarsal joint supination, like subtalar joint supination, serves to raise the medial arch, and due to the relationship described above between the subtalar and midtarsal joints, is a more stable, rigid position for the foot.

Tarsometatarsal Joint

Closed kinetic chain motion at the tarsometatarsal joint occurs in much the same manner as open chain movement of this joint. The forefoot pronates or supinates at the tarsometatarsal joint to bring the metatarsal heads evenly to the ground during stance. Forefoot pronation brings the medial part of the forefoot closer to the ground by plantarflexing the first ray and dorsiflexing the fifth ray, also creating a raised medial longitudinal arch. Forefoot supination brings the lateral part of the forefoot closer to the ground by plantar flexing the fifth ray and dorsiflexing the first ray, lowering the medial arch of the foot.
The biomechanics of walking involve a complex relationship between virtually all joints of the body. The pelvis, leg, and foot in particular demonstrate this biomechanical complexity, with motions occurring in the sagittal, frontal, and transverse planes simultaneously. Although difficult, it is important to understand the biomechanical relationship between the foot and the rest of the lower extremity during gait. This understanding will provide insight as to how lower extremity injuries may result from foot pathomechanics. The following paragraphs will be used to explain the relationship between foot biomechanics and lower extremity transverse plane rotations during gait, as well as how the foot functions as both a mobile adaptor and a rigid lever.

Definitions of the Walking Cycle

To clearly describe the lower extremity biomechanics of gait, it is best to divide gait into subunits of time throughout the gait cycle. The subunits include initial contact, loading response, midstance, terminal stance, and preswing, all part of stance phase, along with initial swing, midswing, and terminal swing, all part of swing phase.

In normal gait initial contact is the first subunit of stance phase and begins when the heel of the foot contacts the ground. Loading response begins immediately after initial contact and lasts until the contralateral extremity leaves
the ground. Midstance follows loading response, lasting to the time when the body is directly over the supporting leg. The next period of time in gait is terminal stance, occurring from the end of midstance until the time just before initial contact of the contralateral lower extremity. Preswing is the final subunit of gait in stance phase, covering the period of time from the end of terminal stance to the moment before the reference leg leaves the ground.

Lift off of the reference leg begins swing phase, with initial swing being the first subunit of this phase. Initial swing covers the period of time from lift off to maximal knee flexion of the same leg. Midswing is next, lasting until the tibia has fallen back to a vertical position. Terminal swing follows midswing, and with initial contact of the reference leg, completes the normal gait cycle.

Gait Biomechanics

Certain biomechanical events occurring in the lower extremity during gait are intricately linked to subtalar joint movement. Subtalar joint supination during the stance phase of gait causes external rotation of the tibia, and external rotation of the tibia during stance causes supination of the subtalar joint. Subtalar joint supination also creates a rigid foot.

Subtalar joint pronation and tibial internal rotation are tied together in much the same manner as subtalar joint supination and tibial external rotation, with pronation of the subtalar joint allowing the foot to become mobile and adaptable. How and why these biomechanical relationships exist between the subtalar joint and the remainder of the lower extremity can now be discussed, with the biomechanical events of the lower extremity divided into subunits of time in the gait cycle.
Swing Phase

The simplest place to start with analysis of gait is the beginning of swing phase. During swing phase, the subtalar joint is in a neutral position and the ankle is dorsiflexed. Throughout swing phase, the swing side innominate is rotating anteriorly.\textsuperscript{14,16} The anterior movement of the pelvis causes femoral and tibial internal rotation of the swing leg, putting the leg in a position of mild internal rotation when the calcaneus contacts the ground. Movement of the pelvis during this phase also causes the lower extremity to be slightly adducted at initial contact.

Initial Contact and Loading Response

Because the lower extremity is in a slightly adducted position at initial contact, the lateral aspect of the calcaneus will contact the ground first. Ground reaction forces will then cause subtalar joint pronation so that the calcaneus may rest evenly on the ground. The pronation movement caused by ground reaction forces is accentuated by the fact that the weight of the body is directed medially to the point of contact between the ground and the calcaneus. During initial contact and loading response, subtalar joint pronation is also reinforced by the movement of the pelvis. At this time the pelvis continues to move anteriorly, transmitting internal rotation forces to the femur, then the tibia, causing further subtalar joint pronation.\textsuperscript{4,20,21}

There is also evidence that subtalar joint pronation during initial contact and loading response may cause tibial internal rotation, rather than tibial internal rotation increasing subtalar joint pronation at this time. As the subtalar joint pronates, the anterior socket, formed by the calcaneal and navicular facets
which support the talus, rolls inferiorly and medially. The weightbearing forces on the talus cause the talus to follow this movement, resulting in talar plantarflexion and adduction. In the closed kinetic chain this talar movement will cause further tibial internal rotation to occur. Data collected from Levens et al. show that from initial contact through loading response the tibia is rotating internally more rapidly and to a greater degree than the femur. This indicates internal rotation is transmitted superiorly by the subtalar joint during initial contact and loading response, rather than inferiorly by the pelvis.

During initial contact and loading response the midtarsal joint unlocks as the subtalar joint pronates. As the midtarsal joint unlocks, the joints of the midfoot and forefoot become more mobile and are more free to move and adapt to uneven terrain. Thus, by unlocking the midtarsal joint, subtalar joint pronation converts the foot into a mobile adaptor.

In addition to converting the foot into a mobile adaptor, subtalar joint pronation plays an essential role in providing shock absorption against ground reaction forces during gait. With subtalar joint pronation and unlocking of the midtarsal joint, the increased mobility of the joints of the foot helps to dissipate some of the force between the foot and ground at initial contact and loading response. Also, subtalar joint pronation at initial contact provides an immediate shortening of the lower extremity, perhaps as much as 1 cm. This shortening works as a shock absorber to dampen ground reaction forces. Finally, subtalar joint pronation provides shock absorption in the lower extremity by initiating knee flexion in stance. During initial contact and loading response subtalar joint pronation causes the tibia to internally rotate relative to the knee. This
internal rotation unlocks and flexes the knee, providing an important shock absorption mechanism in the lower extremity.\textsuperscript{2,24}

According to Mann\textsuperscript{20} subtalar joint pronation during initial contact and loading response is an entirely passive mechanism, limited only by the shape of the joint, capsular attachments, and extra-articular ligaments. However, Perry\textsuperscript{22} states that the tibialis anterior plays a role in controlling subtalar joint pronation during initial contact and loading response. Other authors\textsuperscript{2,13} state that the supinator muscles of the lower extremity, especially the tibialis posterior, play a role in controlling subtalar joint pronation during initial contact and loading response. It should also be noted that electromyographic activity may be present in the tibialis posterior and soleus in the latter part of loading response and these muscles would serve to decelerate subtalar joint pronation.\textsuperscript{2}

Midstance

After loading response, the stance leg enters the midstance time frame as the body begins a period of single limb support. As the foot comes to rest flat on the ground, definite electromyographic activity of the tibialis posterior, gastrocnemius, soleus, and peroneus longus is recorded.\textsuperscript{2,25,26} The activity of the tibialis posterior and gastroc/soleus causes the subtalar joint to move toward a supinated position. Contraction of the peroneus longus creates a moderate pronation force at the subtalar joint and works against the contraction of the tibialis posterior and gastroc/soleus to help provide stability to the foot and body.

During midstance the weight of the body creates a force that tends to pronate the subtalar joint. The ability of the muscles mentioned above to
continuously counteract the subtalar joint pronation force supplied by the weight of the body during midstance should be questioned.

Several factors come into play to help explain why the subtalar joint supinates without causing excessive muscle fatigue during this phase of the gait cycle. Force plate readings show that during midstance the foot is not supporting the full weight of the body\textsuperscript{26} The load on the foot during midstance may actually be as little as 50 - 60% of bodyweight. Also, during midstance the body tends to laterally displace over the stance leg\textsuperscript{16,26} This lateral displacement of the body will shorten the bodyweight’s effective lever arm, decreasing the pronation force supplied by the body’s weight.

Another important reason the foot is able to move toward supination during midstance is that at this time the swing of the contralateral leg causes the stance side pelvis to move posteriorly\textsuperscript{4,14,20,22} The posterior movement of the pelvis is transmitted inferiorly, resulting in tibial external rotation. Tibial external rotation in the closed kinetic chain then causes the subtalar joint to supinate\textsuperscript{4,20,22}

In summary, during midstance the movement at the subtalar joint changes from pronation to supination. This change results from movements taking place at the pelvis and contraction of the tibialis posterior and gastrocnemius. At the end of midstance the subtalar joint has reached a neutral position.

Terminal Stance

During the next phase of gait, terminal stance, the subtalar joint continues to supinate. The supination movement is a result of further pelvic
external rotation and continued firing of the supinator muscles active in midstance. The supination of the foot occurring in this phase brings the midtarsal joint to a locked position. It is necessary for the midtarsal joint to lock during terminal stance so that the forefoot may become rigid and capable of acting as a lever to propel the body forward in the next phase of gait, preswing. A rigid forefoot is also necessary to provide stability for the lower extremity during preswing.

Subtalar joint supination also plays an important role in increasing the efficiency of the peroneus longus muscle.\textsuperscript{2,21} The angle of insertion of the peroneus longus during subtalar joint pronation does not allow this muscle to stabilize the first ray (Figure 3). Subtalar joint supination changes the angle at which the peroneus longus inserts into the first ray, allowing it to be a more efficient plantarflexor of the first ray (Figure 4). Subtalar joint supination also locks the midtarsal joint and stabilizes the cuboid, allowing it to better function as a pulley for the peroneus longus. With subtalar joint supination and locking of the midtarsal joint, the peroneus longus is able to do a better job of stabilizing the first ray during late stance phase.

In terminal stance, the intrinsic muscles of the foot also begin to fire. According to Mann and Inman,\textsuperscript{27} the intrinsics provide a stabilizing function by virtue of their origin on the medial calcaneal tubercle. Contraction of these muscles results in a supination pull on the subtalar joint and further locking of the midtarsal joint. Gray and Basmajian\textsuperscript{28} feel that firing of the intrinsic foot muscles during late stance phase is important only in subjects with flat feet. In this case, the intrinsic muscles may be called upon to provide additional
Figure 3. Position of the peroneus longus tendon in subtalar joint pronation.
Figure 4. Position of the peroneus longus tendon in subtalar joint supination.
stabilization of the forefoot because the midtarsal joint cannot be adequately locked due to excessive foot pronation.

Preswing

Preswing completes the period of time breakdown of stance phase. During preswing, the muscular activity in the leg and foot aiding in supination drops off as the foot passes through a heel-off, then toe-off position. The “push-off” of the stance leg occurs in this time period. The term push-off is somewhat misleading, as this is really a passive mechanism caused by the body’s momentum. In actuality, the body vaults over the foot during preswing. It is important that the foot be able to maintain the forward momentum of the body during preswing without collapsing as the body’s weight passes over it. Since subtalar joint supination locks the midtarsal joint and provides a rigid forefoot, subtalar joint supination must be maintained during preswing for effective push-off.

There are two mechanisms responsible for maintaining supination of the subtalar joint in this time period. First, the pelvis continues to externally rotate, creating a supination force at the subtalar joint. Second, a windlass mechanism as described by Hicks occurs during preswing to increase subtalar joint supination. As the toes are passively dorsiflexed at toe-off, the insertion of the plantar aponeurosis is pulled around the fulcrum of the metatarsophalangeal joints. This creates a pull of the plantar aponeurosis away from its insertion on the medial calcaneal tubercle. The pull of the plantar aponeurosis on the calcaneus causes supination of the subtalar joint along with raising of the medial longitudinal arch. By supinating the subtalar joint and
raising the medial arch, the windlass mechanism locks the midtarsal joint and leads to greater stability of the foot.

Summary of Stance Phase Biomechanics

In the stance phase of gait, the subtalar joint begins in a supinated position, fully pronates, then returns to a supinated position by the end of stance. Subtalar joint pronation occurs during initial contact and loading response and is thought to be primarily a passive mechanism, although some muscle activity may be responsible for decelerating this movement. The pronation of the subtalar joint allows the foot to function as a mobile adaptor and shock absorber. Subtalar pronation during initial contact and loading response also helps to absorb the internal rotation of the lower extremity that is taking place in early stance phase.

Through the remainder of stance phase the subtalar joint supinates, due mostly to contraction of the foot supinators and external rotation of the pelvis. Subtalar joint supination allows the foot to function as a rigid lever for efficient gait propulsion and provides a mechanism by which the external rotation of the lower extremity during late stance phase can be absorbed. It should be noted that the entire stance phase cycle just described occurs in approximately 0.6 seconds.30
STRUCTURAL FOOT DEFORMITIES

Structural or positional changes in one part of the body may lead to a change in the biomechanical function of another part of the body. This change in biomechanical function is termed compensation. In the lower extremity, the subtalar joint often compensates to adjust for changes in terrain or to adjust for changes in the position of the trunk or lower extremity. Due to the subtalar joint's ability to move in all three planes of the body, this joint has the capability to adjust to lower extremity deviations in any direction.

When changes in position of the lower extremity or trunk occur only on occasion, subtalar joint compensation is a normal function of the foot, providing balance and stability for the body. For example, transverse plane motions of the trunk or lower extremity are transmitted inferiorly to the subtalar joint. The subtalar joint may pronate or supinate to absorb these transverse plane motions which, without subtalar joint compensation, would cause the foot to rotate on the ground, compromising the body's stability.

When subtalar joint compensation must take place because of a permanent structural abnormality, such as hip anteversion, genu valgum, or forefoot varus, the subtalar joint is forced to compensate on a continued basis. The compensation is usually required in just one plane of the body. If compensation in the subtalar joint were ideal, compensatory motion would occur in only that plane which caused the demand for compensation. However,
because the subtalar joint is a triplanar joint, motion must occur in the other two body planes as well. Constant compensatory motion in the two body planes which do not require compensation frequently leads to abnormal function and pathology.\textsuperscript{2,13} Thus, although subtalar joint compensation is useful in that it can adjust for structural abnormalities in the lower extremity, it may also lead to faulty biomechanics and lower extremity injuries.

Throughout the remainder of this chapter, compensation for foot malalignment in either the rearfoot or the forefoot will be discussed in detail. Foot malalignment is defined as a deviation of the rearfoot or the forefoot from the body planes when the foot is in subtalar joint neutral. The subtalar joint neutral position is used because this is the position in which there is the least amount of stress to the joints and soft tissues of the foot.

In subtalar joint neutral the vertical bisection of the posterior calcaneus should be parallel to the vertical bisection of the lower one-third of the tibia, and the plane of the metatarsals should be perpendicular to the vertical bisection of the posterior calcaneus (Figure 5).\textsuperscript{31} Another way of stating this is that the bisection of the posterior calcaneus should be perpendicular to the ground and the plane of the metatarsal heads should be parallel to the ground. Although there are various methods used to determine the subtalar joint neutral position of the foot, congruency of the talar head with the talonavicular joint line appears to be the most useful and operational technique for assessing subtalar joint neutral.\textsuperscript{31,32}

The basic biomechanical role of the foot is to achieve a flat-on-the-ground position during weightbearing activities. Assessing the orientation of the calcaneus and metatarsal heads in subtalar joint neutral provides
Figure 5. Normal calcaneal and forefoot position.
information about how the foot will respond to ground reaction forces and the weight of the body so that it may achieve this flat-on-the-ground position. If the foot doesn’t line up with the vertical bisection of the calcaneus perpendicular to the ground and the plane of the metatarsal heads parallel to the ground in subtalar joint neutral, compensation may occur in the subtalar joint to allow the foot to rest flat on the ground during stance.

The fact that subtalar joint compensation usually occurs to help the foot attain a more flat-on-the-ground position means that the compensations for specific positional deviations of the calcaneus or metatarsal heads are predictable. To be able to understand how subtalar compensation may lead to injuries in the lower extremity, it is helpful to have some knowledge of common structural deformities of the foot and the compensations that often occur with these deformities. A description of common structural foot malalignments and the compensations and pathomechanics which occur with these malalignments follows.

Calcaneal Varus

Calcaneal varus is a deformity of the calcaneus on the talus. The calcaneus is inverted relative to the vertical bisection of the posterior one-third of the tibia when the foot is in subtalar joint neutral (Figure 6). This deformity is caused by failure of the calcaneus to fully derotate from its infantile position. The mechanism for compensation, (achieving a stable, flat-on-the-ground position), is pronation of the foot. Pronation takes place primarily at the subtalar joint, although pronation can also occur at the midtarsal joint if the subtalar joint does not have enough range of motion available to allow the forefoot to reach
Figure 6. Calcaneal varus.
the ground. In addition, supination of the tarsometatarsal joint or plantarflexion of the first ray may take place to compensate for calcaneal varus if the subtalar joint doesn’t have enough range of motion to fully compensate for this deformity.

With a calcaneal varus deformity, the subtalar joint pronates rapidly and with great momentum at initial contact. The subtalar joint must also pronate through a large range of motion to bring the varus aligned calcaneus evenly to the ground. Because the speed and amount of subtalar joint pronation during initial contact and loading response are increased in this foot type, soft tissues and muscles responsible for limiting subtalar joint pronation during this time frame are placed under a great deal of stress and eccentric loading.1 If the subtalar joint cannot pronate fast enough to bring the calcaneus quickly to ground, a valgus force may be transmitted to the knee, stressing soft tissue structures of the medial knee and creating knee alignment problems.1,34

Forefoot Varus

Forefoot varus is a fixed osseous deformity of the forefoot in which the plane of the metatarsal heads is inverted relative to the bisection of the posterior calcaneus with the foot in subtalar joint neutral (Figure 7). It is caused by insufficient developmental rotation of the head of the talus.33 The resulting weightbearing compensation of this deformity is again pronation, primarily at the subtalar joint. If enough range does not exist at the subtalar joint to allow the forefoot to reach the ground, pronation can occur at the midtarsal joint. Tarsometatarsal supination or first ray plantarflexion may also occur as a compensation for this deformity.
The compensatory pronation that occurs with forefoot varus is pathological in that it is both excessive and untimely. A much larger amount of pronation than normal is needed to bring the forefoot to the ground. The pronation is untimely in that the foot must remain pronated throughout stance phase in order to stay flat on the ground. Therefore, supination of the subtalar joint which creates a rigid foot for efficient gait propulsion cannot occur. Soft tissue structures of the foot may then be stressed excessively as they become the primary stabilizers of the foot in late stance phase.\textsuperscript{2} Also, subtalar joint pronation into late stance phase transmits internal rotation up the lower extremity. This internal rotation is out of phase with the external rotation force the pelvis is transmitting inferiorly to the femur and tibia. Pathology can then occur in the soft and bony tissues of the lower extremity secondary to conflicting transverse plane rotations.\textsuperscript{1}

Forefoot Equinus

A forefoot equinus deformity can be defined as a condition in which the forefoot is in a more plantarflexed plane than the rearfoot or calcaneus (Figure 8). With this foot type, the ankle must dorsiflex greater than normal to allow the tibia to advance forward during late stance phase. If the ankle doesn't have enough dorsiflexion range of motion, compensation must occur somewhere in the lower extremity. Because the oblique axis of the midtarsal joint allows this joint to function like a "little ankle" joint, the midtarsal joint is capable of becoming an effective dorsiflexor of the forefoot when the midtarsal joint is unlocked.\textsuperscript{1} However, since foot dorsiflexion is needed at midstance and terminal stance during gait, if the midtarsal joint is going to compensate for lack
Figure 8. Forefoot equinus.
of ankle dorsiflexion, the subtalar joint must remain pronated throughout this time frame so that the midtarsal joint stays unlocked and is able to dorsiflex.

For a forefoot equinus deformity the compensatory pronation of the subtalar joint is occurring when the subtalar joint should be supinating to lock the midtarsal joint and create a rigid foot for efficient gait propulsion. The compensation for forefoot equinus is similar to the compensation for forefoot varus and will create the same biomechanical dilemmas in the lower extremity, namely, excessive stress to the soft tissues of the foot during gait propulsion, and internal rotation forces transmitted superiorly by the subtalar joint when the pelvis is transmitting external rotation forces inferiorly.

Besides forefoot equinus, a short heel cord, a bone block limiting ankle dorsiflexion, neuromuscular spasm, or trauma can also limit ankle dorsiflexion and lead to the same type of pathological subtalar and midtarsal joint compensations during gait.35

Forefoot Valgus/Rigid plantarflexed first ray

Forefoot valgus is an osseous deformity of the forefoot in which the plane of the metatarsal heads is everted relative to the bisection of the posterior aspect of the calcaneus in subtalar joint neutral (Figure 9). A rigid plantarflexed first ray is described by the neutral position of the first metatarsal head remaining below the level of the second through fifth metatarsal heads despite pressure from an outside force. Causes of this deformity include congenital torsion of the head of the talus which results in an eversion deformity of the forefoot, post cerebrovascular accident, congenital plantarflexion of the first ray, or trauma.1,35
Figure 9. Forefoot valgus.
With this foot type the medial side of the forefoot contacts the ground before the lateral side, causing the subtalar joint to supinate to bring the forefoot evenly to the ground. This compensation occurs early in the stance phase, during loading response. Since full, normal pronation does not occur, the foot cannot complete its role as a mobile adaptor and the foot has a difficult time adjusting to uneven terrain, causing postural instability at the ankle.\textsuperscript{1,13}

The lack of full pronation also compromises the shock absorbing mechanisms of the lower extremity during gait by failing to shorten the lower extremity and by failing to unlock the knee through tibial internal rotation. Also, the supination moment of the foot is transmitted to a varus moment at the knee, producing stress to the soft tissues of the lateral knee and altering knee alignment.\textsuperscript{34}

Combined Rearfoot and Forefoot Varus

With this structural deformity both the calcaneus and plane of the metatarsal heads assume an abnormally inverted position in subtalar joint neutral. This foot type causes the compensations of rearfoot varus to be combined with the compensations of forefoot varus. Subtalar joint pronation occurs too rapidly and to too great an extreme at initial contact due to the varus position of the calcaneus, and the pronation lasts too long through stance phase due to the varus position of the forefoot. The problems associated with pronation that occurs too fast, to too great an extreme, and at the wrong time are the same as those described for the rearfoot varus and forefoot varus deformities.
Rearfoot Varus with Rigid Forefoot Valgus

This deformity consists of a calcaneus that is inverted in subtalar joint neutral, combined with a forefoot which is everted (Figure 10). Compensations with this foot type again work to bring the foot flat onto the ground. At heelstrike the ground reaction and weightbearing forces acting on the rearfoot varus cause subtalar joint pronation to occur. Then, as the valgus forefoot contacts the ground, the subtalar joint supinates to bring the front of the foot evenly to the ground.

Because the ground reaction forces for this foot type cause opposing subtalar joint motions separated by a very brief moment in time, this type of foot is often called a torque foot.\(^1\) The sudden movement from pronation to supination subjects the bones of the foot to high torsional stresses. The rapid change from pronation to supination is also transmitted to a rapid change from tibial internal rotation to tibial external rotation, with high torsional stresses placed on the structures of the lower leg. Due to the forefoot valgus, problems with lateral ankle instability and an excessive varus moment at the knee can also occur.\(^1\)

Rearfoot Varus with Flexible Forefoot Valgus

In this foot type the calcaneus is in an inverted position in subtalar joint neutral, with the forefoot everted relative to the posterior bisection of the calcaneus. The forefoot eversion deformity is not rigid and will not exist under outside pressure. This deformity often develops when the subtalar joint is not able to fully compensate through subtalar joint pronation for the varus position.
Figure 10. Rearfoot varus with rigid forefoot valgus.
of the calcaneus during initial contact and loading response. The midtarsal joint then pronates to further bring the medial forefoot flat onto the ground.

Because the forefoot valgus is not a fixed deformity, the subtalar joint may remain in its overpronated position during late stance phase. When the subtalar joint is pronated in late stance phase, the midtarsal joint will not lock and the foot is forced into further pronation as the weight of the body is transferred to the anterior, medial part of the foot. The same pathomechanical events that occur with the other overpronator foot types will also occur with this foot type.
LOWER EXTREMITY INJURIES

From the information presented earlier in this paper on the biomechanics of gait, it is apparent that a complex relationship exists between the foot and the lower extremity during human locomotion. Because of the triplanar axis of the subtalar joint, all subtalar motions in the closed kinetic chain are converted to motion or forces in the tibia, femur, and pelvis. Subtalar joint supination leads to external rotation forces transmitted superiorly to the lower extremity chain and subtalar joint pronation leads to internal rotation forces transmitted superiorly. Likewise, the pelvis, femur, and tibia are able to influence the closed kinetic chain motion of the subtalar joint. External rotation of the pelvis, femur, and tibia leads to subtalar joint supination while internal rotation of these structures leads to subtalar joint pronation.

When the biomechanics of the foot do not coincide with the biomechanics of the pelvis, femur, or tibia, lower extremity injuries can result. If motions at the subtalar joint are out of phase with motions in the lower extremity, such as subtalar joint pronation occurring when the pelvis is externally rotating, internal rotation forces transmitted up the lower extremity chain from subtalar joint pronation will conflict with the external rotation forces transmitted down the lower extremity chain from the pelvis. This will result in torsional stresses to soft tissues and bone where these conflicting forces meet. In repetitive situations these conflicting forces can lead to injury of the tissues being stressed.
Proper functioning of the foot as a mobile adaptor and a rigid lever is also necessary in order to avoid lower extremity pathology. At initial contact of stance phase in gait, the subtalar joint must pronate to allow the shock absorption mechanisms of the lower extremity to take place. Without adequate pronation during early stance phase, a rigid foot transmits excessive shock from ground reaction forces up the lower extremity. The excessive shock can lead to microtrauma in soft tissues and osseous components of the lower extremity. Pronation in early stance phase also allows the foot to become mobile and loose, enhancing the ability of the foot to adapt to the ground and provide stability for the body.

The foot must also function as a rigid lever during gait. The foot does this by supinating at the subtalar joint to lock the midtarsal joint. With a foot that suffers from excessive subtalar joint pronation in stance phase, the midtarsal joint does not lock and the foot does not have the bony stability to efficiently propel the body forward. The soft tissue connections between the bones of the foot may then be stressed as these bones move excessively during late stance phase due to lack of rigidity in the foot.

The causes of lower extremity injuries related to foot biomechanics can be numerous and quite detailed. For each injury there may be several mechanisms by which abnormal foot biomechanics could lead to the injury. The remainder of this paper will focus on describing how different lower extremity pathologies may be caused by abnormal foot biomechanics.
Patellofemoral Pain

Both excessive and insufficient subtalar joint pronation can lead to patellofemoral pain for a variety of reasons. A foot that doesn't pronate enough, such as a foot with a forefoot valgus deformity, can cause a varus moment at the knee with each step. As the foot is thrown into supination, a laterally directed force is transferred to the tibia, producing a varus force at the knee. This can cause both the quadriceps origin and patellar tendon insertion to be pulled medially relative to the patella, which moves laterally with the proximal tibia and distal femur. Contraction of the quadriceps could then result in irritation between the patella and its opposing joint surfaces on the femur.

Forefoot varus malalignment, on the other hand, can cause ground reaction forces to be directed medially to the knee joint. This can throw the knee into an excessive valgus alignment, with the patella rubbing on the edge of the patellofemoral groove due to the same mechanism described above.

A problem with abnormal foot biomechanics is that they often cause tibial transverse plane rotations to be out of phase with the transverse plane rotations of the femur. Pretorius et al state that this can lead to patellofemoral pain by simply pulling the patella out of its normal alignment. Other authors have described a more detailed explanation for this mechanism of patellofemoral pain development. Prolonged pronation of the subtalar joint past midstance causes the tibia to be significantly internally rotated. The posterior movement of the pelvis at this time is transmitting an external rotation force to the femur. Because the knee allows a good deal of joint play, the femur is able to rotate externally relative to the tibia. The external rotation of the femur will pull the origin and insertion of the quadriceps muscle lateral to the patella. Thus,
contraction of the quadriceps will cause a lateral pull on the patella, contributing to the development of chondromalacia and mechanical knee pain. There may also be stress to the patellar tendon as abnormal internal rotation of the tibia pulls the tibial tubercle away from the patella.

Iliotibial Band Syndrome

Iliotibial band syndrome (ITB syndrome) is defined as inflammation of the iliotibial band either at its insertion into the lateral tibial tubercle or over the lateral femoral epicondyle. This injury can be related to the abnormal biomechanics of a foot that pronates for too long of a time period, or from the abnormal biomechanics of a foot which doesn't pronate enough.

Prolonged subtalar joint pronation can lead to ITB syndrome because the tibia is forced to internally rotate in late stance phase in order to follow the pronation of the subtalar joint. The tibial internal rotation is then occurring at a time when the pelvis and femur are externally rotating. This may cause increased stress at the insertion of the ITB on the lateral tibial tubercle, as the tubercle is being rotated away from the more proximal tissues of the ITB. Internal rotation of the tibia while the femur is externally rotating may also work to pull the ITB anteriorly across the lateral femoral epicondyle, and with enough repetition, may result in injury to the ITB in this area.

A supinated foot may lead to another mechanism of ITB injury. This type of foot may cause ground reaction forces to throw the knee into a varus alignment. Since the ITB runs over the lateral knee, varus stresses may strain this structure as it is pulled tightly against the lateral femoral epicondyle, or as the tissues near its insertion are stressed. When this stress is repeated often,
such as in walking on a supinated foot, injury to the ITB at its insertion or over the lateral femoral epicondyle may result.

Knee Collateral Ligament Sprains.

As with patellofemoral pain and ITB syndrome, collateral ligament sprains of the knee can be produced by frontal plane forces at the knee joint resulting from abnormal biomechanics of the foot. With a foot that remains supinated throughout the gait cycle, ground reaction forces which cause the foot to supinate also create a lateral force which is directed to the knee with each step. When every step an individual takes results in a varus stress to the knee, cumulative trauma to the lateral collateral ligament may occur.

With a foot that pronates excessively ground reaction forces are directed medially to the knee, producing a valgus stress with each step. Again cumulative trauma to the medial collateral ligament may occur as the knee is subjected to repeated valgus stresses.

Plantar Fasciitis

This foot pathology is most often associated with excessive subtalar joint pronation. Overpronation of the foot causes a flattened and stretched arch at midstance. If the foot remains pronated as terminal stance and preswing are reached, the midtarsal joint cannot become locked. The plantar fascia’s role in maintaining the arch of the foot then increases dramatically as there is little support from inherent bony stability when the midtarsal joint is not locked. This places a large amount of stress on the plantar fascia, with microtrauma and tearing resulting.
A foot which pronates quickly and with much force, such as the calcaneal varus foot type, may also damage the plantar fascia. With rapid subtalar joint pronation the plantar fascia is pulled away from its origin on the medial aspect of the calcaneus. Under repetitive situations, this may lead to inflammation and damage to the plantar fascia.

A foot that does not pronate enough can also lead to plantar fasciitis. Without sufficient subtalar pronation there is little subtalar joint shock absorption at initial contact and the knee flexion mechanism of shock absorption is compromised as the tibia is not forced to internally rotate enough to unlock the extended knee. In this situation, the plantar fascia absorbs a much greater amount of the shock caused by ground reaction forces than is normally expected. The excessive shock to the plantar fascia can lead to microtrauma and plantar fasciitis.38

Achilles Tendonitis

This injury, like many of the previous injuries already discussed, can also be attributed to both excessive and insufficient pronation. With individuals who pronate excessively, the foot may still be in a pronated position when the knee starts to extend in terminal stance. As the knee extends, the tibia externally rotates. Because the foot is pronating and the tibia is attempting to externally rotate to allow knee extension, there are conflicting rotatory forces affecting the Achilles tendon. The tendon experiences a "wringing out" which results in vascular impairment and degenerative changes.39 These conflicting rotatory forces may also result in microtearing and inflammation of the Achilles tendon.
With a foot that remains supinated throughout stance phase, the shock from ground reaction forces is not absorbed by the appropriate structures of the lower extremity and is transmitted to the Achilles tendon, causing damage to the tissues carrying this tendon's blood supply. Chronic hypoxic changes result which can lead to Achilles tendonitis.

Stress Fracture

Stress fractures are micro fractures of bone due to inability of the bone to adapt to slow rhythmic stress applied in an abnormal manner. This injury can occur both in individuals who overpronate at the subtalar joint and in individuals who have insufficient subtalar joint pronation.

Prolonged subtalar joint pronation can lead to stress fractures because pronation into late stance during gait is out of phase with the external rotation of the lower extremity during this time period of gait. Great torsional force in the tibia may develop when these forces meet, possibly resulting in tibial stress fractures.

Prolonged pronation can also lead to stress fractures of the metatarsals. During the late stance phase of gait, the weight normally transfers to the hallux at pushoff. With a foot that is pronated in late stance phase, there is not enough rigidity present in the foot to allow the first ray to take on the weightbearing forces of the body. In addition, the efficiency of the peroneus longus is decreased during subtalar joint pronation and this muscle is not able to adequately stabilize the first ray. A pronated foot may allow the first ray to abduct and dorsiflex during late stance, with the body's weight transferred to the second and third metatarsals. The second and third metatarsals are not as well
suited to handle the weight of the body as the first ray is and in this instance become susceptible to stress fractures.\textsuperscript{43} Lack of pronation, such as in a forefoot valgus foot type, may lead to stress fractures because the mechanisms of shock absorption in the lower extremity, which are based on pronation of the subtalar joint, do not occur.\textsuperscript{35} With this foot type the full load of the ground reaction forces is transmitted to the lower extremity, excessively stressing the bones of the foot and lower leg.

A foot type which combines a rigid forefoot valgus with a rearfoot varus also increases the stress to the bones of the foot.\textsuperscript{1} This foot undergoes rapid pronation, then rapid supination, all before the midstance period of gait. The quick change between pronation and supination, combined with fact that the foot does not fully pronate to allow adequate shock absorption, leads to a great deal of torsion in the bones of the foot and lower leg.

**Recurrent Ankle Sprains and Peroneal Tendonitis**

Recurrent lateral ankle sprains and peroneal tendonitis, similar to the other lower extremity pathologies related to abnormal foot biomechanics, are due to the weight of the body causing the foot to assume a flat-on-the-ground position. Forefoot valgus foot types cause the foot to assume a position in which the ankle is inverted excessively and the peroneal musculature is called upon to control the abnormal ankle inversion.\textsuperscript{44} The pathomechanics of this foot type take place primarily during midstance and terminal stance.

During midstance the subtalar joint is undergoing supination in response to muscle activity and external rotation of the pelvis. The subtalar joint supinates until further supination would bring the medial forefoot off the ground.
The midtarsal joint will pronate to its end range during this time to allow the forefoot to remain flat on the ground while the subtalar joint supinates. The weight of the body prevents the rise of the medial forefoot, and thus serves as a restriction to further subtalar joint supination in terminal stance. The subtalar joint supination locks the midtarsal joint in preparation for preswing, when the body's weight passes over the metatarsals. In the normal foot the midtarsal joint should become locked and prevent further subtalar supination when the calcaneus has reached a vertical position.²

A foot which demonstrates increased range of motion for midtarsal joint pronation, the forefoot valgus foot type for example, will allow the subtalar joint to supinate past vertical with the forefoot still remaining flat on the ground. This excessive subtalar supination results in lateral postural instability and predisposes an individual to inversion ankle sprains.¹²⁴⁴ The foot may respond to this postural instability by supinating the midtarsal joint to bring the subtalar joint back to a more vertical, stable position. If the midtarsal joint won't supinate enough to bring the calcaneus to a more vertical position, then the subtalar joint may pronate to achieve a more vertical calcaneal position.² The subtalar joint pronation will however unlock the midtarsal joint, leaving a flexible forefoot during terminal stance and preswing. This may result in chondromalacia and ankylosis of the hallux, metatarsalgia, bunions, or interdigital neuromas.² Other lower extremity symptoms associated with lack of a rigid foot during late stance phase, such as plantar fascitis and hallux valgus, may also occur.

If, for some reason, the midtarsal joint fails to supinate or the subtalar joint fails to pronate, or if the combined midtarsal joint supination and subtalar
joint pronation isn't enough to combat the forefoot valgus, then lateral postural
instability can only be prevented by a powerful sustained contraction of the
peroneal musculature. The excessive late stance phase subtalar joint
supination associated with the forefoot valgus foot type causes marked external
rotation of the tibia. This results in added stress to the peroneals, as they are
responsible for decelerating external rotation of the tibia. In addition to the
stresses the peroneals are already undergoing, they also need to be attempting
to stabilize the first ray. As one can see, the forefoot valgus foot type can
dramatically increase the late stance phase demands of the peroneal
musculature, leading to peroneal tendonitis.

The fact that the forefoot valgus foot type can predispose an individual to
both lateral ankle sprains and peroneal tendonitis can set up a difficult
treatment situation. Peroneal tendonitis may lead to decreases in
proprioception and strength of the peroneal musculature, thus making the
peroneals less effective in preventing lateral ankle sprains. Lateral ankle
sprains may also damage the peroneals, producing deficits in the
proprioception and strength of the peroneal musculature. Thus, the mechanism
by which lateral ankle sprains are avoided, powerful contraction of the
peroneals, can lead to peroneal damage and deficits which may in turn result in
lateral ankle sprains.

Michaud states that in individuals with forefoot valgus, there is usually
enough subtalar joint pronation and midtarsal joint supination to allow the
calcaneus to achieve a vertical, stable position in midstance. Thus, many of
these individuals are susceptible to lower extremity injuries associated with
excessive subtalar joint pronation and lack of a rigid foot in late stance phase rather than recurrent ankle sprains and peroneal tendonitis.

Because pronation of the subtalar joint decreases the efficiency of the peroneus longus, hindering this muscle's ability to plantarflex the first ray, foot types which lead to late stance phase pronation may also result in peroneal tendonitis. In this instance, the peroneus longus is contracting in a futile effort to stabilize the first ray for push-off of gait. The weight of the body will then cause the unstable first ray to abduct and dorsiflex during gait. This movement of the first ray will increase the tension and damage to an already over stressed peroneus longus.

Cuboid Syndrome

This condition involves dislocation or subluxation of the cuboid and may be seen as a result of trauma or as an insidious onset from an athletic overuse injury. Newell and Woodie\textsuperscript{45} found that most cuboid subluxations occurred in a pronated foot. Pronation unlocks the midtarsal joint and allows the peroneus longus to rotate the cuboid as it uses the cuboid for a pulley, pulling the lateral aspect in a dorsal direction and the medial aspect in a plantar direction.\textsuperscript{45}

Marshall and Hamilton\textsuperscript{46} have not found this to be the mechanism of cuboid subluxation, stating subluxation of the cuboid seems to result from movement between extreme plantarflexion and dorsiflexion of the midtarsal joint. Their evidence for this mechanism of cuboid subluxation comes from studying ballet dancers, among whom cuboid subluxation seems to be somewhat common. In particular, Marshall and Hamilton\textsuperscript{46} have found cuboid subluxation to occur as ballet dancers go to and from pointe.
It could be hypothesized that the dancers may be putting their foot in a functional forefoot valgus position as they are attempting to get maximum plantarflexion by using the peroneal muscles. They may then experience the lateral postural instability problem discussed earlier in this paper and, as a compensation, will supinate the midtarsal joint while on pointe to achieve a flatter foot and better body balance. With forceful contraction of the peroneals to maintain the pointe stance, the subtalar joint is undergoing a pronation force which may unlock the midtarsal joint. The unlocking of the midtarsal joint in combination with the strong contraction of the peroneus longus and supination of the midtarsal joint may then work to sublux the cuboid. This hypothesis seems plausible as one would think some unlocking of the midtarsal joint would be necessary for the cuboid to sublux.

Hallux Valgus

This type of foot pathology can result from a foot that pronates excessively. During the end of stance phase, the body's weight normally transfers to the first ray of the foot. The rigidity of a supinated foot and contraction of the peroneus longus normally allow the first ray to be stable enough to support the weight of the body in late stance phase. However, if the foot isn't locked because of prolonged pronation, the normal rigidity of the foot in late stance is gone. Also, in a pronated foot the mechanical advantage of the peroneus longus is lost as this muscle no longer has a downward pull on the first metatarsal. Without the normal rigidity and mechanical advantage of the peroneus longus in late stance phase, the first ray isn't stable enough to support the body's weight and is pushed into a dorsiflexed and abducted position.
during the preswing phase of gait. As the body passes over the unstable first metatarsal, the hallux is forced into a valgus position by the weight of the body. Subluxation at the first metatarsophalangeal joint may eventually occur.\textsuperscript{47}

**Posterior Tibialis Tendonitis**

Overpronation at the subtalar joint is a frequent cause of this lower extremity injury. The tibialis posterior is active in gait from shortly after initial contact until early preswing.\textsuperscript{2} This muscle is working during stance phase to first decelerate subtalar joint pronation, then aid in subtalar joint supination. When a foot continues to pronate past loading response into midstance and terminal stance, the tibialis posterior can undergo excessive stress. The insertion of the tibialis posterior on the navicular will be pulled away from its origin on the interosseous membrane and tibia as the foot pronates. The internal tibial rotation that accompanies closed kinetic chain subtalar joint pronation will also increase the strain to the tibialis posterior by lengthening the distance between the origin and insertion of the muscle. The result of prolonged pronation at the subtalar joint is that the origin and insertion of the tibialis posterior are being pulled away from each other at a time when the muscle is contracting to attempt to supinate the foot.\textsuperscript{48} This will create an increase in tension and eccentric stress to the tibialis posterior, with possible microtearing in the muscle.\textsuperscript{5,48}

**Shin Splints**

For the purposes of this paper, shin splints will be defined as regular, long lasting pain at the medial distal 2/3 of the tibia without diagnosis of stress
fracture or specific tendonitis.\textsuperscript{5} Viitasalo and Kvist\textsuperscript{49} found significantly more calcaneal eversion in standing in a shin splint group when compared to a normal group, suggesting that this pathology can result from excessive subtalar joint pronation.

Strain to the tibialis posterior has been cited as a possible cause of shin splints.\textsuperscript{5,6} This muscle plays a large role in controlling subtalar joint pronation and would thus go along with the results of Viitasalo and Kvist.\textsuperscript{49} When the effects of stress to the tibialis posterior are manifested at its origin, symptoms of shin splints could easily result.

Soleus strain is another possible mechanism leading to shin splints. As dorsiflexion is a component of subtalar joint pronation, the soleus may be stressed by a foot that pronates excessively. If the insertion of the soleus on the medial 1/3 of the calcaneus is considered, it would seem that pronation of the subtalar joint could indeed stress the soleus. Again, if the stress to the soleus manifests itself at the origin of the soleus, the symptoms of shin splints could appear.

With proper knowledge of the biomechanics of the foot, it becomes easier to understand why a certain lower extremity injury may occur as a result of a structural deformity in the foot. However, lower extremity injuries cannot be predicted by assessing the structure of a foot. Any injuries which occur in the lower extremity as a result of structural foot deformities depend on how and where the compensation for the deformity takes place.\textsuperscript{1,6}

For example, a structural foot deformity leading to compensatory overpronation will increase the amount of internal rotation occurring at the tibia.
If the tibia is internally rotating during late stance phase, a problem may be anticipated at the knee joint as the femur could be following the external rotation of the stance side pelvis. However, if the femur avoids this forthcoming problem by internally rotating to match the tibial motion, the site of pathology can be transmitted proximally to the external rotators of the hip. Muscles such as the piriformis are working to externally rotate the femur while the femur is internally rotating to avoid stress at the knee. Eccentric stress and pathology can then occur in the hip external rotators as the insertion is being pulled away from the origin of a contracting muscle. If the pelvis instead internally rotates with the femur, the stress can be transferred to the sacroiliac joint or to the lumbosacral spine. In summary, while the basic compensatory mechanisms for structural foot deformities can be predicted, the site where these compensatory mechanisms lead to abnormal function and pathology can be quite variable.

Further complicating matters is the fact that the foot may fail to compensate for structural abnormality. The subtalar joint may not have enough range of motion to compensate for the deformity, or may simply choose not to compensate for the structural deformity. In this case, the pathomechanics of lack of compensation must be considered as causes of possible resultant lower extremity pathology. For instance, a foot that fails to pronate for a structural deformity may not get the needed shock absorption associated with subtalar joint pronation. In this case, lower extremity symptoms would correspond to pathologies associated with an oversupinated or rigid foot.
SUMMARY

The foot is a very complex structure when viewed from the perspective of biomechanical function. At times in the gait cycle the foot must function as a mobile adaptor, being able to adjust to whatever terrain over which we walk. At other times, the foot must function as a rigid lever, propelling the body forward without collapse. Yet another function of the foot is to absorb the transverse plane rotations of the lower extremity that occur in normal gait. This is necessary to enable the body to continuously move forward without having the foot rotate on the ground.

Under normal conditions the biomechanics of the subtalar joint enable the foot to accomplish its necessary functions during gait. When structural deformities exist within the foot, the normal biomechanics of the subtalar joint and foot are altered as compensation for structural deformities now becomes the major biomechanical role of the foot. The compensation taking place in the subtalar joint and foot may result in a variety of lower extremity pathologies. With any type of pathology, proper physical therapy treatment requires accurate diagnosis of both the specific structures which are injured and the causative factors of the injury. Diagnosis of the causative factors of the injury becomes particularly important with injuries produced by foot pathomechanics. If the injury is treated with regard to only tissue healing factors, recurrence of the injury can be expected when the patient returns to normal activity, as the same
biomechanical mechanism which produced the injury originally will again present.

While treatment considerations to counteract abnormal foot biomechanics are beyond the scope of this paper, this paper does provide the background for the development of treatments which attempt to correct abnormal biomechanics of the foot, when it is determined that these altered biomechanics are the underlying cause of certain lower extremity pathologies. Correcting these abnormal biomechanics can serve to treat and subsequently prevent recurrence of the diagnosed pathologies.
REFERENCES


