TUTORIAL

Diagnosis and Management of the Painful Ankle/Foot Part 1: Clinical Anatomy and Pathomechanics

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■ **Abstract:** Distinctive anatomical features can be witnessed in the ankle/foot complex, affording specific pathological conditions. Disorders of the ankle/foot complex are multifactoral and features in both the clinical anatomy and biomechanics contribute to the development of ankle/foot pain. The superior tibiofibular, distal tibiofibular, talocrural, subtalar, and midtarsal joint systems must all participate in function of the ankle/foot complex, as each biomechanically contributes to functional movements and clinical disorders witnessed in the lower extremity. A clinician's ability to effectively evaluate, diagnose, and treat the distal lower extremity is largely reliant upon a foundational understanding of the clinical anatomy and biomechanics of this complex complex. Thus, clinicians are encouraged to consider these distinctions when examining and diagnosing disorders of the ankle/foot. ■

Key Words: Ankle, Biomechanics, Foot, Midtarsal, Pathoanatomy, Subtalar, Talocrural

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INTRODUCTION

Painful disorders of the ankle foot complex present many challenges to clinicians. Complexities in structure and function can create difficulties in diagnosis and management. The distal location, while sharing many structural similarities with the wrist and hand, creates complicated behavioral distinctions when the lower extremity is functioning in the closed chain (with the foot planted on the ground). Likened to the wrist/hand, symptom localization is trustworthy, due to relatively small sensory receptive fields and reduced corresponding convergence of the afferent signals in the dorsal horn of the spinal cord. Like the proximal row of the carpals, the talus acts as an intercalated segment between the rigid mortise and semi-rigid tarsals.[1] However, unlike the wrist/hand, the ankle/foot is required to frequently function in the close chain. As a consequence, the talus moves in reaction to the positions and movements of the surrounding architecture while the lower extremity bears weight.[2] This behavior accounts for the multiple instantaneous axis orientations demonstrated by the talus with movements,[3] whereby as these axes change, talar movement can be initiated by different forces and actions.

There are five different mechanisms involved in ankle foot function, including the superior tibiofibular joint, the talocrural coupling mechanism, the tarsal mechanism intercalated between the lower leg and the distal half of the foot, the tarsometatarsal mechanism, and finally, the metatarsophalangeal mechanism.[4] Each of these contributes to the overall composite function of the entire lower extremity during any weightbearing behavior.[2] Conversely, limits within any component can adversely influence the overall function of this entire system, resulting in compensatory behaviors in adjacent structures and potential tissue failure.

THE LOWER LEG

The superior tibiofibular joint (STFJ) anatomically belongs to the knee but functionally belongs to the ankle/foot. The STFJ is comprised of an oval synovial joint compartment located between the fibular head and proximal posterolateral tibia just distal to the tibial plateau. The joint maintains a capsular compartment lined with synovial tissue and is reinforced by anterior and posterior capsular ligaments. In addition, the lateral collateral ligament of the knee inserts on the fibular head, contributing to structural support. The common peroneal nerve circumvents the fibula just distal to the joint, lending to potential nerve irritation in response to joint laxity. Finally, the orientation of the joint's surface is 45° anterolateral to posteromedial. The fibular head should be moved in this direction when a clinician examines the mobility of this joint, so the complete movement can be appreciated.

The biceps femoris inserts directly into the fibular head on the lateral side of the knee.[5] Moreover, several muscle groups indirectly influence the function of the STFJ by virtue of their insertion into the fibula and interosseus membrane, including extensor digitorum longus, peroneus longus and brevis, tibialis posterior, flexor hallucis longus, and the soleus.[6] While the STFJ cannot be moved in an isolated voluntary fashion (similar to the distal radioulnar joint and acromioclavicular joint in the upper extremity), its movement is no less vital to the function of the ankle/foot. This joint moves in response to movement in the talocrural joint and limitations in the STFJ can create end-range limitations and possible pain in the anterior ankle with functional weightbearing.

The STFJ contributes to several pathological scenarios. First, the joint is prone to locking behavior when it functions as a component of a complete kinematic chain. As a consequence, the STFJ can lock after a plantarflexion-inversion trauma to the ankle/foot. During the plantarflexion inversion trauma, increased tension is imposed on the lateral ligament structures of the ankle. These forces apply an inferior longitudinal traction to the distal fibula, creating a fibular rotation about its oblique axis in the parasagittal plane. As a consequence, the distal fibula moves anterior inferior while the STFJ glides inferior-posterior and locks. This locking reduces the movement of the entire fibula during ankle movement, lending to end-range limitations of talocrural dorsiflexion.

Runners can develop local pain at the STFJ as a consequence of movement disturbances at the joint. These symptoms typically increase with every cycle of terminal lower extremity swing in the running sequence. The mechanism behind this clinical condition is STFJ hypermobility. During terminal swing the biceps femoris eccentrically contracts to decelerate the lower leg. As a consequence, the fibular head is pulled posteriorly and the common peroneal nerve is tension loaded as it circumvents the proximal fibula. Repetitive mechanical irritation to the nerve injures the epineurium, resulting in local pain.

Finally, patients can develop STFJ hypomobility without pain. This motion loss can contribute to end-range movement limitations in the talocrural joint, lending to disturbances in the propulsion phases of gait and possible anterior tibiotalar compression syndrome. In response, clinicians should always include an assessment of STFJ mobility when treating limitations of the talocrural mechanism.

The interosseus membrane (IOM), spanning the space between the tibia and fibula, is a very firm structure. The fibers of the IOM course in a distal lateral direction from the tibia to the fibula and stop approximately one inch proximal to the facet of the distal tibiofibular joint (DTFJ; or syndesmosis). The IOM functions as a divider of the lower leg compartments, demonstrating only two openings for the passage of nerves and vessels. These openings are bordered by a small group of fibers that run perpendicular to the IOM fibers, so to prevent compression of the neurovascular bundle during movement and weight bearing. Moreover, the IOM transfers up to 30% of the weightbearing load from the tibia to the fibula. Thus, the fibula provides an important contribution to shock absorption in gait. Moreover, the lateral talus contacts the fibula with dorsiflexion, pushing it proximal lateral at the end-range of movement. As a consequence, the membrane fibers become taut at end-range dorsiflexion and the mortise is stabilized. This stabilizing feature is augmented by the interosseus ligament (IOL), which is located distal to interosseus membrane and proximal to the DTFJ. The IOL demonstrates a very high strength modulus compared to other connective tissue structures. When cut, relative movement and change in position of the lateral malleolus with respect to the tibia is magnified in weightbearing.[7]

The DTFJ is actually a syndesmosis at the end of the distal tibia and fibula. Through this very stable union the tibia and fibula create the roof over the talus, or mortise. The tibial articular surface is oriented 30° anterolateral to posteromedial and is interrupted in its center by a fibular notch, increasing the stability of the syndesmosis during weight bearing functions.[8] The anterior and posterior inferior tibiofibular ligaments stabilize the connection, with the posterior demonstrating the greatest strength modulus of the two. The anterior ligament is confluent with the anterior talofibular ligament (ATFL) of the ankle. Tension in the ATFL induces tension in the anterior inferior tibiofibular ligament. When the ATFL is damaged with inversion trauma, the anterior inferior tibiofibular ligament is at risk for instability, thus compromising the integrity of the distal tibiofibular joint and mortise. Likewise, traumatic supination and external rotation of the talus can forcefully separate the mortise, resulting in anterior ligament compromise and subsequent mortise instability.[8] Fibers of the posterior inferior tibiofibular ligament course in same direction as the interosseus membrane and thus interact with the membrane to increase stability.

THE TALOCRURAL MECHANISM

Anatomy

The Talo-Crural Joint (TCJ) is comprised of the talar dome resting within the rigid roof of the mortise. Stability of this joint is provided by architecture (primary constraint) and ligaments (secondary constraint). The joint demonstrates a great deal of motion, whereby it passively dorsiflexes up to 30° and passively plantarflexes up to 50°. As previously noted, the mortise is comprised of the junction between the tibia and fibula, with the medial malleolus creating the medial wall and the lateral malleolus creating the lateral wall.[10] However, this structure is not symmetrical. The lateral malleolus is larger, more distal, and more posterior versus the medial malleolus.[6] As a result, the lateral talus cannot be easily palpated due to the fact that it is covered by the lateral malleolus.[10] Conversely, the medial talus is easily palpated, providing the clinician with an accessible handhold for talocrural mobilization.

The mortise is concave in the sagittal plane and convex in frontal plane, creating a sellar configuration. A ridge is found in the center of the tibial mortise surface, coursing from anterolateral to posteromedial. The roof of the mortise is angulated, coursing from anteroproximal to posterodistal (see Figure 1). If it were not for the stabilizing features of the ankle ligaments, weightbearing would force the mortise to slide posteriorly on the talar dome.[10]

The medial tibial articular surface courses from posterolateral to anteromedial. On the other hand, the lateral fibular articular surface courses posteromedial to anterolateral, which is the same orientation as the STFJ, but not to the same degree. These relationships create a wedge shape to the mortise in the transverse plane.[10]

The talar dome is convex in the sagittal plane and concave in frontal plane. In addition, it is wider anteriorly and narrower posteriorly, creating a wedge shape in the transverse plane that fits into the mortise. However, the shape of this wedge is not completely complementary to the mortise. While the lateral talar surface courses posteromedial to anterolateral in a similar direction as the lateral wall of the mortise, the medial surface courses straight anterior-posterior. This incongruity contributes to the rotatory spin demonstrated by the talus in the transverse plane during talocrural joint movements.[9,11] Finally, a groove exists

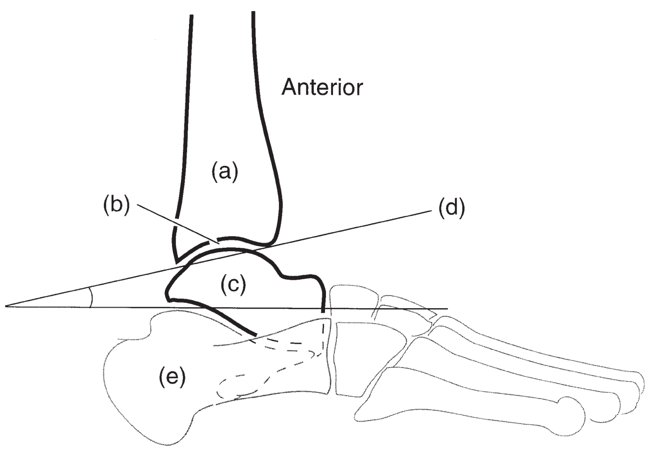

Figure 1. Orientation of the (R) talocrural joint in the parasagittal plane: (a) Tibia; (b) Talocrural joint compartment; (c) Talus; (d) anterior-proximal to posterior-distal orientation of the talocrural joint in the parasagittal plane; (e) calcaneus.

on top of the dome that courses posteromedial to anterolateral, complementing the ridge in the roof of the mortise and contributing to the rotatory spin previously described.

Two tubercles are present on the posterior aspect of the talus: the posteromedial and posterolateral talar tubercles. The posterolateral tubercle is longer and more centrally located, just anterior to the Achilles tendon. Developmentally the growth plate at that tubercle closes and osseus junction occurs at approximately 12 to 13 years of age. This closure occasionally fails to take place and the junction remains cartilaginous or ligamentous. This condition is called Os Trigonum and may result in pathology, whereby the Os impacts against the posterior tibia during forced plantar flexion.[12,13] However, pain may arise in the same region under the same mechanical constraints without the presence of an Os Trigonum. During this posterior tibiotalar compression syndrome (PTTCS), the posterolateral talar tubercle compresses against the posterior rim of the mortise, lending to periosteal irritation. This lesion can be witnessed in ballerinas who dance "On Points." In addition, PTTCS can result from talocrural joint laxity because of increased plantar flexion and insufficient constraint by the ankle ligaments. Finally, tenosynovitis of the flexor hallucis longus (FHL) can emerge as a sequel to irritation in this region. The FHL tendon is surrounded by a sheath that courses through a narrow bony groove under a retinaculum that spans between the two tubercles. The sheath can become inflamed at this site, compromising any normal tendon gliding.[14] As a consequence, the patient develops limitation to great toe extension, or "pseudo-hallux rigidus."

Stability of the ankle, which is paramount to function in weightbearing, is achieved through an interaction between architecture, capsuloligamentous support and muscular control.[15,16] The TCJ capsule, which is extensive and redundant both anteriorly and posteriorly, extends 2 cm proximally into the DTFJ syndesmosis producing a capsular recess.[17] The capsule is reinforced by several ligamentous structures on both the medial and lateral sides. The anterior talofibular ligament that reinforces the anterolateral capsule is the most frequently injured ligament in the ankle (see Figure 2).[18] This short, wide ligament is very flat and fused to the capsule, originating from the anterior / inferior lateral malleolus and inserting on the lateral talar neck. Trauma to the ligament can be sustained with inversion in a plantarflexed position and can produce a capsular pattern limitation, as a consequence of a reactive synovitis of the TCJ.

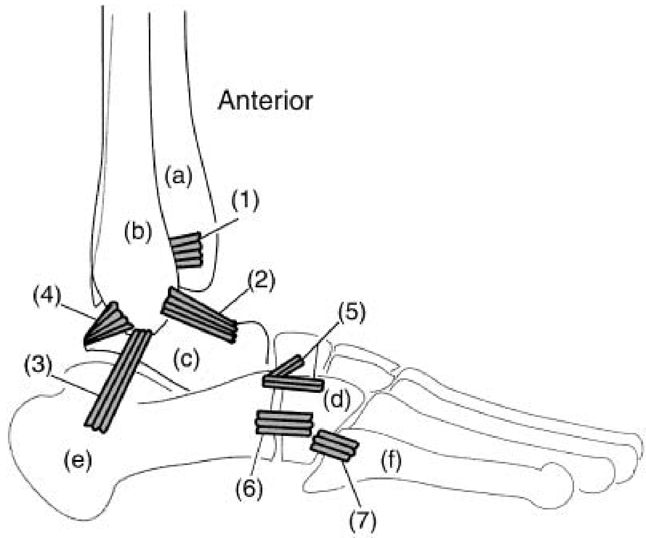

Figure 2. Lateral ligaments of the (R) ankle and foot. (a) Tibia; (b) Fibula; (c) Talus; (d) Cuboid; (e) Calcaneus; (f) 5th metatarsal; (1) Anterior tibiofibular ligament; (2) Anterior talofibular ligament; (3) Calcaneofibular ligament; (4) Posterior talofibular ligament; (5) Bifurcate ligament; (6) Calcaneocuboidal ligament; (7) Cubometarsal ligament.

The calcaneofibular ligament originates from the inner aspect of the most inferior tip of the lateral malleolus and inserts on the proximal lateral aspect of the calcaneus (see Figure 2).[15] Clinical palpation of the ligament mid-substance is impossible, as palpation is obstructed by the overlying peroneal tendons. Tears in the ligament can affect both the capsule and the tendon sheath, due to close proximity of these structures. With joint arthrography, contrast fluid in the peroneal sheath could indicate tenosynovial pathology. The ligament provides significant contribution to stability, as it is stressed during inversion in both neutral and dorsiflexed positions.[15] The posterior talofibular ligament, originating on the posterior inferior fibula and coursing in a posteromedial direction to insert on the posterolateral talar tubercle, serves as the strongest of all lateral ligaments and is rarely injured.

The bifurcate ligament courses from the most dorsal aspect of the dorsal distal calcaneal "trumpet" to both the dorsolateral navicular and dorsomedial cuboid, stabilizing both bones to the calcaneus. Accompanying this ligament system is the lateral calcaneocubiod ligament that courses from the lateral calcaneal trumpet to the lateral cuboid, and the cubometatarsal ligament that courses from the lateral cuboid to the base of the 5th metatarsal. All of these ligament systems can be overstretched during a plantarflexion-inversion trauma, especially if the individual has preventatively taped at the talocrural and subtalar joints. Consequently, they should not be overlooked when appraising the extent of injury after such an event (see Figure 2).

The medial ligamentous structures of the ankle, or "deltoid complex," are significantly denser than those on the lateral side (see Figure 3). These fibers are comprised of both superficial and deep branches that cross one to two joints. The deep anterior tibiotalar branch originates on the anterior medial malleolus and inserts on the medial talar neck. Superficial to this ligament is the tibionavicular ligament, coursing from the anterior medial malleolus to the tubercle of the navicular (see Figure 4). Both of these ligaments are most stressed during eversion in a plantarflexed position.

Proximal to these ligaments, the medial tibiocalcaneal ligament system courses from the tip of the medial malleolus to the sustantaculum tali (see Figure 3). Along with this dense fiber system, the posterior tibiotalar ligaments course from the posterior medial malleolus to the posteromedial talar tubercle. These ligaments are less frequently afflicted than the lateral ones, due to greater load tolerance. As a consequence, they serve as a key component in translatory and rotatory stability at the ankle, which is especially appreciated during the landing sequence of gait.[19]

TCJ Biomechanics

The instantaneous axes of rotation for the talocrural joint change in accordance with changes in the joint's position, producing changes in the coupled motions of the joint.[11] In the frontal plane, the axis is horizontally oriented when the joint is in neutral between plantar and dorsiflexion. The axis courses in a plantar-medial to dorsal-lateral direction when the joint is positioned in full plantarflexion. The axis changes to a plantar-lateral to dorsal-medial orientation, (ie. through the tips of the malleoli), when the TCJ is fully dorsiflexed. As a result, changes in the axis and joint architecture induce 3-dimensional movement in the TCJ. The talus internally rotates and supinates in relation to the tibia when dorsiflexing from 30° plantarflexion to 10° plantarflexion. Conversely, the talus externally rotates and continues to supinate when dorsiflexing from 10° plantarflexion to neutral. Finally, when moving from neutral to full dorsiflexion, the talus externally rotates without supinating.[3,11,20]

Joint arthrokinematic behaviors are different in open- versus closed-chain movements and are strongly influenced by the joint's architecture. For open-chain dorsiflexion (DF), the convex talus rolls anterior-proximal and slides posterior-distal on the concave mortise. In addition, the talus externally rotates (or

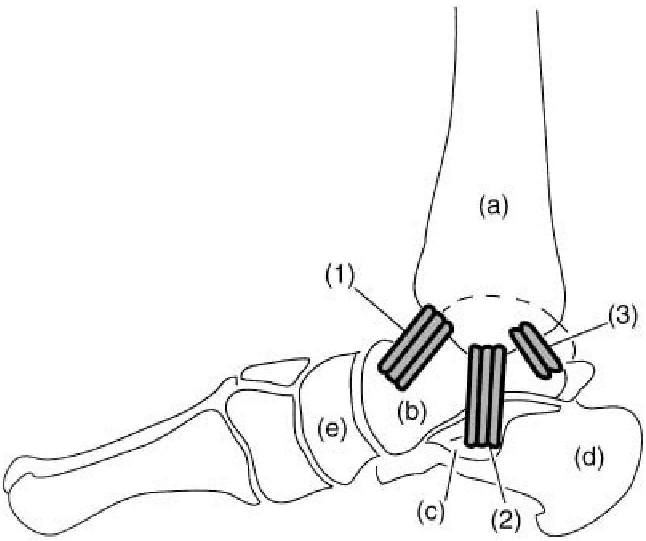

Figure 3. Medial ligaments of the (R) ankle and foot, Part 1. (a) Tibia; (b) Talus; (c) Sustantaculum tali of the calcaneus; (d) Calcaneus; (e) Naviculum; (1) Anterior Anterior tibiotalar ligament; (2) Tibiocalcaneal ligament; (3) Posterior tibiotalar ligament.

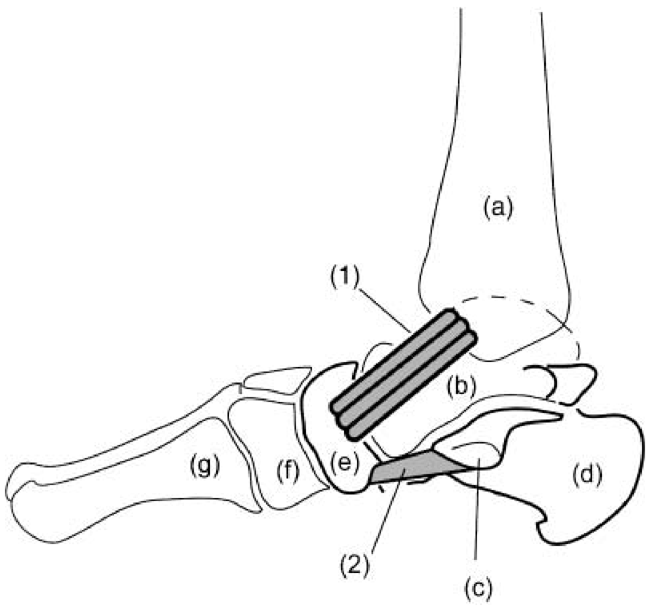

Figure 4. Medial ligaments of the (R) ankle and foot, Part 2. (a) Tibia; (b) Talus; (c) Sustantaculum tali of the calcaneus; (d) Calcaneus; (e) Naviculum; (f) Medial cuneoform; (g) 1st metatarsal; (1) Tibionavicular ligament; (2) Calcaneonavicular, or "Spring", ligament.

externally spins) in the transverse plane as previously described. During this movement, the mortise opens as the wedge-shaped talar dome pushes the lateral malleolus in a dorsolateral direction. Closed-chain DF incorporates anterior superior rocking and gliding of the concave mortise on the convex talus. At the same time the mortise internally rotates on the talar dome, in response to previously described architectural constraints. If the talus is forced to externally rotate and supinate in a dorsiflexed position, there is an increased risk of fracturing the lateral malleolus (known as supination-external rotation, or an SER, fracture).[21,22]

In concert with the significant congruency of the talocrural joint, even slight alterations in architecture after fracture or dislocation could significantly alter loading distribution within the joint, resulting in possible aberrant articular cartilage responses.[9] Dorsiflexion decreases the joint surface contact area and increases the load between the various facets of the joint.[9,23] Similarly, plantarflexion increases the contact pressure within the facets.[11,23] In addition, increased loads associated with weightbearing increased the contact pressure and intra-articular load between the joint surfaces.[23] Finally, investigators have demonstrated that cartilage defects in the talar dome could significantly alter contact pressure amplitudes and locations within the joint,[24] leading to pain and/or early degeneration.

SUBTALAR MECHANISM

Anatomy

The skeleton of the foot can be divided into 4 transverse segments: tarsus (rearfoot), lesser tarsus (midfoot), metatarsus, and digits.[25] Within the tarsus one finds the talus and calcaneus. The talus is the 2nd largest of the tarsals and is considered to be the mechanical keystone to the apex of the foot. The talus can be considered an intercalated segment between the rigid distal tibia / fibula and the planted calcaneus.[1] Thus, the talus functions as a torque converter between the internally rotating tibia and the everting calcaneus. This suggests that talar motion is relegated in reaction to influences on the moving lower leg and calcaneus in concert with a symphony of forces being produced from the ground and responding musculotendinous influences on the lower leg and foot. Under the talus, the calcaneus provides firm elastic support for the body weight, as the weight is transferred to more proximal aspects of the body. In addition, the calcaneus acts as an effective lever for the calf muscles that insert into its most proximal tubercle.[25]

The subtalar joint (STJ) is comprised of the articulation between the talus (superiorly) and calcaneus and navicular (inferiorly; see Figure 5).[25,26] This joint is one of the most complex weightbearing joints and is responsible for control of rotatory forces of the lower extremity (LE) as well as dictating the motions of the midtarsal joints (MTJ).[27] The STJ interface is composed of two separate compartments (posterior and anterior; see Figures 5, 6).[25,28] These compartments function symbiotically, represented by their single oblique axis and the fact that neither compartment can move without the other moving in a correspondent fashion.[25]

The posterior compartment of the STJ, also called the talocalcaneal articulation, consists of the inferior posterior facet of the talus and the superior posterior facet of the calcaneus (see Figures 5, 6). Within the posterior articular compartment, one finds the posterior talar and calcaneal facets. The posterior talar facet is the largest of the three inferior talar articular surfaces, is oval in shape, and is concave posteriorly.[25] The corresponding posterior calcaneal facet is also oval in shape and convex posteriorly, complementing its talar coun-

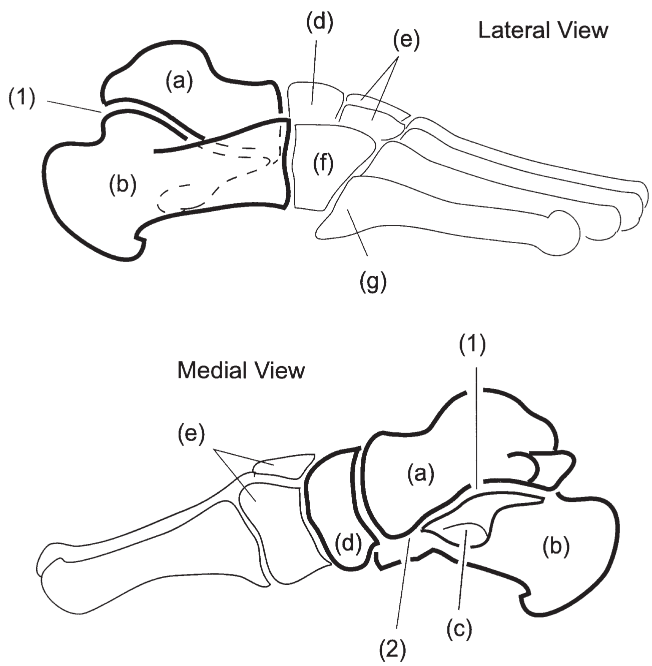

Figure 5. Subtalar joint (R) from a medial view. (a) Talus; (b) Calcaneus; (c) Sustantaculum tali of the calcaneus; (d) Naviculum; (e) Cuneoforms; (f) Cuboid; (g) base of the 5th Metatarsal; (1) Posterior Compartment of the subtalar joint; (2) Anterior compartment of the subtalar joint.

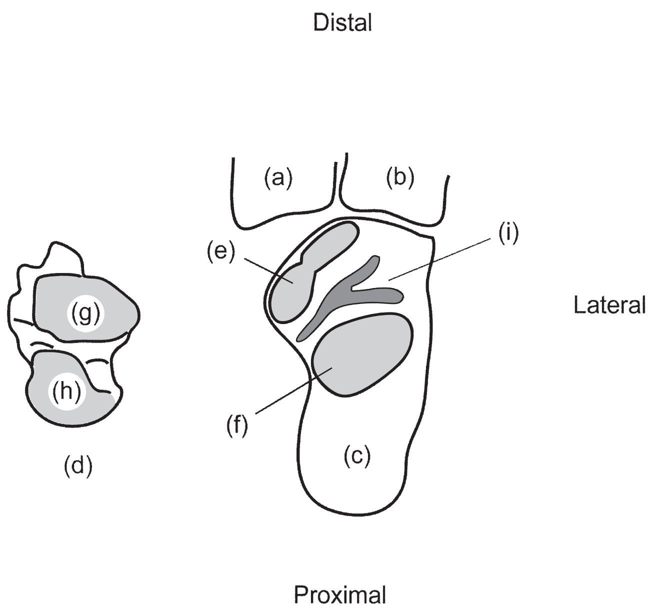

Figure 6. Subtalar joint (STJ) from a superior view; (a) Naviculum; (b) Cuboid; (c) Superior view of calcaneus; (d) Inferior view of talus, where talus has been flipped over; (e) Anteromedial calcaneal articular surface of the STJ; (f) Posterior calcaneal articular surface of the STJ; (g) Anteromedial talar articular surface of the STJ; (h) Posterior talar articular surface of the STJ; (i) talocalcaneal interosseus ligament within the tarsal canal.

terpart in shape and form. These facets are difficult to visualize radiologically, due to their complex orientations.[28]

The anterior compartment consists of the anterior articular facet of the talus with the corresponding anterior articular facet of the calcaneus (see Figure 6). The floor of the anterior chamber is formed by the plantar surface of the talar head with the dorsal surface of the spring (or talo-calacaneo-navicular) ligament. This articulation is also called the talocalcaneonavicular joint. Within the anterior compartment both middle and anterior articulations between the talus and calcaneus can be seen. Within the middle articulation, the middle talar facet is large and just posterior to the plantar talar head. It is oval and slightly convex and rests on the middle facet of the calcaneus, which is elliptic in shape and is part of the sustentaculum tali. For the anterior articulation, the anterior subtalar joint includes a slightly convex talar facet that compliments a concave calcaneal facet located on the anterior calcaneal process. The anterior talar facet is often continuous with the middle facet. This relationship makes the distinction between the anterior and middle facets ambiguous.[25,26]

Immediately distal to the anterior talar facet, lies the talar head. The talar head presents with two different regions: plantar and distal. The plantar aspect of the talar head articulates with the dorsal aspect of the spring ligament (see Figure 4). This articulation is at the most medial aspect of the articular talar head and lies anterior / medial to the middle facet.[28]

Between the calcaneus and talus, the tarsal canal is found (see Figure 6). The tarsal canal is created by the sulcus calcanei of the calcaneus and the sulcus tali of the talus. This canal opens to the sinus tarsi on the lateral dorsal surface of the foot and courses in a medial-plantar direction to open just proximal to the sustentaculum tali. Within the tarsal canal lie the interosseus and cervical ligaments, which are significant to both stability and coordination of the STJ.[4,25,29] A fibrous capsule and synovial membrane surrounds the posterior STJ.[25] A similar capsular structure surrounds the anterior STJ (talocalcaneonavicular joint) system, but is imperfectly developed; thicker posteriorly, it is confluent with the cervical ligament system in the tarsal canal.

The dense, broad talocalcaneal interosseus ligament (TCIL) system resides in the tarsal canal, just anterior to the posterior-inferior calcaneal facet of the talus and in proximity to the instantaneous axis of rotation (IAR) for the STJ (see Figure 6). It is obliquely oriented proximally and medially and inserts into the sulcus of the talus.[30] The TCIL divides the anterior and posterior chambers of the STJ and is the primary ligament of support for the posterior STJ.[30–32] This interosseus ligament restrains the STJ by 9°, regardless of the position of the ankle / foot.[33] It is comprised of two fibrous bands: (1) the anterior band coursing in an oblique direction from the sinus calcanei anteriorly to the inferior talar neck; and (2) the posterior band coursing in an oblique direction from the sinus calcanei to the posterior sinus tali. These ligaments are confluent with the fibers of the talocalcaneal and talocaneonavicular joints.[25] Stability of the STJ is selectively affected by the integrity of the TCIL. Sectioning of the ligament produces significant increases in the supination screw axis rotation, whereas pronation screw axis rotation remains unchanged. Thus, the TCIL contributes to subtalar supination stability but is of less significance for pronation stability.[30]

Additional ligaments can be observed surrounding the posterior STJ.[30] The lateral talocalcaneal ligament courses from the lateral talar tubercle to the lateral posterior calcaneus. The posterior talocalcaneal ligament courses from lateral talar tubercle to the proximal medal calcaneus. The medial talocalcaneal ligament courses from the medial talar tubercle to the posterior aspect of the sustentaculum tali. These ligaments serve to reinforce the already-stable posterior STJ system.

The anterior STJ (talocalcaneonavicular joint) is supported by the talonavicular ligament, the calcaneonavicular ligament, the spring ligament, and the calcaneonavicular portion of the bifurcate ligament (see Figures 4–6).[25] The spring ligament is comprised of two distinct structural regions (see Figure 7).[34] The largest region is the superior medial calcaneonavicular (SMCN) ligament system, originating from the superior medial aspect of the sustentaculum tali and the anterior edge of the anterior facet of the calcaneus. These fibers are confluent with the superficial fibers of the anterior tibiotalar, tibionavicular, and tibiocalcaneal branch of the deltoid complex.[25] Additionally, these fibers fan out and insert onto the edge of the navicular facet, without inserting onto the tubercle of the navicular.[34] The tendons of the tibialis posterior, flexor hallucis longus and flexor digitorum longus further support the spring ligament medially and plantarly. This is consistent with the report of a relationship between tibialis posterior insufficiency and medial ankle laxity.[25]

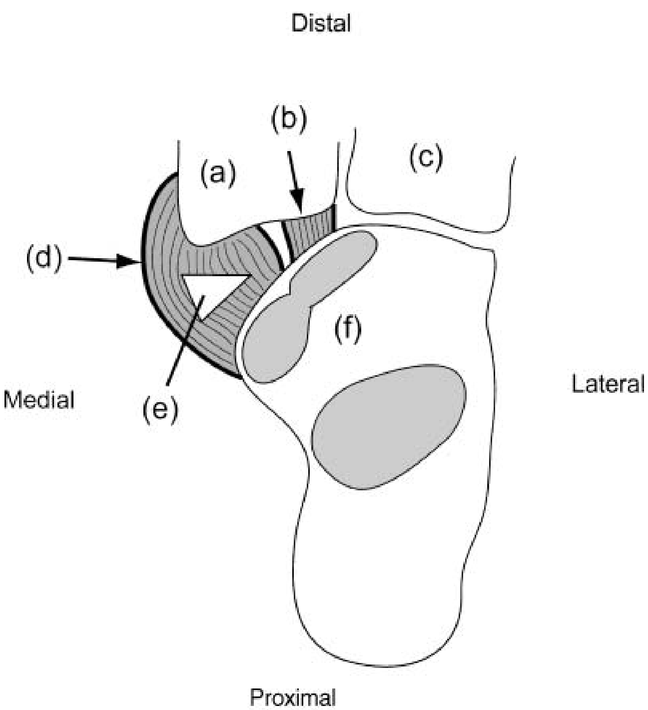

Figure 7. Spring Ligament Complex from a superior view; (a) Naviculum; (b) Inferior calcaneonavicular (ICN) ligament; (c) Cuboid; (d) Superior medial calcaneonavicular, or SMCN, ligament; (e) Triangular fibrocartilage region of the SMCN ligament; (f) Superior view of calcaneus.

Histologically, the SMCN is comprised of packed collagen bundles that course lengthwise and are most organized centrally. The ligament lacks elastin, and a vascular supply is scarce. The medial superficial substance on the plantar surface of the ligament articulates with the tendon of the tibialis posterior. Additionally, tendon fibers are confluent with the distal insertion of the SMCN as it inserts into the navicular.[34] Furthermore, a triangular fibrocartilage region can be observed on the dorsal midsubstance of the SMCN ligament (see Figure 7). Here the plantar medial surface of the talar head articulates, where the ligament serves as an articular sling for the talar head. This region is scarce of hyaline or a synovial membrane, is relatively avascular, and accepts compressive rather than tensile loads.[34]

The other region of the spring ligament, the inferior calcaneonavicular ligament system (ICN), is found plantar and lateral to the SMCN (see Figure 7). Originating from the notch between the middle and anterior calcaneal facets at the anterior aspect of the sustentaculum tali, it courses longitudinally and medially to insert onto the inferior surface of the mid-navicular cortex, just lateral to the insertion of the SMCN. Histologically, the uniformly organized ICN is comprised of packed collagen bundles that course lengthwise. These fibers lack any trace of fibrocartilage and appear to purely resist tensile loads.

One can see from a cranial view that the talar head articulates in a socket created by the SMCN, ICN, calcaneus, and navicular. However, each of these elements plays a different role in the stability of the talar head. From an analysis of the load-elongation response, Davis et al found that the stiffness and modulus of the system indicates that the ICN plays a minor role in joint stability, whereas the tensile strength of the SMCN is the same or greater than that of the lateral collateral system.[34]

Conclusively, the spring ligament system should be better named the "sling ligament complex" vs. the "spring ligament complex", due to several features: First, the system functions as a harness to the talar head. Secondly, the system lacks a density of elastin fibers, thus reducing any "spring" effect. And finally, the potential static / dynamic synergistic effect of the tibialis posterior with the ligament in restraining medial or plantar migration of the talar head reduces the perception of the ligament as an isolated "spring."[34]

Additional extrinsic structures of the ankle / foot complex contribute to STJ stability. Along with the extensor retinaculum, the lateral ankle ligaments augment lateral STJ stability (see Figure 2). Hollis, et al suggest that although the anterior talofibular ligament (ATFL) is considered the weakest of all ankle ligaments, its disruption could result in STJ instability.[35] The STJ demonstrates rotation in the pronation/supination directions after the ATFL is cut in an isolated fashion. This increase is most profound when the joint is placed in a dorsiflexed position and least when fully plantar flexed. This rotational instability is escalated when the calcaneofibular ligament (CFL) is sectioned simultaneously with the ATFL. Additionally, isolated CFL sectioning results in unstable inversion,[30] as well as an undue stress imposed on the cervical ligament system. When this occurs, the cervical ligament is elongated to potentially twice the original length. This elongation behavior may produce the irritation necessary for the development of Sinus Tarsi Syndrome, which typically plagues patients with a lateral ankle instability disorder.[31]

Cass, Morrey, and Chao have disputed the role of the lateral collateral system at the ankle in stabilizing the STJ.[36] In response to their investigation with selective cutting, they suggest that the lateral ligament system has little effect on the control of STJ motion. Additionally, they propose that the "giving way" that an individual with an unstable lateral ankle experiences appears to be due to sudden external rotatory subluxation of the tibia on the talus rather than a sudden talar tilt. They argue that talar tilt does not occur in weightbearing and the ATFL is most important in the constant restraint of tibia external rotation versus inversion at all angles of the ankle. However, this study does not consider the influence of the lateral collateral instability on movement behaviors of the STJ in the closed chain. Regardless, one must consider the role of the lateral collateral system in controlling rotatory instability in the transverse plane and its influence on function at the STJ.

STJ Biomechanics

The STJ is a very complicated motion system, and functional motions of the talus in relation to the calcaneus depend greatly on the weightbearing status of the lower extremity. In concert with the medial position of the talus with respect to the calcaneus and the joint's waveform congruency, the joint is prioritized for stability. Consequently, the STJ can function with other joints to provide shock absorption, conformity of the foot with the ground, weight support, and stability during propulsion phase of gait.[37]

A great deal of the functional movement of the STJ is primarily due to ligament tension and cartilage deformation.[38] Motion of the anterior and posterior STJ compartments occurs about a single axis. The axis courses from proximal-plantar-lateral to distal-dorsal-medial in the following angles: 16° (8–24°) from the sagittal plane and 42° (29–47°) from the transverse plane (see Figure 8).[37,39] This oblique axis, while variable and dispersive in nature,[38] produces an obligatory triplaner behavior between the talus and calcaneus.

As a foundation to the discussion of functional subtalar movements, one must define movements of the ankle / foot in each of three planes. In the frontal plane the ankle / foot produces inversion and eversion, where inversion elevates the medial foot border and depresses lateral foot border, while eversion produces the opposite behavior. In the transverse plane the ankle / foot abducts, where the foot rotates outward, and adducts, where the foot rotates inward. Finally, the foot dorsiflexes and plantarflexes in the sagittal plane, producing

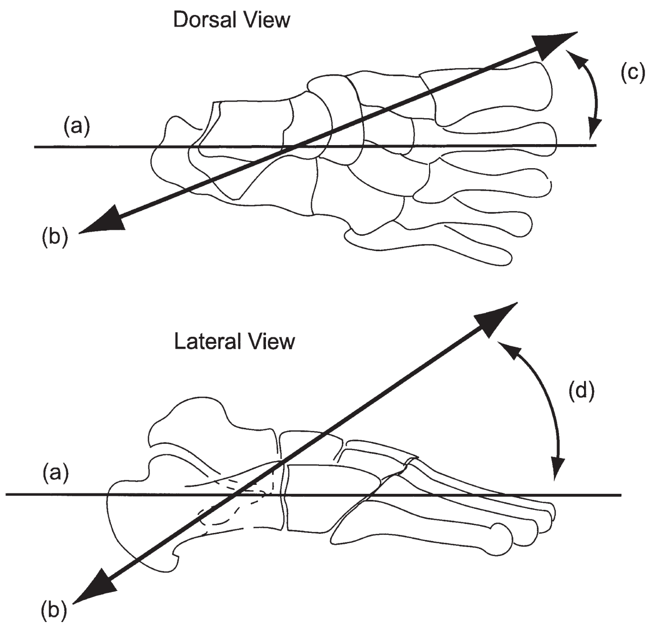

Figure 8. Oblique orientation of the instantaneous axis of rotation (IAR) for the STJ; (a) Long axis of the foot; (b) IAR of the STJ; (c) 16° (8–24°) orientation *from* the sagittal plane; (d) 42° (29–47°) *from* the transverse plane.

an upward and downward movement of the foot in relation to the tibia, respectively.[25]

When discussing the triplanar movements of the STJ, differentiation is made between open chain and closed chain functions. In the open chain the calcaneus moves about a fixed talus and tibia in two different composite directions: (1) Supination, which is composed of plantarflexion in the parasagittal plane, inversion in the frontal plane, and adduction in the transverse plane (see Figure 9)[38]; and (2) Pronation, which is composed of eversion in the frontal plane, abduction in the transverse plane, and dorsiflexion in the parasagittal plane (see Figure 10).[40] Normally, the ratio of supination : pronation from a subtalar neutral position of the foot is approximately 2 : 1.[25] Additionally, it appears that the STJ is the predominant source of inversion/eversion and abduction/adduction in the entire ankle/foot region. When comparing the STJ to the talocrural joint (TCJ), the STJ : TCJ ratio for movements in inversion/eversion in the frontal plane is 3 : 1, whereas the comparison of the same joints for abduction/adduction in the transverse plane is 4 : 1.[41]

In the closed chain, the triplanar composite motions at the STJ are more complex. With either supination or pronation, the calcaneus cannot produce the sufficient motions in either the transverse or parasagittal planes, due to its weightbearing status and consequential stability against the ground. Thus, for supination the calcaneus can only produce inversion in the frontal plane, forcing the talus to generate an obligatory motion about the same axis in the directions of abduction and dorsiflexion. This talar motion is produced with equal amplitude and opposite direction to the calcaneal supinatory motions that are produced in the transverse and parasagittal planes during open chain motion. The net result is an elevated talus and medial longitudinal arch.[42–44]

During closed chain pronation, on the other hand, the calcaneus is only allowed to evert, forcing the talus to adduct and plantar flex around the same axis in the same obligatory fashion (see Figure 11). Additionally, pronation forces the forefoot to evert, increasing the load born on the first metatarsal head. The clinical consequence is a depressed talus and medial lon-

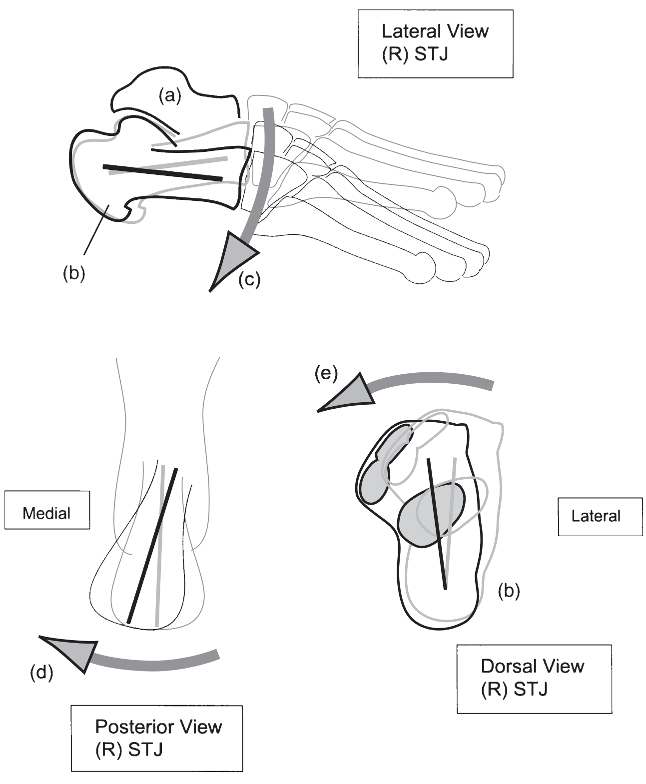

Figure 9. Triplanar movement components of STJ supination. (a) Talus; (b) Calcaneus; (c) Plantarflexion in the parasagittal plane; (d) Inversion in the frontal plane; (e) Adduction in the transverse plane.

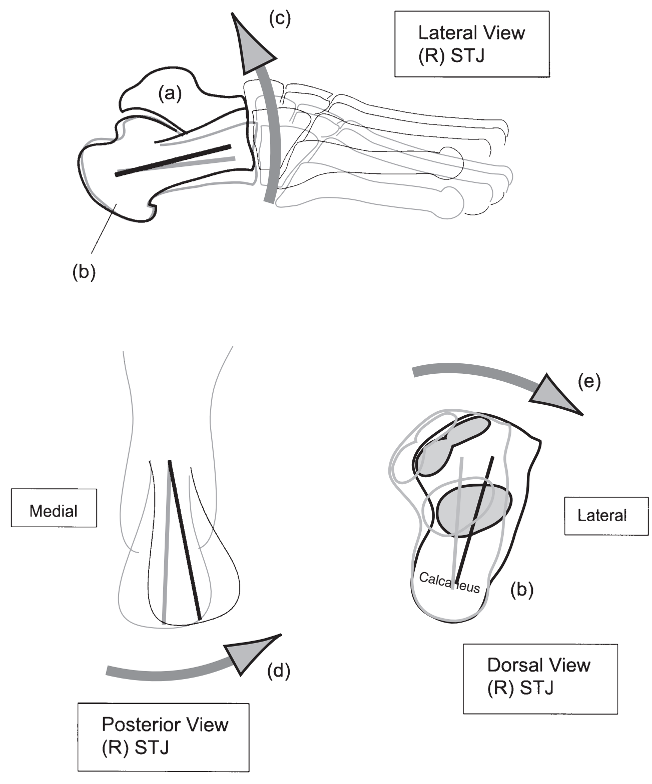

Figure 10. Triplanar movement components of STJ pronation. (a) Talus; (b) Calcaneus; (c) Dorsiflexion in the parasagittal plane; (d) Eversion in the frontal plane; (e) Abduction in the transverse plane.

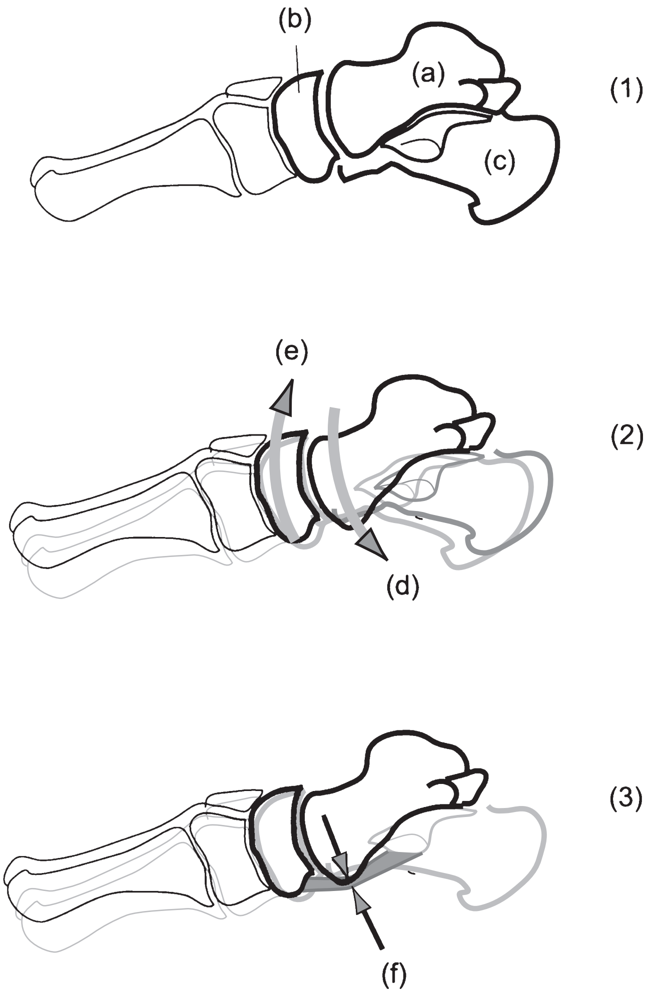

Figure 11. Pronation in the closed kinematic chain. (1) (R) Medial STJ in a normal CKC configuration, where (a) is the talus, (b) is the naviculum, and (c) is the calcaneus; (2) (R) Medial STJ demonstrating CKC Pronation, where (d) the talus plantarflexes and (e) the naviculum dorsiflexes; (3) (R) Medial STJ demonstrating CKC pronation, where (f) the talus compresses the spring ligament.

gitudinal arch that may translate into a clinical flat foot.[2,42–44]

Weightbearing associated with static standing induces a pronatory behavior in the STJ. Astrom and Arvidson determined that the mean value of rearfoot eversion in relaxed standing for 121 healthy subjects was 7°, accompanying a tibia varus of 6°.[40] These behaviors are activated by prenatally developed medial torsion in the calcaneus and talar head, which results in a medial twist of the rearfoot and forefoot (average 6° in the forefoot). These torsions induce a reactive pronation in the entire foot as the foot's plantar surface attempts to flatten on the ground and allow the foot to adapt to uneven terrain. Additionally, these behaviors do not appear to be significantly influenced by leg length discrepancies.[45]

Torburn et al evaluated motion in the talocrural and subtalar systems during the loading sequence of gait using a customized electrogoniometer (ELGON).[46] They found that maximum rearfoot eversion occurred at midstance, with a mean value of 7.9° lateral to subtalar neutral, (a position of the STJ where the joint is neither supinated nor pronated, as determined by neutral position of a palpated talus with respect to the navicular).[47] Additionally, they found that maximum rearfoot inversion occurred during the propulsion phase just prior to toe off with a mean value of 2.9° medial to subtalar neutral. Moreover, they observed a total arc of motion produced during gait that was significantly less than the total movement available during a non-weightbearing (NWB) condition (10.5° versus 28.8°, respectively). Furthermore, the maximum inversion produced during gait was significantly less than the inversion ROM available during a NWB condition (2.9° versus 18°, respectively). Finally, the maximum eversion produced during gait was not significantly different than the eversion available during a NWB condition (7.9° vs. 10.9°, respectively) or recorded during single-legged standing (9.8° from STJ neutral). In addition to these results, they found that only 2° of the inversion / eversion behavior of the rearfoot was contributed to by the TCJ. Thus, the investigators concluded that the majority of movement in the rearfoot during gait is contributed to by the STJ.[46]

Normal subtalar function is paramount to normal function in the lower extremity at the knee, ankle, and foot.[48] In the closed chain, the tibia appears to react to talar movements during the loading sequence. The tibia rotates symbiotically during the motion of the joints at the ankle/foot when weightbearing. Full foot closed-chain supination produces tibial external rotation (ER), while full foot closed chain pronation results in tibial internal rotation (IR).[49] Specifically, tibial IR accompanies pronation in the landing phase at nearly a 1 : 1 ratio.[1] This behavior may be a consequence of the talus being forced to move around the calcaneus in various loading conditions. For example, additional tibial IR occurs during the landing sequence as the talus is forced to adduct around the calcaneus. Conversely, additional tibial ER occurs during propulsion as the talus is forced to abduct around the calcaneus.[25] Moreover, Nester et al (2000) observed greater motion of the joints in the ankle/foot in the transverse plane than in the frontal

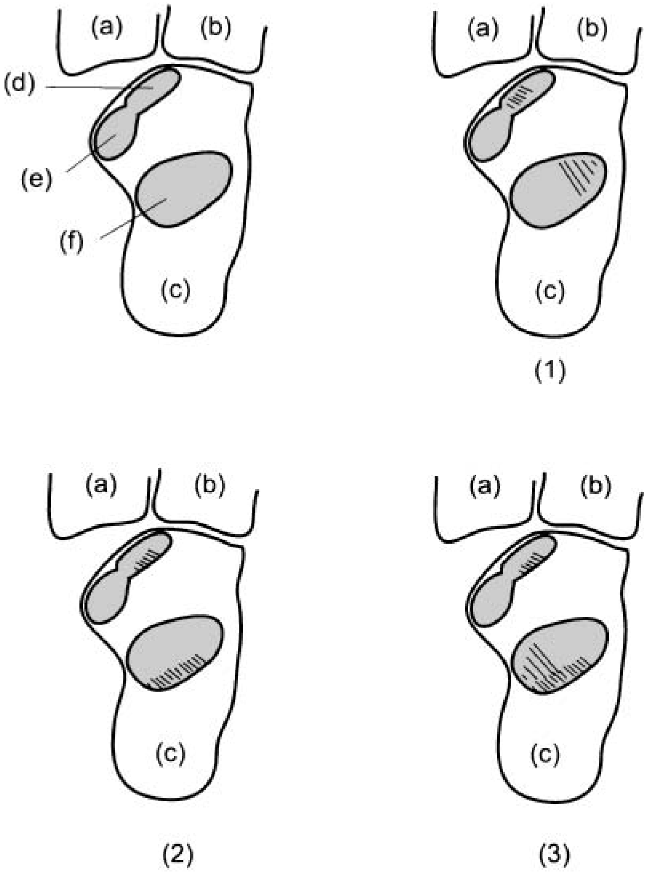

Figure 12. Contact pressures on various facets of the calcaneus at the subtalar joint (STJ). (a) Naviculum; (b) Cuboid; (c) Calcaneus; (d) Anterior calcaneal facet; (e) middle calcaneal facet; (f) posterior calcaneal facet; (1) Normal loadbearing with contact pressure at the anterior and posterior facets; (2) Loadbearing in plantarflexion, with altered contact pressure zones; (3) Loadbearing in inversion, with altered contact pressure zones.

plane during gait. Consequently, they suggested that motion of the shank (tibia) in the transverse plane may be a better representation of triplanar motion of the three joints at the ankle/foot versus motion of the calcaneus (in relation to the tibial shank) in the frontal plane during the loading sequence of gait.[49]

The intricate motions of the STJ during the loading sequence alter the pressures exerted between joint surfaces (see Figure 12). Contact pressures within the facets of the STJ are focused primarily over the anterolateral posterior facet and the anterolateral middle facet. The area of contact increases as the load of weightbearing is increases. As the load increases, the posterior facet accepts more of the load. Contact pressures within the facets of the STJ are increased in area and shift posterior medially when weightbearing is enacted in a plantar-flexed rather than dorsi-flexed position. This is related to the fact that the STJ becomes more perpendicular to the ground in a plantar-flexed position. Moreover, contact pressures within the facets of the STJ increase in area and shift medially when weightbearing changes from an everted to inverted foot position. This is accompanied by a shift of compressive forces from the STJ to the talonavicular joint (TNJ) as the axes of motion for the TNJ and calcaneocuboid joint (CCJ) become more perpendicular in the frontal plane. These changes may contribute to altered degeneration patterns in the STJ with altered postures in the foot during gait.[27,50]

The contact area between the talus and calcaneus can vary with changes in the position and stability of the STJ. Functional flatfeet are the consequence of extreme pronation at the subtalar joint that is often related to joint instability. As many as 20% of adults present with functional flatfeet, based on presentations drawn from footprint analysis. Smaller numbers of individuals present with clinical conditions that arise from true functional disorders or limitations,[51] which suggests that the extent of excessive pronation may not be directly related to the onset of musculoskeletal overuse injuries.[52]

THE MIDTARSAL COMPLEX

Anatomy

The midtarsal complex is comprised of three joint compartments: (1) the calcanocuboid joint (CCJ) on the lateral side; (2) the talonavicular joint (TNJ) on the medial side; and (3) the cubonaviculocuneiform joint (CNJ) coursing along the length of the midfoot. Movement in this system always accompanies movements in the subtalar region. The three compartments are seen functionally as a single ball and socket joint. However, an appreciation of each joint's architecture can be helpful to the clinician for understanding functional movements in the complex, as well as appreciating specific joint motions during clinical examination.

For the talonavicular joint, the concave navicular rests against the convex talus, where the concave treatment plane courses plantar-proximal to dorsal-distal (see Figure 13). Conversely, the relatively flat calcaneocuboid joint courses plantar to dorsal in a direction that is perpendicular to the lateral border of the foot (see Figure 13). Finally, the concave cuboid rests on the convex navicular and lateral cuneiform along a plane that courses from plantar-medial to dorsal-lateral (see Figure 13).

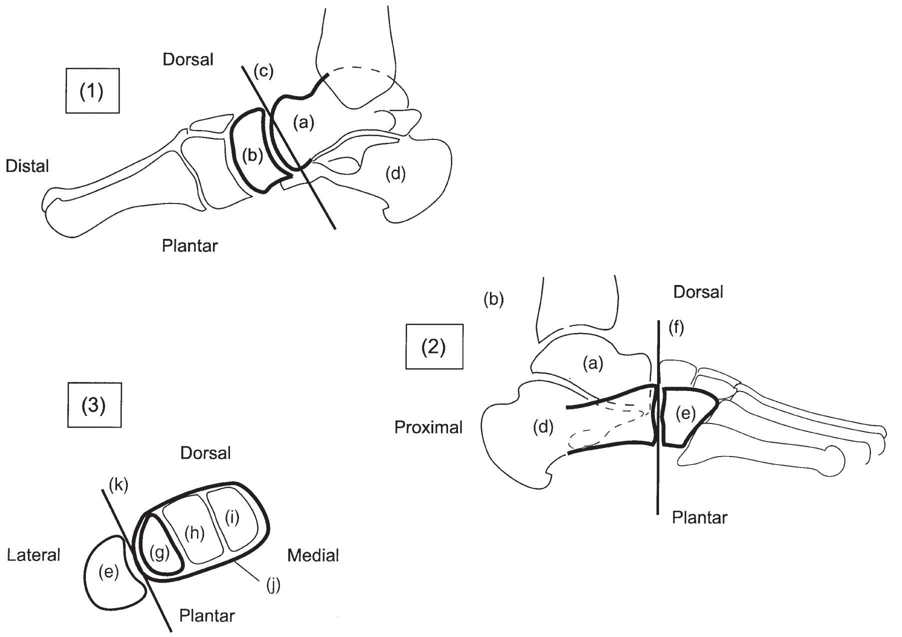

Figure 13. Orientation of the midtarsal joints in the (R) foot. (1) Lateral view; (2) Medial View; (3) Axial View; (a) Talus; (b) Naviculum; (c) Talonavicular joint plane, oriented in a dorsal-distal to plantar-proximal direction; (d) Calcaneus; (e) Cuboid; (f) Calcaneo-cuboidal joint plane, oriented in a dorsal to plantar direction, perpendicular to the lateral border of the foot. (g) Lateral cuneiform; (h) middle cuneiform; (i) medial cuneiform; (j) Cubonavicular joint plane, oriented in a dorsal-lateral to plantar-medial direction.

Midtarsal Biomechanics

Ninety percent of the motion in the parasagittal plane of the joints distal to the TCJ occurs in the MTJ system. In addition, approximately 25% of the dorsiflexion of the ankle/foot complex is produced at the midtarsal complex, whereas it produces 45% of total plantarflexion. Furthermore, ankle/foot motion in the transverse plane is greater in the forefoot than the rearfoot. Finally, motions in the parasagittal and transverse planes are greater than those in the frontal plane during ambulation.[37]

The axes for functional motion in these three compartments are instantaneous and converge in the bifurcate ligament over the navicular.[37,53] Forefoot dorsiflexion/plantarflexion and abduction/adduction occur about the peritalar axis, which courses from dorsal-medial-distal to plantar-lateral-proximal approximately 57° in the transverse plane and 52° in the parasagittal plane from the long axis of the foot through the second metatarsal. Forefoot pronation/supination occurs about the transverse tarsal axis, which courses from dorsal-medial-distal to plantar-lateral-proximal approximately 9° in the transverse plane and 15° in the parasagittal plane from the long axis of the foot through the second metatarsal (see Figure 14).[54]

As consequence of these architectural configurations, the forefoot actively moves at the joints simultaneously in three different planes. For example, when the forefoot moves in the direction of eversion, the tarsals move

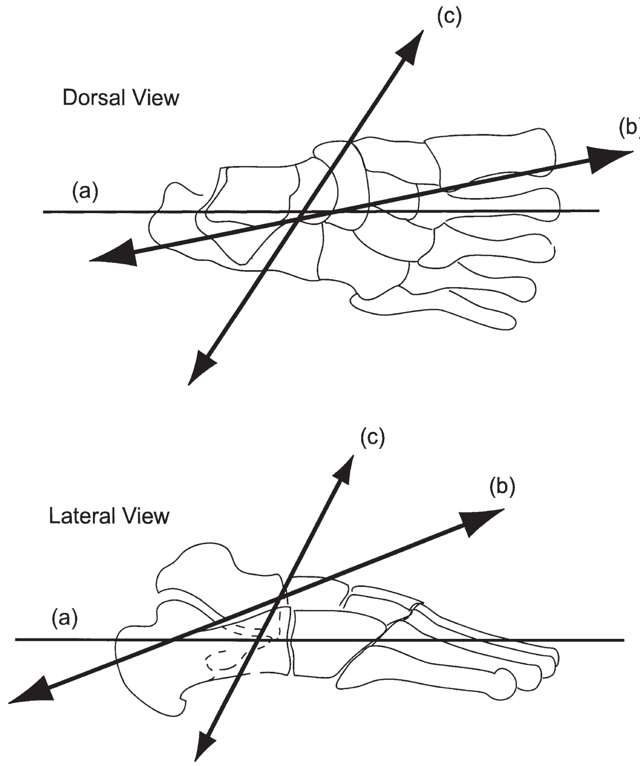

Figure 14. Oblique orientation of the instantaneous axes of rotation (IAR) for the MTJ; (a) Long axis of the foot; (b) Transverse Tarsal Axis of the MTJ oriented ± 9° in the transverse plane and ± 15° in the parasagittal plane from the long axis of the foot; (b) Peritalar Axis of the MTJ oriented ± 57° in the transverse plane and ± 52° in the parasagittal plane from the long axis of the foot.

at these joints in the directions of dorsiflexion in the parasagittal plane, abduction in the transverse plane, and pronation in the frontal plane. On the other hand, forefoot inversion includes plantarflexion in the parasagittal plane, adduction in the transverse plane, and supination in the frontal plane.

Actively, it is impossible for an individual to move one compartment with out obligatory movement in the other two. However, a clinician can passively produce motion in each compartment and in each plane. Moreover, the extent of collective functional movements in these compartments is dependent on the position of the foot. For example, when the foot is inverted, the MTJ is relatively "locked", reducing dorsiflexion and plantarflexion. When the foot is everted, the MTJ is relatively "mobile", increasing motion and reducing stability. This behavior is related to changes in the relative alignment of the plantarflexion-dorsiflexion axes for both the calcaneocuboid and talonavicular joints seen in an axial view of the MTJ. The axes are relatively parallel when the foot is everted, which allows the forefoot to move. This behavior is useful during gait, where individuals need a relatively mobile foot to adapt to terrain changes during midstance. Conversely, inversion misaligns the axes, locking the midfoot and reducing motion (see Figure 15). This corresponds with a requirement for a stable foot during propulsion, where individuals push off on an inverted relatively rigid foot.[55]

The navicular and cuboid move in their respective joints during weightbearing activities. Kitaoka et al evaluated the complex movements associated with weightbearing in pronation and observed a considerable amount of movement between the navicular and talus during the loading sequence.[56] These investigators documented the mean values of motion at each of the joints in the subtalar system and observed the following outcomes with loading: (1) Talonavicular joint rotated 9.4° ± 2.2°, where the navicular moved primarily in the eversion direction (also included abduction and dorsiflexion) with respect to the talus; (2) 1st metatarsal-navicular joint rotated 7.2° ± 1.5° where the metatarsal moved primarily in the dorsiflexion and inversion directions (also in the adduction direction); and (3) Calcaneotalar joint rotated 4.4° ± 1.7°, where the calcaneus moved primarily in the eversion direction (also included only slight abduction and dorsiflexion).

Kitaoka et al mentioned two noteworthy issues. First, one may ask "how could the navicular dorsiflex in relation to the talus while loading, while the navicular tubercle drops appreciably toward the floor during midstance?" The investigators suggested that, while the navicular dorsiflexes on the talus, it plantarflexes toward the floor *with respect to the tibia*. This drop corresponds with talus plantarflexion during load; and the talus simply plantar flexes further than the navicular, creating a *relative* dorsiflexion of the navicular on the talus. Secondly, the investigators discovered that the reported motions decreased proportionally with higher loads. However, the percentage of motions in the three different directions did not greatly waver with higher loads. The investigators postulate that the decrease in motion with increased loading is related to an increase in stiffness that develops in the subtalar joint.

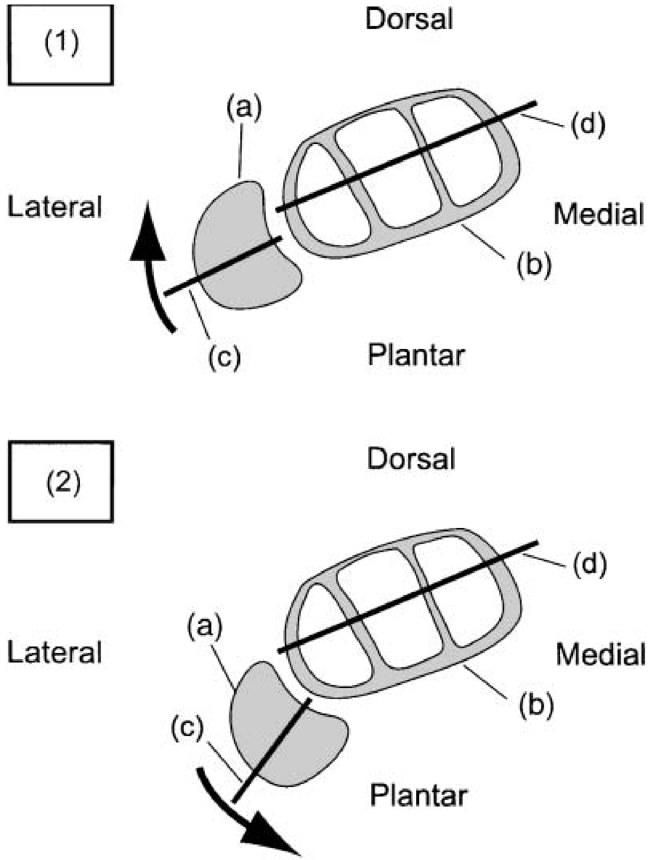

Figure 15. Physiological locking mechanism of the forefoot seen from an axial view; (1) Parallel, or unlocked, position of the tarsals and flexion-extension axes in pronation; (2) Non-parallel, or locked, position of the tarsals and flexion-extension axes in supination; (a) Cuboid; (b) Naviculum-cuneiform complex; (c) flexion-extension axis of the calcaneocuboidal joint; (d) flexion-extension axis of the talonavicular joint.

HEEL STRUCTURES

The plantar surface of the heel is covered by skin and a subcutaneous fat pad. Histological analysis of the pad reveals a meshwork of fibroelastic septae arranged in closed-cell configurations.[57] These configurations are central to the loadbearing capacity of the heel, whereby imposed loads are distributed over the entire region of contact.[58] These septal chambers maintain a significant blood and nerve supply, including Pacinian corpuscles and free nerve endings.[57] As a consequence, this springy heel pad may assist in repositioning of the foot when load is transferred from the heel to the forefoot during locomotion.[59]

The thickness of the pad is paramount to compressive load tolerance and reduced fad pad height is consistent with increased incidence of heel pain.[58,60] The shock absorbing capacity of the fat pad appears to change over an individual's lifetime, where this quality decreases with advancement in an individual's age.[61,62] The function of the fat pad appears to be influenced by an individual's footwear, in which the pad serves to protect the calcaneal bone during the landing sequence when an individual is barefoot, versus the pad's role in shock absorption with the foot landing in a shoe.[63] In addition, an increased stiffness in the shoe's midsole decreases the compression of the fat pad.[64] Furthermore, the integrity of the shoe's heel counter appears to influence the pad's shock-absorbing capacity, where a more substantial heel counter increases heel containment and improves fat pad height, resulting in improved shock absorption while landing.[65–66]

PLANTAR FASCIA

The plantar fascia, or plantar aponeurosis, consists of longitudinally arranged dense fibrous connective tissue bands that originate from the calcaneal tuberosity.[6] This proximal insertion becomes inflamed and hypertrophic during proximal plantar fasciitis. Edema, bone erosion, and bone spurs can accompany these changes.[67,68] After leaving the calcaneal tuberosity, these fibers course distally, fanning out over the sole, where they become thinner and broader. They divide and attach to the plantar fibrous digital sheaths of the lateral four toes and the sesamoids of the great toe.[69] Vertical septa extend dorsally from the aponeurosis to divide the plantar aspect of the foot into three compartments: lateral, central, and medial.[6] Unfortunately, the plantar fascia is capable of rupturing spontaneously,[70] after microtraumatic and macrotraumatic events,[71,72] or iatrogenically as result of therapeutic steroid injection.[73,74]

The plantar fascia serves as a functional windlass in the foot complex. This structure helps to support the foot's longitudinal arch, contributing as much as 25% to the stiffness of the foot and carrying as much as 14% of the total load imposed on the foot in weightbearing.[39,55,75] Moreover, the plantar fascia functions to stabilize the toes during dynamic loadbearing activities.[69] Plantar fascia failure or surgical release can alter the previously discussed biomechanical behaviors of the talocrural and subtalar joints, significantly lengthening and lowering the medial longitudinal arch of the foot, as well as altering the forefoot loading response during the propulsion phases of gait.[56,76–79]

LOCOMOTOR SYSTEM

Anatomy

The anatomy of the locomotor system about the ankle/foot, with exception to the gastrocsoleus complex, can be visualized in terms of quadrants that correspond to diagonal ankle/foot movements. In the dorsomedial quadrant the clinician finds the tendons of the tibialis anterior and extensor hallucis longus. The tendon of the tibialis anterior, along with its tenosynovium, courses under the superior and inferior extensor retinacula and then proceeds distally to insert at the medio-plantar aspect of the first metatarsal base and medial cuneiform.[6,80] This musculotendinous unit is involved in dorsiflexion, adduction and supination of the ankle/foot[80] and can demonstrate prolonged reaction time latencies after inversion plantar flexion trauma.[81,82] Rupture of the anterior tibial tendon is a very rare injury in sports and is based on a forced plantarflexion of an ankle with a degenerated tendon.[83]

Extensor hallucis longus (EHL) can be found coursing through its own tenosynovium in the same distal direction just lateral to the tibialis anterior.[80] This tendon inserts into the middle of the dorsal aspect of the base of the distal phalanx at the great toe, producing dorsal extension of the entire great toe.[6,84] Denk et al. discovered anatomical variation in the insertion of the tendon, whereby a significant number of cadaveric specimens demonstrated dual tendon insertions into the base of the phalanx.[84] Clinically, the EHL tendon is at risk of rupture, especially after hallux valgus surgical correction.[85,86] Equally, the EHL serves as an important marker for nerve injury or disease. When painless weakness in EHL function is noted, the clinician should rule out lesions to the L4 and L5 nerve roots,[80,87,88] the common peroneal nerve in the proximity of the fibular head,[89–91] and or the deep peroneal nerve anterolateral and distal to the proximal tibia.[92–95]

In the distal one third of the leg, Lawrence and Botte report that the deep peroneal nerve can be found superficial to the anterior tibial artery between the tibialis anterior and EHL muscles. The nerve crosses deep to the EHL tendon to enter the interval between the EHL and extensor digitorum longus tendons. The lateral terminal branch penetrates the extensor digitorum brevis, providing it with motor innervation. The medial terminal branch courses superficial to the talonavicular joint capsule and courses just lateral to the first tarsometatarsal joint line. This branch courses deep to the extensor hallucis brevis tendon within the forefoot, providing sensory innervation to the first webspace.[96] Branches of this nerve cross the ankle and foot just lateral to the EHL tendon, and are at risk for injury through portal site placements in this vicinity during ankle arthroscopy.[97]

The tendinous complex of the extensor digitorum longus courses through the same dorsal retinacular structures in the anterior/dorsal lateral quadrant of the ankle/foot, inserting into the middle and distal phalanges of the second through fifth toes.[6,80] Not only is this complex responsible for dorsal extension of the lateral four toes, but also for the dorsiflexion, abduction and pronation of the ankle/foot. This complex is at risk for tendinitis and tenosynovitis, especially after extensive overuse.[98,99] Moreover, failure of the inferior dorsal retinaculum can lead to spontaneous dislocation of the tendons across the dorsal ankle/foot,[100] resulting in reduced mechanical advantage and distorted function during gait.

Lateral to the extensor digitorum tendon complex one observes the tendon of the peroneus tertius, which inserts on the dorsal base of the 5th metatarsal.[6] This tendon provides a small contribution to dorsiflexion and eversion of the ankle/foot. The superficial peroneal nerve accompanies the peroneus tertius tendon after coursing between the peroneals and extensor digitorum longus in the lower leg. At the distal third of the lower leg the nerve divides into three branches. The medial branch courses across to innervate the skin over the first two toes. The intermediate branch courses over the talocrural joint between the tendon and the lateral malleolus. The lateral branch contributes to the sural nerve, which is discussed later. The branches of the superficial peroneal nerve can be damaged by impact, inversion trauma or sub-retinacular compartmental effusion, leading to radiating pain and or sensory changes on the dorsum of the lateral foot.[80,97,101–103]

The peroneus longus and brevis tendons can be found in the posterolateral quadrant of the ankle/foot, coursing under the superior and inferior peroneal retinacula and around the lateral malleolus toward their insertions on the foot.[6] Proximal to the malleolus, the longus tendon is superficial to the brevis. Posterior to the malleolus, the brevis tendon crosses under the longus to emerge more superficially and insert on the base of the 5th metatarsal. The longus courses plantar to the peroneal tubercle of the calcaneus and then deep to the brevis to a groove on the lateral plantar edge of the cuboid. Once it curves around the cuboid it courses distal medial to insert on the base of the 1st metatarsal and medial cuneiform.[8]

The peroneus longus tendon is at risk for developing stenotic tenosynovitis and or traumatic tears in the presence of tubercle hypertrophy or os perineum.[104–106] In addition, the peroneus longus tendon is found to have two avascular zones.[107] A proximal zone can be observed on the anterior surface of the tendon where the tendon curves around the lateral malleolus and the peroneal tubercle of the calcaneus. This region is prone to overuse tendopathy and partial tears.[108] A distal avascular zone is found in the region where the tendon wraps around the cuboid. Accompanying this zone, one finds that the surfaces of the medial side of the peroneus longus tendon and lateral side of the cuboid are covered with fibrous and hyaline cartilages, respectively. This peroneocuboid joint has its own joint capsule that does not communicate with the sheath of the peroneus longus tendon.[109] While the configuration of this tendon could help to reduce cuboid subluxation in a midtarsal instability,[110] these features subject this region of the tendon to traumatic complete tears,[108] especially in context with chronic lateral ankle instability.[111]

The intratendinous vascular network associated with the peroneus brevis tendon is interrupted in the region where it courses through the groove on the dorsal distal fibula, creating a zone of lability.[107] The tendon is at risk for traumatic tears in this region that are predisposed by tendon subluxation, a sharp posterior ridge of the fibula, overcrowding of the peroneal groove, laxity of the superior peroneal retinaculum, and lateral ankle instability.[112,113]

The Achilles tendon, found between the posterolateral and posteromedial quadrants of the ankle, is the terminal inserting structure of the gastroc-soleus complex into the calcaneus. This is the thickest and strongest tendon in the human body.[80,114] The tendon demonstrates similar mechanical tensile properties to other tendons, although higher stresses are imposed on this structure during the loading and propulsion gait responses. Because no obvious adaptation to higher stress is demonstrated, the tendon is at higher risk for injury versus other tendons at the ankle/foot.[115] However, as tendon fibers run distally to the calcaneus, they make a 90° spiral, in which the medial fibers become most posterior,[112,116] thereby contributing to an elaborate elastic energy storage system used during the propulsion phase of gait.[117,118]

Tendon fibrils of the achilles are organized in a hierarchical fashion, where collagenous endotenon surrounds subfascicles and fascicles. The fascicles are bundled together by the epitenon to form the tendon. A paratenon, or pertendinous sheathe, surrounds the tendon and produces a potential space between it and the tendon. This loose, highly elastic fibrillar tissue reduces friction during movement in context with the surrounding tissues.[119] Additionally, the paratenon can remain intact even during complete tendon rupture; while it is rarely involved in chronic tendinosis,[120] it is the primary source of affliction with peritendinitis, where the space can be filled with fibrotic adhesions.[121–122]

The midsubstance of the tendon demonstrates a relative avascular zone at 3 to 6 cm proximal to the bony insertion.[123] Here, the tendon is subject to stenotic thickening of the vascular intima, lending to a relative ischemic state.[124] The fibers of the tendon fan out to connect with the calcaneal tuberosity and then become confluent with the fibers of the plantar fascia.[80,125] This confluence, although pronounced in the neonate, are less developed in the young adult and non-existent in the elderly population.[126] The fibers of the soleus course primarily in the medial part of the tendon, where the tendon is prone to developing insertion tendopathy. At the proximal region of the insertion, the tendon is separated from bone by a subtendinous bursa.[80,127]

One can witness the sural nerve coursing in close proximity to the achilles tendon. The sural nerve is formed by the variable contributions from the medial sural cutaneous nerve (MSCN) and the lateral sural cutaneous nerve (LSCN). The MSCN and LSCN are branches of the tibial and the superficial peroneal nerves, respectively.[97,128,129] The sural nerve can contribute variably to the superficial innervation of the lateral half of the foot and toes,[130] where a lesion to the nerve can produce persistent neuropathic lateral ankle/foot pain.[131] Because of the nerve's close proximity to the achilles tendon, symptoms can emerge from external pressure against the nerve,[132] tendon rupture[133] or as a complication following surgical achilles tendon repair.[134]

The tibialis posterior can be found on the posteromedial quadrant of the ankle, where its tendon courses most medial and anterior into the tarsal tunnel. It continues to run distally through the tunnel to the posterior medial malleolus, where it crosses over the malleolus and goes on to insert into the plantar aspect of the navicular tubercle. The tendon demonstrates anatomical torsion (mean = 47.5°) as it courses through tunnel, which may be useful for elastic energy storage during the loading and propulsion gait responses.[135] In the region where the tendon curves around the medial malleolus, the anterior portion of the tendon that contacts the malleolus is composed of a fibrocartilagenous substance with a specific collagen fibril texture, lending this portion of the tendon to rupture under excessive loads (Petersen & Hohmann, 2001).[136] At the insertion, the distal tendon fans out to all other tarsals and metatarsals, with most fibers coursing to 1st metatarsal and medial cuneiform.[80] This tendon serves as the main eccentric stabilizer of the subtalar complex during pronation in weightbearing, especially during a landing sequence.[42,137]

The tibialis posterior tendon and tenosynovium are exposed to excessively high tensile forces during the landing sequence, leading to overuse tensosynovitis,[138] traumatic dislocations,[139] and partial or complete ruptures.[140] Complete ruptures, although very rare, emerge as a sequel to macrotrauma and can subject the subtalar and midtarsal system to significant mechanical alteration.[141] More commonly, the tibialis posterior can partially rupture as a result of excessive tension loading and microtraumatic tearing, lending to longitudinal arch alterations.[141]

The flexor digitorum longus courses in an intermediate position in the tarsal tunnel, interposed between the tibialis posterior and flexor hallucis longus. Distal to the tunnel the tendon diverges from the tibialis posterior to a more plantar position in order to continue on to its branched insertions into the plantar base of the distal phalanges of the second through fifth toes. While the tenosynovium surrounding this tendon is capable of becoming inflamed, the tendon is less frequently involved in clinical afflictions, partly because of its diverse insertions. However, the tendon is clinically important, as it has been surgically transferred in augmenting subtalar arthrodesis and or spring ligament repair after tibialis posterior insufficiency and arch failure.[142–144]

As previously mentioned, the flexor hallucis longus is the deepest tendon in the posteromedial quadrant, coursing through the sulcus found between the posteromedial and posterolateral talar tubercles, through the tarsal tunnel just plantar to the sustantaculum tali and then on through the soft tissue of the foot to insert on the plantar base of the great toe distal phalanx. The tendon is at risk for developing afflictions in the talar sulcus, due to the confined fit between the talar tubercles under the retinaculum at that site.[12] Tenosynovitis, longitudinal tears, and complete ruptures of this structure have all been reported.[145–147] Additionally, an avulsion of the tendon can be responsible for the onset of tarsal tunnel syndrome.[148] While disorders to this tendon have been classically associated with dancing and ballet,[146] similar symptoms have emerged in concert with other athletic endeavors, such as football[149] and long distance running.[150]

The tibial nerve is the largest terminal branch of the sciatic nerve. It courses along with the vascular supply between the flexor digitorum and flexor hallucis longus through the tarsal tunnel to the plantar aspect of the foot. Proximal to the tarsal tunnel, the nerve sends a cutaneous branch over the medial malleolus at the level of the proximal flexor retinaculum. Within the tunnel, the nerve is at risk for tension or compression loads, leading to tarsal tunnel syndrome.[151–153]

Distal to the tunnel, the tibial nerve divides into the medial and lateral plantar nerves, along with cutaneous branches that course to the calcaneus.[153] These two branches course through two fibrous tunnels (or "arcades") deep to the abductor hallucis. The medial branch pierces the fascia more distal than the lateral branch, lending to a less aggressive angle of approach to the deep plantar aspect of the foot in comparison to the lateral plantar nerve. Conversely, the lateral plantar nerve enters the fascia more proximally and then must turn toward the lateral border of the foot, producing greater vulnerability for irritation and entrapment.

Locomotor Biomechanics

Functional movements in the ankle/foot are the consequence of symbiotic motions in each respective joint.[154] These motions are strongly influenced by actions of different components of the locomotor system. Actions of the tendons about the ankle/foot are dependent on four factors: (1) The tendons' relationships to the joint axes, (2) The tendons' distances from the axes, (3) The relative strength of the tendons, and (4) the weightbearing status of the body. Tendons medial to the oblique axis of the STJ are invertors/supinators, while tendons that are lateral to the same axis act as evertors/pronators. Additionally, the tendons move the ankle/foot complex in diagonal directions in a non-weightbearing condition. Although the tibialis anterior is a weak supinator due to its proximity to the instantaneous axis of rotation (IAR), it moves the system in a dorsiflexion/adduction/supination diagonal. A plantarflexion/adduction/supination diagonal is activated by the tibialis posterior (a very effective supinator), flexor digitorum longus, and flexor hallucis longus. A dorsiflexion/abduction/pronation diagonal is produced by the extensor digitorum longus, and the peronus longus and brevis are responsible for plantar flexion/abduction/pronation.[25,80]

A diagonal plantar flexion/adduction/supination movement is augmented by the soleus, which also functions as a strong supinator.[25] However, as a whole the triceps surae demonstrate an eversion moment when the STJ is inverted and an inversion moment when the STJ is everted. Additionally, the triceps is neither an invertor nor evertor in a slightly inverted position. This suggests a dynamic quality to the location of the axis of motion for the STJ, as well as a multifaceted function of the triceps muscle in the support and behavior of the subtalar complex.[42,55]

In the closed chain the tendons about the knee and ankle/foot function in a complex fashion to aide acceleration and deceleration behaviors at the ankle/foot during gait. Additionally, they augment foot postures, as it is possible that muscle activity (especially from the tibialis posterior) may contribute to the influence of the plantar fascia in supporting the longitudinal arch.[55,155,156]

Arch position may influence muscle moment arm length. When the STJ is positioned in inversion with the medial arch elevated, the inversion moment is decreased for those muscles that demonstrate an inversion moment arm and the eversion moment is increased for those muscles that demonstrate an eversion moment arm. When the STJ is positioned in eversion and the medial arch is flattened, the inversion moment is increased for those muscles that demonstrate an inversion moment arm, while the eversion moment is decreased for those muscles that demonstrate an eversion moment arm.[42]

The influence of the locomotor system on the dynamic stability of the longitudinal arch is best witnessed in the contribution of the tibialis posterior in supporting the medial longitudinal arch, along with the spring ligament system. This tendon comprises the principle dynamic stabilizer of the STJ against eversion/pronation and subsequent plantar migration of the arch.[42] Additionally, tibialis posterior insufficiency has been documented as a cause for pes planus, or functional flat foot.[144,153] This disorder may be traumatic, spontanenous, or degenerative in origin. With the falling of the arch, the hindfoot everts and the forefoot abducts. These findings can develop spontaneously, or over several months (and even years).

SUMMARY

Examination and subsequent specific treatment of ankle/foot afflictions require dedication of the clinician to understanding not only the anatomy and pathophysiology of each joint complex, but also knowledge of the complex biomechanical functions and interdependence of each system. Afflictions of any of the numerous ligaments, musculotendinous structures, or articulations about the foot and ankle will have an immediate effect on the integrity of function and as well as loads placed throughout the lower extremity. Restoration of maximum possible function in each of the joints, ligaments, and musculotendinous structures should be considered by clinicians while working with patients who have disorders of the ankle/foot. Not only localizing and effectively treating the pain generating structure, but also ensuring that the remainder of the structures are providing the necessary stability or mobility as needed for daily function, is paramount.

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Appendix: Continuing Medical Education Questions

1. The superior tibiofibular joint can demonstrate all of the following clinical pathomechanical scenarios, **except for**:
   a. Painless hypomobility, resulting in dorsiflexion limits and anterior talotibial compression syndrome.
   b. Pathological hypermobility, resulting in common peroneal nerve irritation while running.
   c. Pathological locking after plantarflexion/inversion trauma, resulting in talocrural dorsiflexion limits.
   d. Proximal fibular head subluxation, lending to subtalar joint hypermobility in the direction of eversion.
2. All of the following clinical conditions are witnessed in association with the posteromedial and or posterolateral talar tubercle, **except for**:
   a. Fibrous entrapment of the sural nerve.
   b. Flexor hallucis longus tenosynovitis.
   c. Os trigonum.
   d. Posterior talotibial compression syndrome.
3. Which of the following ankle ligaments is constrains talocrural plantarflexion and inversion?
   a. Anterior talofibular
   b. Calcaneofibular
   c. Tibionavicular
   d. Tibiocalcaneal
4. Talocrural dorsiflexion in the closed chain is accomplished through
   a. Anterior rocking and anterior gliding of the talus on the tibia
   b. Anterior rocking and anterior gliding of the tibia on the talus
   c. Posterior rocking and posterior gliding of the talus on the tibia
   d. Posterior rocking and posterior gliding of the tibia on the talus
5. Of the following ligaments, which is the most medially located?
   a. Inferior Calcaneonavicular ligament
   b. Lateral talocalcaneal ligament
   c. Superior medial calcaneonavbicular ligament
   d. Talocalcaneal interosseus ligament
6. Which of the following orientations best describes the course of the instantaneous axis of rotation belonging to the subtalar joint?
   a. Proximal-plantar-lateral to distal-dorsal-medial
   b. Proximal-plantar-medial to distal-dorsal-lateral
   c. Straight medial to lateral
   d. Straight proximal to distal
7. Subtalar joint triplanar pronation in the open kinematic chain is comprised of which three motions?
   a. Eversion, plantar flexion, and abduction of the calcaneus
   b. Eversion, dorsi flexion, and abduction of the calcaneus
   c. Inversion, plantar flexion, and adduction of the calcaneus
   d. Inversion, dorsi flexion, and adduction of the calcaneus
8. Subtalar joint triplanar supination in the closed kinematic chain is comprised of which motions?
   a. Calcaneal eversion accompanied by talar dorsi flexion and abduction
   b. Calcaneal eversion accompanied by talar plantar flexion and adduction
   c. Calcaneal inversion accompanied by talar dorsi flexion and abduction
   d. Calcaneal inversion accompanied by talar plantar flexion and adduction
9. Which of the following joints of the midtarsal complex exhibits a joint plane that courses from plantar-proximal to dorsal-distal?
   a. Talocaneonavicular
   b. Talonavicular
   c. Calcaneocuboidal
   d. Cubonaviculocuneiform
10. The forefoot is relatively locked when the midtarsal complex is positioned in:
    a. Tarsal dorsiflexion, abduction, and pronation
    b. Tarsal dorsiflexion, adduction, and supination
    c. Tarsal plantarflexion, abduction, and supination
    d. Tarsal plantarflexion, adduction, and pronation
11. Which of the following locomotor components of the dorsal ankle/foot is most laterally located?
    a. Extensor digitorum longus
    b. Extensor hallucis longus

c. Peronius tertius
d. Tibialis anterior

12. Which of the following structures demonstrates the potential to develop partial tears at it's avascular zone around the cuboid?
    a. Peroneus brevis
    b. Peroneus longus
    c. Peroneus quadratus
    d. Peroneus tertius
13. All of the following tendons are reported to exhibit a relative avascular zone of liability, except for:
    a. Achilles
    b. Peroneus brevis
    c. Tibialis anterior
    d. Tibialis posterior
14. Which of the following nerves contributes to the superficial innervation of the lateral half of the foot?
    a. Deep peroneal nerve
    b. Saphenous nerve
    c. Superficial peroneal nerve
    d. Sural nerve
15. Longitudinal arch alterations (ie fallen arch) can emerge out of a traumatic rupture to which of the following tendons?
    a. Achilles
    b. Peroneus brevis
    c. Tibialis anterior
    d. Tibialis posterior

Answers:

1. d
2. a
3. a
4. b
5. c
6. a
7. b
8. c
9. b
10. d
11. c
12. b
13. c
14. d
15. d