Chapter 17

Biomechanics of the Foot and Ankle

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17 Biomechanics of the Foot and Ankle

Introduction

The foot and ankle comprise a combined unit that has a significant role in the human being's ability to be bipedal. The anatomic structures of the lower leg and foot all have key attributes in their position, morphology, and interaction to allow locomotion utilizing a minimum expenditure of energy. Surgeons treating foot and ankle pathology need to have a sound understanding of the biomechanical factors surrounding the lower limb and gait to primarily improve the patient's condition while being aware of the possible detrimental effect intervention may have.

Foot and Ankle Biomechanics in Gait Cycle

To fully understand the biomechanical workings of these structures and their interactions, we need to consider that the principal function of the lower limb is to carry and propel the weight of the torso. Essentially, the foot and ankle are a dynamic entity functioning within the locomotive system, rather than simply a stable support for stance. Foot and ankle function, with hip and knee function, transfers the weight of the torso in a rhythmical motion of vertical, lateral, and rotational displacement with a minimum of energy expenditure. This maintains a minimal transfer of the center of gravity, with a slight transition over the weight-bearing foot (**Fig. 17.1**). It minimizes any sudden, jarring movements that would result in energy loss and potential discomfort.

The gait cycle has been described in many different forms by various authors. This reflects the complexities of action occurring through the gait cycle.[1] However, with reference to the foot, an appropriate description involves gait having two major phases through the walking cycle. The stance phase comprises approximately 60% of the gait cycle, and the swing phase, the remaining 40% of the cycle (**Fig. 17.2**).

Gait Cycle

There are three main phases of stance, namely, heel strike progressing through to mid-stance (or foot flat), and subsequently through to toe off. This final phase can also be separated further into an initial heel lift progressing to the propulsive toe off. Some authors refer to the three phases of stance as rockers.[1] The first rocker corresponds to heel strike, second rocker to foot flat, and the third rocker to heel rise. There is a period where both feet are in contact with the ground (double stance), which occupies nearly 25% of a full gait cycle. This is a combination of one foot heel striking as the other progresses to toe off and vice versa within the one cycle.

Through a normal gait cycle, vertical lift of the torso is minimized. During normal gait, at no time is an individual's height greater than their standing height. Such movement would be

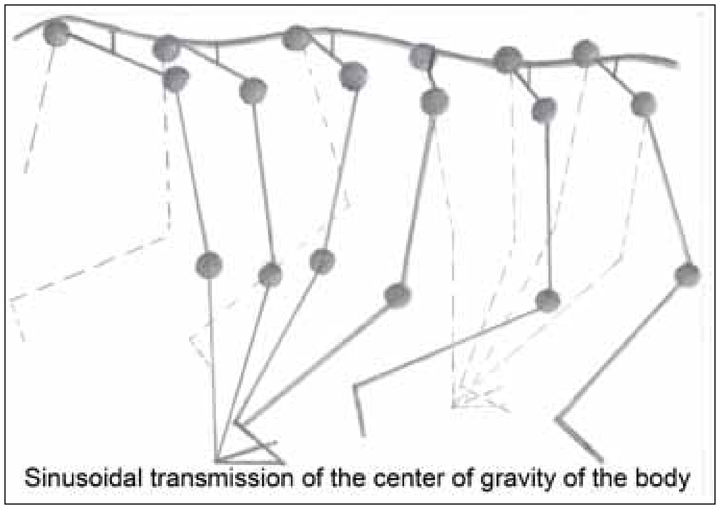

Fig. 17.1 Diagrammatic demonstration of oscillation of center of the gravity in sagittal plane during normal gait cycle.

Fig. 17.2 Clinical pictures depicting different phases during normal gait cycle. The stance phase comprises 60% and swing phase 40% of the gait cycle.

inefficient in terms of energy expenditure and fatigue would ensue. The maximum vertical height reached in gait is just after the mid-stance phase (**Fig. 17.3**).

The normal foot and ankle needs to provide a stable base for weight bearing with shock absorption, while having the capacity to propel the body forward during weight bearing. This allows the center of gravity to progress over the weight bearing foot in transition from heel to forefoot. This requires strength of balanced muscles, ligamentous stability, and joint motion throughout the ankle and foot.

Ankle Joint

The ankle joint is the pivot point for the lever of the foot (**Fig. 17.4**).

When consistent energy is applied to the gait cycle, the range of movement of the ankle joint has a major effect on stride length. A reduced range of motion will result in a shorter stride length. Similarly, greater muscle exertion on a constant ankle range of motion will result in a greater stride

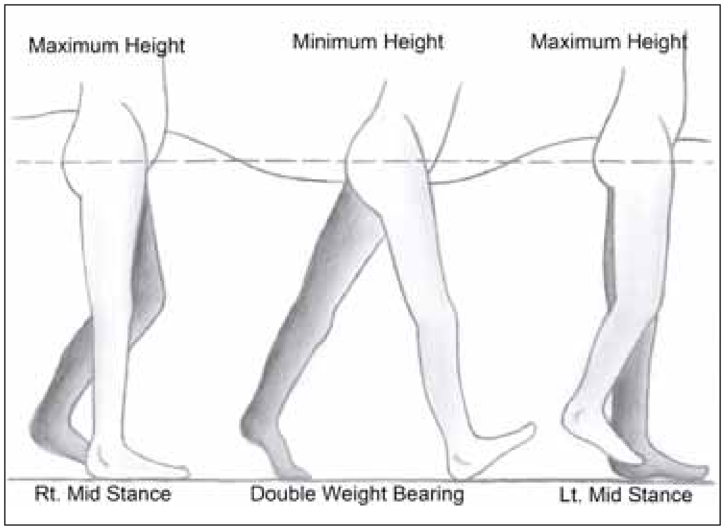

Fig. 17.3 Different positions of foot and ankle reflecting in the position of the center of gravity during normal gait cycle.

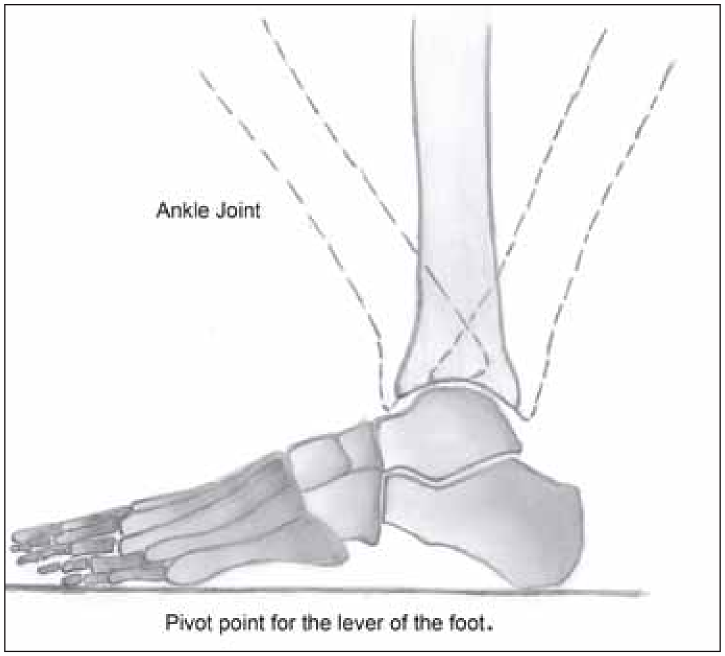

Fig. 17.4 Biomechanical interpretation of the ankle joint as the pivot point for the lever of the foot.

length. The joint is oblique to both the vertical and horizontal planes of limb axis and allows up to 50% of the dorsiflexion and plantarflexion seen through the foot and ankle unit (**Fig. 17.5**).

The ankle's obliquely aligned hinge also results in rotation about a vertical axis. The obliquities result in a laterally directed foot in dorsiflexion and a medially directed foot in plantarflexion. That is, with the dorsiflexion of heel strike, the axis of the foot is directed laterally to the frontal axis of the limb. With toe off, the plantarflexed position of gait, the foot is directed medially (maximizing the position of weight-bearing force under the hallux) (**Fig. 17.6**).

The bony and ligamentous anatomy of the normal ankle provides an appropriate balance of constraint and suppleness to allow transfer of muscular force from lower limb musculature for propulsive movement with stability.

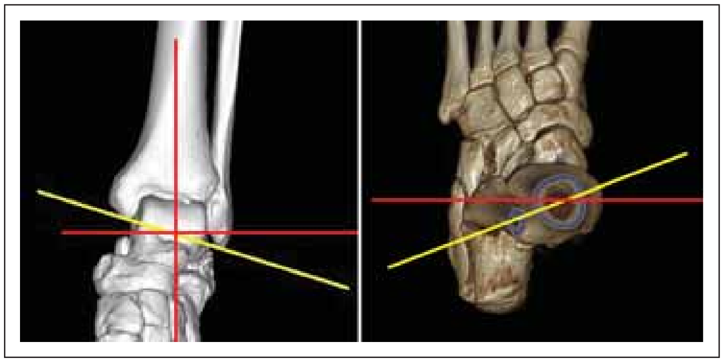

Fig. 17.5 Three dimensional orientation of the axis of the ankle joint.

The talus is wider anteriorly and locks into the bony mortise of the medial and lateral malleoli as the ankle dorsiflexes (**Fig. 17.7**).

Subtle external rotation of the fibula occurs during dorsiflexion, constrained by the syndesmotic ligaments and facilitated by the proximal and distal tibiofibular joints. In plantarflexion, the medial and lateral ligamentous ankle structures provide pivots for muscular force to position the attached foot. Anomalies of the anatomical structures of the ankle result in altered ranges of motion and foot progression angle. Most commonly, a restriction in range occurs, particularly in the more constrained motion of dorsiflexion. As this is most required in the end phases of mid-stance through to heel rise, it will result in a poor second to third rocker progression.

Subtalar Joint

The subtalar joint is also a joint of double obliquity in reference to the vertical and horizontal axes (**Fig. 17.8**).

The inversion and eversion movements, by virtue of the ligamentous constraints and the action of the Achilles tendon, tibialis anterior and posterior, and peronei, grossly results in midfoot positions of supination and pronation respectively (**Fig. 17.9**).

The heel strike phase of gait occurs over nearly 15% of the gait cycle. From heel strike to the foot flat phase, passive

Fig. 17.6 Obliquity of axis of the ankle joint reflecting in pointing of foot on lateral side on dorsiflexion and medial pointing of foot on plantarflexion.

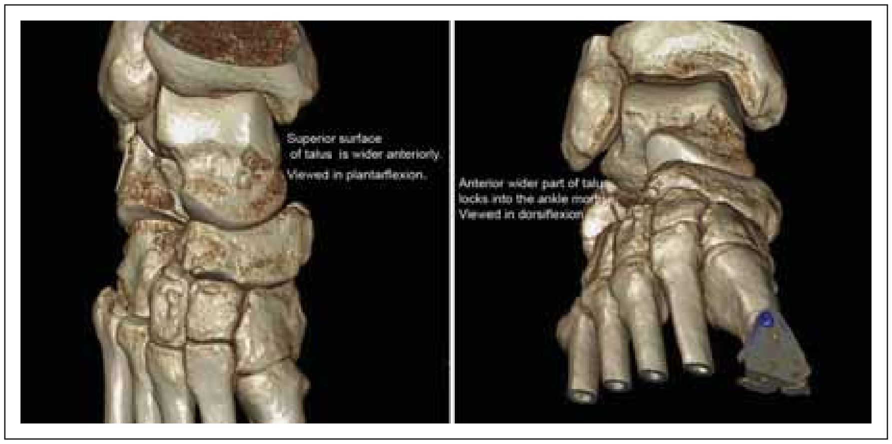

Fig. 17.7 Wide anterior part of the superior surface of talus is responsible for the locking of the talus in the ankle mortise on dorsiflexion.

Fig. 17.8 Orientation of the axis of the subtalar joint. It is oblique in both planes.

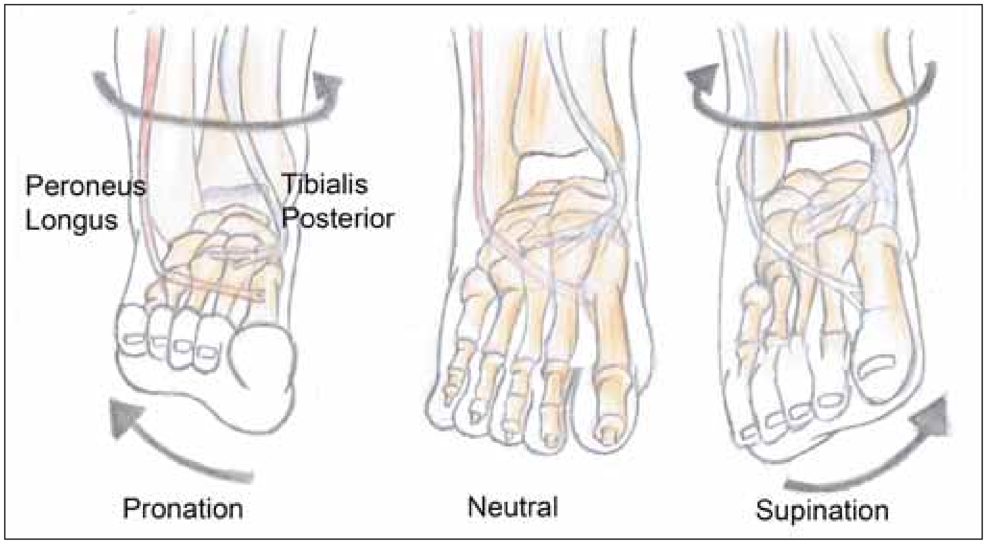

Fig. 17.9 Position of the foot and the relationship of the midfoot joints and tibia during supination and pronation movements.

plantarflexion occurs under a loading response. This is assisted by eccentric contraction of the anterior compartment muscles avoiding a sudden foot slap. During this phase, the posterior compartment muscles are not required to fire, nor are the intrinsic muscles of the foot. Failure of the anterior muscles (most commonly through common peroneal nerve palsy) results in poor dorsiflexion and a foot drop, or a slapping foot gait. The calcaneus, in normal heel strike, everts as the force of weight bearing is exerted on the subtalar and Chopart joints. Eversion at the subtalar joint is transmitted through ankle joint in internal rotation of tibia (**Fig. 17.9**). The arch flattens as the midfoot pronates. During this period, the muscles of the posterior compartment (normally responsible for arch maintenance) are inactive. This passive movement requires the stabilizing features of medial hindfoot ligaments as well as ankle and hindfoot joint integrity.

The transverse tarsal joints (calcaneocuboid and talonavicular joints) are mobile in eversion as they align congruently, but with inversion they lose their congruent alignment and produce rigidity through the hindfoot.[2–4] This occurs in the later phase of stance to provide stability for heel rise and forefoot weight bearing.[5] This is explained by the orientation of the longitudinal and oblique axes of the Chopart joints in eversion and inversion (**Fig. 17.10**). In subtalar eversion these axes are parallel, hence mobile. In subtalar inversion the axes are not parallel, hence rigid or locked.[6]

Transverse Tarsal Joints

The foot needs to provide the flexibility in the first two stages of stance to allow shock absorption and foot progression while accommodating rotation of the limb above. This is particularly true when walking on uneven ground. Following this, it then needs to provide the rigid lever to transfer the ground reactive force of movement and force of muscle propulsion to the ground.[7] A flexible foot in toe off will result in significant energy loss during that energy transfer. As mentioned, the transverse tarsal joint becomes rigid in the later phases of stance. The actions of the intrinsic muscles of the foot, along with the plantar fascia and posterior compartment muscles (the tibialis posterior and flexor digitorum longus, which is traverse medial to the longitudinal hindfoot axis), including action of the Achilles tendon (**Fig. 17.11**), create inversion of the hindfoot, thus stability of the forefoot for propulsion and toe off.

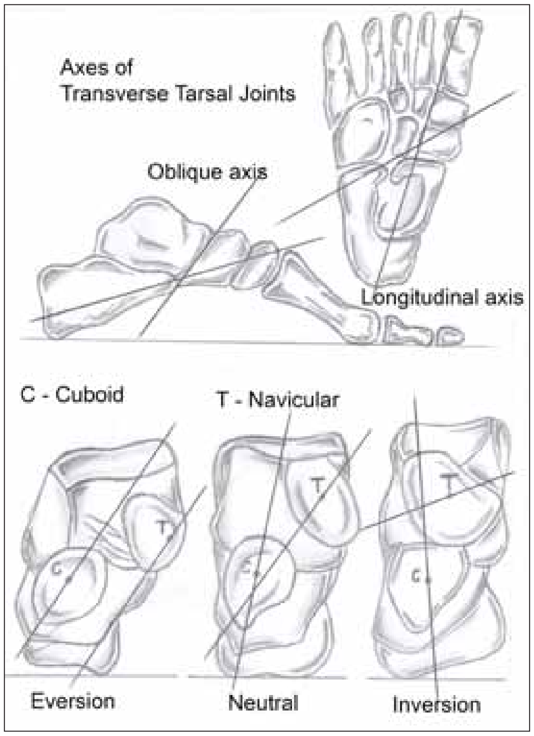

Fig. 17.10 Orientation of the longitudinal and oblique axes of the Chopart joints during inversion and eversion. They are parallel in eversion and nonparallel in the neutral and inversion positions.

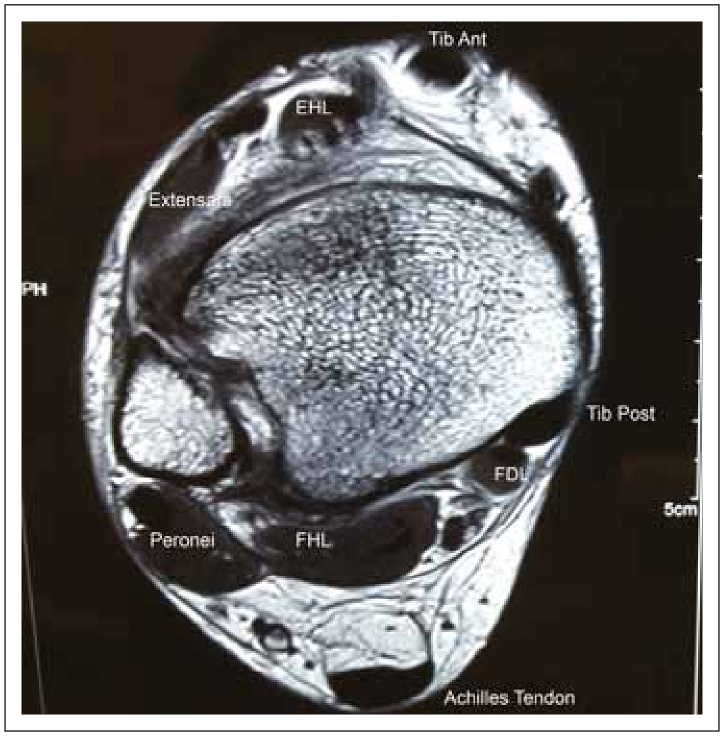

Fig. 17.11 Axial section of MRI of ankle joint demonstrating different muscles responsible for different ankle movements.

Contraction of the peronei also aids in maintenance of the midfoot arch (through peroneus longus plantarflexing the first ray) and a balance to hindfoot inversion (through eccentric peroneus brevis contraction). It is this progressive inversion from mid-stance through to toe off that alters the transverse tarsal articulation and promotes midfoot rigidity to allow heel rise and the propulsive force of toe off to be transferred. The peronei provides 63% of total hindfoot eversion strength, with peroneus longus providing 35% and peroneus brevis contributing 28%. They are relatively weak plantarflexors, providing 4% of total plantar flexion strength compared with the contribution of the gastrocnemius–soleus complex, which contributes 87%.[8] The peroneal tendons also play a key role as dynamic stabilizers of the lateral ankle complex.

The talonavicular and calcaneocuboid joints are essentially a single functional entity, thereby also known as the transverse tarsal or Chopart joint. There is controversy in the literature about the effect of their independent motion, but essentially the talonavicular joint has the greatest role to play in transition of hindfoot inversion and eversion to the midfoot and the calcaneocuboid a lesser role. However, it is best to think of them working as a unit with the subtalar joint to convert rotational forces from the longitudinal axis of the limb to the horizontal axis of the foot and vice versa.

The five midfoot bones are the rigid links that distribute load between the more mobile hindfoot and forefoot with minimal movement. Hansen has often referred to the concept of the "midfoot block" and the "nonessential" nature of these joints due to their lack of motion and stability function.[9] The midfoot has strong ligamentous support, primarily on the plantar surface, to augment its morphology as an arch. There is no bony contact in the tarsal base of metatarsal region in normal gait, highlighting the load distributing role played by the midfoot.

Tarsometatarsal Joints

The arrangement of the midfoot has also been described by several authors in relation to the function of the various rays.[10] There are essentially three columns, related to metatarsal function. Their function is reflected in the relative movement of their tarsometatarsal joints. Movement of the second and third tarsometatarsal joints (central column) is minimal. They have a stabilizing role and are felt to be the keystone (particularly the base of second metatarsal) of the midfoot arch[10] (**Fig. 17.12**).

The first tarsometatarsal joint (medial column) has twice the range of movements of the middle column and allows plantarflexion of the hallux metatarsal (under peroneus longus action) to be the dominant weight bearing surface of the forefoot. This allows for transfer of propulsive forces to the distal forefoot. There is proportionately greater movement in the fourth and fifth tarsometatarsal joints and this reflects the primary shock absorption role of the lateral column.

Metatarsals and Metatarsophalangeal Joints

The forefoot has a significant weight bearing role. The metatarsal heads (with the plantar sesamoids of the first metatarsal) provide six weight bearing surfaces. The toes provide an increase in surface area for that weight bearing to dissipate load. The structures work as a unit, dissipating load, with the greatest force being absorbed by the hallux.

A concept of a metatarsal break through the cascade of the metatarsophalangeal joints of the forefoot is used to explain several factors of gait culminating in the third rocker. It runs obliquely to the long axis of the foot (**Fig. 17.13**), allowing initial lateral column metatarsal weight bearing rapidly progressing through to hallux dominant weight bearing in gait progression to toe off. This movement allows absorption of tibial external rotation in the latter stages of stance phase and through the plantar fascia attachments, to each metatarsophalangeal joint. This assists in the maintenance of a longitudinal arch with MTPJ dorsiflexion through the windlass mechanism.

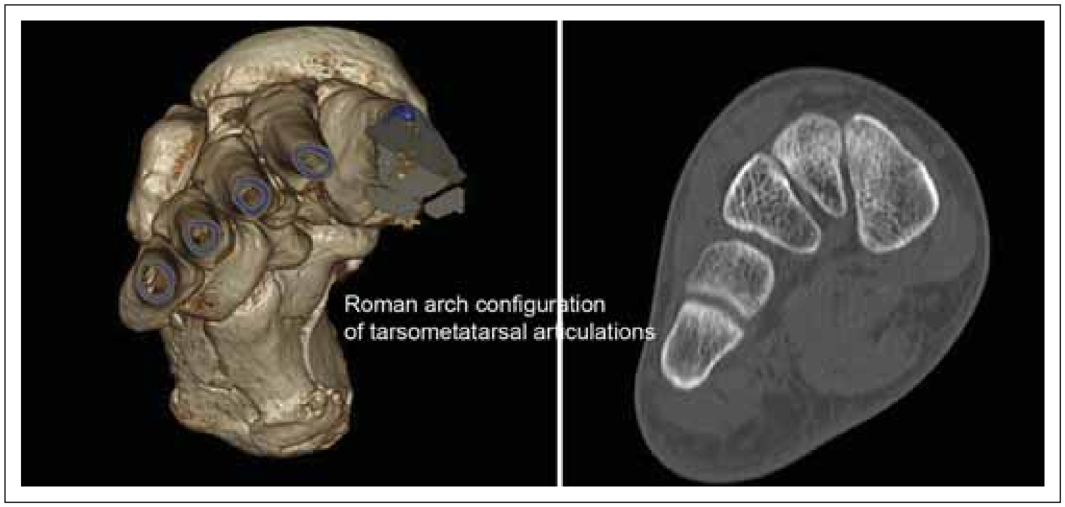

Fig. 17.12 CT scans showing Roman arch orientation of the metatarsal bases forming the transverse arch of the foot. The metatarsals are wider dorsally and the second metatarsal is the keystone structure.

Fig. 17.13 Oblique orientation of the metatarsal axis to the longitudinal axis known as the “metatarsal cascade.”

The plantar fascia or aponeurosis, acts as a cable arising adjacent to the tubercle of the calcaneus inserting to the base of each of the digital proximal phalanges. As the body passes over the forefoot the forced dorsiflexion of the MTPJsAQ1 (particularly of the hallux), depresses the metatarsal heads, tightens the plantar fascia, and increases the arch height as the calcaneus to metatarsal head distance is reduced. Disruptions to MTPJ alignment, such as hallux valgus, result in an inefficiency of this action. Weight-bearing load is then transferred to the other regions of the forefoot, usually second metatarsal head, and often results in metatarsalgia. Tarsometatarsal joint malalignment, metatarsophalangeal joint subluxation or dislocation, or disruption of metatarsophalangeal joint cascade results in metatarsalgia due to excessive weight bearing on the prominent lesser metatarsal heads.

Biomechanics of Normal Weight Bearing

The weight-bearing foot is commonly referred to as a tripod.[9] The heel, and the first and fifth metatarsal heads are the dominant structures of ground contact in the gait cycle. Weight bearing and ground reactive forces are best transmitted centrally through this tripod.

The position for forefoot weight bearing, and therefore tripod position, is dictated by the movements and positions of the proximal structures.

Biomechanics of Weight Bearing in Pathological Conditions

Malalignment, either rigid (through joint pathology) or dynamic (through muscle strength imbalances), in the structures of the lower leg, hindfoot, or midfoot often results in most symptomatology in the forefoot. This is due to inappropriate force loads through relatively small structures not functioning as a shared unit.

One needs to maintain this concept in mind when assessing and treating foot and ankle pathology. One must appreciate how the pathology may affect the patient’s functional situation, the tripod and transfer of movements described earlier and how might any intervention improve or disrupt such mechanisms (**Table 17.1**). Ultimately, any foot and ankle intervention should be designed to alleviate symptoms and maximize possible gait function.

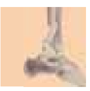

Table 17.1 Clinical manifestations due to change in normal biomechanics in pathological conditions

Pathology	Biomechanical changes	Clinical manifestations
Weakness of anterior musculature	Weakness ankle or digital dorsiflexion	Foot drop Catching toe through early swing phase Accommodated by high stepping gait
Weakness of posterior musculature	Weakness of plantarflexion Weakness of inversion ~~(tib post)~~	Poor toe rise and toe off Flatfoot position maintained through stance Weight bearing through medial prominences Heavy heel strike
Weakness of peronei	Weakness eversion of hindfoot Weakness plantarflexion first ray	Cavovarus position Weight bearing through lateral prominences Dorsiflexed first ray relative to midfoot
Distal tibiofibular stiffness	Loss of fibular external rotation Poor accommodation of anterior talus in dorsiflexion	Restricted dorsiflexion; poor progression of second to third rocker
Ankle stiffness (reduced dorsiflexion)	Restricted to heel strike, first rocker	Poor progression of first to second rocker Affected leg held in external rotation or walks with affected leg held in front of torso
Position of hindfoot valgus	Maintained mobility at Chopart joint Inability to varus	Flatfoot maintained through stance Poor toe-off strength
Position of hindfoot varus	Stiffness through Chopart joint	Poor shock absorption at heel strike Weight bearing through lateral border of foot
Lisfranc disruption of TMTJsAQ2	Poor transition of forces across 1 to 3 TMTJs Insufficiency of midfoot plantar ligaments	Pain in medial and central midfoot in weightbearing Progressive flatfoot deformity
Hallux valgus deformity	Lateralization of sesamoids Inefficiency first ray Windlass mechanism Increased weight bearing through lesser ~~MTSLs~~	Progressive valgus deformity and poor toe off Poor arch maintenance Metatarsalgia
Lesser toe MTPJ dislocation	Plantar prominence ~~MTSL~~ head Dorsal prominence of affected toe Tightening of digital flexors	Metatarsalgia Digital prominence against closed footwear Hammer/Claw toe deformity

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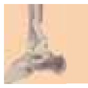

Author Queries

AQ1. AQ: Do you mean "metatarsophalangeal joints"? Please confirm. Yes

AQ2. AU: Please provide the expansions of "TMTJ" and "MTSL."

TMTJ- Tarsometatarsal Joint
MTSL- Please remove the short form - MTSL.
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