Update

Anatomy and Biomechanics of the First Ray

The medial longitudinal arch serves as the chief load-bearing structure in the foot[1–3] and is dependent on the kinematics of the first ray for optimal support during gait.[4] The first ray is a single foot segment consisting of the first metatarsal and first cuneiform bones.[5] Pronation of the subtalar joint lowers the first ray to the ground in early stance[5] and dissipates the shock of heel impact.[3] As body weight moves forward, the mechanics of supination stabilize the medial arch, preparing the foot for the propulsive phase of gait. The dichotomous actions of weight acceptance and weight-bearing stability required of the first ray underscore the importance for clinicians who treat the foot to understand the biomechanics of the first ray.

The importance of the first ray to the mechanics of the foot is, in part, because of the metatarsocuneiform joint's location, which intersects the transverse and medial longitudinal arches.[6] A curved beam and a truss (Fig. 1) are frequently used when modeling the medial arch.[7–10] Beams are designed to withstand bending under an applied force. A truss is a triangular framework with 2 rigid supports connected together at its base. Because the ends of the foot are not secure at the beginning of stance, the foot functions like a beam. As the weight of the body transfers forward, the calcaneus and the heads of the metatarsals are pressed to the ground, with the arch functioning as a truss. Truss-and-beam mechanics of the foot rely on the first ray to function as the pillar for the medial arch. The first ray, therefore, is a critical element in controlling the structural integrity of the foot.[4]

Altered biomechanics of the first ray have been implicated as a factor in various foot pathologies.[4,11–18] The purposes of this update are to present an anatomical overview of the first ray as it relates to gait function and to describe faulty mechanics of the first ray that can contribute to pathology.

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Functional Anatomy of the First Ray

Standing on level ground, the heads of the metatarsals and the calcaneus are in the same horizontal plane. Suspended off the ground are the talus, the navicular, and the cuneiform bones. The head of the talus has a relatively large convex joint surface that articulates with the corresponding concave posterior facet of the navicular.[19] The distal joint surface of the navicular has individual facets that articulate with the first, second, and third cuneiforms. Cuneonavicular and intercuneiform articulations are planar joints that glide or slightly gap when moving apart.[19]

The cuneiform bones articulate distally with the first 3 metatarsals. Neighboring metatarsals adjoin at their base, although the joint between the first and second metatarsals is often poorly developed.[17,19,20] Intermetatarsal support is provided by the transverse metatarsal ligaments, the deep plantar aponeurosis, and the Lisfranc ligament. Intermetatarsal ligaments connect all adjacent metatarsals except between the first and second metatarsals. The Lisfranc ligament extends from the first cuneiform to the base of the second metatarsal and prevents separation between the first ray and second metatarsal.[17] The second metatarsal is mortised between the first and the third cuneiform bones, making it relatively immobile, whereas the other metatarsals have greater freedom of movement.[19]

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The first metatarsal is the shortest and thickest of the metatarsals.[19] Two sesamoid bones, encased in the tendons of the intrinsic muscles, lie beneath the head of the first metatarsal. Suggested sesamoid functions[17,21,22] include (1) to elevate the first ray so the first metatarsal can plantar flex during extension of the hallux, (2) to enhance the load-bearing capacity of the first metatarsal, and (3) to improve the mechanical leverage for the attached intrinsic muscles.

The first metatarsocuneiform joint combines with the surrounding ligaments to form a stable segment.[6,23] The triangular base of the first metatarsal has a lateral joint surface, a medial joint surface, and an inferior joint surface. The metatarsal joint surface is concave, with a near-vertical central groove that aligns the metatarsocuneiform joint axis in slight inversion relative to the foot.[6,19] A mediodorsal and lateroplantar protuberance is commonly found, which adds rotational stability to the joint.[6] The dorsal capsule of the joint is thin, whereas the plantar capsule is thickened with ligamentous support.[6]

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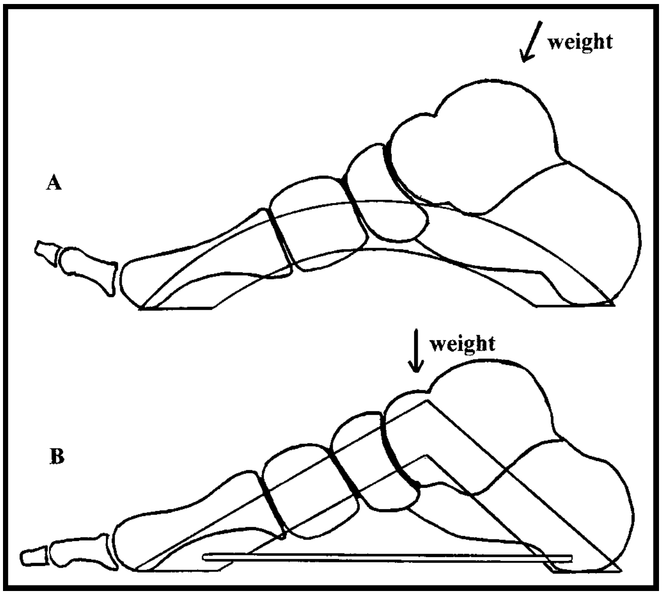

Figure 1.
During early stance (A), the medial longitudinal arch functions like a curved beam to support the weight of the body. At mid-stance (B), the load is more vertical and the arch functions like a truss, with the plantar aponeurosis tightened for support in the foot.

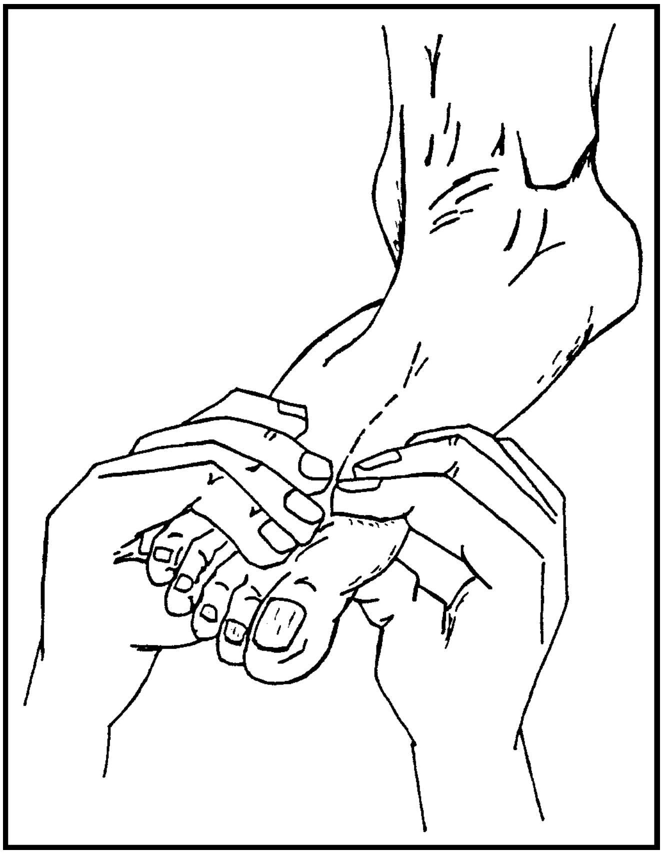

Figure 2.
Mobility of the first ray is assessed by applying a displacement force to the head of the first metatarsal while the remainder of the forefoot is stabilized.

Muscle activity can provide support to the first ray. Tendons of the tibialis posterior, tibialis anterior, and peroneus longus muscles insert onto the first ray.[6,19] The tibialis posterior muscle inserts on the navicular tuberosity, with additional plantar attachments to the cuboid, the cuneiforms, and the second, third, and fourth metatarsals. The tibialis anterior muscle inserts on the medial cuneiform and the base of the first metatarsal. The peroneus longus muscle inserts on the first metatarsal. The flexor hallucis brevis muscle divides into 2 bellies encasing the sesamoid bones and inserts on the base of the proximal phalanx. Passing under the first metatarsal, the tendon of the flexor hallucis longus muscle inserts on the distal phalanx.[19]

Hicks[5] conducted the seminal investigation locating the joint axis of the first ray. Using an external jig mounted in alignment to spikes embedded into the bones of cadaver feet, he caused movement and estimated that the axis of rotation ran nearly horizontal from the posteromedial foot in an anterolateral direction. The orientation of this axis primarily couples dorsiflexion with inversion and plantar flexion with eversion.[24] The terms "first ray rotation" and "first ray pronation" have been used interchangeably when describing the triplanar movement of the first metatarsal.[5,25,26]

The measure of dorsal excursion of the first ray has clinical importance because ground reaction forces act principally in the dorsal direction during gait. Dorsal mobility of the first ray has been measured by devices[27–30] and by roentgenograms.[31,32] Dorsal mobility averaged 6 mm (range=4–9 mm) in young adults without foot pathology.[27] The origin of motion may happen solely at the first metatarsocuneiform joint,[29] or more likely, some motion occurs at other joints along the medial arch.[6,32]

Assessment of first ray mobility is advisable when considering treatment for any patient with foot difficulties.[12,13,17,33,34] Clinical testing (Fig. 2) is performed using one hand to stabilize the lateral 4 metatarsals while the examiner's other hand applies a dorsal or plantar displacement force to the head of the first metatarsal.[33,35] Although this method of testing has uncertain interexaminer reliability, manual testing may be adequate for an individual clinician or orthotist to classify the mobility of the first ray as being stiff, normal, or hypermobile.[30,35] Comparison with the patient's other side and with a large number of patients helps the examiner get a sense of what is normal and abnormal. With the ankle in a neutral position, a dorsiflexion stress applied beneath the first metatarsal head normally will bring the inferior aspect of the first metatarsal to the sagittal-plane level of the lesser metatarsal heads. If the inferior aspect of the first metatarsal head does not reach the plane of the lesser metatarsals, the first ray may

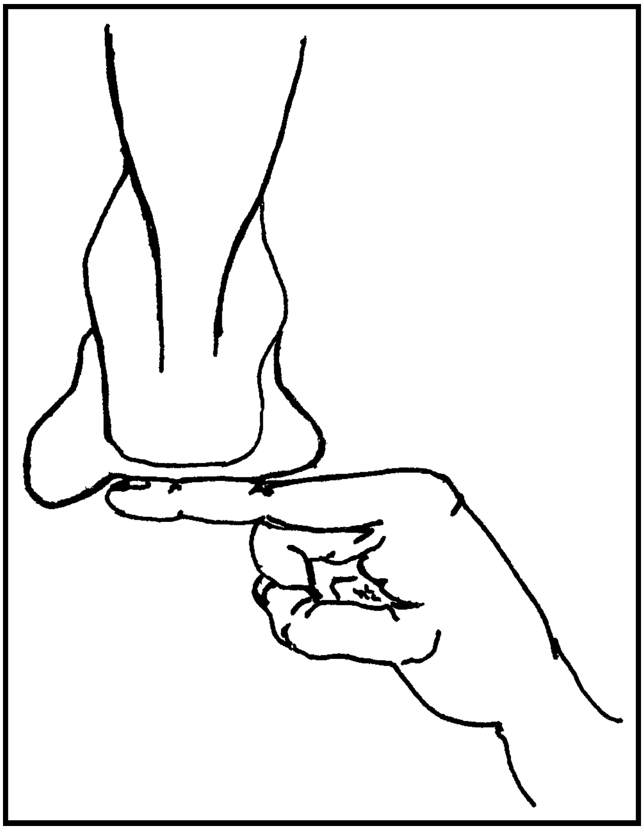

Figure 3.
A plantar-flexed first ray foot deformity has the first metatarsal fixed in a plantar-flexed position relative to the heads of the other metatarsals.

be classified as stiff. Conversely, if the inferior aspect of the first metatarsal head rises above the plane of the lesser metatarsals, the first ray may be classified as hypermobile.

Pathomechanics of a Stiff First Ray

A stiff first ray interferes with the mechanics of weight acceptance.[11,36] Stance begins with the heel making contact lateral to the ankle joint and concludes in late support with body weight centered near the first metatarsal.[37] The foot deforms at heel contact, absorbing shock and distributing the plantar pressure to the heel and the heads of the metatarsals.[3] A mobile first ray will dorsiflex on weight acceptance to prevent traumatizing the head of the first metatarsal.[24] Limited dorsal mobility can cause higher plantar pressure beneath the first ray and can increase the risk of ulceration to the fat pad under the first metatarsal head in individuals with insensitivity associated with diabetes.[11]

A plantar-flexed first ray foot deformity (Fig. 3) also can cause dysfunction. A rigid plantar-flexed first ray is identified when the first metatarsal is plantar flexed in a fixed position relative to the other metatarsals.[24] The plantar-flexed position of the first ray restricts medial (internal) rotation of the tibia in early support[36] and results in lack of calcaneal eversion and foot shock absorption. Individuals with a plantar-flexed first ray commonly have calluses beneath the heads of the first metatarsal and the hallux.[38] Callus formation provides evidence that shear and compressive forces acting on the first metatarsal may be abnormally high during stance. These findings suggest that a rigid plantar-flexed first ray compromises the ability of the medial arch to attenuate the shock of impact during weight acceptance.

Pathomechanics of a Hypermobile First Ray

The biomechanics that make the foot rigid during terminal stance are disrupted by the hypermobile first ray.[4] When positioned flat on the ground, the medial arch lowers and the foot widens, increasing tension on the plantar ligaments and plantar aponeurosis.[10] As the contralateral limb swings forward, the stance phase tibia obligatorily rotates laterally (externally), causing the medial arch to rise.[3] Supination of the foot improves the congruency of the talonavicular and the calcaneal cuboid articulations, which “locks” the transverse tarsal joint.[39] Plantar flexion of ankle joint occurs after heel-off, forcing the metatarsophalangeal joints to dorsiflex.[3,40] This dorsiflexion activates the “windlass” mechanics of the medial arch, tightening the plantar aponeurosis, elevating the arch, and further stabilizing the foot.[9] A hypermobile first ray collapses the truss framework of the medial arch,[4] decreasing the effectiveness of the foot-lever system needed for efficient forward propulsion.[12]

Pronation of the midtarsal joint lasting into the late support phase diminishes the ability of the peroneus longus muscle to stabilize the first ray.[39] Electromyographic profiles in individuals without foot pathologies show that a large burst of peroneus longus muscle activity occurs at heel-off.[41] The long peroneal tendon runs beneath the cuboid canal, crosses the foot, and inserts into the base of the first metatarsal. The effectiveness of the peroneus longus muscle in limiting dorsal excursion of the first ray is contingent on the direction of pull of the tendon insertion.[16,24,39] The components of force generated by contraction of the peroneus longus muscle can be separated into a lateral force[42] and a smaller plantar force. Supination of the foot provides a mechanical advantage for restraining dorsal excursion of the first ray. In supination, the medial arch elevates so that the cuboid canal is located inferior to the insertion of the peroneus longus muscle, thus increasing the plantar force moment arm of the peroneus longus muscle. A prolonged period of pronation lowers the medial arch, diminishing the ability of the peroneus longus muscle to help stabilize the first metatarsal.[16,24,39] As a consequence, ligamentous tissues that limit end-range dorsiflexion movement of the first metatarsal are overly stressed, resulting in joint laxity.

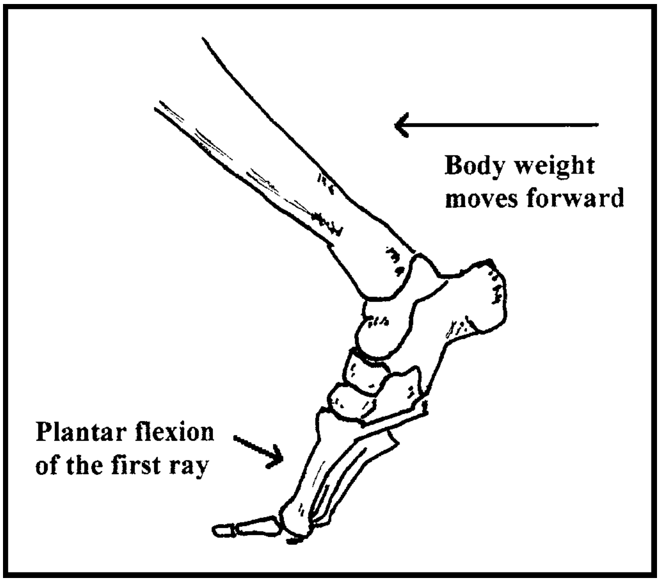

Figure 4.
Hallux dorsiflexion coupled with plantar flexion of the first ray provides the first metatarsophalangeal joint with full range of motion at terminal stance.

Nearly 70 years ago, Morton[4] proposed that hypermobility of the first ray was a problem for normal mechanics of the foot. He believed excessive dorsal excursion of the first metatarsal rolls the foot inward, which results in the second metatarsal carrying most of the weight. Described as "first ray insufficiency,"[12,17] this foot structure has been implicated as a causative factor in hallux valgus.[6,13,15,25,29] The first ray elevates, diverges medially, and rotates,[25] with the valgus deformity of the hallux considered compensatory to the malaligned position of the first ray.[6]

Hypermobility of the first ray is thought to contribute to acquired flatfoot deformity,[16] metatarsalgia and metatarsal stress fractures,[18] and central forefoot ulceration in the insensate foot.[14] The vertical ground reaction force elevates the hypermobile first ray, transferring the load to the lesser metatarsals. Myerson et al[35] identified the medial cortex of the second metatarsal to be hypertrophied, indicating overload, in patients classified as having a hypermobile first ray.

Failure of the first ray to plantar flex relative to the hallux during the propulsive sequence decreases the range of available dorsiflexion motion of the first metatarsophalangeal joint. Approximately 65 degrees of hallux dorsiflexion is required in gait.[38] Root and associates[24] measured hallux dorsiflexion to be 20 degrees from the ground in a standing position and postulated that, to some degree, the first metatarsal must plantar flex away from the hallux during gait (Fig. 4). Phillips and colleagues[43] found that the initial 20 degrees of hallux dorsiflexion is accomplished without movement of the first metatarsal during gait. The remainder of the first metatarsophalangeal joint motion couples 1 degree of metatarsal plantar flexion for every 3 degrees of hallux dorsiflexion. In theory,[8,16,38] the unstable first ray elevates, decreasing the amount of dorsiflexion required of the first metatarsophalangeal joint at terminal stance. First ray plantar flexion may be essential to normal biomechanics of the first metatarsophalangeal joint.[8,38,44,45]

Conclusion

Pathologies related to a stiff or hypermobile first ray are complex and can be influenced by a variety of neuromuscular and structural factors. Examining the mobility of the first ray and assessing the relatively static position of the first metatarsal are only part of a careful foot evaluation. Information gathered with this type of testing is useful, but does not represent the true dynamics of the first ray during gait. Future research that investigates how variations in range of motion and first ray position affect the mechanics of gait has the potential to improve the clinical treatment of people with foot disorders.

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