Orthopaedic Knowledge Update®

OKU® 7

Foot and Ankle

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Foot and Ankle

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Preface

Orthopaedic Knowledge Update®: Foot and Ankle continues to be an excellent resource for the prevailing body of literature. OKU® is renowned to offer reviews and summaries of the most relevant and critical studies for the reader. Recent information can be easily accessed, and the annotated references allow for perusal. *OKU® Foot and Ankle 7* will be helpful to residents, fellows, and practicing orthopaedic surgeons.

This seventh volume contains 29 chapters contributed by more than 40 authors, all of whom are leaders in foot and ankle surgery. Like prior volumes, the chapters focus on significant discoveries, materials, methods, and studies that are new since the sixth volume was published in 2019. We are excited to include a new section titled Contemporary Surgical Techniques. This section includes chapters on surgical management of Charcot neuroarthropathy, minimally invasive surgery of the foot and ankle, and revision total ankle arthroplasty. All chapters have been updated to include the latest treatment guidelines, surgical techniques, and literature reviews, along with illustrations.

I thank the authors for completing the enormous task of reviewing and researching an immense amount of up-to-date literature. The authors have done a first-rate job of summing up these articles and adding to established knowledge. Also, I thank the section editors of *OKU® Foot and Ankle*. They are indeed leaders in the field. They, too, have expended a great deal of time and exercised their expertise to ensure the quality and comprehensiveness of the chapters. The result is chapters that are thorough and up to the rigors of OKU®.

It is a privilege to have edited the fifth and sixth volumes, and now the seventh volume, of *OKU® Foot and Ankle*. I am grateful to the American Academy of Orthopaedic Surgeons for their support and confidence in me to prepare this new volume. Special thanks to Lisa Claxton Moore, Senior Manager, Editorial, publishing team of AAOS. Her expertise and guidance were much needed and appreciated every step of the way. This acknowledgment includes Marisa Solorzano-Taylor, Editorial Coordinator, Health Learning, Research & Practice, and Stacey Sebring, Senior Development Editor, Medicine and Advanced Practice at Wolters Kluwer. I am indebted to their steady availability to answer many questions, as well as their know-how of OKU® production.

We hope this new volume of *Orthopaedic Knowledge Update®: Foot and Ankle* with up-to-date information on clinical, imaging, and surgical procedures aids the physician to evaluate, diagnose, and treat patients with disorders of the foot and ankle.

Loretta B. Chou, MD, FAAOS
Editor

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SECTION 1

General Foot and Ankle Topics

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CHAPTER 1

Biomechanics of the Foot and Ankle

RICHARD J. DE ASLA, MD, FAAOS

ABSTRACT

Understanding biomechanics and functional anatomy of the foot and ankle is mandatory if there is to be any meaningful attempt at formulating new ways of addressing pathoanatomy. It is important to provide an introduction to foot and ankle biomechanics and functional anatomy as a basis for managing disorders.

Keywords: ankle anatomy; ankle biomechanics; foot anatomy; foot biomechanics; gait cycle

INTRODUCTION

The foot is a marvelous mechanical structure. Its unique anatomy and biomechanics allow it to play several seemingly conflicting roles. During push-off, it is a rigid lever arm for efficient propulsion. In stance, it is a stable platform for balance. It is also a part-time shock absorber that adeptly navigates uneven surfaces and terrain. The average person's foot is remarkably durable, logging more than 100 million steps during an average lifetime.

With continued advancements in imaging technology, such as weight-bearing CT, knowledge of foot and ankle biomechanics continues to steadily improve.[1-5] This improved understanding of how the foot works provides better insight into disorders of the foot and ankle, which are often biomechanically based.

A thorough understanding of the biomechanics and functional anatomy of the foot and ankle is mandatory to ensure successful treatment of patients and the development and advancement of new procedures.

Dr. de Asla or an immediate family member serves as a paid consultant to or is an employee of Arthrex, Inc. and has stock or stock options held in Pfizer.

STRUCTURAL ANATOMY

The foot is divided into three regions: the forefoot, midfoot, and hindfoot. The tarsometatarsal joints (or Lisfranc joint complex) separate the forefoot from the midfoot, and the talonavicular and calcaneocuboid joints (transverse tarsal or Chopart joint) separate the midfoot from the hindfoot.

In the forefoot, the metatarsals are unique in that they are the only long bones in the body to support weight perpendicular to their long axis. In most feet, the first metatarsal is somewhat shorter than the second, with a progressive cascade of shortening from the second to the fifth metatarsal. This metatarsal break angle encourages the foot to supinate during push-off. In the sagittal plane, all metatarsals incline to some extent; the first metatarsal has the highest inclination angle (range, 15° to 25°), and the remaining metatarsals demonstrate decreasing inclination angles from medial to lateral. Alterations and subtleties in the length and position of the metatarsals affect loading patterns that may influence alignment and contribute to the development of painful callosities, metatarsalgia, and metatarsophalangeal joint pathology.

The first, fourth, and fifth metatarsals have mobility in the sagittal plane, whereas the second and third metatarsals have relatively fixed positions. The lesser metatarsal bases are connected by a series of plantar metatarsal ligaments. No such connection exists between the base of the first and second metatarsals. The absence of an intermetatarsal ligament provides the first metatarsal a degree of mobility in the transverse plane not afforded to the lesser metatarsals. This anatomic feature may play a role in the development of hallux valgus deformities.

The forefoot is connected to the midfoot through the Lisfranc joint complex. Here, the cross-sectional wedge-shaped cuneiforms and metatarsal bases form a transverse arch across the midfoot, enhancing stability in the coronal plane (**Figure 1**). In addition, the base of the second metatarsal is recessed proximally between the medial and lateral cuneiforms, providing stability in the horizontal plane. Stability is further enhanced by a series of very strong plantar tarsometatarsal ligaments and a short, thick interosseous ligament that courses between the lateral aspect of the medial cuneiform and medial aspect of the second metatarsal base. This interosseous ligament is often referred to as the Lisfranc ligament. Disruption of the midfoot complex may result in an avulsion fracture off the base of the second metatarsal. The bony fragment, still attached to the Lisfranc ligament, can be seen between the bases of the first and second metatarsals on plain radiographs—the so-called fleck sign.

The midfoot contains the navicular, the cuboid, and three cuneiform bones. These five bones are relatively immobile with respect to one another and provide a mechanical link between the hindfoot and the more mobile forefoot. The midfoot allows for the safe passage of neurovascular structures and tendons as they course from the leg to the foot. The disk-shaped navicular bone has a convex anterior surface and a concave posterior surface—both of which are covered with cartilage. Small vessels enter the navicular dorsally from the dorsalis pedis artery and medially from the posterior tibial artery. Blood supply to its central portion is relatively sparse, and certain foot types may accentuate shear across this portion of the bone.[6] The navicular is also the primary attachment site of the tibialis posterior tendon. These features may combine to make the navicular bone relatively susceptible to stress fracture and poor healing.

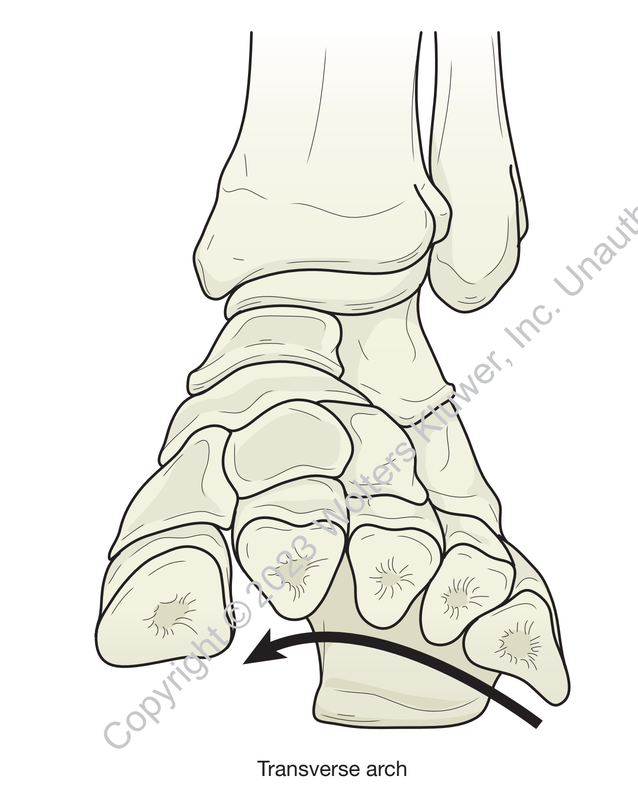

FIGURE 1 Illustration of the wedge-shaped bases of the second, third, and fourth metatarsals and the middle and lateral cuneiforms that create a keystone effect that stabilizes the arch in the coronal plane.

The midfoot is separated from the hindfoot by the talonavicular and calcaneal cuboid joints, known collectively as the transverse tarsal joint or Chopart joint. The talonavicular joint is a ball-and-socket–type joint. The socket that receives the talar head is deepened by the anterior and middle facets of the calcaneus, the calcaneonavicular slip of the bifurcate ligament, and the superomedial and inferior calcaneal navicular ligaments, which together comprise the spring ligament. The superomedial component of the spring ligament originates from the superomedial aspect of the sustentaculum tali and is confluent with the superficial deltoid ligament, forming a large medial ligament complex. The superomedial component of the spring ligament serves to suspend the head of the talus, functioning like an anatomic hammock. The portion in contact with the talar head is a region of fibrocartilage tissue providing a smooth surface on which to articulate. This acetabulum pedis allows for transverse, sagittal, and longitudinal planes of motion and plays a vital role in foot biomechanics (**Figure 2**). Any motion of the talonavicular joint or subtalar joint also involves motion at the calcaneocuboid joint. Maximum congruency of the calcaneocuboid joint is achieved when the hindfoot is in varus and the forefoot is supinated. This is the position the foot assumes with push-off.

The hindfoot consists of the calcaneus and the talus. Their articulation forms the subtalar joint as the talus sits sidesaddle over the superomedial aspect of the calcaneus. The subtalar joint consists of three separate articulations, or facets. More than 90% of all tarsal coalitions occur at either the anterior facet (calcaneonavicular coalition) or the middle facet (talocalcaneal coalition). For simplicity's sake, subtalar motion is often depicted as inversion and eversion around a mitered hinge. In reality, subtalar motion is quite complex, is difficult to measure, and includes rotational motions and translations in multiple planes. The subtalar joint is stabilized by the deltoid ligament, the interosseous and cervical ligaments, and a series of lateral ligaments and structures. These lateral stabilizers include the calcaneofibular ligament (CFL), the lateral talocalcaneal ligament, and the inferior extensor retinaculum. Because of its role as a subtalar joint stabilizer, the inferior extensor retinaculum is often used

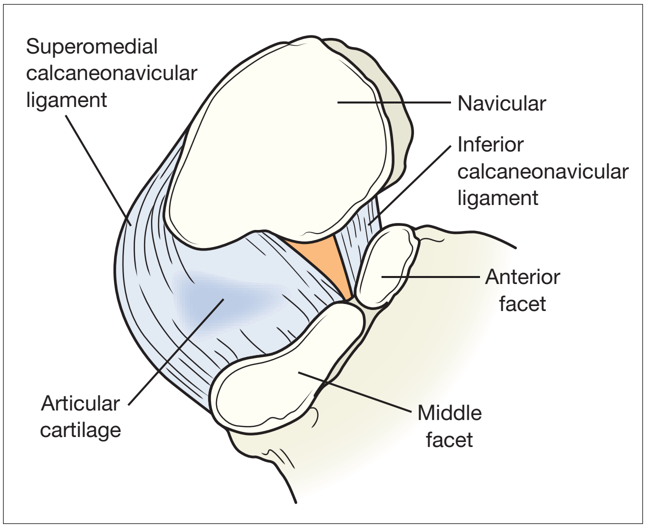

FIGURE 2 Illustration of the acetabulum pedis from a dorsal view with the head of the talus removed. (Redrawn with permission from de Asla RJ: Anatomy and biomechanics of the foot and ankle, in Thordarson DB, ed: *Orthopaedic Surgery Essentials: Foot and Ankle*, ed 2. Lippincott Williams & Wilkins, 2012.)

in Broström-type lateral ankle ligament reconstruction procedures[7-9] (**Figure 3**).

The body of the talus resides in a bony housing created by the articulation between the distal fibula and tibia. The mortise is formed by the tibial plafond and medial and lateral malleoli. Composed of the talus, distal tibia, and fibula, the ankle joint includes three articulations: tibiofibular, tibiotalar, and talofibular. The tibiofibular joint represents the inferior extent of the lower extremity syndesmosis. The syndesmosis is stabilized by four ligaments: the anterior inferior tibiofibular ligament, the posterior inferior tibiofibular ligament, the transverse tibiofibular ligament, and the interosseous tibiofibular ligament. Occasionally, a thickened accessory slip of the anterior inferior tibiofibular ligament (Bassett ligament) may insert too distally on the fibula, causing symptoms as it impinges against the anterolateral aspect of the talar dome. The transverse tibiofibular ligament originates on the posterior aspect of the fibula and extends to the posterior margin of the medial malleolus. In between, it forms the posterior labrum, which effectively deepens the tibiotalar joint. The syndesmosis allows fibula rotation and proximal migration when the wider anterior aspect of the talar body rotates into the ankle mortise during dorsiflexion. This relationship also allows the fibula to share approximately 16% of the axial load transmitted across the ankle.[10-12]

The ankle is stabilized by the inherent bony configuration of the mortise,[13] as well as the medial and lateral ligament complexes. In one study, the articular surface of the talus was compared with a truncated cone in which the medial aspect is oriented toward the apex and the lateral aspect is oriented toward the base. Therefore, this cone has a smaller medial radius and a larger lateral radius[14] (**Figure 4**). The articular surface

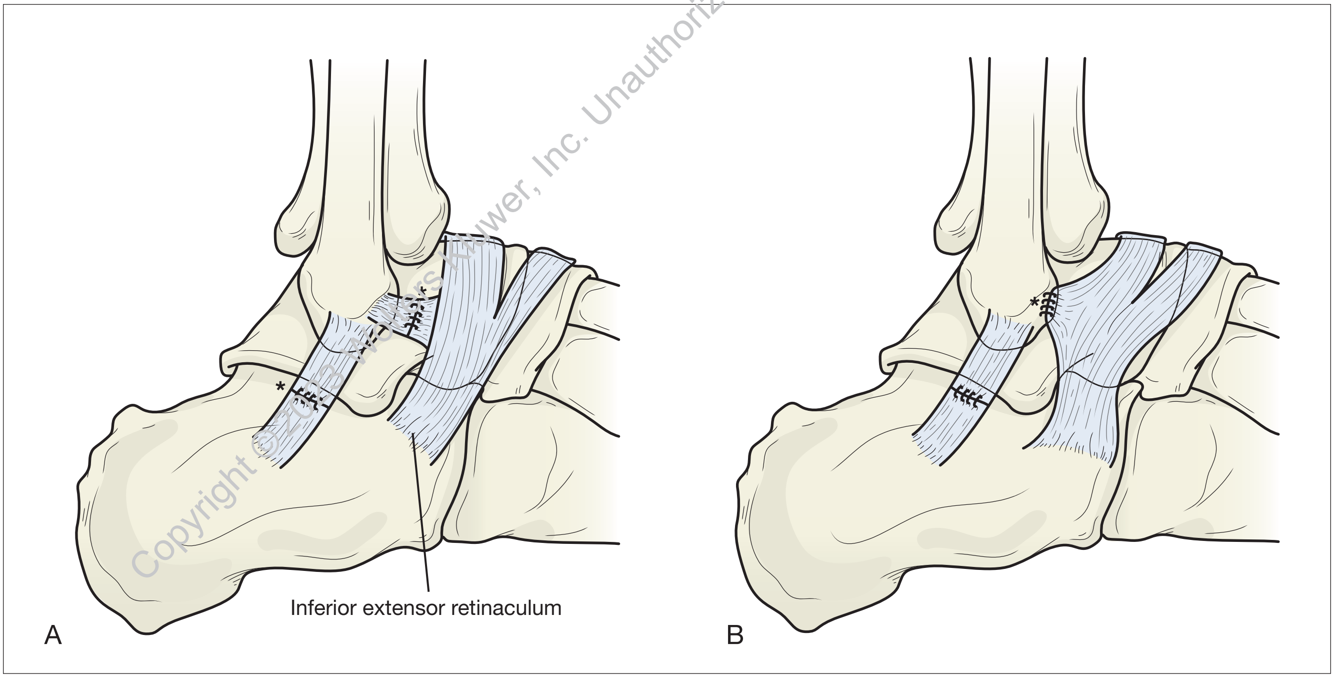

FIGURE 3 **A**, Drawing depicts a Broström procedure. **B**, Drawing depicts a modification of the Broström procedure. Note that a portion of the inferior extensor retinaculum is mobilized for incorporation into the repair.

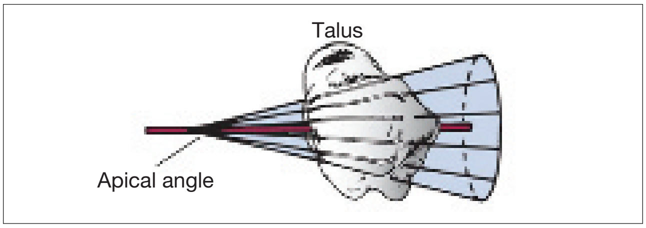

FIGURE 4 Illustration of the cone-shaped trochlear surface of the talus. The apex is oriented medially, whereas the base is oriented laterally. (Adapted with permission from Inman VT: *The Joints of the Ankle*. Williams & Wilkins, 1976 and reproduced with permission from Haskell A, Mann RA: Biomechanics of the foot and ankle, in Coughlin MJ, Saltzman CL, Anderson RB, eds: *Mann's Surgery of the Foot and Ankle*, ed 9. Saunders, 2014, pp 3-36.)

of the talus is also narrower posteriorly than anteriorly. When the ankle is dorsiflexed, the widened anterior portion of the talus fills the mortise more effectively, improving bony stability. In plantar flexion, the bony contribution to stability decreases and the surrounding ligaments assume an increased role. The deltoid ligament complex is well configured to stabilize the medial aspect of the ankle where the apex of the deltoid meets the apex of the cone. The deltoid ligament complex is divided into two anatomically distinct layers: superficial and deep. The superficial deltoid crosses both the tibiotalar and subtalar joints, whereas the deep deltoid only crosses the tibiotalar joint. The superficial layer is fan-shaped and has no discrete bands, although in the most accepted description there are four fascicles. The anatomically separate deep layer is short and thick and divided into two distinct ligaments: the anterior and posterior tibiotalar ligaments. Both layers act to resist valgus talar tilting and act as secondary restraints to anterior translation of the talus. According to a 2020 study, force probe studies performed without ligament transection found that the different fascicles of the deltoid serve differing stabilizing roles depending on the direction and rotation of the force applied[15] (**Figure 5**). The lateral ankle ligament complex is configured more broadly to accommodate a wider radius and larger arc of rotation. The lateral ankle ligament complex comprises the anterior talofibular ligament (ATFL), the CFL, and the posterior talofibular ligament. Lateral ankle stability depends on the orientation of the fibers of each of these ligaments, which changes with ankle position. The ATFL is a thickening of the anterolateral ankle joint capsule that is visible from the articular side of the capsule. Among all lateral ligaments, the ATFL has the lowest load to failure but the highest strain; it lengthens the most before failure. When the foot is plantarflexed, the fibers of the ATFL orient parallel to the leg, providing collateral restraint to inversion. The CFL is a distinct extracapsular, cordlike ligament that spans the ankle and the subtalar joints. This ligament is always perpendicular to and stabilizes the subtalar joint.

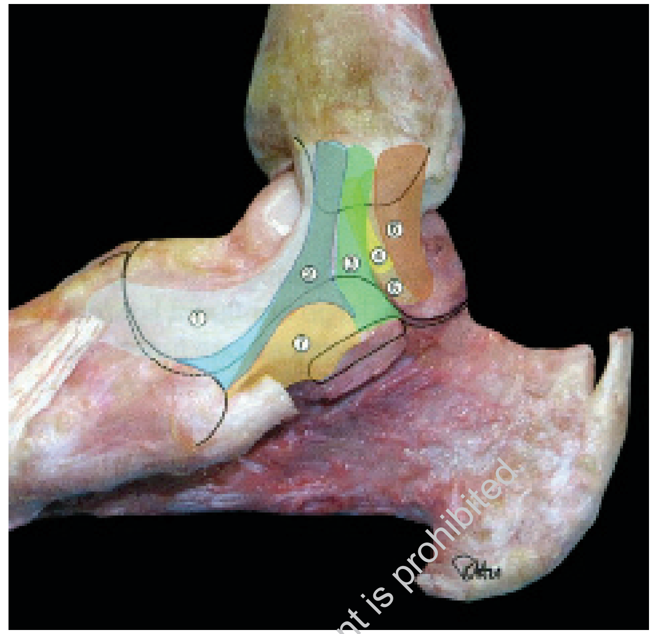

FIGURE 5 Medial view of the ankle depicting the deltoid ligament. Fascicles from the deltoid span from the medial malleolus to the navicular, talus, and calcaneus. Its fascicles are inseparable from the calcaneonavicular ligaments (spring ligament). The superficial component of the deltoid consists of the tibionavicular (1), tibiospring (2), tibiocalcaneal (3), and superficial posterior tibiotalar fascicles (4). The deep component of the deltoid ligament is composed of the anterior tibiotalar (5), posterior tibiotalar fascicles (6) and superomedial component of the spring ligament (7).

However, when the ankle is plantarflexed, this ligament assumes a relatively horizontal orientation with respect to the tibiotalar joint, rendering it ineffective as a stabilizer. When the foot dorsiflexes, the roles of the ATFL and CFL are reversed.[16,17]

CLINICAL BIOMECHANICS

At its most basic level, the foot can be conceptualized as a tripod. In stance, weight is distributed collectively between the head of the first metatarsal, the heel, and the four lesser metatarsal heads. Malalignment and alterations in biomechanics may disrupt this balance, resulting in painful conditions (**Figure 6**). For example, a cavus foot type is more prone to increased loading under the first metatarsal head and lateral aspect of the foot. A patient with a dorsiflexion malunion of a metatarsal fracture is at increased risk for a painful callus under another metatarsal head. A hallux valgus deformity may lead to second metatarsal phalangeal joint overload, plantar plate attenuation, and eventual crossover second toe

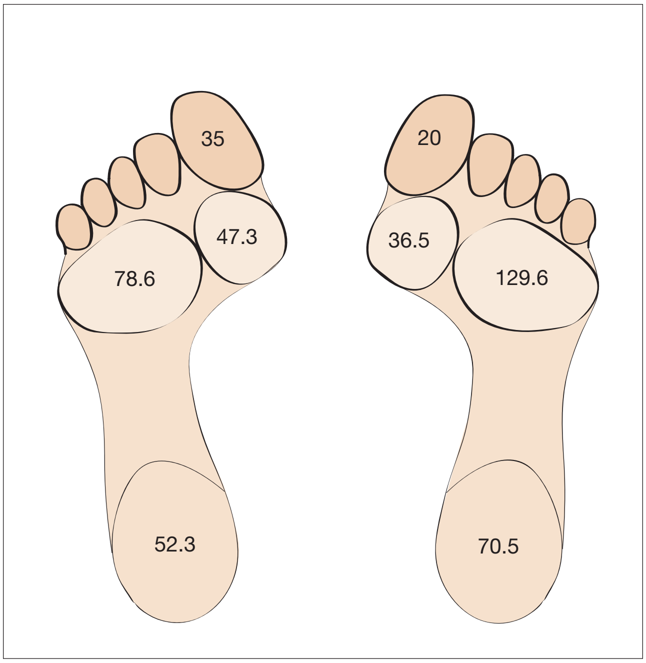

FIGURE 6 Illustration of peak forces, in newtons, measured on the plantar foot before and after silicone arthroplasty of the first metatarsophalangeal joint. (Adapted with permission from Springer Nature. Beverly MC, Horan FT, Hutton WC: Load cell analysis following silastic arthroplasty of the hallux. *Int Orthop* 1985;9[2]:101-104, Copyright 1985.)

deformity.[18] In such cases, the extensor digitorum longus tendon is the greatest deforming force. Furthermore, foot deformity and position may ultimately affect more proximal joints, as seen in patients with planovalgus foot deformities. The rotational forces created by the planovalgus foot may eventually result in attenuation of the deltoid-spring ligament complex and valgus tilting of the talus. When a foot and ankle surgeon attempts to correct a deformity, the tripod concept must be kept in mind.

The true axis of rotation of the tibiotalar joint consists of a series of instant centers of rotation as the talus translates in the horizontal plane with dorsiflexion and plantar flexion. However, for most purposes, this axis can be estimated using a line that passes through the distal aspects of both malleoli. This empirical axis lies in approximately 20° to 30° of external rotation with respect to the coronal plane and is obliquely oriented at approximately 82° from the axis of the tibia (**Figure 7**). With the foot free and the leg in a fixed position, the oblique ankle joint axis causes the foot to externally rotate with dorsiflexion and internally rotate with plantar flexion (**Figure 8**). Conversely, when the foot is fixed to the floor, the oblique axis imposes an internal rotation force to the leg as the body passes over the foot,

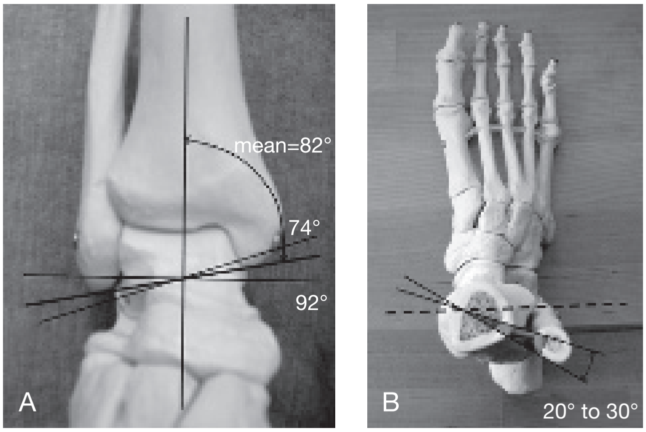

FIGURE 7 **A**, Ankle joint axis of rotation as viewed in the coronal plane. **B**, Ankle joint axis of rotation as viewed from the horizontal plane. (Reproduced with permission from de Asla RJ: Anatomy and biomechanics of the foot and ankle, in Thordarson DB, ed: *Orthopaedic Surgery Essentials: Foot and Ankle*, ed 2. Lippincott Williams & Wilkins, 2012.)

and the foot dorsiflexes. As the foot pushes off, ankle plantar flexion results in external rotation of the leg. Rotation of the tibia is coupled with the inversion and eversion motion of the subtalar joint. The normal coupling mechanism depends on the integrity of the deltoid and interosseous ligaments.[19] One study suggests that when tibiotalar motion is markedly reduced by arthritis, the normal motion coupling seen in healthy ankle joints breaks down.[20]

Motion of the subtalar joint has been compared with that of a mitered hinge. Its axis passes obliquely from

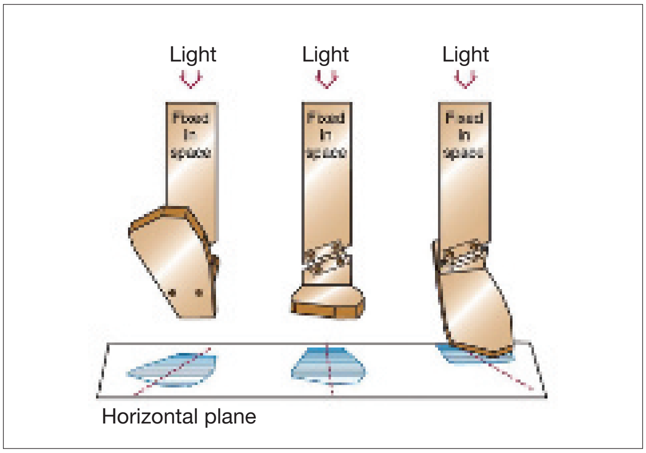

FIGURE 8 Illustration showing that, with the leg fixed in position and the foot free, the oblique ankle joint axis causes outward rotation with dorsiflexion and inward rotation with plantar flexion. (Reproduced with permission from Haskell A, Mann RA: Biomechanics of the foot and ankle, in Coughlin MJ, Saltzman CL, Anderson RB, eds: *Mann's Surgery of the Foot and Ankle*, ed 9. Saunders, 2014, pp 3-36.)

plantarlateral to dorsal medial, deviating from the horizontal plane by approximately 41° and from the sagittal plane by approximately 23°.[14,21] The subtalar axis of rotation is highly variable between patients. Using the model in **Figure 9** as a visual aid, a more horizontally oriented axis appears to translate to more rotation of the horizontal component with every degree of vertical component rotation. The reverse is true with a more vertically oriented axis. Clinically, it is recognized that patients with flatter feet (a more horizontal axis) have more subtalar motion, whereas patients with a cavus foot type (a more vertical axis) tend to experience stiffer motion.

The transverse tarsal joint allows for hindfoot motion while the forefoot remains plantigrade to the ground. This relationship is facilitated by the acetabulum pedis. The heel strikes the ground in varus and then quickly everts. Anatomically, the everted hindfoot places the axis of rotation of the calcaneal cuboid joint parallel to the axis of rotation of the talonavicular joint. This parallel configuration permits motion across the transverse tarsal joint, which accommodates uneven terrain and absorbs impact forces. As the body's center of mass moves forward over the foot, the tibia externally rotates, causing the hindfoot to rotate into varus through coupled motion. The changing position of the hindfoot causes the once-parallel axes of the transverse tarsal joints to converge. This convergence effectively locks the transverse tarsal joint, effectively changing the foot from an accommodating platform for stance into a rigid lever arm for efficient push-off.

Motions of the subtalar joint and transverse tarsal joint (also called the triple joint complex) are inextricably linked, with the talonavicular joint playing the key role. In conditions requiring arthrodesis of the talonavicular joint, motion through the remaining joints of the triple joint complex is virtually nonexistent.[22] Acting in conjunction with the bony architecture of the foot and ankle is a series of dynamic and static soft-tissue stabilizers. At heel strike, the tibialis anterior tendon eccentrically contracts to control foot descent, serving to dissipate forces and prevent slapping of the foot against the ground. The tibialis posterior tendon plays a vital role in producing hindfoot inversion during push-off through its action across the transverse tarsal joint. The pull of the tibialis posterior tendon adducts the navicular over the head of the talus, helping to invert the calcaneus, which follows the cuboid. The ability to perform an efficient heel rise depends on the tibialis posterior tendon's ability to secure the transverse tarsal joint in adduction. At heel rise, the triceps surae pulls the Achilles tendon to become the strongest hindfoot inverter. This ensures the midfoot will remain locked for toe-off.

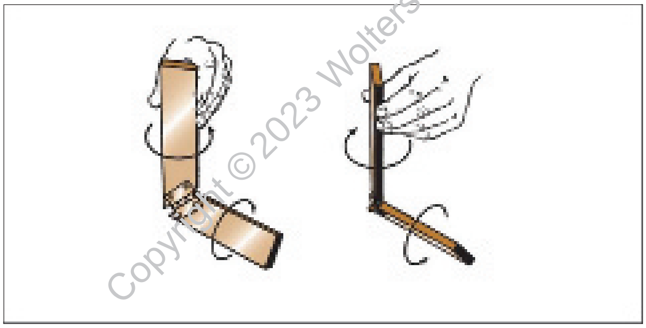

FIGURE 9 Illustration of a mitered joint hinge. (Reproduced with permission from Haskell A, Mann RA: Biomechanics of the foot and ankle, in Coughlin MJ, Saltzman CL, Anderson RB, eds: *Mann's Surgery of the Foot and Ankle*, ed 9. Saunders, 2014, pp 3-36.)

When disease renders the posterior tibial tendon ineffective, the transverse tarsal midfoot locking mechanism is compromised. When the midfoot fails to lock, the stability of the medial longitudinal arch becomes solely dependent on plantar soft-tissue static stabilizers for support. Without dynamic stabilization and bony protection of the transverse tarsal joint, these stabilizers will attenuate and eventually fail under tension, resulting in progressive collapse of the medial longitudinal arch, abduction of the forefoot, and the eventual failure of the hindfoot to invert with toe rise. As a consequence, the Achilles tendon will pull on an everted hindfoot, ensuring that midfoot locking does not occur. In this scenario, the Achilles tendon becomes a deforming force that leads to an accelerated progressive collapsing foot deformity.

Traditional teaching and most literature concerning the topic of the progressive collapsing foot deformity (also referred to as an adult acquired flatfoot) suggest that an incompetent posterior tibial tendon serves as the initial catalyst preceding deformity. However, this concept is being challenged on a number of fronts. Using weight-bearing CT, investigators found that in patients with symptomatic flatfoot deformities the coronal orientation of the posterior facet was in significantly more valgus than in control patients.The investigators hypothesized that an excessively valgus subtalar joint leads to increased medial force vectors that, over time, lead to medial soft-tissue failure and progressive deformity.[23,24] More recent studies show the deltoid-spring ligament complex plays the primary role in maintaining the medial longitudinal arch while the posterior tibial tendon provides dynamic support of the ligaments function. In this secondary role, the posterior tibial tendon is incapable of preventing a progressive flatfoot deformity once the ligamentous structures have failed, as discussed in two studies published in 2019.[25,26]

The medial longitudinal arch is a dynamic structure that aids in shock absorption and terrain accommodation on heel strike and in midstance, and then allows for efficient propulsion at toe-off. Two models have been proposed to help describe the biomechanics of the medial longitudinal arch.[27] In one model, the arch is conceptualized as a curved, segmented beam. The beam comprises the calcaneus, talus, navicular, cuneiforms, and the medial three metatarsals. The segments are stabilized by static plantar ligamentous connections. With weight bearing, compression forces develop on the dorsal aspect of the beam whereas tensile forces are created on the plantar aspect. The dorsal compression forces are resisted by the bony architecture of the arch, whereas plantar tensile forces are resisted by the ligaments (**Figure 10**).

The beam model of the medial longitudinal arch does not consider the role of the plantar fascia. This structure is incorporated in the truss model of the arch (**Figure 11**). In the truss model, the arch is conceptualized as a triangular structure composed of two oblique beams with a dorsal pivot connected plantarly by a tie rod. Anatomically, the plantar fascia functions as a tie rod, originating from the posterior calcaneal tuberosity and inserting onto the sesamoids and the bases of the proximal phalanges of the lesser toes. With loading, the plantar fascia resists the plantarly generated tensile forces.[28] Total or partial release of the plantar fascia may decrease arch height.[29]

During late midstance and toe-off, the hallux and lesser toes dorsiflex, which effectively tightens the plantar fascia and adds to the stability of the midfoot. The mechanism by which this occurs has been likened to a windlass device (**Figure 12**). A windlass is used to transport or lift objects vertically. It makes use of a lever arm (the hallux and lesser toes) that is attached to a cable or rope (the plantar fascia) wound around a cylinder (the metatarsophalangeal joints), which acts as a fulcrum.

Weight-bearing CT is gaining prevalence in both research and clinical settings. This relatively new modality is changing how the normal foot configuration is defined and how deformity is measured and determined.[30,31] Weight-bearing CT is also creating new biometric tools such as the foot-ankle offset. Foot-ankle offset is a semiautomated software-driven calculation that uses biometric data to reconstruct the foot tripod to determine a virtual point where the ground reaction force is applied and find the center of the ankle where body weight is applied. The offset between the two represents

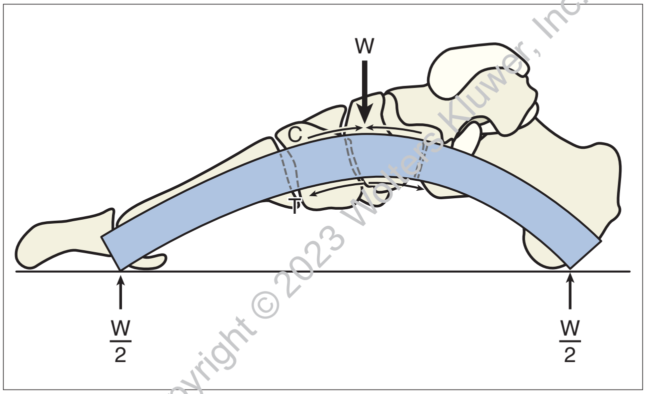

FIGURE 10 Illustration of the beam model of the medial longitudinal arch. Compression occurs through bony structures dorsally and tension occurs across plantar ligamentous structures. C = compressive force, T = tensile force, W = weight bearing force. (Redrawn with permission from Sarrafian SK: Functional characteristics of the foot and plantar aponeurosis under tibiotalar loading. *Foot Ankle* 1987;8[1]:9.)

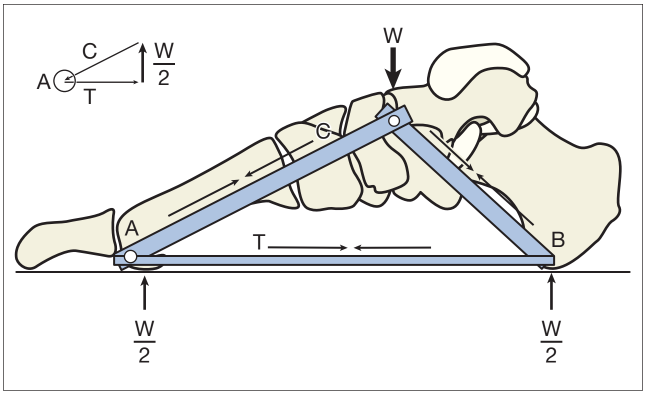

FIGURE 11 Illustration of the truss model of the medial longitudinal arch. The bony architecture of the foot is conceptualized as two beams connected by the plantar fascia, which functions as a tie rod. A = the insertion of the plantar fascia, B = the origin of the plantar fascia on the calcaneus, C = compressive force, T = tensile force, W = weight bearing force. (Redrawn with permission from Sarrafian SK: Functional characteristics of the foot and plantar aponeurosis under tibiotalar loading. *Foot Ankle* 1987;8[1]:9.)

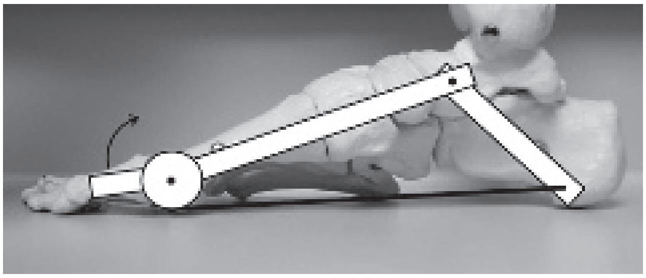

FIGURE 12 Windlass mechanism. A truss is shown superimposed over a skeletal model of the foot. As the toes dorsiflex, the drum (metatarsophalangeal joints) rotates, applying tension to the tie rod (plantar fascia) and effectively supporting the arch. (Reproduced with permission from de Asla RJ: Anatomy and biomechanics of the foot and ankle, in Thordarson DB, ed: *Orthopaedic Surgery Essentials: Foot and Ankle*, ed 2. Lippincott Williams & Wilkins, 2012.)

a coronal plane rotational torque lever arm.[32] The technique has been found to be reproducible with excellent correlation with pedobarographic data.[33] Foot-ankle offset may offer an entirely new way to assess normal and altered foot mechanics.

GAIT

Human gait is defined as the process by which the lower extremities are used for forward locomotion. Many biomechanical events unfold during human gait that simply occur too rapidly to evaluate clinically. Numerous techniques developed in the field of biomechanics can potentially quantitatively assess body segment motions and forces. Such techniques, however, usually necessitate the use of a formal gait laboratory and a dedicated team. Techniques include video gait analysis, force plates, fluoroscopic imaging, three-dimensional reconstruction software, electromyography, and a host of other technologies.

Despite the accuracy of certain gait analysis techniques, widespread clinical use has yet to occur and debate remains as to their clinical relevance. Criteria have been proposed regarding the inclusion of gait analysis as a routine part of an orthopaedic examination.[34,35]

Normal human gait is extremely efficient with regard to energy and oxygen consumption. The gait cycle is a pattern of recurring predefined events that can be analyzed in terms of stride. A single stride starts from the moment of heel strike to the moment the same heel strikes the ground again. Stride length is defined as the distance covered between these two consecutive heel strikes. A step is the distance between the heel strike of one foot and the heel strike of the opposite foot. Cadence is defined by the number of steps taken during a given unit of time. In walking, a single stride is divided into two phases: the stance phase and the swing phase. The stance phase begins when the foot strikes the ground and continues until the toes of the same foot leave the ground (or toe-off). This represents approximately 60% of the gait cycle. Swing phase is the remaining 40% of the cycle and extends from toe-off until the heel strikes the ground.

The stance phase is further divided into three intervals. The first interval starts at heel strike and ends at foot flat. This segment is characterized by weight acceptance and rapid ankle plantar flexion under eccentric control of the anterior leg musculature. The second interval extends from foot flat to opposite foot strike. During this interval, the body's center of gravity passes forward of the plantar foot. This controlled fall is halted when the contralateral heel strikes the ground. The final interval extends from the end of the second interval through toe-off. This interval is characterized by rapid ankle plantar flexion and the cascade of biomechanical events that creates a rigid foot for efficient push-off.

Electromyographic measurements provide insight into muscle function during gait analysis. At heel strike, the anterior muscles of the leg actively control the descent of the foot to avoid slapping. This eccentric action also absorbs ground reaction forces. Activity of the extensor muscle group is followed by activity of the flexor groups. Flexor activity starts with the tibialis posterior tendon preparing the foot for heel rise. The peroneal tendons provide varus stability as the ankle rotates in dorsiflexion during single-limb stance. The triceps surae then activates, followed by recruitment of the toe flexors, causing heel rise, rapid plantar flexion, and eventual toe-off. In the early swing phase, the plantar muscles relax and the extensors act to dorsiflex the foot again, allowing for clearance and preparation for the next heel strike. As the foot progresses from foot strike to toe-off, the center of load progresses from the center of the heel through the hallux.

In the setting of gastrocnemius tightness, the risk of pain in the forefoot by increased plantar forefoot pressures appears when the muscle is maximally stretched. As a biarticular muscle this happens when both the knee is in extension and the ankle is in dorsiflexion.[36] Some studies have recommended stretching exercises to remedy this biomechanical disturbance, but others found no difference in gait analysis between stretched and nonstretched groups.[37]

Running alters the gait cycle in several important ways. During walking, one foot is always in contact with the ground. With running, however, there are two float phases where both feet are off the ground. In addition, there is no longer a period of double-limb support. Finally, with running, ground reaction force increases, the phasic activity of muscles is altered, and the range of motion of the lower extremity joints increases.

Alterations of normal gait can result in gait dysfunction. In general, a dysfunctional gait pattern leads to insufficiencies that cause increased energy and oxygen consumption. Pain is probably the most common cause of gait disturbance. One study demonstrated that patients with ankle arthritis who underwent either ankle arthroplasty or arthrodesis returned to a more normal gait pattern.[38] In another study, patients who underwent ankle arthrodesis had decreased stride length.[39] Among patients who have undergone amputation, the more proximal the amputation, the higher the required energy expenditure for gait.[40]

Many disorders of the foot and ankle result in discernible and characteristic patterns in human gait. An antalgic gait results from pain and is defined by the shortened stance phase of the affected limb. A steppage gait results from footdrop or weakness of the anterior musculature of the leg. It is characterized by lifting the affected limb higher during the swing phase so the foot adequately clears the ground. A calcaneal gait is characterized by exaggerated heel weight bearing and results from weakness or paralysis of the posterior compartment musculature. A waddling gait is the result of proximal myopathy and is characterized by a broad-based stance with the pelvis drooping toward the leg being raised during the swing phase. This gait abnormality is in contrast to a Trendelenburg gait, which is caused by weakness of the hip abductors and results in compensatory lurching of the trunk toward the weakened side during stance.

SUMMARY

With the advent of new technologies and techniques over the decades, the ability to measure foot and ankle biomechanics has substantially expanded. If surgeons are to create and optimize new treatment options for patients, the knowledge base must continue to expand.

KEY STUDY POINTS

- The foot is divided into three functional zones, the hindfoot, midfoot, and forefoot, each with its own functional role to play.
- At its most basic level, the foot can be likened to a tripod. Alterations in this balance can have biomechanical consequences.
- The transverse tarsal joint locking mechanism results from a complex interplay of both static and dynamic components and is critical for normal foot function.
- Motion coupling occurs between the tibia and the hindfoot through the ankle. Limitations in motion of one component affect the other.

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CHAPTER 2

Shoes and Orthoses

JESSE F. DOTY, MD, FAAOS

ABSTRACT

An understanding of orthosis and bracing biomechanics will provide the foot and ankle clinician with opportunities to improve both surgical and nonsurgical outcomes. A team approach among the patient, physician, and orthotist will ensure success. A fundamental understanding of the basic elements of orthosis and shoe design will allow accurate assessment of contemporary footwear development and market trends. A multitude of commercially available shoes designed with sport-specific purpose or with therapeutic features incorporated into the engineering are now available for more purposeful application of footwear.

Keywords: brace; footwear; insole; orthosis; shoe

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INTRODUCTION

The foot and ankle specialist should be familiar with bracing biomechanics and the effects of footwear components on the lower extremity. A successful bracing program for pathologic foot conditions is the result of history and physical examination characteristics coupled with feedback from both the patient and treating clinician. An orthotist may see the patient and modify the brace multiple times during the manufacturing and fitting process. It is important to discuss the fundamentals of shoe and insole design with updates on recent footwear trends. Knowledge of these topics will help clinicians more effectively communicate with orthotists regarding patient-specific clinical goals and anticipated outcomes.

SHOES

Shoes may protect the sole of the foot from the environment, but they also change the way one walks. A 2019 study showed that, when shod as opposed to walking barefoot, children demonstrated increased velocity, step length, and step time and decreased cadence.[1] Similarly, a 2021 study found that gait characteristics certainly affect shoe lifespan such as treadwear on the outsole.[2] Certain shoe modifications may offer protective advantages or enhance performance. A steel-toe, stiff-sole shoe may protect a manual laborer, whereas a soft-soled, cushioned shoe can prevent skin ulcers in patients with diabetes (**Figure 1**). Athletic shoes are now sport-specific and sometimes customizable. A survey of adolescent cross-country runners revealed that 73% identified arch-type compatibility with shoe design as the most important factor in choosing a shoe. Seventy-four percent reported not knowing how many miles they had logged before shoe replacement, even though loss of midsole cushion recoil is a risk factor for overuse injuries.[3] With injury prevention and playing surface type now being important topics in

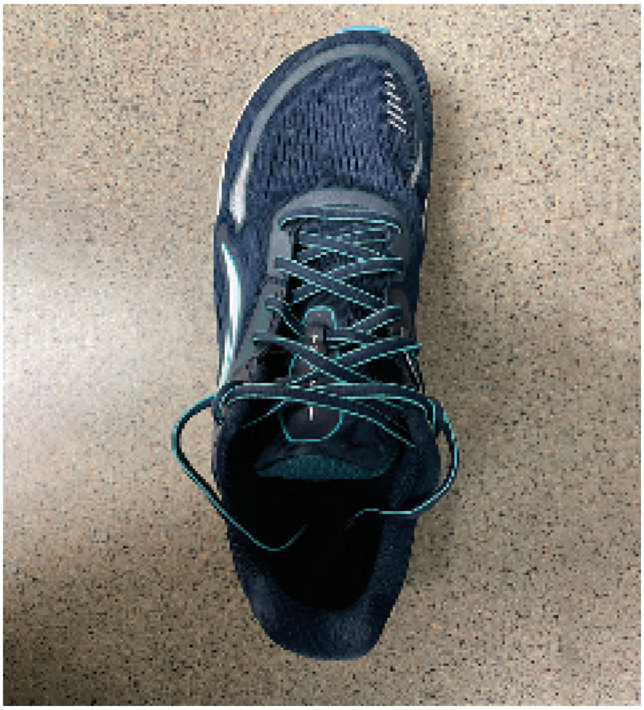

FIGURE 1 Photograph showing a shoe with a wide toe box that can be used to accommodate patients with hallux valgus or hammer toe deformities.

professional sports, organizations such as the National Football League have provided financial support for shoe research and development. Athletic footwear is now considered an integral piece of protective equipment rather than simply an extension of uniform apparel[4] (**Figure 2**). Some evidence suggests that artificial surfaces may increase the rate of injury by failing to release the shoe outsole from the playing surface. Some cleat designs tend to lose friction on natural grass surfaces and sheer more quickly, thereby decreasing torque transferred to the lower extremity.[5] New shoe designs with incorporation of inertial sensors, pressure sensors, and global positioning systems will allow temporospatial data analysis with application for athletics and everyday gait control mechanisms.[6]

Running sports have expanded with increasing popularity of barefoot-style running shoes and maximalist cushioned running shoes. Safety and efficacy of these design concepts are not completely backed by scientific validity. In the case of barefoot-style running, well-designed studies are necessary to prove whether this minimalist running style is beneficial or harmful to overall musculoskeletal health. There is some evidence that peak ground forces are reduced as a runner changes their gait pattern from a hindfoot strike, typical of shod runners, to a forefoot and midfoot strike described by minimalist runners.[7] When transitioning from running in cushioned shoes to minimalistic shoes, runners have increased pressures in the forefoot and may be at risk for stress fractures.[8] Proponents of minimalist running reference studies show decreased exertional compartment syndrome and anterior knee pain.[9] A study[10] evaluated barefoot runners, runners in a minimalist shoe, and runners in a cushioned running shoe. Runners could estimate direction and amplitude of terrain more accurately with a minimalist shoe model. No substantial differences were found between runners using the minimalist shoe model and those who ran completely barefoot. The authors suggested that cushioned shoes substantially impair foot position proprioception compared with less-structured shoes or barefoot conditions. Increased coordination and improved intrinsic muscle foot strength have also been suggested.[11] When comparing 18 runners transitioning to minimalist shoes with 19 control runners who did not switch, the abductor hallucis muscle cross-sectional area increased by 10.6%, but all other muscles tested did not change. Bone marrow edema developed in eight of the minimalist runners, whereas edema developed in only one control runner.[12] A prospective survey followed 107

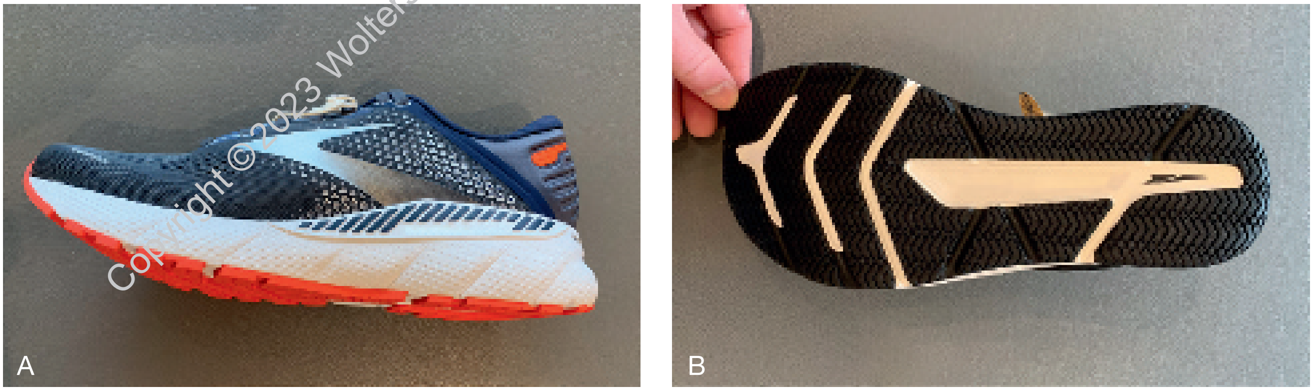

FIGURE 2 **A** and **B**, Photographs showing the design features of this shoe including extension of the midsole proximally to encompass hindfoot and enhance stability.

barefoot runners and 94 shod runners over the course of a 1-year period. Both groups had similar injury rates, although different types of injuries were seen depending on the running style.[13] Electromyographic studies have been used to evaluate the effects of habitual minimalist running on muscle activation. During stance phase, compared with shod runners, minimalist runners had greater muscle activity in the gastrocnemius medialis and gluteus maximus and lower activity in the tibialis anterior. During swing phase, minimalist running exhibited increased muscle activity in the vastus lateralis and medial gastrocnemius.[14]

Increasing variability of running sports has led to another popular alternative running shoe. Running in a thickly cushioned rocker sole has been termed maximalist running. Multiple maximalist running shoe companies such as HOKA and Altra have entered the global footwear market. Proponents of the maximalist running style suggest the extra cushion may prevent lower extremity injuries, particularly in long-distance running. Oxygen consumption with maximalist rocker shoes was found to be 4.5% higher than with standard shoes and 5.6% higher than with minimalist shoes, but this may be due to the larger mass effect of the rocker soles.[15] It has been reported that thicker soles evoke a stronger protective eversion response from the peroneal muscles to counter an increasing moment arm at the ankle-subtalar joint complex following sudden foot inversion.[16,17] Theoretically, thicker soles could increase risk of lateral ligament injury when the protective response of the peroneal tendons is overwhelmed (**Figures 3** and **4**).

Introduction of energy-storing mechanisms into athletic shoes has also seen a recent trend in running developmental technology. The Nike VaporFly shoe was introduced as a new concept in 2017 incorporating a lightweight upper with a new compliant and resilient foam sole providing energy return, and carbon fiber

FIGURE 4 Photograph showing a zero-drop shoe with minimal cushioning to allow the foot to lie flat on the level surface of the outsole.

inserted in the midsole with the goal of improving longitudinal bending stiffness. Some evidence from a 2021 study suggested improved athletic performance in marathon runners shod with this new technology[18] (**Figure 5**).

The influence of high-fashion footwear on foot and ankle pathoanatomy has long been a subject of concern. Some injuries, such as ankle sprains, are more likely to occur based on the positioning of the ankle mortise while in an extremely positive heel drop shoe. Habitual high-heeled shoe wearers have additionally been shown to have decreased range of motion in dorsiflexion and eversion compared with flat-shoe wearers.[19] The authors recommended ankle exercises and gastrocnemius stretching for habitual high-heeled shoe wearers. High heels also adversely affect muscle control and reduce loads in the quadriceps and spine musculature, and it has been suggested that the addition of a total-contact insert to a shoe might improve comfort rating and foot stability.[20] Despite continued evolution and specialization of footwear, many of the basic components that make up a shoe remain the same (**Table 1**).

FIGURE 3 Photograph showing a maximally cushioned athletic shoe.

FIGURE 5 Photograph showing lightweight advanced foam incorporated with a carbon-fiber reinforcement to store energy and provide recoil.

Table 1

Basic Shoe Components

Upper	Encloses the dorsal foot above the insole; includes the toe box, vamp, and quarter
Lower	Plantar to the foot; includes the insole, midsole, and outsole
Toe box	Distal portion of the upper that provides space for the toes
Vamp	Midsection of the upper that covers the dorsum of the midfoot
Quarter	Posterior portion of the upper that covers the hindfoot; may have a reinforced area around the heel known as a heel counter
Insole	Portion of the lower that directly contacts the plantar surface of the foot and is frequently removable
Midsole	Cushioned area designed for shock absorption between the insole and outsole
Outsole	Portion of the lower that contacts the ground and provides traction

SHOE MODIFICATIONS

Historically, commercially available shoes were designed to protect the sole of the foot from the environment with few anatomic or pathologic considerations. Over the past few decades, consumer demand and industry marketing resulted in further shoe specification. Now patients with subtle anatomic deviations or chronic conditions may achieve pain relief through strategic footwear selection. For instance, forefoot malalignment can be accommodated by a shoe with a wide toe box to relieve pressure on the metatarsals and toes. Shoe companies market styles with varied degrees of arch support to accommodate runners with either planus or cavus alignment to increase comfort and stability. Patients with diabetes now have easier access to therapeutic in-depth shoes designed to relieve pressure over bony prominences by incorporating soft uppers with cushioned insoles. In-depth shoes feature an additional 0.25 to 0.375 inch of insole cushioning and can be modified by removing the factory inlay and inserting a custom orthosis without affecting the overall fit.[21]

Shoes can be modified to increase ambulation efficiency and compensate for decreased motion secondary to pain, fusion, arthritis, or deformity (**Table 2**). Typically, this is done by modifying the insole or midsole to increase stability or offload high-pressure areas.[21] Modifications may delay the need for surgical intervention or provide temporal relief for poor surgical candidates. The upper portion of a shoe can be stretched with a ball-and-ring stretcher to soften the material and make room for bony spurs, hallux valgus deformity, or a hammer toe. The vamp of the shoe may cause increased pain by compressing the sensory nerves over osteophytes in midfoot arthritis, and this can sometimes be relieved with simple alterations such as alternate lacing patterns or elastic laces. For plantar pain, a factory insole can be

Table 2

Shoe Types and Modifications

In-depth shoe	Additional 0.25 to 0.375-inch depth to accommodate deformity; may come with easily exchangeable insoles
Custom shoe	Fabricated from a mold or a CT scan to provide additional accommodation and protection
Relasting	Customization of a commercial shoe to accommodate deformity while maintaining the normal appearance. The outsole is removed and a cut is made through the remaining sole to add material, and then the outsole is reapplied
Flare	A firm strip of material added as an outrigger to provide a wider base of support on the sole for increased stability
Shank	Steel or carbon composite embedded in the sole to stiffen it from heel to toe; used to decrease bending forces
Rocker sole	Additional material generally added to the midsole to create a cam to allow rolling from heel strike to toe-off with decreased bending
	In general, the apex of the rocker is placed proximal to the area where pressure relief is desired

supplemented or removed and replaced with a commercially available insole or a custom insole. A metatarsal bar pad may additionally offload the metatarsal heads and relieve metatarsalgia during gait. Pads and insoles are manufactured in multiple sizes and shapes and are often commercially available.

Simply exchanging a thin, standard factory insole for a thick gel, foam, or air-cushioned insole may help relieve metatarsalgia, heel pain, or generalized foot discomfort. An orthosis redistributes forces by increasing support and contact area under the midfoot while decreasing pressure under the hindfoot and forefoot.[22] Some conditions may be relieved by retaining the cushioned insole and reducing shoe flexibility by adding a shank to the sole. A shank may stiffen the shoe enough to relieve pain from hallux rigidus, metatarsalgia, and midfoot arthritis by decreasing painful joint excursion. According to a 2019 study, some companies have engineered a carbon plate into insoles or into commercially available shoe midsoles to add recoil and propulsion for running.[23] Because of stress shielding, this carbon-fiber plate could also be therapeutic for the treatment of midfoot and forefoot stress syndromes or arthritis (**Figure 6**). Additionally, shoes should fit appropriately, which necessitates correct shape and depth with at least 0.375 inch of length past the longest toe to avoid impingement and to accommodate devices such as an orthosis.

A cobbler or pedorthist may add a rocker to the shoe by adding material to the midsole. This may decrease floor-reaction forces and bending forces on the foot. The rocker bottom may limit painful arthritic joint excursion, offload metatarsalgia, or improve gait in patients after arthrodesis procedures.[24] It may also be effective in reducing the windlass effect contributing to plantar fasciitis.[25] A negative heel rocker outsole design will alter the gait of a patient with diabetic neuropathy by reducing push-off power and thereby decrease ground reaction forces and peak forefoot pressures. However, a rocker sole can also compromise stability and gait symmetry, which may contribute to limited patient acceptance and limited use in clinical practice.[26]

Wedges or posts can be used to address varus or valgus deformities at the forefoot and hindfoot. A medial heel wedge provides a varus moment to the hindfoot, which may decrease lateral impingement or improve hindfoot position in patients with pes planus. Runners with pes planus have reported a decreased incidence of foot and knee pain when a medial heel wedge was added to their soft insole.[27] A lateral heel wedge provides a valgus moment to the hindfoot, which may relieve tension on the peroneal tendons and treat symptoms of lateral instability. Posting the forefoot can also indirectly alter hindfoot mechanics. Medial posting of a varus forefoot can decrease the valgus moment transferred to the hindfoot. Lateral posting of a valgus forefoot can decrease the varus moment transferred to the hindfoot.[28] A wedge insole also has the potential to affect other more proximal joints along the kinetic chain, such as a lateral wedge insole to unload medial knee osteoarthritis.[29]

ORTHOSES

An orthosis is a device used to support, align, prevent, or correct deformities or to improve functions of body motion. A basic understanding of the terminology and the clinical applications of orthoses ensures effective fabrication and biomechanical accuracy. Although much of this is based on clinical diagnosis and patient feedback, as discussed in a 2021 study new technology including computerized analysis with three-dimensional limb scanners has proved beneficial.[30] A foot orthosis extends from the heel to the forefoot area, whereas an ankle-foot orthosis (AFO) extends above the ankle joint. The goal is to alter the biomechanics or to achieve comfort and protection by offloading certain areas and distributing weight to a broader surface area. An orthosis can be designated as accommodative, supportive, or corrective. An accommodative orthosis is generally made of softer material shaped much like the patient's native anatomy to

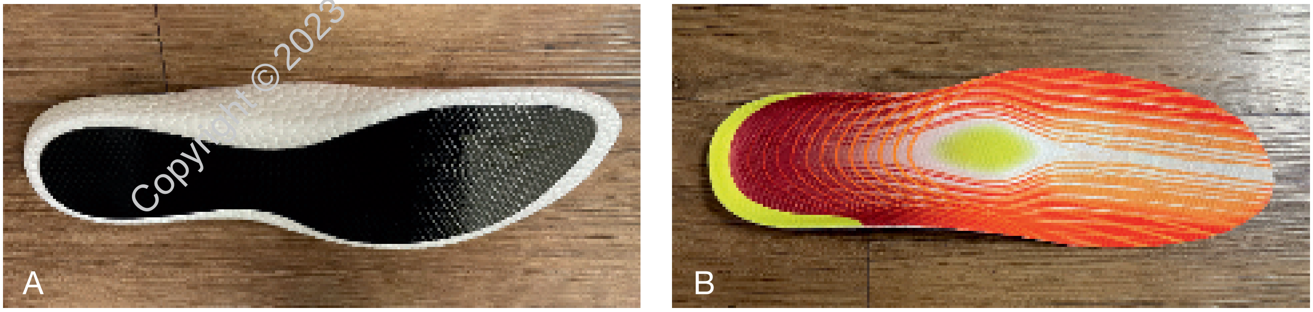

FIGURE 6 **A** and **B**, Photographs showing commercially available insoles that can be inserted into footwear for treatment of certain pathology or to enhance the exercise experience.

more evenly distribute weight along the plantar surface of the foot for cushioning and pressure relief. A supportive orthosis may be used to help stabilize a flexible deformity such as a flexible flatfoot treated with an arch support. A corrective orthosis is manufactured to intentionally alter alignment with anatomy deviation. Molded thermoplastic is a popular material used to provide and preserve the shape of an orthosis.

When writing an orthosis prescription, it also helps if the clinician designates the length of the desired orthosis. A full-length orthosis extends to the tip of the toes, a sulcus-length orthosis extends to the base of the toes, and a three-quarter–length orthosis ends proximal to the metatarsal heads. Ankle and hindfoot pathology may often be managed with a three-quarter–length orthosis. However, when forefoot pathology exists or when forefoot posting is desired, a full-length or sulcus-length orthosis is most effective. Sometimes when pathology is primarily localized to the midfoot or hindfoot, it may be even more effective to extend the orthosis above the ankle. This can be done using an articulation, which allows sagittal ankle motion while decreasing varus and valgus forces. An articulated AFO may be beneficial for treatment of tendon pathology such as posterior tibial tendinitis or peroneal tendon dysfunction.[31]

A nonarticulated or solid-ankle AFO more completely immobilizes the ankle and can be used for ankle arthritis treatment. A dorsal wrap across the midfoot can be incorporated on the AFO to add rotational control for additional stability of the midfoot and hindfoot. An articulated AFO with a dorsal midfoot wrap will preserve ankle motion but also decrease rotational stresses contributing to pain from subtalar or midfoot arthritis. An AFO allows patient-specific customization, although noncustomized braces are readily available for some pathologies. Common AFO modifications are listed in **Table 3**.

Table 3

Ankle-Foot Orthosis Types and Modifications

Solid-ankle AFO	Trim lines fully enclose the malleoli to substantially decrease mobilization of the foot and ankle complex
Semisolid-ankle AFO	Trim lines enclose the posterior soft tissues but do not project anteriorly along the malleoli; allows limited ankle motion with weight bearing but dampens ground reaction forces
Posterior leaf spring AFO	Trim lines are narrow posteriorly and flexible to allow weight-bearing motion; retains shape memory to assist in dorsiflexion during swing phase
Articulated AFO	Foot and leg segments connected by an articulating mechanism aligned with the axis of the ankle to allow controlled sagittal motion. The hinge can be modified to restrict or assist in certain motions
Wrap-around AFO	Completely encloses the foot, ankle, and lower leg; maximizes skin contact area and may more effectively maintain desired alignment
Double upright AFO	Often attaches to the exterior of the shoe; skin contact is avoided; may be desirable for patients with swelling or skin breakdown
Carbon-fiber AFO	Many of the same designs and functions of plastic AFOs; carbon decreases bulk and returns recoil energy to the patient during gait
Post	Wedge under the medial or lateral forefoot to bring the floor up to a varus or valgus deformity or used in the hindfoot medially or laterally to tilt the heel
Cutout	Well, recess, or depression that can be used to unload a specific area
Lift	Generally used as a neutral heel wedge to lift the heel and relax the Achilles tendon
Cushion	Foam or other soft material used plantarly to relieve plantar pressure
Extension	Rigid lengthening of the sole to the tips of the toes to decrease bending forces of the midfoot and forefoot
Flange	Semirigid rim or lip extension on the orthosis to help support a certain area such as a collapsed arch
Metatarsal bar	Pad placed proximal to the metatarsal heads to unload plantar pressure at the area distal to the pad

AFO = ankle-foot orthosis

In a systematic review of 11 randomized controlled trials, it was reported that custom foot orthoses may produce clinically important improvements.[32] Custom foot orthoses appeared to be slightly beneficial in juvenile idiopathic arthritis, rheumatoid arthritis, pes cavus, and hallux valgus deformities. However, surgical treatment was reported to be more beneficial for hallux valgus deformities, and prefabricated orthoses were just as effective as custom orthoses for juvenile idiopathic arthritis.[32,33] A separate report found no difference in progression of the hallux valgus deformity with or without an orthosis.[34] A meta-analysis and a separate randomized controlled trial on the use of foot orthoses for the treatment of plantar fasciitis reported that custom and prefabricated orthoses were equally effective in diminishing pain.[35,36] When a foot orthosis is combined with a rocker bottom sole, it may be more effective in reducing plantar fasciitis pain.[37] A study on the use of nighttime AFOs in treating plantar fasciitis pain reported that an anterior orthosis was more comfortable and more effectively decreased pain than a posterior orthosis.[38]

A foot orthosis may have a positive effect on chronically unstable ankles because it influences multiple levels of somatosensory feedback and neuromuscular control.[39] A cavus foot orthosis that included a recess at the first metatarsal head and a ramp (post) at the lateral forefoot was effective in reducing ankle instability by decreasing forefoot-driven hindfoot varus. In an evaluation of flexible severe flatfoot treated with foot orthoses, the authors randomized 160 children to control, custom orthosis, and prefabricated orthosis treatment groups.[40] At 3- and 12-month follow-up, motor proficiency, self-perception, exercise efficiency, and pain were evaluated, and the authors found no evidence to justify the use of orthoses. The consideration of soft insoles with an elastic support orthosis in patients who find it comfortable and supportive may be the most practical, as discussed in a 2021 study.[41] In a meta-analysis of foot orthoses for lower limb overuse conditions,[42] no difference in custom versus prefabricated orthoses was seen. Although an orthosis appears to help prevent a first incidence of an overuse condition, little evidence supports therapeutic effectiveness after the overuse condition has developed.

Investigators looked at 25 feet and ankles with Charcot arthropathy in an attempt to identify an alternative to the Charcot Restraint Orthotic Walker and total-contact casting.[43] They reported that a prefabricated pneumatic removable walker brace (Aircast) fitted with a custom insole can successfully be used to manage Charcot arthropathy. The brace was an effective immobilizer during healing and was associated with a high satisfaction rate and safety profile.

Prefabricated walking boots or controlled ankle motion boots are often prescribed for foot and ankle patients in the immediate postinjury or postoperative period. Although therapeutic on the braced extremity, this may result in limb-length discrepancy, with gait deviations leading to pain in other joints or the lower back. The EVENup Shoe Lift was designed to eliminate the gait disturbance from the boot by applying more thickness to the shoe sole of the uninjured limb. In a group of patients undergoing unilateral lower extremity orthopaedic care, clinically relevant differences were found between the EVENup intervention group and the control group[44] (**Figure 7**).

Military combat injuries have been characterized by high-energy explosive wound patterns to the extremities. Surgical advances and rehabilitation programs have been developed to pursue limb salvage. The Intrepid Dynamic Exoskeletal Orthosis (IDEO, TechLink) was created to improve functional capabilities of the limb-salvage wounded warrior population and to be used in a high-intensity rehabilitation program known as the Return to Run clinical pathway. The IDEO is a custom AFO in which a proximal patella-bearing clamshell cuff helps offload the extremity and the foot-plate limits extremes of ankle motion. The IDEO's plantar flexion design shape and

FIGURE 7 Photograph showing an orthotic shoe lift to provide equilibrium for patients wearing a boot on the contralateral extremity.

FIGURE 8 Photograph of an energy-storing orthosis commonly used in military veteran amputees.

carbon-fiber material store and deliver energy that simulates plantar flexion power. Researchers evaluated participants' functional performance in the IDEO and soldiers had improvements in multiple functional tests. After completion of the Return to Run clinical pathway with utilization of the IDEO, 70% of those who initially desired amputation chose to keep their limb, as discussed in a 2022 study[45] (Figure 8).

SUMMARY

Patients with painful lower extremity conditions and especially those who are poor surgical candidates may experience symptomatic relief with an orthosis, brace, or shoe modification. Basic knowledge of bracing treatment allows the clinician to accurately communicate goals to an orthotist. Some patients will inevitably opt for surgical intervention as wearing a brace can change walking speed, step length, and cadence and create limb asymmetry. Updated technology continues to be studied and incorporated into shoes and orthoses to further optimize safety, function, and patient satisfaction.

KEY STUDY POINTS

- A concerted effort including the patient, physician, and orthotist will ensure an effective bracing algorithm.
- Commercial footwear may be engineered with sport-specific purpose and therapeutic features incorporated into the overall design.
- Scientific evidence is limited and both risks and benefits exist to new running styles such as barefoot-style or maximalist cushioned running.
- An evolution to the final orthotic product is based on clinical examination and diagnosis coupled with feedback from the patient and global treatment team.
- Commercially available insoles, custom insoles, and orthoses extending above the ankle all have efficacy with purposeful utilization in the appropriate patient subsets.

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    The elastic foot orthosis brace decreased foot strain and may help support the arch during movement. Level of evidence: II.