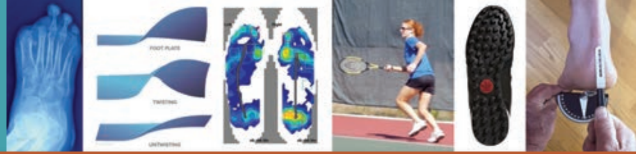

Using the Twisted Plate Mechanism to Optimize Orthotic and Surgical Treatments of the Human Foot

These 6 proposed recommendations should improve these devices.

BY DOUGLAS H. RICHIE JR., DPM

Introduction

In 1945, Michael MacConaill, an Irish anatomy professor, published an article titled "The Postural Mechanism of the Human Foot" in the Proceedings of the Royal Irish Academy.[1] MacConaill's rather simple but novel observations laid the groundwork for an evolving understanding of foot function which has now been embraced around the world by experts in lower extremity biomechanics, surgery and orthotic therapy.

Figure 1: The Twisted Plate arrangement of the foot bones: The talus and calcaneus are "compressed" vertically while the metatarsals are "compressed" horizontally.

MacConaill's original paper made observations about the unique configuration of the bones of the foot compared to the hand in humans. Specifically, he noted that the "footplate" bones are twisted upon themselves, creating multiple arches spanned by ligaments whose tension is in an alterable state (Figure 1).

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The opening paragraph of MacConaill's article states:

"The bones and ligaments of the human foot form a twisted osteo-fibrous plate of irregular thickness; the degree of torsion of the tarsometatarsal part of this plate is alterable. The torsion of the foot skeleton is brought about in intra-uterine life."

The Footplate of Bones Twists In-utero

Indeed, Saraffian showed how the footplate of bones twists in-utero.[2] The cartilaginous bones of the foot of the 6 week human embryo are all oriented in a single horizontal plane, while 2 weeks later, the calcaneus has migrated medial and inferior to the talus. The vertical orientation of the talus stacked over the calcaneus, with the metatarsals remaining in the horizontal plane, represents the "twisted" alignment of the bones of the human foot, not seen in any other primate species.

Saraffian also demonstrated how "twisting" of the footplate bones continues thru the 9th month of fetal development. The head of the talus undergoes valgus rotation from a position of 19 degrees pronated at 5 months, increasing to 26 degrees valgus at 9 months and finally achieving 37 degrees of lateral rotation in the adult (Figure 2).

These changes in the structure of the talus initiate a twisting of the forefoot relative to the rearfoot in the direction of pronation and also carry the first ray into adduction towards the second metatarsal. Ultimately, this places the plane of all of the metatarsals flat on the ground.

Besides introducing the twisted plate arrangement of the bones of the foot, MacConaill made important observations about the changes which occurred as the foot is moved from a pronated to a supinated position in

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both open and closed kinetic chain. He observed that:

1) The talus moves with the leg while the remaining bones of the foot, named by MacConaill the "lamina pedis", rotate beneath the talus in a three-dimensional pattern.

2) Pronation of the forefoot bones on the rearfoot bones "twists" the footplate to raise the medial longitudinal arch and the transverse tarsal arch (Figure 3).

3) Supination of the forefoot bones on the rearfoot "untwists" the footplate. This lowers the medial longitudinal arch and transverse tarsal arch while increasing tension on the spring ligament, the plantar aponeurosis and the long and short plantar ligaments.

4) The footplate bones primarily rotate around the head of the talus in a socket which MacConaill called the "acetabulum pedis" due to its resemblance to the hip socket. It should be noted that MacConaill was not the first to use the term acetabulum pedis, as it was originally described in 1806 by Scarpa.[3]

5) During rearfoot supinaton and pronation, the forefoot will twist on the rearfoot in order to keep all five metatarsal heads on the ground. This had actually been previously described by the noted surgeon Arthur Steindler in 1929.[4]

6) Rearfoot pronation will induce forefoot supination while forefoot supination will induce rearfoot pronation.

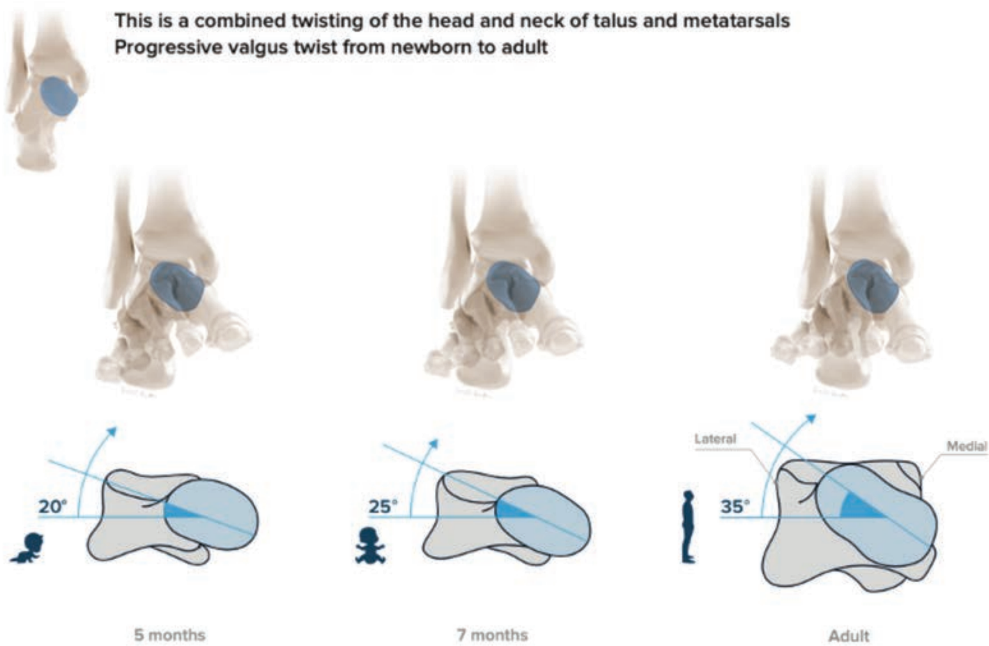

Figure 2: This sequence shows the combined twisting of the head and neck of the talus and metatarsals. There is a progressive valgus twist from that of a newborn to an adult.

Unloaded vs Loaded

It should be clarified that the rotation of the footplate is quite different in the unloaded (off-weight-bearing) foot compared to what occurs during a loaded condition in dynamic gait. When the examiner point loads the plantar surface of the unloaded foot, the entire footplate bones rotate as a single unit at the posterior facet of the subtalar joint and rotations occur at the simplistic axis originally described by Hicks.[5]

However, with weight-bearing, multiple joints in the foot are engaged. The center of rotation occurs, according to MacConaill, at the acetabulum pedis. which is the combined articulations of the talonavicular joint as well as the anterior and middle facets of the subtalar joint (Figure 4). This complex is often referred to as the talocalcaneonavicular joint.[6]

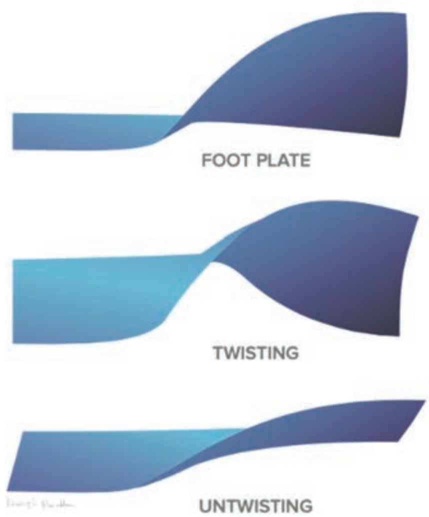

Figure 3: Twisting a plate of bones establishes the medial, lateral, and transverse arches of the foot.

Shape of the Talus

Verification that the shape of the talus determines the direction and magnitude of rotation of all the bones rotating beneath was provided in a recent study conducted by Behling, et al. This study showed that the navicular, cuboid, and calcaneus rotate about a commonly-oriented axis which is established by the articular surface morphology of the talus.[7]

Sarrafian expanded upon MacConaill's twisted plate observations to show how rotation of the forefoot on the rearfoot was strongly coupled with transverse plane rotation of the talotibiofibular unit.[8] In a cadaver model, Sarrafian showed how internal rotation of the tibia induces rearfoot pronation coupled with forefoot supination (Figure 5).

Reciprocally, he demonstrated how a supinated position of the forefoot increased tensile strain in the plantar aponeurosis and restricted dorsiflexion of the 1st MTPJ, a phenomenon previously described by Hicks as the "reverse windlass mechanism" (Figure 6).

Saraffian also demonstrated how twisting of the footplate by pronating the forefoot on the rearfoot, or supinating the rearfoot on the forefoot, would raise the height of the medial longitudinal arch as well as the transverse tarsal arch (Figure 3).

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The establishment of the transverse tarsal arch is a unique feature of the human foot not seen in other primates. Recently, Venkadesan and co-workers demonstrated how the curvature of the transverse arch is responsible for more than 40% of the longitudinal stiffness of the human foot.[9]

The concept that the footplate bones, i.e. "lamina pedis", rotates beneath the talus has been embraced by many authorities since the work of MacConaill and Basmajian.[10-12] The term "lamina pedis" was renamed the "calcanopedal unit" by several French orthopedic surgeons, including Meary and Queneau (Figure 7).[13]

The Calcaneopedal Unit

In 2019, a renowned group of international pediatric orthopedic surgeons published "Understanding the Foot's Functional Anatomy in Physiological and Pathological Conditions: The Calcaneopedal Unit" in the Journal of Children's Orthopedics.[14] These surgeons proposed the concept that rotation of the footplate bones beneath the talus can explain congenital talipes equinovarus (clubfoot), cavus foot and pes planovalgus deformities. More important, they outlined specific surgical strategies to correct the multiplane rotational deformities seen in these conditions based upon the twisted plate concept originally described by MacConaill.

With this rationale, a cavus foot represents an overly pronated forefoot and is remedied by a dorsiflexion osteotomy of the medial cuneiform. A pes planovalgus deformity has forefoot supination, which is corrected by a plantarflexion osteotomy of the medial cuneiform while hindfoot valgus is corrected with a calcaneal osteotomy. In every case, correction of forefoot alignment is the primary strategy to secondarily correct rearfoot alignment.

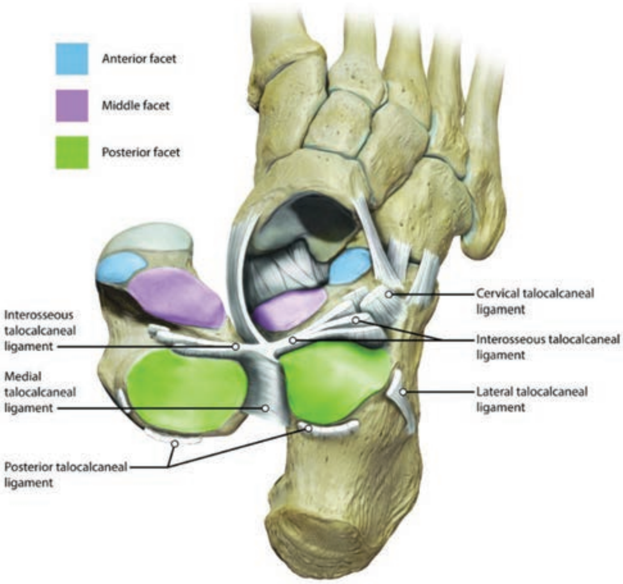

Figure 4: The acetabulum pedis: The talus is reflected to show the socket containing the navicular as well as the anterior and middle facets of the calcaneus.

Figure 5: Twisting the plate.

Figure 6: Untwisting the plate.

Figure 7: Horizontal segmentation between the foot and the leg.

Merton Root

Merton Root and colleagues followed the twisted plate principles of foot mechanics in their description of compensation for foot deformities.[15] Root, et al. described proper positioning of the patient when performing negative impression casting for functional foot orthoses.[16]. They advocated pronating the forefoot on the rearfoot maximally during the impression casting procedure, which incidentally enhances the twisted plate mechanism.[16]

Root, et al. did not specifically discuss the twisted

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plate when describing ideal positioning of the human foot, but instead believed that pronating the forefoot on the rearfoot would "lock" the midtarsal joint. In reality, this would only promote osseous locking at the calcaneocuboid joint, described by Bojsen Moeller.[17]

More importantly, pronating the forefoot on the rearfoot would favorably "twist" the footplate to restore the medial and lateral longitudinal arches as well as the transverse tarsal arch while reducing tension on the critical spring and plantar ligaments. A foot orthosis fabricated to this shape would theoretically optimize plantarflexion of the first ray, dorsiflexion of the hallux and reduced strain on the plantar aponeurosis.

The lateral longitudinal arch is the critical area of the functional foot orthosis to resist forefoot supination.

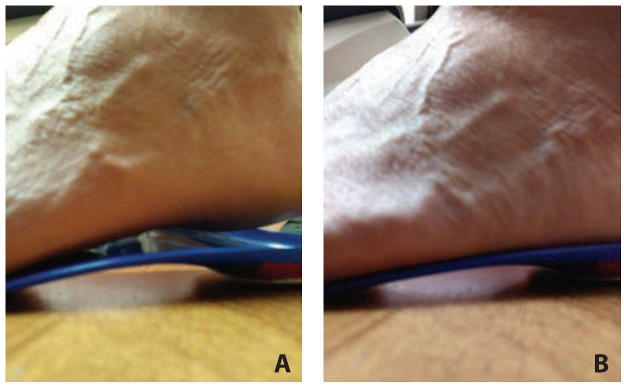

Figure 8: The lateral side of the foot orthosis should not deform with loading, thus preventing forefoot supination. (A) Unloaded foot orthosis. (B) Loaded foot orthosis: no lateral column collapse, no forefoot supination.

Proposed Guidelines for Optimizing Foot Orthotic Therapy

The following guidelines are proposed for optimizing foot orthotic therapy using the twisted plate mechanism of the human foot:

1) A forefoot varus or forefoot valgus deformity is captured when the forefoot is pronated on the rearfoot while maintaining the subtalar joint in a neutral position.[15] Forefoot to rearfoot deformity should still be supported by the functional foot orthosis.[16]

2) A comparison of surface area and moment arm shows that the forefoot has greater leverage against the rearfoot compared to vice versa.[13,14]

3) Forefoot position can be used to optimize rearfoot position using the following two twisted plate concepts:

a) Pronation of the rearfoot during weight bearing cannot occur without reciprocal supination of the forefoot.

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b) Rearfoot pronation can be blocked by preventing forefoot supination

4) Pronation of the forefoot on the rearfoot during impression casting/scanning will produce an orthosis shape which will resist forefoot supination

5) The lateral longitudinal arch is the critical area of the functional foot orthosis to resist forefoot supination.

6) This lateral section of the foot orthosis should be non-yielding and conform to the lateral column of the foot in order to resist forefoot supination (Figure 8). **PM**

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