FALL 2021

Paris ORTHOTICS

INDUSTRY BULLETIN

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MODELS OF PODIATRIC BIOMECHANICS

PART I: SAGITTAL PLANE FACILITATION MODEL

Over the next few Industry Bulletins, we will be reviewing three of the models of podiatric biomechanics that have emerged over the past 35 years: Sagittal Plane Facilitation Model (SPFM), Tissue Stress Model (TSM) and the Kirby Model (Subtalar Joint Axis Location and Rotational Equilibrium Theory). In addition to this, we will touch on how custom foot orthotic solutions have evolved with these emerging theories.

For efficient foot function through the sagittal plane, there must be a coordinated effort between power generation and the foot's autosupportive mechanisms. The SPFM is heavily reliant on the healthy function of the 1st MTPJ and the contribution it makes to the three autosupportive mechanisms of the foot including: 1) the Windlass mechanism; 2) close-packing of the calcaneocuboid joint (C-C joint); and 3) the Truss and Locking Wedge Model.

Hicks (1954) originally introduced the concept of the windlass mechanism as a winch whereby the hallux acts as a lever arm (Figure 1). With dorsiflexion of the digits, there is a pull on the insertion of the plantar fascia which in turn shortens its base from the digits to the rearfoot. This tightening of the plantar fascia thus increases tension and stability of the midtarsus. Additionally, this mechanism facilitates inversion of the foot and external rotation of the leg during propulsion.

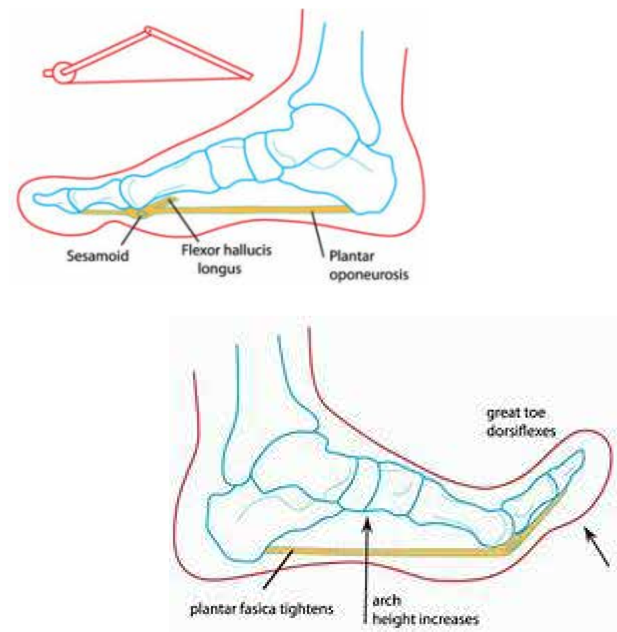

Figure 1: Hicks Windlass Mechanism

According to the SPFM, the supination of the foot and the tightening of the plantar aponeurosis helps to ensure the next autosupportive mechanism: close-packing of the calcaneocuboid joint (C-C joint). Bosjen-Moller first described this mechanism in the late 1970s. Close-packing of the C-C joint compresses the joint prior to heel lift and requires that weight flow be transferred through the ½ interspace (Figure 2). The net effect of this mechanism is that the rearfoot is stabilized by a compression of the C-C joint just before heel lift. It has been suggested that the close-packing of the C-C joint likely requires that the 1st MTPJ dorsiflexes greater than 50-60°.

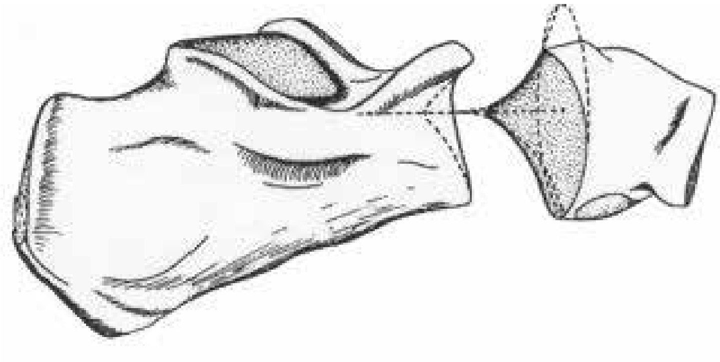

Figure 2: Close-packing of the calcaneocuboid joint.

Lastly, the Truss and Locking Wedge Model was also contributed by Hicks along with a contribution from Lapidus (1955). These authors suggested that the foot can function either as a beam or as a truss. Beams have the ability to withstand applied force by utilizing their ability to resist bending. Trusses provide support through compression of internal components. During the propulsive phase of walking, as the heel rises from the ground the MTP joints dorsiflex, the metatarsals are oriented vertically while at the same time increasing weight to the supporting surface.

The SPFM had its origin in the Podiatry office of Dr. Howard Dananberg, DPM in the early 1980s. Lee (2001) described in his publication that Dananberg first observed what was later termed functional hallux limitus (FHL) in 1983. At the time, Dr. Dananberg was using a Electrodynogram (EDG) to assess the plantar pressure/force in individuals during gait examinations (Figure 3). The EDG was a clinical tool that allowed practitioners to measure pressures/forces inferior to six anatomical locations including: the 1st, 2nd and 5th metatarsal heads; the hallux; and the medial and lateral condyles of the calcaneus.

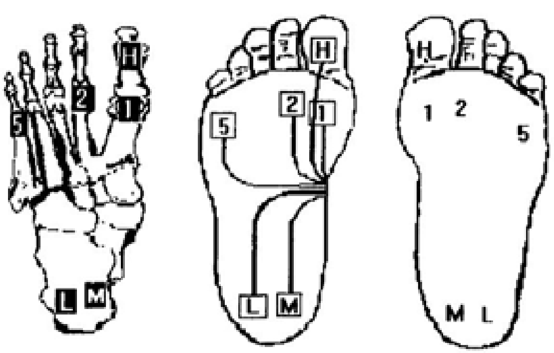

Figure 3: Electrodynogram

Dananberg was assessing a patient who had chronic lower back pain. On non-weightbearing exam, the patient presented with within normal limits, 1st MTPJ dorsiflexion but dynamically the patient exhibited an asymmetry whereby the sub-hallux pressures were markedly increased on the left side. Additionally, Dananberg observed that the tibialis anterior was firing during midstance and that there was inversion compensation on the left side. Dananberg recognized that this was a typical compensation for classic hallux limitus but given that there was full range-of-motion, non-weigtbearing, realized that this was a unique clinical presentation.

This appears to be the first documented case of what Dananberg coined a functional sagittal plane blockage of 1st MTPJ dorsiflexion or what is know known as functional hallux limitus (FHL).

Quantitatively using the EDG, Dananberg established that functional hallux limitus is likely present if:

1.The force pattern is constant (flat line) through the greatest weight transfer (single support). With healthy walking, one would expect to see an unloading of the calcaneus coupled with increasing force under the forefoot. If the force curve is constant/flattened, this is indicative of an interruption in the raising of the centre of mass (COM) that is likely caused by a failure in the progressive weight transfer caused by functional hallux limitus.
2. There is a breakdown in the timing of hallux vs 1st MTPJ loading. If it is observed that there is loading under the hallux before the 1st MTPJ sensor, functional hallux limitus is likely present.
3. Prolonged contact of the heel/calcaneus greater than 62% of the stance phase.
4. Heel strike before heel lift on the ipsilateral side.
5. Increased loading under the 5th metatarsal.

This breakdown will be helpful to those who incorprate pressure mapping in their clinical practice.

In the years that followed, Dananberg published papers describing functional hallux limitus and defined it broadly as:

The failure of the hinge apparatus of the 1st MTPJ to flex at any time during the single support, weight bearing phase of gait. Normal, full range of motion of the 1st MTPJ is detectable during non-weight bearing examination. However, locking occurs during the course of a step. This may occur for moments in time and be undetected by standard visual observation.

COMPENSATORY MOVEMENT PATTERNS

With a blockage in sagittal plane motion of the 1st MTPJ, it has been postulated that there are likely several compensatory motions that occur including: 1) altered heel lift; 2) vertical toe off; 3) inverted step; 4) adducted or abducted toe off; 5) forward flexion response.

In healthy individuals, heel lift typically occurs at approximately 60% of single limb stance. Using the EDG technology, Dananberg observed that the timing of heel lift was delayed in individuals exhibiting FHL. For healthy dynamics, this progression is reliant on 1st MTPJ dorsiflexion. If this is absent, there is typically compensation whereby the midfoot dorsiflexes about its oblique axis, i.e. midfoot break (Albert & Curran, 2013). Secondly, a vertical toe off will likely be present whereby the individual simply lifts the foot, straight off the ground. This results in laborious or apropulsive gait.

Thirdly, individuals with FHL will exhibit an avoidance strategy referred to as an inverted step or forefoot inversion where there is lateral weight flow to the forefoot (Albert & Curran, 2013). This lateral deviation in weight flow results in the failure of one or more of the foot's autosupportive mechanisms. Clinically, footwear inspection and wear patterns can provide clues that this is occurring, dynamically. Typically, one will observe lateral distortion/bulging of the shoe upper or compacting out of the lateral forefoot of the sock liner.

Individuals will often present with an adducted (in-toeing) or abducted (out-toeing) toe off. Again, when there is deficient 1st MTPJ dorsiflexion, the foot will take the path of least resistance that does allow for sagittal plane facilitation. The compensation is believed to include either an internal or external rotation of the hip and leg to detour around the sagittal plane blockage at the 1st MTPJ.

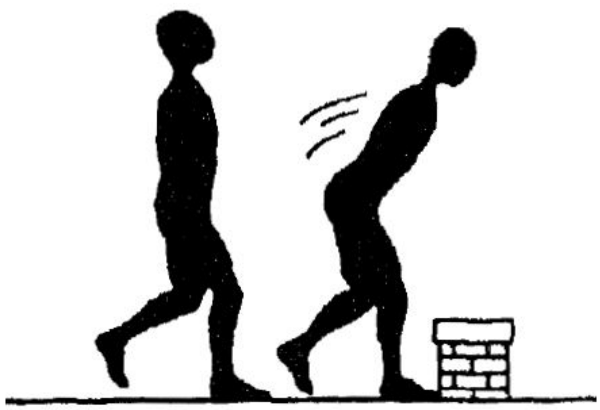

Figure 4: Flexion Response

Lastly, the forward flexion response is a postural compensation and is the result of a breakdown in knee and hip extension in the later phase of single-limb stance (Figure 4). With FHL, the hip and knee tend to be maintained in a flexed position. Higher up the chain, this results in a straight spine, or a lack of the natural lumbar lordosis required for force absorption and stability (Figure 5). Dananberg has attributed postural malalignment and low back pain to this compensatory motion.

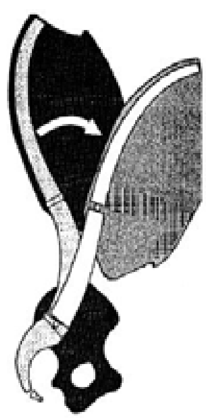

Figure 5: Reduced lumbar lordosis with flexion response.

ALTERNATIVE IDEAS

The SPFM is primarily suggesting that there are proximal compensations occurring (breakdown of autosupportive mechanisms, instability of the midtarsus) because of a distal blockage (decreased 1st MTPJ dorsiflexion), i.e. distal-to-proximal compensation.

An alternative approach has been suggested by Richie (2021). The SPFM suggests that it is the windlass mechanism that pre-tightens the plantar fascia and subsequently facilitates close packing of the C-C joint, i.e. distal-to-proximal compensation.

Richie (2021) provides an alternative interpretation of Bojsen-Moller's work suggesting that it may be the pronation of the forefoot on the rearfoot that pre-tightens the plantar fascia and leads to the close-packing of the C-C joint. If this were the case, this mechanism would therefore occur before the windlass mechanism. In essence, it is the pronation and close-packing of the C-C joint caused by ground reaction forces that facilitates eventual load to the 1st MTPJ. It is plausible that increased or prolonged pronation leads to decreased 1st MTPJ dorsiflexion and there have been studies showing this association, i.e. proximal-to--distal compensation (Gatt et al., 2014). Intuitively, increased pronation would result in increased tensile strain on the medial slip of the plantar aponeurosis. This would likely increase the internal plantar flexion moment of the 1st MTPJ and potentially restrict dorsiflexion, i.e. reversed windlass mechanism (Figure 6 from Harradine et al., 2006).

Not unlike knee pain, the question is how do you intervene? From the distal aspect, the proximal aspect, or both.

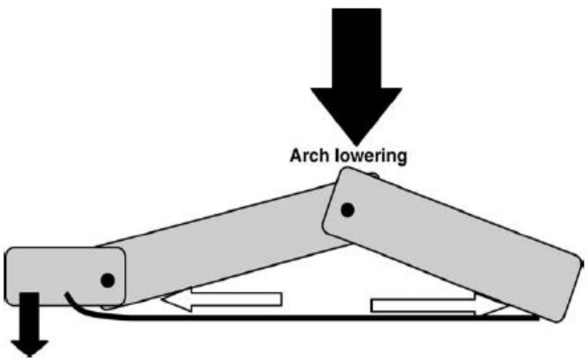

Figure 6: Reverse windlass mechanism.

CUSTOM FOOT ORTHOTIC INTERVENTIONS

With foot orthotic therapy, we are ultimately addressing both the proximal and distal contributors of sagittal plane blockage at the 1st MTPJ. A functional foot orthosis that addresses increased pronation equipped with an appropriate accommodative extension can achieve this goal. The orthosis is essentially designed to: 1) stabilize the foot; and 2) facilitate motion in the sagittal plane.

At Paris Orthotics, we recommend a Functional Hallux Limitus (FHL) Accommodation in conjunction with the desired functional orthotic design (Figure 7).

Our lab standard design incorporates an EVA extension with a 1st met cut of the orthotic shell and an accommodation under the 1st MTPJ. From Figure 7 you can also observe there is a small 1st IPJ raise. The lab can offer variations of the cut-out design so it is important that you communicate with Technical Support regarding any variations that you might want to incorporate.

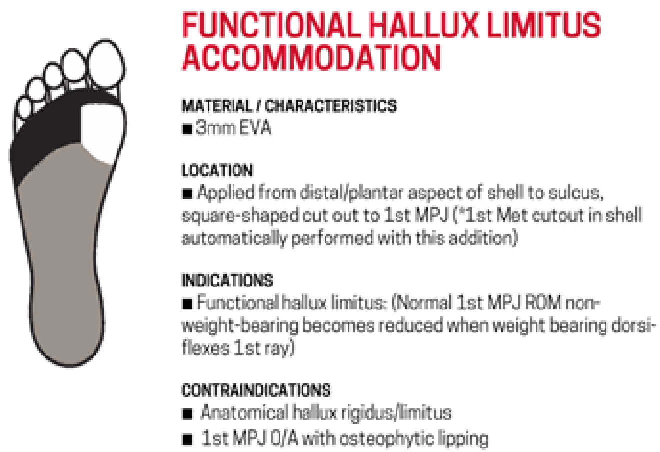

Figure 7: Lab standard FHL accommodation

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If you are interested in any of the publications cited please contact Chris MacLean at:
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