Podiatric physicians have been using in-shoe appliances and varied theories and therapies to treat gait-related symptoms since the profession began to develop in the 18th century. More recently, three main theories have become established in the podiatric literature in relation to treating foot-related lower-quarter symptoms. The subtalar joint neutral (STJN) theory, tissue stress (TS) theory, and sagittal plane facilitation (SPF) theory make up the most accepted approaches to the foot in relation to gait dysfunction. Although these theories appear to be diverse in their application, the common consensus is that foot orthoses outcomes are generally positive.

**Foot Morphology Theory**

Between 1958 and 1959, Merton L. Root, DPM, pioneered functional foot orthoses, conducted hundreds of biomechanical assessments, and began to define the STJN position. The theory that he and his colleagues created is based on the premise that a foot is functioning normally when STJN position occurs immediately after heel strike and at the end of the midstance phase of gait. Foot morphology (FM) was characterized and referenced to this STJN position, and the relationship between this and normal or abnormal foot function was established. Although Dr. Root may have been developing orthoses as part of his clinical practice, no further descriptive text on foot orthotic prescription or manufacture was ever made available. However, many authors have cited Dr. Root in their interpretation of their own texts and literature on foot orthoses, often using terminology such as *Rootian* or *Modified Rootian* foot orthoses. It may be unwise to assume that Dr. Root would agree with the interpretation of his work, although all of these contributors base their description of or-
thotic therapy on FM and the STJN position in some element. The premise of this model of management seeks to identify FM that is abnormal, eg, forefoot varus, and prescribe an orthotic device to prevent subsequent abnormal joint compensatory motion eg, excessive subtalar joint (STJ) pronation. It may be fair to assume that this method of pediatric assessment and treatment is the most popular biomechanical approach to foot function and orthoses used worldwide by both podiatrists and other professions.

The majority of texts that describe orthoses in relation to Roots’ work agree with the following prescriptive methodology, which is generally taken from the most comprehensive available literature on FM theory orthoses. The FM theory orthosis is designed to balance a foot deformity with posting applied to a rigid bespoke shell. Prescription protocol begins with a cast of the foot in a non-weightbearing neutral position. The shape of the neutral cast is of prime importance, because it is essential to capture the correct forefoot-to-rearfoot alignment and calcaneal inclination angle. The cast is then angled with an intrinsic forefoot post to place the bisection of the heel at the required position. The degree of posting to achieve this required position is calculated by taking the value of a patient’s neutral calcaneal stance position (NCSP) and subtracting a set number of degrees in order to allow normal pronation. The height of the STJ axis is used to determine the amount of pronation to be allowed. The rearfoot post is ground so that it is angled an additional 4° varus for an average STJ axis. A high STJ axis rearfoot post allows 2° of motion, and the low STJ axis post allows 6°, which will control the movement of the foot from NCSP to the prescribed pronated position. To maintain the posting and shape of the orthosis, only rigid materials are recommended, such as acrylic or carbon fiber plus an acrylic rearfoot post. The shell is classically cut to 25% of the width of the first ray.

**Sagittal Plane Facilitation Theory**

Howard Dananberg, DPM, first published his theories of SPF in 1986. He and his colleagues have since developed a theory that highlights the importance of the foot as a pivot that rocks forward from heel to toe, thereby allowing adequate hip extension leading up to the propulsive phase of gait. He proposes that this hip extension allows a normal stride and therefore an efficient and erect gait. Functional hallux limitus and ankle equinus are two examples of pathology that can restrict foot movement and result in what Dananberg terms a *sagittal plane blockade*. Ankle equinus is stated to be the inability to dorsiflex to 100°, and functional hallux limitus is defined as a first metatarsophalangeal joint (MTPJ) that structurally has a normal range of motion but is unable to dorsiflex adequately at the appropriate time in gait. Dananberg has mostly related SPF theory to more proximal posture-related problems, such as low-back pain, although it is possible to use this theory to explain foot pains and abnormalities. Sagittal plane facilitation theory is now well published, and like the FM theory, is apparently being well accepted by other professions.

Orthotic prescription is based upon the premise of informed trial and error using video gait analysis and in-shoe pressure system measures. Therefore, the means of determining what posting, shell thickness, heel raise, and so forth is determined without reference to the foot-to-rearfoot relationship or axis height as in the FM model. Dananberg also cites the use of shell modifications, such as cut-outs beneath the first ray and specific forefoot extensions to encourage medial propulsion. In fact, the amount of posting is relatively very small, eg, 1°, and potentially totally different from what may seem necessary from a standard static examination.

Although a specific SPF theory outcome study is available, the actual prescription method remains sparsely documented. Dananberg has not yet produced a step-by-step guideline of his methodology, making it difficult for practitioners to replicate this often technologically intricate approach. Experience guides the choice of shell modifications. Dananberg has always stated orthoses should be fabricated on functional rather than static examination. However, there is one reference available in which there appears to be an attempt to link SPF theory prescription methodology with deformities identified by Root et al. Sample prescriptions are provided based on three vaguely defined foot types. This appears to be the closest we get to a simple prescription guideline.
of physical laws such as moments, levers, stress, and strain curves. Tissue stress theory is based more on the concept of kinetics as opposed to kinematics of gait. The central concept is that pronation or supination does not cause harm but stopping the pronation or supination does. If the center of pressure is medial to the STJ axis during gait, a supinatory moment will be applied to the STJ. The opposite will also occur. If the center of pressure is lateral to the STJ axis during gait, a supinatory moment will be applied to the STJ axis. A medial or lateral shift in the tibialis posterior would oppose a pronatory moment magnitude. For example, the plantar fascia and the plantar aponeurosis will operate against the pronation by applying a moment of the same magnitude. For example, the plantar fascia and the plantar aponeurosis will operate against the pronation by applying a moment of the same magnitude. For example, the plantar fascia and the plantar aponeurosis will operate against the pronation by applying a moment of the same magnitude. For example, the plantar fascia and the plantar aponeurosis will operate against the pronation by applying a moment of the same magnitude.

Abbreviation: SPF, sagittal plane facilitation.

### Table 1. Summary of Treatment Options from the SPF Perspective

| Orthoses are custom made from foot impressions, but the method of casting is not highlighted. Dananberg has recently been part of a venture to produce a noncustom prefabricated appliance, the Vasyli Howard Dananberg (VHD) orthotic (Vasyli Medical, Queensland, Australia), which may eliminate the need for casting. Use static and dynamic assessment to establish any need for correcting a leg length difference with heel raises. Manipulate areas of reduced motion such as the first metatarsophalangeal joint and talocrural joint, if required. Supply firm heel raises to reduce the effects of an ankle equinus. Use first-ray shell excisions if there is functional hallux limitus. The size of the cut-out is dependent on dynamic findings. Use a kinetic wedge and digital platform if necessary. Dananberg believes a rearfoot post can be potentially harmful due to encouraging lateral avoidance and advocates the use of flat rearfoot posts. Rearfoot posting is recommended in situations such as a medial heel strike; the maximum required is considered to be 3°. Identify and strengthen weakness in muscles that are pivotal in the SPF theory such as the peroneus longus or tibialis posterior. Depending on dynamic findings, post the forefoot no more than 3° varus or valgus. Use semirigid-to-flexible materials. Both allowing and controlling motion is a central concept. If early heel lift is a problem, use soft poron heel lifts as dampeners under the rearfoot post. | Orthotic prescription choices are forefoot posting, rearfoot posting, and forefoot extensions in a valgus or varus orientation. Negative casts are often modified at the time of impression, depending on the required shell shape, to apply the correct moments to the foot, eg, the first ray is dorsiflexed or plantarflexed to alter forefoot to rearfoot alignment. Large degrees of forefoot posting can be used, up to 5° to 10°. The magnitude of pathologic moments dictates the amount of posting required rather than modifying a cast or orthotic shell based on the STJN position. The general width of the orthoses is not specified, although they appear commonly wider than FM theory prescriptions. In contrast to the FM theory, a change in magnitude of forces, not in joint position, is required to reduce symptoms. Greater orthotic reaction force is required if the ground reaction force is producing abnormal moments. To supply this increased orthotic reaction force, Kirby designed and published a shell modification called the heel skive. By modifying the positive cast, the heel skive can be applied, as required, to the medial or lateral aspect of the STJ axis. As with the SPF theory, there is no actual prescription protocol available for the production of orthoses based on the TS theory, although more literature is available. |

### A Unified Theory

It is reasonable to assume that no clinician would continue to use a theory that was not working to relieve their patients’ symptoms. Rationally there must be beneficial aspects of treatment from FM, SPF, and TS theory perspectives. Although the three main podiatric biomechanics paradigms conflict in principle (Table 2), all demonstrate an agreement that the foot essentially has three main areas of function: (1) to be stable and maintain a congruent structure
through the stance phase; 2) to allow the leg to pivot over the point of ground contact, permitting a normal stride; and 3) to allow internal and then external rotation of the leg in relation to the ground through STJ pronation and supination.

A common underlying corrective mechanism may exist, or there may be more than one way to improve symptoms with the use of orthoses. We present a theory to explain normal and abnormal foot function, which can be used to unify and explain benefits reportedly obtained from the three established theories. For the purpose of this article, we discuss methods of normalizing foot function to improve symptoms rather than the limitation of normal motion that can be provided by orthoses to relieve specific symptoms, for example, the Morton’s extension.53

**Theoretical Mechanism for Normal Foot Function**

As the foot hits the ground, initial double-limb stance occurs. At this stage, the contact phase lower limb, in relation to the ground, is internally rotating.54 To allow this internal rotation, the STJ pronates and the arch lowers. As the arch lowers, it becomes longer and structures that originate proximal and insert distal to the midtarsal joint have increased tension. Relevant examples of these structures are presented in Table 3. This increased tension from these structures applies a longitudinal compressive force through the convex and concave joints of the midtarsus, theoretically close-pack these joints and increasing the congruent stability of the foot. In specific relation to the plantar fascia, a reverse windlass mechanism has been proposed.55, 56 Not only does the increased tension in the plantar fascia increase the stability of the midtarsus, it also pulls the digits to the ground because of the insertion of the plantar fascia into the digits (Fig. 1). The normal amount of pronation that occurs with internal leg rotation at contact phase therefore supplies stability of the foot that is essential for a normal gait cycle.

Through midstance, the leg begins to externally rotate in relation to the ground.55 This rotation requires STJ supination. With this supination, the arch begins to rise and therefore the origin and insertion of the structures responsible for aiding the congruent stability of the foot become closer and tension could be lost. This occurs with heel lift, a stage in gait in which the body’s center of mass progresses anterior to the ankle over the midtarsal joint.54 This progression on center of mass creates a peak moment that attempts to lower the arch. The ability of the foot to resist these bending moments and maintain arch raising is paramount. Unless the slack in any of the plantar structures can be taken up, stability may be lost.

The windlass effect was first described by Hicks57 in 1954 and has more recently been expanded on from different perspectives by Fuller57 and Dananberg.40 Involved anatomy is that of the medial arch and medial band of the plantar fascia. The medial band of the plantar fascia originates from the medial tubercle of the calcaneus and inserts distally into the base of the proximal phalanx and sesamoid bones.58 During closed kinetic chain in a foot with a normal structure, dorsiflexion of the hallux will tighten the plantar fascia because of the plantar fascia being wound around the first metatarsal head. This is analogous to a cable being wound around a windlass.56 This effectively draws the head of the first metatarsal

<table>
<thead>
<tr>
<th>Criteria for normalcy</th>
<th>Foot Morphology Theory</th>
<th>Sagittal Plane Facilitation Theory</th>
<th>Tissue Stress Theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>The STJ passes through neutral at key stages of the gait cycle.</td>
<td>The foot functions as a pivot allowing adequate hip extension and correct posture.</td>
<td>The foot functions in a way that does not result in abnormal tissue stress and injury.</td>
<td></td>
</tr>
<tr>
<td>The foot is cast in STJN, unless a large deformity is a contraindication.</td>
<td>Casting methods are not documented, although recent noncustom orthoses from this theory may eliminate the need for casting.</td>
<td>The positive cast is modified when taken to supply the shell shape required to apply the correct forces to the foot.</td>
<td></td>
</tr>
<tr>
<td>To prevent abnormal joint compensation and place the foot into its normal position for key stages of the gait cycle.</td>
<td>To allow the foot to work successfully as a pivot and facilitate sagittal plane motion.</td>
<td>To reduce abnormal stress upon symptomatic structures.</td>
<td></td>
</tr>
</tbody>
</table>

Abbreviations: STJ, subtalar joint; STJN, subtalar joint neutral.
and calcaneus together, causing the foot to shorten and the arch to raise (Fig. 2).

During propulsion, most of the weightbearing is borne through the medial column of the foot while the leg is externally rotating and the arch is rising and shortening. For the heel to lift, the hallux therefore should dorsiflex. This winds the windlass and maintains tension in the plantar fascia, creating a compressive force across the foot. The foot therefore uses the internal rotation of the leg to aid in its own stability by increasing plantar structure tension with pronation through contact and early midstance. As the foot pivots over the hallux, the leg externally rotates and midfoot stability is maintained through the windlass mechanism. Although the plantar fascia may be only one of the many structures involved in maintaining foot structure in relaxed bipedal stance, it is theoretically essential in maintaining midtarsus stability during resupination at heel lift.

### Theoretical Mechanism for Abnormal Foot Function

#### Failure to be Stable and Maintain a Congruent Structure through Stance Phase

If moments resisting STJpronation and arch lowering are not of significant magnitude, abnormal pronation may occur and the midtarsus may move to a position of poor congruency through malalignment. Factors

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**Table 3. Examples of Structures with Theoretically Increased Tension with Lowering of the Arch via STJ Pronation**

<table>
<thead>
<tr>
<th>Structure</th>
<th>Origin and Insertion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plantar fascia</td>
<td>Medial tubercle of the calcaneus inserting into the digits. The medial band is the most substantial and inserts into the proximal phalanx of the hallux.</td>
</tr>
<tr>
<td>Long calcaneocuboid ligament</td>
<td>Plantar aspect of the calcaneum to the plantar aspect of the cuboid and the bases of the third, fourth, and fifth metatarsals.</td>
</tr>
<tr>
<td>Short calcaneocuboid ligament</td>
<td>Plantar anterior tubercle of the calcaneum to the adjoining aspect of the cuboid.</td>
</tr>
<tr>
<td>Calcaneonavicular ligament</td>
<td>Anterior margin of the sustentaculum tali to the inferior surface and the tuberocity of the navicular.</td>
</tr>
<tr>
<td>Peroneal longus tendon</td>
<td>Lateral upper two-thirds of the fibula. The tendon runs forward on the lateral aspect of the calcaneum around the lateral aspect of the cuboid and inserts into the medial cuneiform and base of the first metatarsal.</td>
</tr>
<tr>
<td>Flexor digitorum longus tendon</td>
<td>Posterior surface of the tibia to the bases of the distal phalanges of the lesser digits.</td>
</tr>
<tr>
<td>Flexor hallucis longus tendon</td>
<td>Posterior surface of the tibia to the base of the distal phalanx of the hallux.</td>
</tr>
<tr>
<td>Posterior tibial tendon</td>
<td>Posterior surface of the tibia, fibia, and interosseous membrane to the tuberocity of the navicular and plantar aspects of the cuboid, cuneiforms, and bases of the second, third, and fourth metatarsals.</td>
</tr>
</tbody>
</table>

Abbreviation: STJ, subtalar joint.

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**Figure 1.** Simple model demonstrating the reverse windlass mechanism.

**Figure 2.** Simple model demonstrating the dynamic windlass mechanism.
that either increase pronatory moments or decrease the foot’s ability to resist pronatory moments may be intrinsic to the foot (eg, a medially deviated axis), extrinsic to the foot (eg, weak lateral hip rotators), or even transient to the foot (eg, ligamentous laxity in pregnancy).

In addition, for stability to be maintained after heel lift, the windlass mechanism needs to apply tension to the plantar fascia. If this fails, the midtarsus will be unstable at heel lift and unable to resist the bending moment applied as the heel is pulled off the floor. The lowering of the arch at heel lift is analogous to STJ pronation rather than the required supination. For the windlass to function effectively, dorsiflexion of the hallux through medial column propulsion must occur. If a limitation of first MTPJ dorsiflexion is present, whether structural or functional, a lack of windlass mechanism may arise with resultant sequelae. A common compensation mechanism may be to propulse laterally rather than medially, which has been stated not only to fail to wind the windlass but also to be less efficient in propulsion. Although causes of a structural hallux limitus are well discussed in the literature, the etiology of functional hallux limitus is less reported. Two possible etiologies are a prolonged reverse windlass and functional bony restriction of the first MTPJ. A prolonged reverse windlass occurs as a result of excessive pronation moments at the STJ. These excessive moments may be attributable to a myriad of causes such as a forefoot varus, tibial varum, or weak lateral hip rotators. The resultant prolonged reverse windlass results in drawn out plantarflexory moments at the first MTPJ when dorsiflexion should be occurring. Such increased plantarflexory moments will therefore impede hallux dorsiflexion and reduce the ability of the foot to propel through the first MTPJ. Pressure may remain lateral, engaging the foot in inefficient propulsion. This, in turn, inhibits the arch rising because of the lack of a windlass mechanism.

In a functional bony restriction of the first MTPJ, dorsiflexion of the first ray impedes the ability of the first MTPJ to extend. Pronation will lead to dorsiflexion of the first ray through increased ground reaction forces to the medial column of the foot. This will limit the ability of the foot to pivot over the first MTPJ, leading to sequelae as described with a prolonged reverse windlass mechanism. The resultant effect is similar to that of a structural hallux limitus. Other possible causes of functional hallux limitus include sesamoid apparatus failure and fixed elevated first ray abnormalities.

Failure to Allow the Foot to Pivot and Permit Normal Stride

The three rockers (round underside of the heel, ankle dorsiflexion, and hallux dorsiflexion) need to be correctly timed to coincide with proximally occurring motion. For example, as the center of mass advances and the hip extends, the heel must lift appropriately. Failure of the first MTPJ to extend at this vital moment will impede heel lift and limit hip extension with consequences up the kinetic chain. For appropriate timing of the foot rocker motions, it is essential that the foot is stable under load, as discussed previously. Compensation pathways such as a flattened lordosis and lack of hip and knee extension have been stated in the literature.

Failure to Allow Internal and External Rotation of the Leg in Relation to the Ground Through STJ Pronation and Supination

If the STJ has an inadequate range of pronation to allow normal internal leg rotation at the hip (eg, triple arthrodesis), normal lumbar and pelvic mechanics will not occur. The reverse is also true: if there is a lack of internal rotation at the hip, a normal amount of STJ pronation may not occur to adequately tense the plantar structures of the foot and engage the reverse windlass. An example of this may be a lack of internal hip rotation demonstrated in osteoarthritic hips.

From midstance, in relation to the ground, the leg externally rotates and applies a supinatory moment to the STJ. For the leg to externally rotate, the foot must supinate, and the supinatory moment must be greater than the pronatory moment across the STJ. In abnormal situations, this may not occur and can be attributable to a lack of applied supinatory moments or increased pronatory moments. There are several methods by which compensation may occur. The leg may simply remain internally rotated, or if the friction coefficient between the floor and the foot is overcome, the foot may be seen to rapidly abduct and allow external hip rotation without resupination. This has been called an abductory twist.

Orthotic Prescription Based on the Unified Theory

The fundamental reason for prescribing functional foot orthoses is to improve symptomatic gait dysfunction. This may be caused by one or a combination of factors resulting in a failure of the foot to function as a stable pivot or to allow normal transverse plane hip
motion. It may be argued that symptomatic gait dysfunction was achieved through previous podiatric theories, with combinations of negative cast shapes, varus or valgus posting, or modifications in orthotic width or extension. For example, TS theory orthotic prescription would reduce the prolonged windlass by using varus posting. Sagittal plane facilitation theory would reduce functional bony restriction of the first MTPJ by using cut-outs in the shell beneath the first ray and a kinetic wedge. The FM theory may improve both of the above abnormalities by varus posting and a shell cut narrow to 25% of the width of the first ray. The FM, SPF, and TS theories would all aid the windlass mechanism and improve the foot’s ability to function as a stable congruent pivot and assist normal transverse plane hip rotation. It can, therefore, be demonstrated by the simple examples above that all three theories can be conflicting in nature, and yet coadunate in treatment, by using a unifying theory.

This can also be linked to specific symptom relief. Plantar fasciitis is one of the most common musculoskeletal injuries presenting to the podiatric physician and is commonly treated with orthoses.¹⁴ For the purpose of discussion, we shall assume that the orthoses work by reducing excessive tension through the plantar fascia, correcting timing of both the reverse and normal windlass mechanisms, thereby allowing normal gait to occur. The orthotic prescription based on the FM theory applies posting for feet that demonstrate abnormal compensation. Beneficial effects may therefore be explained by the reduction of abnormal compensation, allowing the foot to function around the STJN. Alternatively, the device may be seen to reduce strain in the plantar fascia due to reduction of excessive pronatory moments placed across the STJ during the reverse windlass phase. Therefore, orthoses make it easier for the hallux to dorsiflex and normal windlass to occur because of a reduction of plantar fascia stress. In addition, the classic FM theory orthotic appliance is often cut narrow, so that only 25% of the first ray width remains. This decreases dorsiflexory moments on the first ray allowing the hallux to dorsiflex more easily and aid first-ray propulsion. Sagittal plane facilitation theory and TS theory achieve this benefit in similar ways while employing particular methods of orthotic construction or modifications. Sagittal plane facilitation theory uses the kinetic wedge and first-ray cut-outs as well as minor posting. This reduces strain on the plantar fascia, decreases dorsiflexory moments on the first MTPJ via the cut-out, and increases dorsiflexory moments on the first MTPJ via the kinetic wedge. Tissue stress theory advocates the use of greater posting and the medial heel skive. These increase supinatory moments across the STJ axis and unload excessive stress in the plantar fascia.

Whether one method is better than the other remains undetermined. Certain orthoses working by a particular orthotic prescription theory may be better at correcting certain gait abnormalities or symptoms than others. However, one might suggest that the relief of symptoms has always occurred through the improvement of normal foot mechanisms, and the method or approach to achieve this is inconsequential. Such conclusions will depend on research outcomes not yet available to us.

Conclusions

We have attempted to summarize the available literature on the three main podiatric theories of gait dysfunction and have proposed a possible unification theory. Our theory may be seen as an oversimplification of orthotic prescription, but it may explain the fundamental principles behind the apparent universal success of different approaches to orthotic therapy. We have not intended to dismiss or prioritize one method of assessment or treatment over another. Theoretical issues highlighted within podiatric biomechanics are not unique. Other clinical specialties have conflicting theories of musculoskeletal treatment and many of these lack evidence.⁷³, ⁷⁴

Until greater research is available, each practitioner should decide which method to use. Podiatric physicians who encompass all approaches may have benefits over those who are more dogmatic. Other determining factors such as bulk of theory-based appliances, material durability, and sporting suitability have not been discussed. As far as the authors are aware, the perfect foot orthosis has not yet been conceived. It is hoped that as evidence-based practice becomes more established, more podiatric physicians and students will undertake areas of required research related to the areas highlighted in this article.

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Conflict of Interest: None reported.

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