

Subtalar Joint Axis Location and Rotational Equilibrium Theory of Foot Function

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A new theory of foot function based on the spatial location of the subtalar joint axis in relation to the weightbearing structures of the plantar foot is proposed. The theory relies on the concept of subtalar joint rotational equilibrium to explain how externally generated forces, such as ground reaction force, and internally generated forces, such as ligamentous and tendon tensile forces and joint compression forces, affect the mechanical behavior of the foot and lower extremity. The biomechanical effect of variations among individuals in the spatial location of the subtalar joint axis are explored, along with their clinical consequences, to offer an additional theory of foot function, which may improve on existing podiatric biomechanics theory. (J Am Podiatr Med Assoc 91(9): 465-487, 2001)

The subtalar joint is a functional joint of the human foot that acts as a mechanical link between the foot and the lower extremity. Transverse plane rotations of the leg are converted into frontal plane rotations of the foot, and vice versa, by the oblique triplanar orientation of the subtalar joint axis. Two of the more important functions of the subtalar joint are: 1) to allow the foot to pronate and act as a mobile adapter when bearing weight on irregular surfaces; and 2) to allow the foot to supinate into a position of increased sagittal plane stability during the propulsive phase of gait. Other functions of the subtalar joint have been discussed previously by other authors.¹⁻⁴

The characteristics of the axis of rotation of the subtalar joint have attracted the attention of researchers over the years. Manter,⁵ Hicks,⁶ Root et al,⁷ and Isman and Inman⁸ all suggested in their experimental studies that the subtalar joint axis is a solitary axis that passes through the talocalcaneal joint and is

directed obliquely from posterior-lateral-plantar to anterior-medial-dorsal. More current research by Van Langelaan,⁹ Benink,¹⁰ and Lundberg and Svensson¹¹ investigated the axis of rotation of the subtalar joint using more accurate methods of subtalar joint axis spatial location with roentgen stereophotogrammetry. By implanting metallic beads into both the talus and the calcaneus and then taking standardized x-rays of the feet in two cardinal planes, these researchers all demonstrated that the subtalar joint axis is not a solitary axis but rather is better described as a number of discrete axes of rotation that, together, form a bundle of axes passing through the talocalcaneal joint (Fig. 1).⁹⁻¹¹

Therefore, the most accurate research to date has demonstrated that the subtalar joint axis no longer can be accurately described as a solitary axis of rotation but is best described as a multitude of axes of rotation that all have different spatial locations. In turn, each discrete spatial location of the subtalar joint axis is dependent on the rotational position of the subtalar joint axis.⁹⁻¹¹ As such, the results from these researchers suggest that the morphology of the articulating surfaces of the talus and calcaneus,

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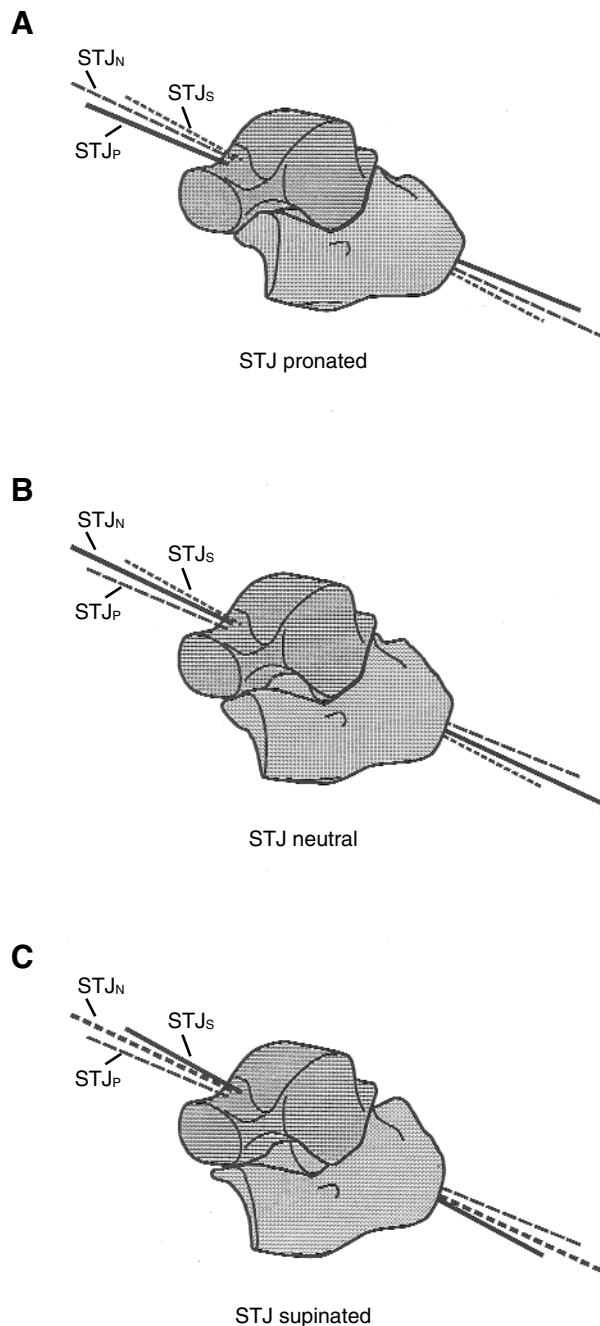


Figure 1. Research using roentgen stereophotogrammetry⁹⁻¹¹ has demonstrated that the subtalar joint axis is not a solitary joint axis but a continuously moving axis that is better represented as a bundle of axes passing through the talocalcaneal joint. Here are examples of how the subtalar joint axis may have different spatial locations in relation to the talus and calcaneus while in the A, subtalar joint pronated position (STJ_p); B, subtalar joint neutral position (STJ_n); and C, the subtalar joint supinated position (STJ_s).

along with their three-dimensional (3-D) relationships to each other at each point within the subtalar joint range of motion, determines the spatial location of the subtalar joint axis for that rotational position of the subtalar joint. (In this paper, “spatial location” is defined as the 3-D location and the angular orientation of the axis of rotation in relation to another point of reference. “Rotational position” is defined as a point within the joint’s range of motion, such as “maximally pronated,” “neutral,” or “3° from maximally pronated,” in the specific case of the subtalar joint.)

It has been determined that closed kinetic chain subtalar joint pronation causes plantarflexion and internal rotation of the talus and closed kinetic chain subtalar joint supination cause dorsiflexion and external rotation of the talus in relation to the plantar calcaneus and the ground.^{1,3} Previous anatomical investigations also have noted that the subtalar joint axis consistently pierces the talus anteriorly at the superior aspect of the talar neck.^{2,5,6,8,12} Therefore, as the talar head and neck rotate and translate within space in relation to the plantar foot and ground during closed kinetic chain rotational motions of the subtalar joint, so does the subtalar joint axis rotate and translate in relation to the plantar foot and ground during these same motions (Fig. 2).¹³⁻¹⁶ The important link between spatial location of the subtalar joint axis and the rotational position of the subtalar joint axis has been discussed in detail in the literature by both the current author¹³⁻¹⁸ and Nester.¹⁹

In 1987, this author described a clinical method of determining the representation of the subtalar joint axis on the plantar foot. How alterations in subtalar joint axis spatial location can affect the relative pronation and supination moment arms that ground reaction force has available on the plantar foot to produce subtalar joint moments were described. The concepts of medial and lateral deviation of the subtalar joint axis were introduced to explain the author’s clinical observations that variations in the spatial location of the subtalar joint axis affected the overall biomechanics of the foot during weightbearing activities (Fig. 3).²⁰ The author also devised a method for quantifying the plantar position of the subtalar joint axis, which was first described in a study by Ruby et al²¹ that measured the effect of certain anatomical variables on the peak knee-loading forces during seated cycling (Fig. 4).

In 1989, the author discussed how pronation and supination moments are produced across the subtalar joint axis by the effects of ground reaction force and muscular contractile force and also described the concept of rotational equilibrium across the subtalar joint axis. A foot with a medially deviated subta-

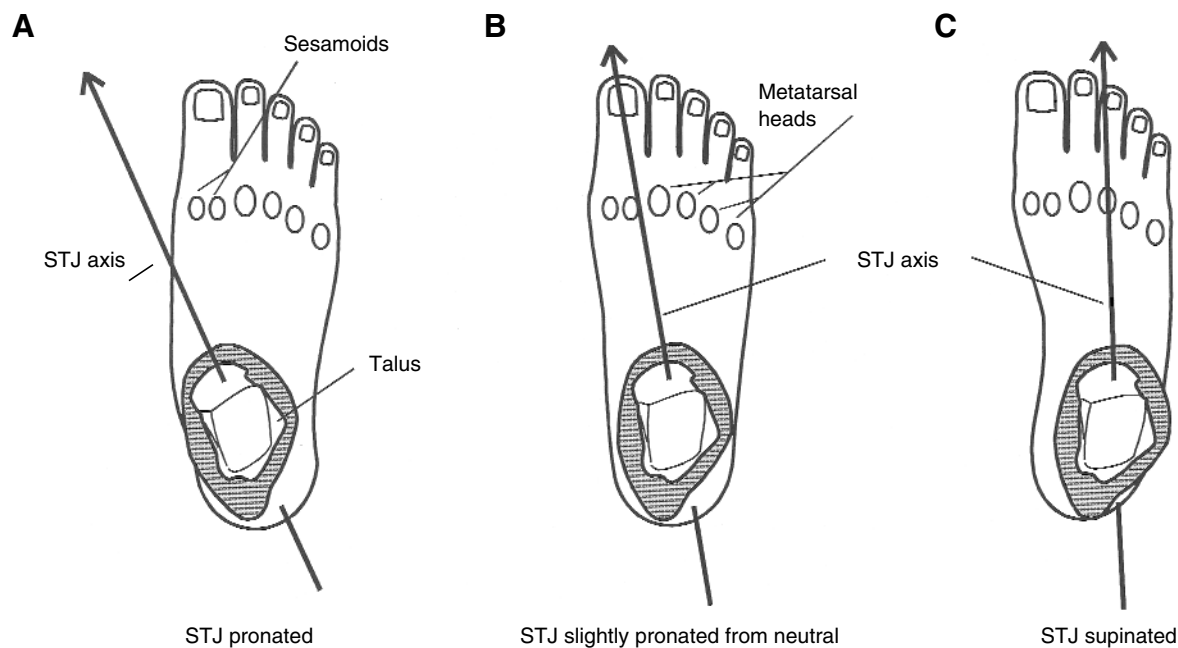


Figure 2. When a foot that functions normally is in relaxed bipedal stance, resting slightly pronated from neutral position, the subtalar joint (STJ) axis passes through the posterior-lateral calcaneus posteriorly and above the first intermetatarsal space anteriorly (center, B). As the subtalar joint undergoes pronation motion, the talus internally rotates and medially translates in relation to the plantar foot, causing the subtalar joint axis to internally rotate and medially translate (left, A). As the subtalar joint undergoes supination motion, the talus and subtalar joint axis externally rotate and laterally translate in relation to the plantar foot (right, C).

lar joint axis causes a net increase in subtalar joint pronation moment, which results in a foot that is pronated in standing and is likely to resist supination motion when supination moments act upon it. In addition, a foot with a laterally deviated subtalar joint axis causes a net increase in subtalar joint supination moment, which results in a foot that is neutral to supinated in standing and is likely to resist pronation motion when pronation moments act upon it. The concept of rotational equilibrium across the subtalar joint axis also was used to describe how the rotational position of the subtalar joint axis during relaxed bipedal stance is the direct result of the balancing of the pronation and supination moments acting across the subtalar joint axis at that time. In addition, the production of interosseous compression forces in the sinus tarsi, which are the result of excessive subtalar joint pronation moments, was used to describe the biomechanics and orthotic treatment of sinus tarsi syndrome.¹⁴

The purpose of this paper is to propose a theoretical model of foot function that is based on the previously described concepts of subtalar joint axis location and rotational equilibrium and that is compatible with the findings from current biomechanical re-

search and the author's clinical observations.^{14, 20} The concepts of subtalar joint axis spatial location and subtalar joint rotational equilibrium will be described in detail and will be used to explain the response of the foot to the external effects of ground reaction force and the internal effects of osseous compression forces, ligamentous tensile forces, and muscular tensile forces. This theoretical model also will be used to describe how alterations in the rotational position of the subtalar joint and various structural deformities of the rearfoot and forefoot affect the spatial location of the subtalar joint axis in relation to the foot and therefore also affect the balance of subtalar joint pronation and supination moments acting on the foot during weightbearing activities.

Normal Location of the Subtalar Joint Axis and Its Biomechanical Effects

In his classic 1941 paper on the experimental determination of the spatial location of the subtalar joint axis in 16 cadaver feet, Manter⁵ demonstrated that the average subtalar joint axis in his samples was angulated 16° from the sagittal plane (the sagittal plane being defined as a line from a bisection of the poste-

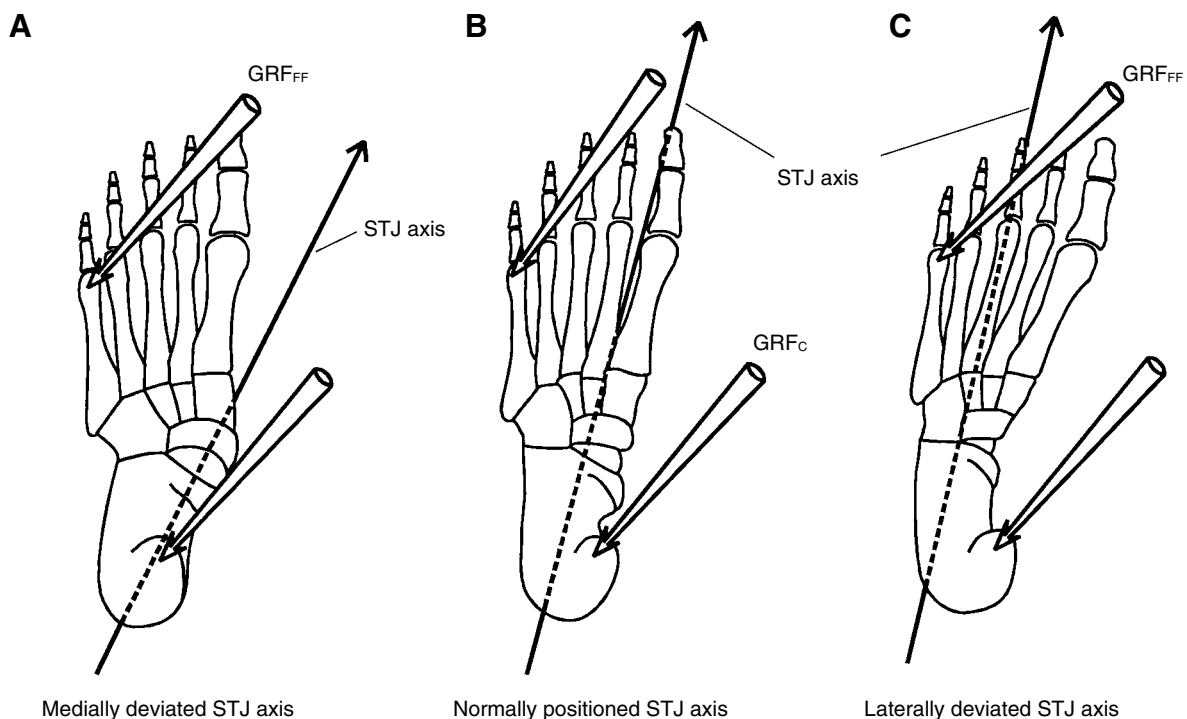


Figure 3. Ground reaction force acting on the plantar calcaneus (GRF_C) in a foot with a normally positioned subtalar joint (STJ) axis will cause a subtalar joint supination moment, and ground reaction force acting on the lateral forefoot (GRF_{FF}) will cause a subtalar joint pronation moment (center, B). In a foot with a medially deviated subtalar joint axis, the moment arm that GRF_C has available to cause a subtalar joint supination moment is decreased and the moment arm that GRF_{FF} has available to cause a subtalar joint pronation moment is increased, which produces a net increase in subtalar joint pronation moment (left, A). In a foot with a laterally deviated subtalar joint axis, the moment arm that GRF_C has available to cause subtalar joint supination moment is increased and the moment arm that GRF_{FF} has available to cause subtalar joint pronation moment is decreased, which produces a net increase in subtalar joint supination moment (right, C).

rior heel to the first intermetatarsal space) and 42° from the transverse plane (the transverse plane being defined as the plantar aspect of the foot). Manter also found that the medially directed angulation of the subtalar joint axis ranged from 8° to 24° and the superiorly directed inclination angle of the subtalar joint axis ranged from 29° to 47° in the 16 cadaver feet.

In addition to Manter, other authors have performed similar experimental studies that demonstrate large variations among individuals in the angulation of the subtalar joint axis. Therefore, even though an “average” spatial location of the subtalar joint axis can be quoted for the samples examined by each researcher, it remains clear in the review of these experimental studies that each researcher found a large variation among individuals in the spatial location of the subtalar joint axis in the samples studied.⁶⁻¹¹

The author has used the palpation method of subtalar joint axis location for the past 16 years on more

than 2,000 feet to determine the plantar representation of the subtalar joint axis.²⁰ In line with what other researchers have noted,⁵⁻¹¹ the author has also found that there is a large variation among individuals in the angulation of the subtalar joint axis in relation to the sagittal plane of the foot. In addition, a large variation among individuals in the medial and/or lateral position of the subtalar joint axis in relation to the plantar foot also has been found consistently.^{13-17, 20} The author has discovered a large variation among individuals in the representation of the subtalar joint axis on the plantar foot that was observed in many feet examined by means of the palpation method of subtalar joint axis location, and the author has hypothesized that this represents a large variation among individuals in the spatial location of the subtalar joint axis.

To determine a normal location for the subtalar joint axis, the author has relied on the basic hypothe-

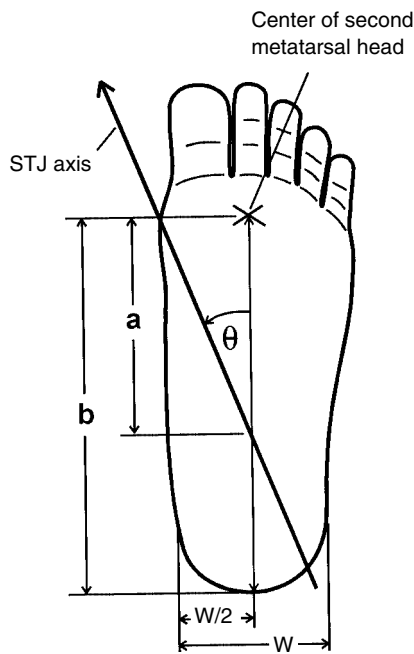


Figure 4. Illustrated above is the method for quantifying the plantar representation of the subtalar joint (STJ) axis as described by the author.²⁰ The longitudinal bisection of the foot is first determined by taking the width (W) of the posterior heel and bisecting it ($W/2$). The line from the bisection of the posterior heel to the center of the second metatarsal head determines the longitudinal bisection of the foot. The first subtalar joint axis measurement parameter determines the angular relationship (θ) of the subtalar joint axis to the longitudinal bisection of the foot (in the example above, $\theta = 23^\circ$). The second measurement parameter of the subtalar joint axis uses the distance from the posterior heel bisection to the second metatarsal head (b) and the distance from the point where the subtalar joint axis crosses the longitudinal bisection of the foot to the second metatarsal head (a) to derive the ratio (a/b) indicating the relative position where the subtalar joint axis crosses the longitudinal bisection of the foot (in the example above, $a = 110$ mm, $b = 203$ mm, and $a/b = 0.542$).

sis that feet that function the most normally^{1, 3, 4} also would have a normal subtalar joint axis spatial location. When using the subtalar joint palpation method, the author has consistently found that the feet that function the most normally during walking gait have a subtalar joint axis that passes through the posterior-lateral heel posteriorly and through the first intermetatarsal space area of the plantar forefoot anteriorly (Figs. 2 and 3).^{13-18, 20} It is this normal position of the subtalar joint axis in relation to the plantar foot, first noted by the author 16 years ago, that has

formed the biomechanical basis for the subtalar joint axis location and rotational equilibrium theory of foot function.

Since the plantar aspect of the foot is the only weightbearing aspect of the human body during walking activities, the ground reaction force that results from the mass and movements of the human body above the foot will have a very significant effect on the function of the foot and lower extremity. At the rearfoot, ground reaction force acts mostly at the medial calcaneal tubercle since the lateral calcaneal tubercle is largely nonweightbearing, on average being angulated 21° from the weightbearing surface of the foot.¹³ In addition, the plantar aspects of the first through fifth metatarsal heads, and to some extent the base of the fifth metatarsal, are the primary weightbearing structures in the forefoot.²²

When the subtalar joint axis is in its normal position, ground reaction force acting on the medial calcaneal tubercle causes a supination moment across the subtalar joint axis since the medial calcaneal tubercle is medial to the subtalar joint axis. Ground reaction force acting on the second through fifth metatarsal heads and the fifth metatarsal base will cause a subtalar joint pronation moment since these plantar structures are lateral to the subtalar joint axis (Fig. 3). The longer the distance between these plantar structures and the subtalar joint axis, the greater the moment arm will be to produce subtalar joint moments. Therefore, the longer the moment arm and the greater the magnitude of ground reaction force acting on these plantar structures, the greater will be the magnitude of supination or pronation moment acting across the subtalar joint axis.^{13-17, 20} (“Moment arm” is defined as the perpendicular distance of the line of action of the force to the axis of rotation. “Moment” is the mathematical product of the magnitude of the force and the length of the moment arm.²³)

The rotational effects of the contractile forces exerted by the extrinsic and intrinsic muscles of the foot also are affected by their position relative to the osseous structures of the foot. All extrinsic muscles that insert or have osseous pulley systems medial to the subtalar joint axis will exert a subtalar joint supination moment with their contraction. All extrinsic muscles that insert on the dorsal aspect of the foot lateral to the subtalar joint axis or that have osseous pulley systems lateral to the subtalar joint axis will exert a subtalar joint pronation moment with their contraction. Therefore, in a foot with a normal subtalar joint axis location, the posterior tibial, gastrocnemius, soleus, anterior tibial, flexor hallucis longus, and flexor digitorum longus all will have varying lengths of supination moment arms across the subta-

lar joint axis. In addition, the peroneus brevis, peroneus tertius, and extensor digitorum longus will have varying lengths of pronation moment arms across the subtalar joint axis. The magnitude of the subtalar joint moments produced by muscular contraction are dependent not only on the perpendicular distance of the line of action of the muscular contractile force to the subtalar joint axis (ie, moment arm) but also on the magnitude of the muscular contractile force.^{14, 15}

Since none of the intrinsic muscles of the plantar and dorsal foot directly cross the subtalar joint, they cannot directly cause either pronation or supination moments of the subtalar joint. However, in a fashion similar to the ligaments of the plantar and dorsal foot, the intrinsic muscles of the foot can resist deformation of the joints of the foot under weightbearing loads.²⁴ Therefore, both the intrinsic muscles and the ligaments of the foot can indirectly affect the overall balance of pronation and supination moments acting across the subtalar joint axis by stabilizing the joints of the foot during weightbearing activities.

Observations from Subtalar Joint Axis Palpation

During the subtalar joint axis palpation method previously described, the examiner uses the thumb of one hand to exert a force plantarly on the foot and uses the contralateral hand to sense any resultant subtalar joint motion at the fifth metatarsal head. If the thumb pushing on the plantar foot is medial to the subtalar joint axis, then subtalar joint supination occurs, and if the thumb pushes lateral to the subtalar joint axis, then subtalar joint pronation occurs. If, however, the examiner detects no motion when the thumb pushes on the plantar foot, then that point is the point of no rotation and is marked on the plantar foot (Fig. 5). Palpation of the plantar foot is started at the plantar heel and is carried out distally at 1- to 2-cm intervals to the metatarsal head level to determine the points of no rotation for the plantar foot, which are hypothesized to be the plantar representation of the subtalar joint axis.^{15, 17, 20}

Early on in the performance of the subtalar joint axis palpation method on many individuals of many age groups and foot types, the author noticed a seemingly unusual finding that seemed contrary to popular podiatric biomechanics theory of the time. The theory taught that when ground reaction force acted on the forefoot, its effect on foot function would be significantly affected by the spatial location of the oblique midtarsal joint axis.^{3, 4, 25} Owing to this popular theory, the author initially assumed that the line of

points of no rotation on the plantar foot would change direction at the midtarsal joint level since the rearfoot points of no rotation should represent the subtalar joint axis location and the forefoot points of no rotation should represent the oblique midtarsal joint axis location. However, in the more than 2,000 feet examined in the past 16 years with the subtalar joint axis palpation method, it has been noted that the points of no rotation of the rearfoot and forefoot always can be represented as a single straight line, with no apparent change of direction in the points of no rotation being at the midtarsal joint level (Fig. 6).^{17, 26, 27}

This consistent experimental observation thus supports the theory that any forces that act on the plantar foot while it is loaded to simulate weightbearing conditions will have a direct effect in producing subtalar joint pronation and supination moments, regardless of whether that force is applied to the plantar rearfoot or plantar forefoot. Therefore, it seems logical to assume that ground reaction force acting on any aspect of the plantar foot that is medial to the subtalar joint axis will produce subtalar joint supination moment and any ground reaction force acting on the plantar foot lateral to the subtalar joint axis will produce a subtalar joint pronation moment, regardless of the orientation of the oblique midtarsal joint axis.^{14-17, 20}

During weightbearing conditions, the combination of tensile loading of the plantar ligaments and compression loading of all the joints of the foot creates, in effect, a more tightly joined and stable architecture to the foot when compared with nonweightbearing conditions, where the forefoot is unloaded and more mobile relative to the rearfoot. Therefore, during many weightbearing motions, the foot may approximate a relatively rigid unit with all the bones of the foot rotating around the central pivot of the talus at the subtalar joint axis. If this concept is valid, then during many weightbearing motions, the foot can be effectively modeled as a rigid body with the calcaneus, cuboid, and navicular all rotating as a single unit around the talus at the subtalar joint axis and the more flexible forefoot undergoing relatively small motions that aid in keeping the forefoot in a plantigrade position.

In regard to the idea of the foot being modeled as a rigid body, Nigg²⁸ has noted that in the field of biomechanics, the rigid body concept may be valid where the deformations of the parts of the structure of interest are insignificant relative to the motion of the structure as a whole. In addition, biomechanics researchers have effectively modeled the foot as a rigid body for years, and this modeling technique is

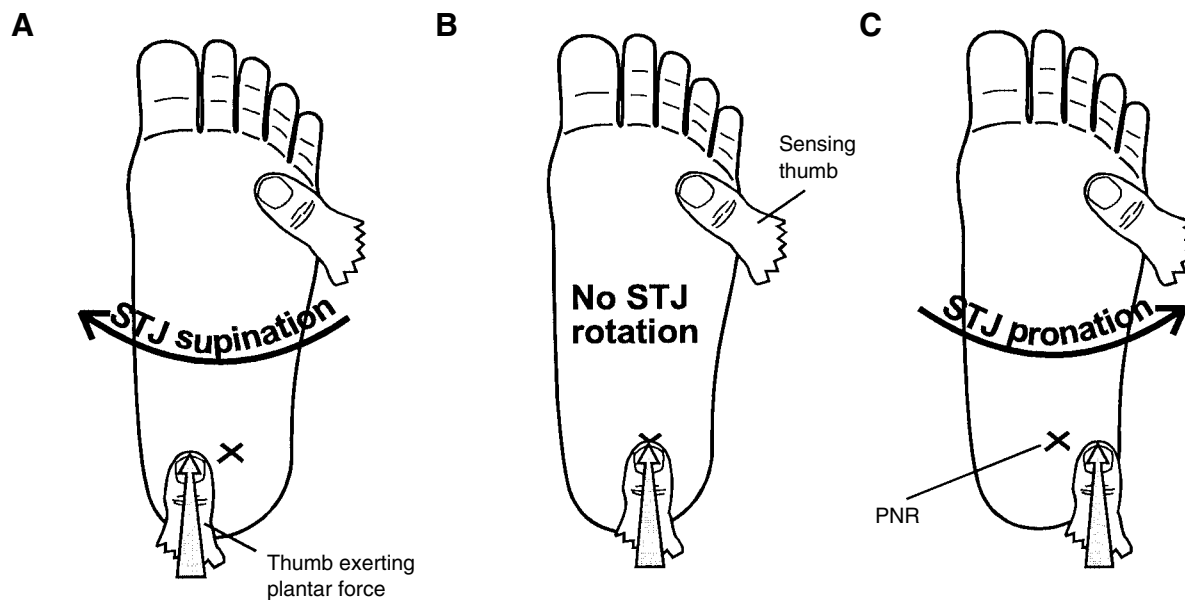


Figure 5. The plantar location of the subtalar joint (STJ) axis is determined by the examiner using one thumb to push on the plantar aspect of the foot and the opposite thumb to detect subtalar joint movements.²⁰ When the thumb presses on the plantar foot medial to the subtalar joint axis, subtalar joint supination motion occurs (left, A). When the thumb presses on the foot lateral to the subtalar joint axis, subtalar joint pronation motion occurs (right, C). Once the thumb presses on a location where no subtalar joint rotational motion occurs, this point on the plantar foot is marked as a point of no rotation (PNR) (center, B). Plotting the points of no rotation on the plantar foot represents the plantar location of the subtalar joint axis.¹⁷

an integral part of the determination of how forces acting on the foot affect the biomechanics of the foot, lower extremity, and body as a whole during weightbearing activities.²⁹

Constraint and Nonconstraint Mechanisms of the Foot

The idea that the foot may rotate in inversion and eversion about the talus mostly at the subtalar joint and only slightly at the oblique midtarsal joint during weightbearing activities is not new or unique. Huson²⁶ proposed that inversion and eversion of the foot occurs about the talus at the subtalar joint axis, rather than at separate subtalar joint and midtarsal joint axes. Huson²⁶ classified the foot as functioning with three osteoligamentous mechanisms: 1) the tarsal mechanism, 2) the tarsometatarsal mechanism, and 3) the metatarsophalangeal mechanism.

Huson²⁶ noted that when multiple joints interact to produce motions, which occurs in the foot, the type of motion that is produced at the joints may be described as being either a “constraint” or “nonconstraint” mechanism. In a constraint mechanism, the movement pattern of the joints is imposed by the

shape of the articular surfaces, the insertion pattern and length of the joint ligaments, the number of joints within the mechanism, and the relative position of these joints to each other. In other words, the motions of the bones in a constraint mechanism are kinematically closely coupled. However, in a nonconstraint mechanism, either muscular or external forces are necessary to determine the direction and magnitude of motion at the joints. In other words, the motions of the bones in a nonconstraint mechanism may occur independently of each other depending on the external forces acting on them and are kinematically only loosely coupled to each other.²⁶

Huson²⁶ described the tarsal mechanism as a constraint mechanism that consists of the calcaneus, navicular, and cuboid being kinematically closely coupled to each other, rotating on the more fixed talus in a defined and predictable manner as a unit during foot inversion and eversion. The tarsometatarsal mechanism was described as being a nonconstraint mechanism since the bones in the tarsometatarsal mechanism may move differently in relation to each other and in relation to the rearfoot, depending on the direction and magnitude of ground reaction force or muscular forces acting on it. The tarsometatarsal

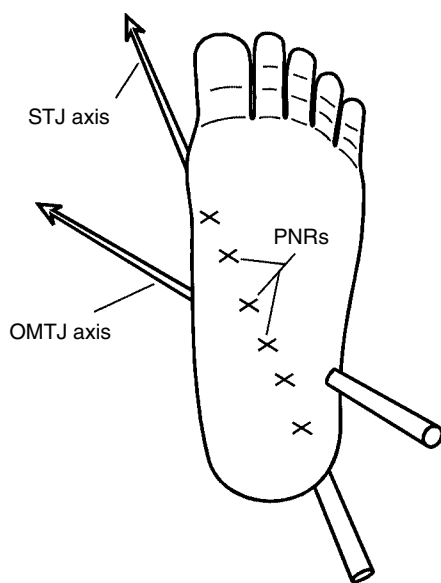


Figure 6. When the points of no rotation (PNRs) are located on the plantar foot by means of the subtalar joint axis (STJ) palpation technique,²⁰ they approximate the plantar representation of the subtalar joint axis. The fact that the points of no rotation follow the line of the subtalar joint axis and not the line of the oblique midtarsal joint (OMTJ) axis indicates that reaction forces on both the rearfoot and forefoot act directly on the subtalar joint axis, regardless of the orientation of the oblique midtarsal joint axis. This also lends support to the theory that the foot may be effectively modeled as a type of rigid body rotating about the talus and subtalar joint axis during closed kinetic chain pronation and supination motion, as has been suggested by other researchers.^{9-11, 26, 27}

mechanism consists of the five metatarsal bones and their connections to the tarsus, which have variable amounts of stiffness to each other, with the second metatarsal acting as the stiffest metatarsal (which Huson²⁶ describes as a “fixed spoke”) during closed kinetic chain inversion and eversion of the foot. Huson²⁶ also considered the metatarsophalangeal mechanism to be a nonconstraint mechanism, consisting of the metatarsophalangeal joints since the bones in the metatarsophalangeal mechanism may move independently of each other, depending on the magnitude and direction of ground reaction force and muscular forces acting on it.²⁶

A recent study by Cornwall and McPoil²⁷ of 153 subjects that measured the 3-D kinematics of the calcaneus, navicular, and first metatarsal during walking has supported Huson’s theory of strong kinematic tarsal coupling during subtalar joint pronation and supination. The study demonstrated that the 3-D

movements of the calcaneus and navicular were nearly identical to each other and that the first metatarsal moved very similarly to the calcaneus and navicular but had slightly more independent motion. The authors thought that the findings of their study supported Huson’s theory of a constraint mechanism of the tarsus and a nonconstraint mechanism of the tarsometatarsal unit.

The study by Cornwall and McPoil,²⁷ as well as the relatively sophisticated roentgen stereophotogrammetry studies done by Van Langelaan,⁹ Benink,¹⁰ and Lundberg and Svensson,¹¹ all indicate that the concept of a two-axis midtarsal joint that determines the direction of motion of the forefoot to the rearfoot during weightbearing activities is probably a great oversimplification of reality and may not be accurate. In support of this view, in a recent commentary on the two-axis model of the midtarsal joint, Payne³⁰ reviewed the available research pertaining to the midtarsal joint and suggested that the two-axis model of the midtarsal joint needs to be improved upon since recent research findings do not support it.

Rotational Equilibrium Across the Subtalar Joint Axis

The basic concept of rotational equilibrium is very straightforward. It states that for an object to meet the conditions of rotational equilibrium, it either must be at rest (ie, not rotating) or must be rotating at a constant velocity. In addition, for rotational equilibrium to exist across an axis of rotation, the sum of the moments acting in one direction must exactly equal the sum of the moments acting in the opposite direction across the axis of rotation (Fig. 7). Therefore, any object with an axis of rotation that is at rest must have a net moment acting across that axis of rotation that is equal to zero since the moments acting in opposite directions exactly counterbalance each other.^{23, 31} Specifically, in regard to the foot, in order to meet the conditions of rotational equilibrium across the subtalar joint axis, the subtalar joint either must not be rotating or must have a constant rotational velocity, and the sum of the magnitudes of subtalar joint pronation moments must exactly equal the sum of the magnitudes of subtalar joint supination moments (Fig. 8).¹⁴

During relaxed bipedal stance, the rotational position of the subtalar joint commonly is determined by measuring the position of the calcaneal bisection to the ground, which is called the relaxed calcaneal stance position.³² Feet that function most normally have a subtalar joint rotational position in relaxed bipedal stance that is approximately halfway between

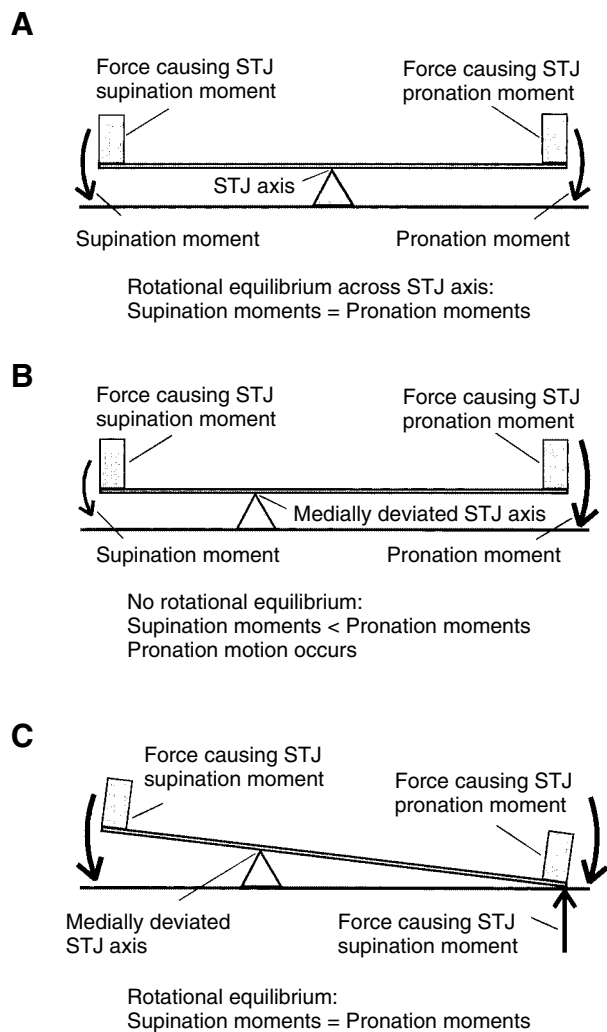


Figure 8. The forces acting on either side of the subtalar joint (STJ) axis may be modeled to be mechanically similar to the seesaw illustrated in Figure 7. In this model, counterclockwise rotation is supination motion, and clockwise rotation is pronation motion. A, Rotational equilibrium cannot be achieved until the supination moments equal the pronation moments. B, If a medially deviated subtalar joint axis is present in a foot (modeled above as the left shift of the subtalar joint axis), the relative moment arms for the forces causing subtalar joint supination and pronation moments are altered so that the supination moments are less than the pronation moments, which results in pronation motion. C, In a foot with a medially deviated subtalar joint axis, the resultant pronation motion will stop only once rotational equilibrium is again achieved by another structure in the foot (eg, the floor of the sinus tarsi of the calcaneus), causing a supination moment to counterbalance the excessive pronation moments caused by the medial subtalar joint axis deviation.¹⁴

nents of the foot has been described previously by the author.¹⁴

Physical Characteristics of Feet with Medially Deviated Subtalar Joint Axes

Since the subtalar joint axis passes anteriorly through the talar neck, a foot that has a talar neck and head that are relatively medially positioned in relation to the plantar surface of the foot will also have a medially deviated subtalar joint axis.^{2, 5, 6, 8, 12} It is this abnormal medial spatial location of the talar head that causes the characteristic clinical appearance of the foot with medial deviation of the subtalar joint axis (Figs. 9–11).

During relaxed bipedal stance, feet with medially deviated subtalar joint axes will demonstrate the following three clinical signs that distinguish them from other types of feet. First, when the foot is viewed from above, the medial border of the midfoot will demonstrate a convex shape within the transverse plane. Second, also evident when viewed from above, the soft-tissue contour of the talar head and neck at the anterior ankle joint area will be more medially positioned and internally rotated in relation to the calcaneus than normal (Fig. 10). Third, when the foot is viewed from its posterior aspect in a standing position, there will be increased convexity in the medial midfoot area just inferior and anterior to the medial malleolus (Fig. 11). All of these clinical signs are directly caused by the abnormal medial position of the talar head in relation to the calcaneus and rest of the foot.

Even though feet with medially deviated subtalar joint axes typically have lower medial longitudinal arch height than normal, some feet with medially deviated subtalar joint axes may also have a normal medial longitudinal arch height during relaxed bipedal stance. In addition, the posterior bisection of the calcaneus may be either inverted, vertical, or everted during relaxed bipedal stance in feet with medially deviated subtalar joint axes. Therefore, measurement of the relaxed calcaneal stance position is not a reliable indicator of the position of the subtalar joint axis or of the prevailing pronation and supination moments acting across the subtalar joint axis during weightbearing activities.¹⁷

Since the concept of subtalar joint axis spatial location dictates that the actions of ground reaction force and muscular contractile force in feet with medially deviated subtalar joint axes will cause increased magnitudes of subtalar joint pronation moment and decreased magnitudes of subtalar joint supination moment when compared with normal, these feet nearly

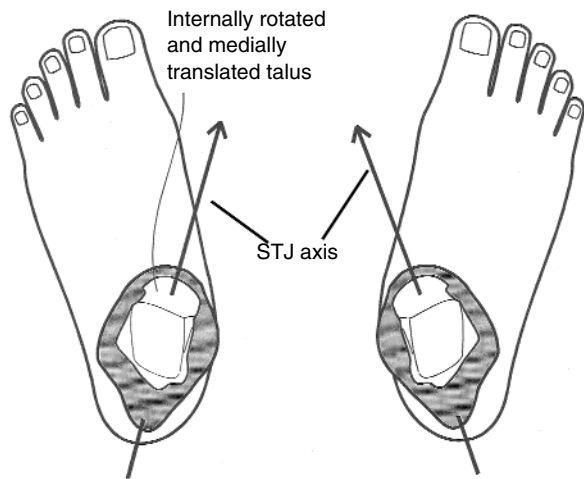


Figure 9. Feet with medial deviation of the subtalar joint (STJ) axis have an internally rotated and medially translated talus that results in excessive subtalar joint pronation moments during weightbearing activities.

will always be maximally pronated at the subtalar joint during relaxed bipedal stance.^{14-17, 34, 35} Owing to the maximally pronated subtalar joint position, these feet will tend to have increased magnitudes of interosseous compression forces acting between the anterior aspect of the lateral process of the talus and the floor of the sinus tarsi of the calcaneus. In general, the greater the medial deviation of the subtalar joint axis, the greater will be the interosseous compression force within the sinus tarsi, owing to the increased subtalar joint pronation moments acting on these feet.¹⁴

Because of the increased subtalar joint pronation moments acting on a foot with a medially deviated subtalar joint axis, this foot type will be much more likely to resist supination motion when subtalar joint supination moments act upon it. For example, foot orthoses designed to increase subtalar joint supination moment will be less likely to supinate feet with medially deviated subtalar joint axes out of their maximally pronated position when compared with feet with more normal subtalar joint axis locations.¹⁴⁻¹⁷ To sufficiently counteract the increased magnitudes of subtalar joint pronation moment acting on these feet, conservative treatment of pronation-related symptoms of the foot and lower extremity should include foot orthoses using antipronation techniques, such as the Blake inverted orthosis³⁶⁻³⁹ and/or medial heel skive techniques.^{16, 17} It is logical to conclude that both the Blake inverted and medial heel skive orthotic techniques effectively increase the subtalar joint

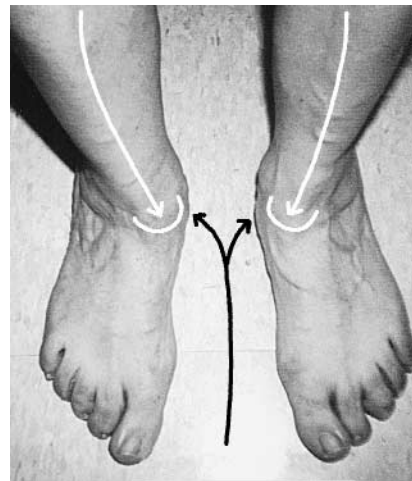


Figure 10. Two signs of medial deviation of the subtalar joint axis, when the foot is viewed from above, are the abnormal medial convexity in the medial mid-foot area (black arrows) and the abnormally medially positioned and internally rotated soft-tissue contour of the talar head and neck (white lines and arrows).

supination moments and decrease the subtalar joint pronation moments by redirecting the reaction forces acting on the plantar foot from a more lateral to a more medial location.¹⁴⁻¹⁷

Characteristic symptoms that the author has noted as occurring with increased frequency in individuals with medially deviated subtalar joint axes include plantar fasciitis, hallux limitus, second metatarsophalangeal joint capsulitis, abductor hallucis muscle strain, sinus tarsi syndrome, posterior tibial tendinitis, posterior tibial tendon dysfunction, medial tibial



Figure 11. When the foot with medial deviation of the subtalar joint axis is viewed from the posterior aspect, there is abnormal medial convexity in the medial midfoot just inferior to the medial malleolus (white arrows).

stress syndrome, chondromalacia patellae, and pes anserinus bursitis. Many other types of painful syndromes of the foot and/or lower extremity also may occur owing to the medial deviation of the subtalar joint axis since the increased subtalar joint pronation moment that results may cause abnormal magnitudes of loading forces on the structural components of the foot and/or lower extremity. Effective treatment of these pathologies with the use of the concepts of subtalar joint axis location and rotational equilibrium are beyond the scope of this paper and are discussed in detail elsewhere.¹⁷

Physical Characteristics of Feet with Laterally Deviated Subtalar Joint Axes

Feet that have laterally deviated subtalar joint axes are much less common than feet that have medially deviated subtalar joint axes. For a foot to have a laterally deviated subtalar joint axis, the talar head and neck must be more laterally positioned in relation to the plantar foot than normal (Fig. 12). In general, the lateral deviation is more evident at the rearfoot than at the forefoot when the subtalar joint axis palpation technique is used in these feet. The lateral deviation of the subtalar joint axis dictates that the actions of the ground reaction force and muscular contractile force will cause increased magnitudes of subtalar joint supination moment and decreased magnitudes of subtalar joint pronation moment relative to normal.¹⁴

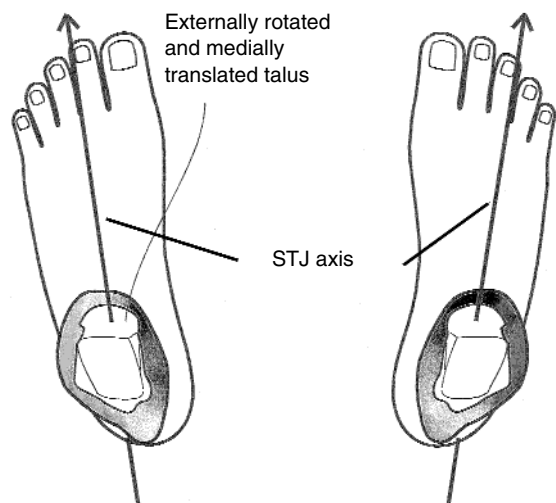


Figure 12. Feet with lateral deviation of the subtalar joint (STJ) axis have an externally rotated and laterally translated talus that results in excessive subtalar joint supination moments during weightbearing activities.

During relaxed bipedal stance, feet with laterally deviated subtalar joint axes will demonstrate the following three clinical signs that are caused by the abnormal lateral location of the talar head. First, when the foot is viewed from above, the medial border of the midfoot will demonstrate a concave shape within the transverse plane. Second, the soft-tissue contour of the talar head and neck at the anterior ankle area will be more laterally positioned in relation to the calcaneus than normal (Fig. 13). And third, when the foot is viewed from posterior in standing, there will be increased concavity in the medial midfoot area just inferior and anterior to the medial malleolus (Fig. 14). Feet with laterally deviated subtalar joint axes tend also to have higher than normal medial longitudinal arch height and commonly demonstrate a pes cavus deformity.

One of the most interesting aspects of this foot type is that when it is observed during relaxed bipedal stance, one or both of the peroneal tendons may be under tension (ie, bowstrung), indicating tonic contractile activity in the peroneal muscles (Fig. 15). This clinical finding is evident only when the standing patient is observed from the lateral aspect. Therefore, the examiner must be sure to directly examine the peroneal tendons for tonic peroneal contraction during the standing examination of the patient.

The increased tonic activity in the peroneus brevis and/or longus produces a subtalar joint pronation moment that is necessary to counteract the excessive subtalar joint supination moments that are common in the foot with a laterally deviated subtalar

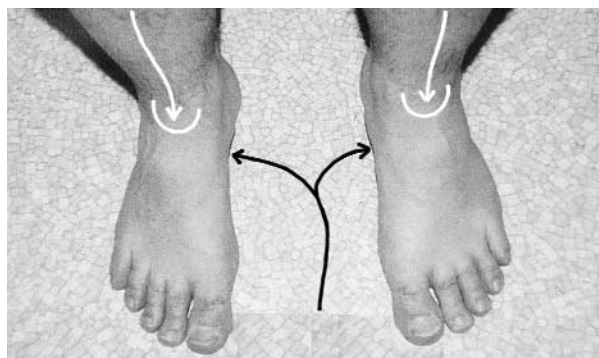


Figure 13. Two signs of lateral deviation of the subtalar joint axis, when the foot is viewed from above, are the abnormal medial concavity in the medial midfoot area (black arrows) and the abnormally laterally positioned and externally rotated soft-tissue contour of the talar head and neck (white lines and arrows).

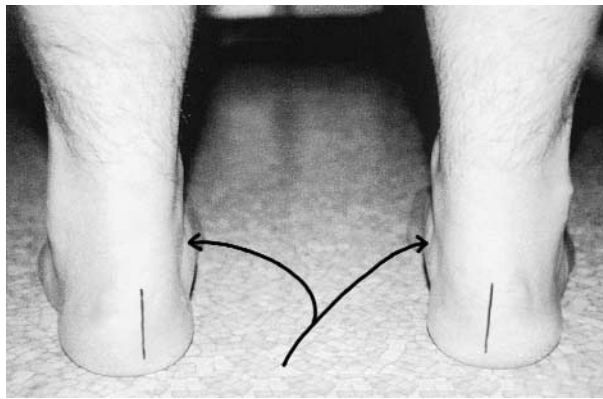


Figure 14. When the foot with lateral deviation of the subtalar joint axis is viewed from the posterior aspect, there is abnormal medial concavity in the medial midfoot just inferior to the medial malleolus (black arrows).

joint axis. The author has repeatedly observed that feet with significant lateral deviation of the subtalar joint axis will maximally supinate at the subtalar joint (ie, the foot will invert until the patient is standing on the lateral aspect of the foot) during relaxed bipedal stance if the patient is instructed or shown how to relax the peroneal muscles during standing. Therefore, the tonic contractile activity of the peroneal muscles that commonly occurs in feet with a laterally deviated subtalar joint axis is probably necessary to allow the foot to function in a plantigrade position during weightbearing activities. Without abnormal contractile activity of the peroneal muscles in feet with a moderate to severe lateral deviation of the subtalar joint axis, the individual would either walk on the lateral aspects of the feet or repeatedly experience inversion ankle sprains.

Because of the increased supination moments acting on feet with laterally deviated subtalar joint axes, these feet characteristically also will be much more difficult to pronate with foot orthoses than feet with more normal subtalar joint axis locations.^{14, 17} To sufficiently counteract the increased magnitudes of subtalar joint supination moment acting on these feet, conservative treatment of supination-related symptoms of the foot and lower extremity should include the judicious use of foot orthoses with everted heel cup shapes (ie, lateral heel skives), everted balancing positions, and forefoot valgus wedges. These in-shoe modifications will redirect the reaction forces acting on the plantar foot from a more medial location to a more lateral location, thereby causing increased subtalar joint pronation moments and a decreased ne-

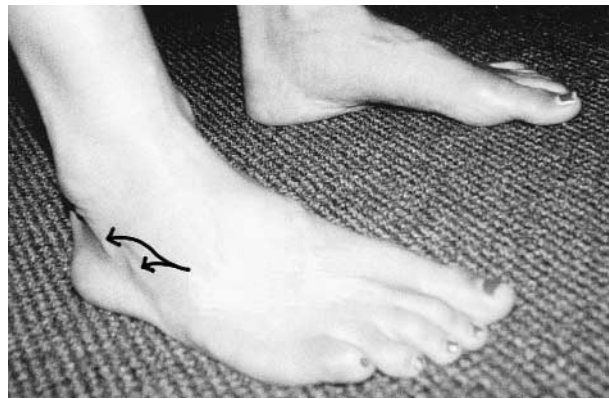


Figure 15. Feet with laterally deviated subtalar joint axes often demonstrate tonic contraction of the peroneus brevis and/or peroneus longus muscles during relaxed bipedal stance (black arrows), which is evident in the visualization and/or palpation of the bowstringing of the peroneal tendons on the lateral aspect of the foot. Tonic peroneal contraction is often present in feet with laterally deviated subtalar joint axes to increase the pronation moment so that the forefoot can remain in a plantigrade position.

cessity for the individual to activate the peroneal muscles to allow a more stable, plantigrade gait pattern.¹⁷ Even though these orthotic modifications are extremely useful in such feet, it also must be strongly emphasized that attempting to excessively pronate a patient's foot past the maximally pronated subtalar joint position with everted orthoses and/or valgus wedges must be done with extreme caution and care to avoid possible degenerative changes to the joints of the foot in the future.

Symptoms that the author has noted as occurring with increased frequency in individuals with laterally deviated subtalar joint axes include inversion ankle sprains and peroneal tendinitis. By clinical application of the above biomechanical theories, the author has successfully and conservatively treated more than 100 patients with chronic peroneal tendinitis who had previously failed treatment with multiple other foot orthosis designs. The methods of conservative treatment of pathologies caused by feet with laterally deviated subtalar joint axes are beyond the scope of this paper and are discussed in detail elsewhere.¹⁷

Effects of Rearfoot Structure and Position on Subtalar Joint Moments

In a normal foot, since the subtalar joint axis is positioned lateral to the plantar weightbearing area of the calcaneus (ie, the medial calcaneal tubercle), ground

reaction force acting on the medial calcaneal tubercle will cause a subtalar joint supination moment. The magnitude of subtalar joint supination moment produced is dependent not only on the length of the moment arm from the subtalar joint axis to the plantar aspect of the medial calcaneal tubercle, but also on the magnitude and direction of the ground reaction force vector acting on the plantar calcaneus.^{13-17, 20, 34}

The morphology of the articulating surfaces of the talus and calcaneus determines the spatial location of the subtalar joint axis in relation to the talus and calcaneus at each rotational position of the subtalar joint.⁹⁻¹¹ However, morphological variations in the calcaneus separate and distinct from the talar articulating facets also will cause an alteration in the spatial location of the subtalar joint axis in relation to the plantar calcaneus. Therefore, the spatial location of the subtalar joint axis relative to the plantar calcaneus will be determined not only by the morphology of the articulating facets of the subtalar joint, but also by the structure of the body of the calcaneus and by the rotational position of the subtalar joint.³⁴

Sgarlato¹ and Root et al³ have described frontal plane deformities of the rearfoot, such as rearfoot varus and rearfoot valgus, and also have proposed theories on how these structural deformities of the foot affect the function of the foot and lower extremity. The author proposes that the biomechanical effects of the frontal plane rearfoot deformities can be more easily analyzed mechanically and more completely understood if they are instead approached with the use of the subtalar joint axis location/rotational equilibrium theory.

Rearfoot varus and rearfoot valgus deformities should be considered as having their effect on foot function not by altering the frontal plane structure of the posterior calcaneus but rather by altering the position of the medial calcaneal tubercle in relation to the subtalar joint axis, which, in turn, effectively alters the length of the subtalar joint moment arm to the medial calcaneal tubercle (Figs. 16 and 17). Rearfoot varus deformity may then be viewed as having an effect on the subtalar joint moments similar to that of surgically shifting the plantar aspect of the calcaneus to a more medial position in relation to the dorsal aspect of the calcaneus since rearfoot varus deformity, in effect, causes the medial calcaneal tubercle to be positioned relatively more medial to the subtalar joint axis. According to the same logic, rearfoot valgus deformity may be viewed as having an effect on subtalar joint moments similar to that of surgically shifting the plantar aspect of the calcaneus to a more lateral position in relation to the dorsal aspect of the calcaneus since rearfoot valgus deformi-

ty, in effect, causes the medial calcaneal tubercle to be positioned relatively less medial (or relatively more lateral) to the subtalar joint axis.^{17, 18, 20, 34} In other words, the spatial location of the subtalar joint axis in relation to the medial calcaneal tubercle is affected by variations in the frontal plane structure of the calcaneus.

To further clarify these ideas, it is helpful to analyze these rearfoot deformities in more specific detail. A foot with a rearfoot varus deformity, which may be caused by a varus structural alignment of either the tibia or the calcaneus, has a calcaneus that is inverted in relation to the ground while in neutral calcaneal stance position.¹ The inverted position of the body of the calcaneus positions the medial calcaneal tubercle more medial to the subtalar joint axis than would be present in a foot without a rearfoot varus deformity (Figs. 16 and 17). An increase in rearfoot varus deformity will then cause an increase in subtalar joint supination moment due to the increased length of moment arm that ground reaction force has available to produce subtalar joint supination moment. A decrease in rearfoot varus deformity will cause a decrease in the subtalar joint supination moment due to the decreased moment arm that ground reaction force has available to produce subtalar joint supination moment.^{17, 40}

Therefore, the common clinical observation that feet with high degrees of rearfoot varus deformity have increased tendency toward supination instability of the rearfoot (ie, inversion ankle sprains) is explained easily by the fact that increased rearfoot varus deformity increases the net subtalar joint supination moment because of the increased length of subtalar joint moment arm to the medial calcaneal tubercle. However, the common clinical observation that lesser degrees of rearfoot varus deformity tend to cause pronation of the foot from the subtalar joint neutral position is explained not by the inverted position of the calcaneus to the ground, but rather by the effect that rearfoot varus deformity has on the position of the forefoot to the ground (Fig. 18).⁴⁰

Rearfoot varus deformity causes the forefoot to be inverted to the ground while the subtalar joint is in neutral position, assuming the foot has no frontal plane forefoot deformity.¹ The inverted position of the forefoot to the ground causes an increase in ground reaction force on the lateral aspect of the forefoot, which causes an increased subtalar joint pronation moment since the lateral forefoot is lateral to the subtalar joint axis (Fig. 18). The increase in subtalar joint pronation moment tends to cause pronation motion away from the subtalar joint neutral position. Therefore, the final rotational position

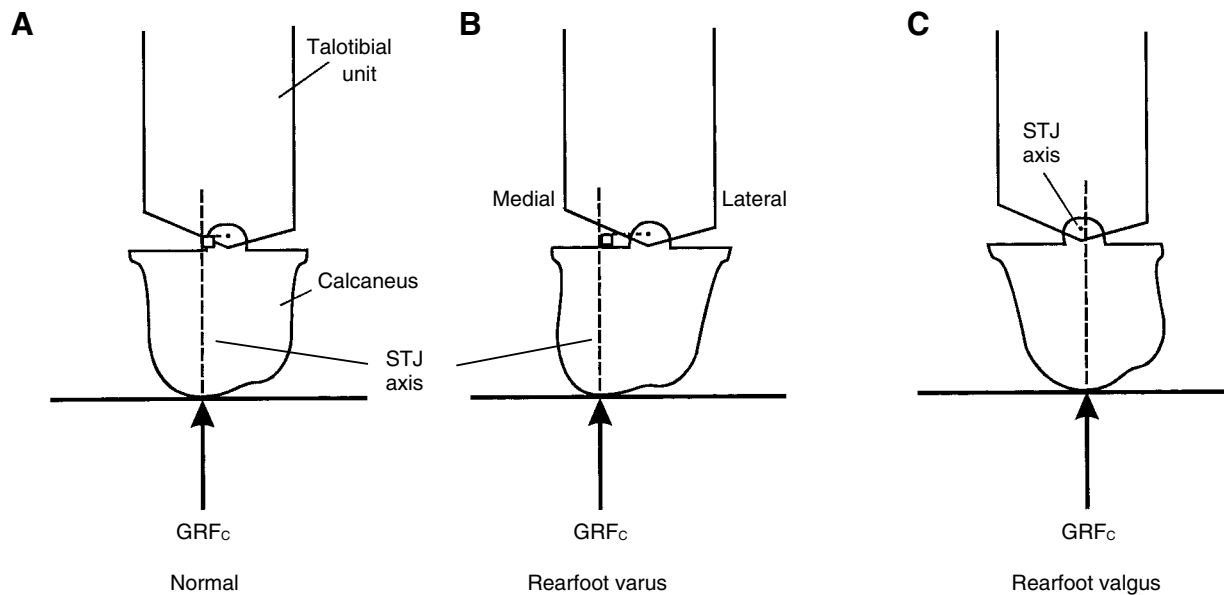


Figure 16. The posterior aspect of the right foot is modeled with the calcaneus resting on the medial calcaneal tubercle connected via the subtalar joint (STJ) axis to the tibia and talus, which are joined together as a talotibial unit. A, Ground reaction force on the calcaneus (GRF_c) in the normal foot causes a subtalar joint supination moment since it acts medial to the subtalar joint axis. B, In a foot with a rearfoot varus deformity, the inverted position of the rearfoot effectively increases the subtalar joint supination moment by moving the medial calcaneal tubercle more medial to the subtalar joint axis. C, In a foot with a rearfoot valgus deformity, the everted position of the rearfoot effectively either decreases the subtalar joint supination moment or increases the subtalar joint pronation moment by moving the medial calcaneal tubercle more lateral in relation to the subtalar joint axis.

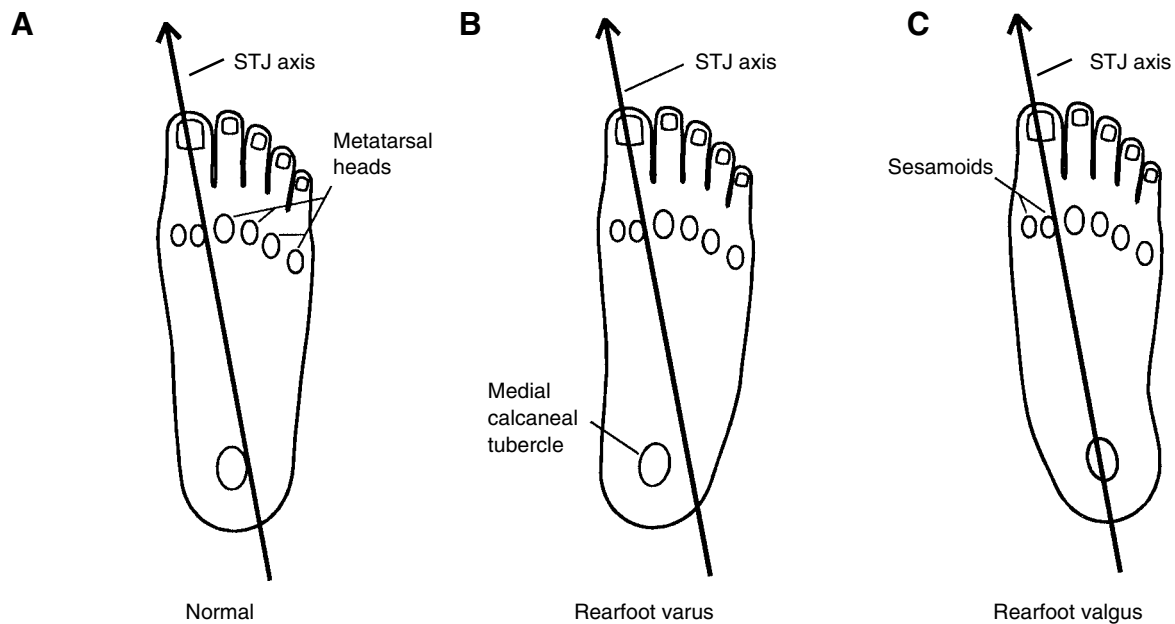


Figure 17. A, In a normal foot, the medial calcaneal tubercle is medial to the subtalar joint (STJ) axis. B, In a foot with a rearfoot varus deformity, the medial calcaneal tubercle is effectively shifted more medial to the subtalar joint axis, which increases the subtalar joint supination moment when ground reaction force acts on the calcaneus. C, In a foot with a rearfoot valgus deformity, the medial calcaneal tubercle is effectively shifted more lateral in relation to the subtalar joint axis, which either decreases the subtalar joint supination moment or increases the subtalar joint pronation moment.

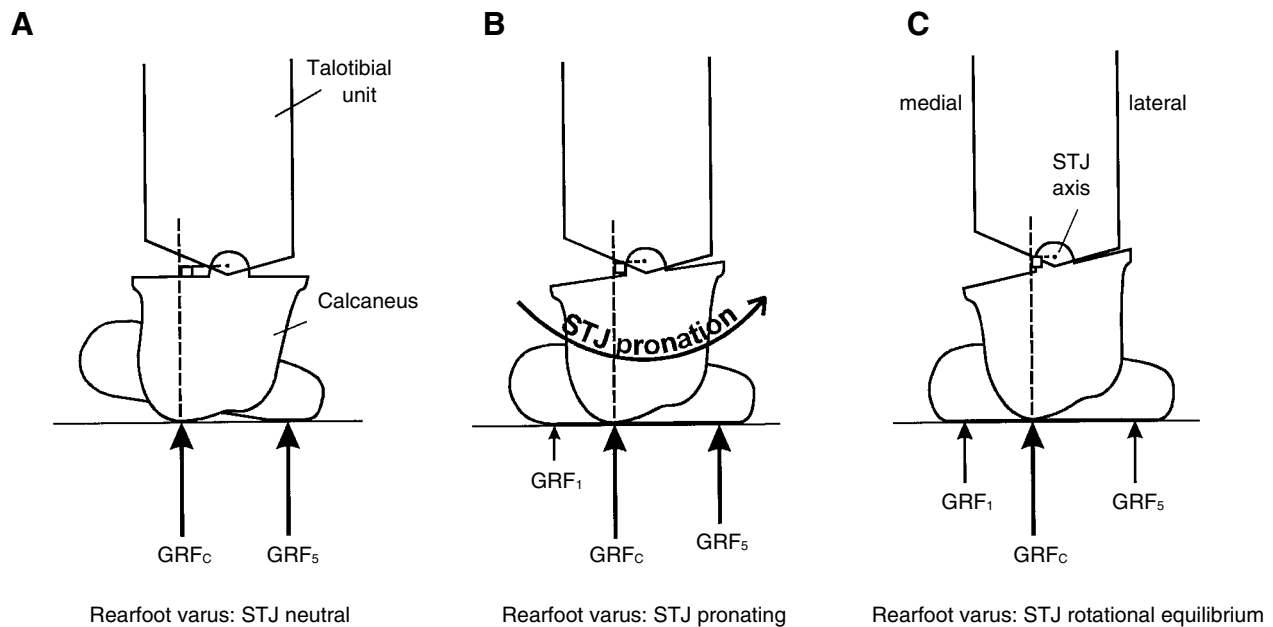


Figure 18. A, In a rearfoot varus deformity standing in subtalar joint (STJ) neutral position, both the calcaneus and forefoot are inverted to the ground. B, Ground reaction force acting on the calcaneus (GRF_c) causes a relatively small supination moment when compared with the pronation moment that results from ground reaction force acting on the fifth metatarsal head (GRF_5). As a result of the larger magnitude of subtalar joint pronation moment, pronation motion occurs until there is ground reaction force acting on the first metatarsal head (GRF_1), which also causes a decrease in the ground reaction force on the fifth metatarsal head. C, Therefore, subtalar joint pronation motion will continue in the rearfoot varus foot until a subtalar joint rotational position occurs in which the supination moments counterbalance exactly the pronation moments (right). This mechanical analysis demonstrates that pronation occurs in a rearfoot varus foot specifically owing to its inverted forefoot position, and not owing to its inverted rearfoot position.

that the subtalar joint assumes during relaxed bipedal stance occurs only when the subtalar joint has reached a rotational position in which an exact counterbalancing of subtalar joint pronation moments and subtalar joint supination moments has been attained (ie, subtalar joint rotational equilibrium).^{14, 17, 35, 40}

Through an analysis similar to the one described above, a foot with a rearfoot valgus deformity has the medial calcaneal tubercle either less medially positioned or more laterally positioned in relation to the subtalar joint axis than normal since a rearfoot valgus has an everted calcaneus-to-ground relationship (Figs. 16 and 17). In addition, many feet that function similarly to a foot with rearfoot valgus deformity may not demonstrate an everted frontal plane deformity, but may show apparent lateral displacement of the calcaneus to the tibia (John Weed, DPM, personal communication, 1981). Either a rearfoot valgus deformity or a laterally displaced calcaneus will cause the medial calcaneal tubercle to be either less medially positioned or more laterally positioned than normal, which will cause a decrease in

the moment arm that ground reaction force has to produce subtalar joint supination moment by its action on the plantar calcaneus. Severe rearfoot valgus deformity or severe lateral displacement of the calcaneus may cause such a large lateral relative movement of the medial calcaneal tubercle to the subtalar joint axis that the medial tubercle becomes positioned lateral to the subtalar joint axis. When this level of deformity occurs, ground reaction force acting on the plantar calcaneus causes a subtalar joint pronation moment rather than the normal subtalar joint supination moment.³²

Therefore, the common clinical finding that feet with rearfoot valgus deformity and/or a laterally displaced calcaneus are maximally pronated at the subtalar joint during relaxed bipedal stance (and during other weightbearing activities) is explained easily by the relative reduction in the moment arm that ground reaction force has available to produce subtalar joint supination by its actions on the medial calcaneal tubercle. Without an adequate subtalar joint supination moment acting across the subtalar joint axis to coun-

terbalance the pronation moments being caused by the effects of ground reaction force on the lateral forefoot and midfoot, the foot is likely to be maximally pronated since the position of subtalar joint rotational equilibrium for these feet in standing is the maximally pronated subtalar joint position. In effect, feet with rearfoot valgus deformity or a laterally displaced calcaneus also have medially deviated subtalar joint axes because of the relative medial position of the subtalar joint axis to the plantar calcaneus.^{14, 15, 17, 20, 33-35}

As mentioned earlier, rotational motion of the subtalar joint during weightbearing activities also alters the relative position of the medial calcaneal tubercle to the subtalar joint axis (Fig. 19). Closed kinetic chain subtalar joint pronation causes the calcaneus to evert in relation to the talus, which causes the talus and subtalar joint axis to translate medially and internally rotate in relation to the medial calcaneal tubercle. Closed kinetic chain subtalar joint supination causes the calcaneus to invert in relation to the talus, which causes the talus and subtalar joint axis to translate laterally and to rotate externally in relation to the medial calcaneal tubercle.^{13-19, 34}

Therefore, because of these relative spatial translations and rotations of the subtalar joint axis in relation to the plantar foot during closed kinetic chain subtalar joint pronation and supination, the subtalar joint moment arms to the medial calcaneal tubercle also are altered. Subtalar joint pronation causes either a decrease in the subtalar joint supination moment arm or an increase in the subtalar joint pronation moment arm that ground reaction force has available by its actions on the medial calcaneal tubercle. Subtalar joint supination causes either an increase in the subtalar joint supination moment arm or a decrease in the subtalar joint pronation moment arm that ground reaction force can produce by its actions on the medial calcaneal tubercle. In effect, pronation and supination motion of the subtalar joint can be thought to influence the relative lengths of the supination and pronation moment arms to the medial calcaneal tubercle, similar to the way in which structural deformities of the rearfoot also influence the moment arm lengths to the medial calcaneal tubercle.^{17, 18, 34}

The above analysis points to one of the most important aspects of the subtalar joint axis location/ro-

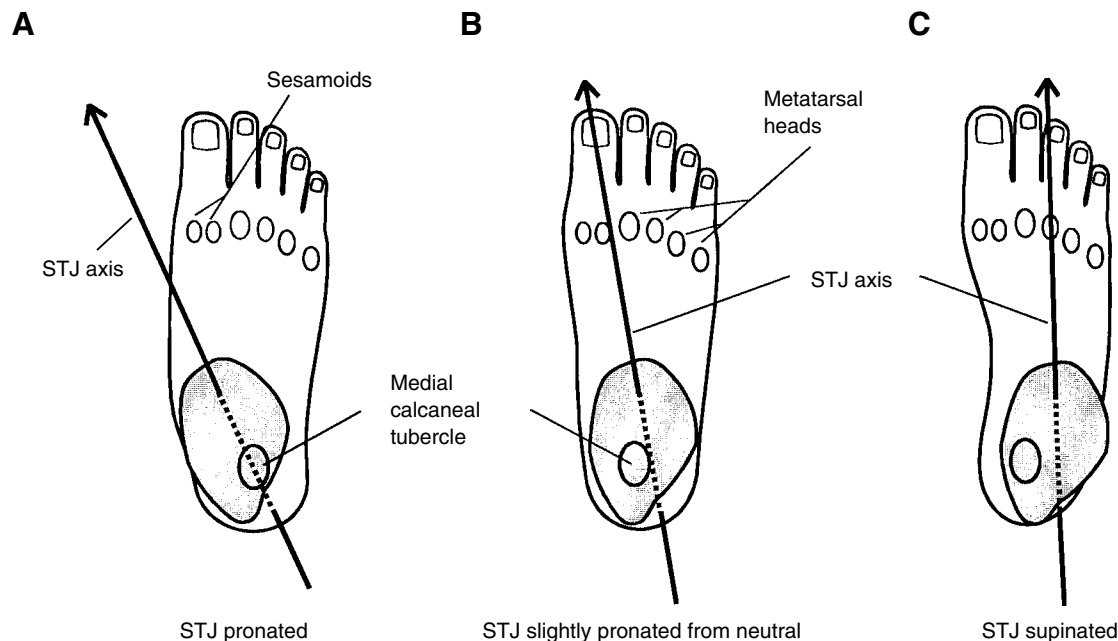


Figure 19. When a normal foot is standing slightly pronated from the subtalar joint (STJ) neutral position, the subtalar joint axis passes just lateral to the medial calcaneal tubercle posteriorly and passes over the first intermetatarsal space anteriorly (center, B). Subtalar joint pronation causes the subtalar joint axis to internally rotate and medially translate in relation to the plantar foot so that it becomes positioned well medial to the first metatarsal head and more medial to the medial calcaneal tubercle (left, A). Subtalar joint supination causes the subtalar joint axis to externally rotate and laterally translate so that it becomes positioned more laterally over the metatarsal heads and more lateral to the medial calcaneal tubercle (right, C).

tational equilibrium theory. By focusing on the determination of the relative lengths of the moment arms from the medial calcaneal tubercle to the subtalar joint axis, it allows both rotational position of the subtalar joint axis and congenital structure of the rearfoot complex to be biomechanically quantified by means of the same parameters. Combining this analysis with the other spatial movements of important anatomical landmarks in the rearfoot (eg, the posterior calcaneus for determining the moment arm length for the Achilles tendon/gastrocnemius-soleus complex) will allow future researchers to more effectively quantify the kinetics of the rearfoot complex during weightbearing activities.

Possibly more importantly, the subtalar joint axis location/rotational equilibrium theory readily explains the biomechanical effects of rearfoot surgeries, such as the posterior calcaneal displacement osteotomy, which commonly are used in the treatment of acquired flatfoot disorders, such as posterior tibial tendon dysfunction.⁴¹⁻⁴⁸ Medial displacement of the posterior fragment in a posterior calcaneal displacement osteotomy alters the relative structural locations of the posterior-plantar calcaneus to the more superiorly located talar articulating facets (Fig.

20). The net mechanical effect of this osteotomy is to cause an overall increase in subtalar joint supination moment since both the moment arm that ground reaction force has available to cause subtalar joint supination moment and the moment arm that gastrocnemius and/or soleus contraction has available to cause subtalar joint supination moment are increased. By analyzing the relative location of the subtalar joint axis in relation to the plantar calcaneus prior to rearfoot surgery, the surgeon may be better able to predict the correct amount of calcaneal displacement necessary to achieve optimal postsurgical results.¹³

Effects of Forefoot Structure and Position on Subtalar Joint Moments

Since the plantar aspect of the forefoot is subjected to ground reaction force in nearly all weightbearing activities, the relative position of the weightbearing structures of the forefoot to the spatial location of the subtalar joint axis has an important effect on the biomechanics of the foot and lower extremity as a whole. Closed kinetic chain pronation of the subtalar joint causes medial translation and internal rotation

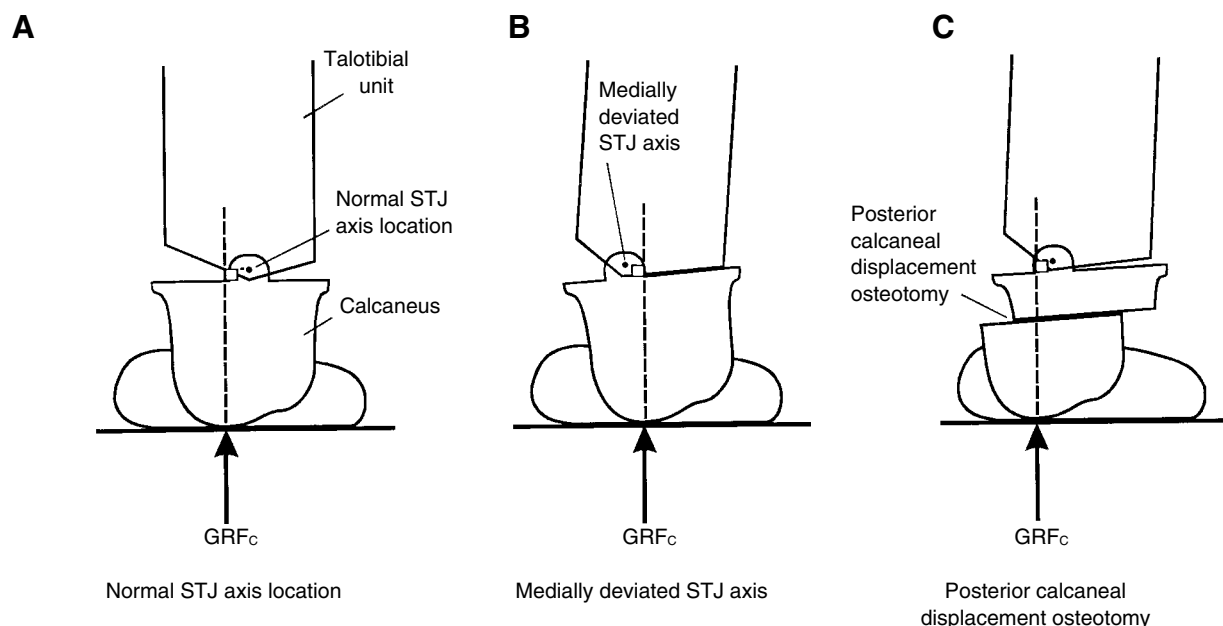


Figure 20. A, In a foot with a normal subtalar joint (STJ) axis location, ground reaction force acting under the calcaneus (GRF_c) causes a subtalar joint supination moment. B, In a foot with a severely medially deviated subtalar joint axis, such as that seen in posterior tibial dysfunction, ground reaction force under the calcaneus actually may cause a subtalar joint pronation moment. C, Posterior calcaneal displacement osteotomies exert their mechanical effect on the feet with severely medially deviated subtalar joint axes by altering the relative location of the plantar and posterior calcaneus so that ground reaction forces and Achilles tendon tensile forces acting on the calcaneus are relatively more medially positioned (B) than preoperatively (C).

of the subtalar joint axis in relation to the stationary forefoot. Conversely, closed kinetic chain subtalar joint supination causes lateral translation and external rotation of the subtalar joint axis in relation to the forefoot (Figs. 2 and 19). Because of the relative translations and rotations of the subtalar joint axis above the weightbearing portions of the forefoot during closed kinetic chain pronation and supination, these motions will have a direct effect on the relative moment arm lengths that ground reaction force has available to produce either pronation or supination moment of the subtalar joint during weightbearing activities.¹³⁻¹⁹

The theory that the ground reaction force acting on the metatarsal heads may, in fact, cause direct production of subtalar joint supination and/or pronation moments is based on the premise, which is often used in biomechanical studies of the lower extremity, that the foot may be modeled effectively as a rigid body rotating about the talus during weightbearing activities.^{28, 29} In support of this theory, the author has noted earlier that during the subtalar joint axis palpation examination technique on more than 2,000 feet, the points of no rotation on the plantar rearfoot and plantar forefoot represent a single line, indicating that the rearfoot and forefoot are basically “locked” into a relatively rigid structure that rotates primarily about the subtalar joint axis (Fig. 6). In addition, Fuller⁴⁹ recently described how the location of the subtalar joint axis in relation to the center of pressure on either the plantar forefoot or the plantar rearfoot can explain the mechanical basis for certain pedal pathology. Finally, Huson’s theory on the constraint mechanism of the human tarsus,²⁶ which has been supported by the tarsal kinematic research of Cornwall and McPoil,²⁷ and the roentgen stereophotogrammetry studies done by Van Langelaan,⁹ Benink,¹⁰ and Lundberg and Svensson¹¹ are all consistent with the current author’s theory that the subtalar joint axis is the primary inversion/eversion axis of the foot.

To further expand on this topic, an example of a normal foot in which the subtalar joint axis passes superior to the first intermetatarsal space area of the foot will be explored. In this foot, ground reaction force acting on the first metatarsal head will produce a small subtalar joint supination moment since the first metatarsal head lies medial to the subtalar joint axis (Figs. 2 and 19). If the foot then pronates so that the subtalar joint axis internally rotates and translates medially, the spatial location of the subtalar joint axis will then be medial to the first metatarsal head. In this pronated foot, ground reaction force acting plantar to the first metatarsal head will now cause a subtalar joint pronation moment since the

first metatarsal head is lateral to the subtalar joint axis. If the same foot then supinates so that the subtalar joint axis externally rotates and laterally translates until it is positioned over the third metatarsal head, then any ground reaction force under the first metatarsal head will have a longer subtalar joint supination moment arm than in the initial resting position. Therefore, the relative spatial location of the subtalar joint axis to the metatarsal heads is altered by closed kinetic chain pronation and supination motions that, in turn, will determine both the magnitude and the direction of moment that is produced across the subtalar joint axis by the actions of ground reaction force on any specific weightbearing area of the metatarsal heads or forefoot.^{13-17, 20}

In a similar fashion to closed kinetic chain subtalar joint pronation and supination, variances in the transverse plane structural relationships of the forefoot to the rearfoot also may alter the relative spatial location of the subtalar joint axis to the forefoot. Weissman⁵⁰ claims that the ideal forefoot adductus angle is 8°. Through radiographic analysis, forefoot rectus foot types have been defined as having a forefoot adductus angle of less than 12° to 14°, and forefoot adductus foot types have been defined as having a forefoot adductus angle of greater than 12° to 14°. ^{1, 32, 50} Therefore, the large variances in the transverse plane relationship of the forefoot relative to the rearfoot in the human population indicates that each foot possesses a unique transverse plane structural angular alignment of the forefoot to the rearfoot, which, in turn, affects the relative alignment of the subtalar joint axis to the plantar forefoot.

The importance of transverse plane structure of the foot on the balance of subtalar joint pronation and supination moments during weightbearing activities can be explained more easily by examining the relative spatial location of the subtalar joint axis to the forefoot in three feet with identical rearfoot structure but variances in forefoot-to-rearfoot transverse plane structure (Fig. 21). Foot A has a relatively normal forefoot adductus angle of 10°. Foot B has an increased forefoot adductus angle of 20°, which would be considered a forefoot adductus foot type. Foot C has a forefoot adductus angle of 0°, which would be considered a forefoot rectus foot type.

In Foot A, with a 10° forefoot adductus angle, the subtalar joint axis passes anteriorly over the first intermetatarsal space. In Foot B, the increased forefoot adductus angle of 20° causes the forefoot to be relatively more medially positioned in relation to the subtalar joint axis. The ground reaction force acting on the first metatarsal head of Foot B now has a longer moment arm to produce subtalar joint supina-

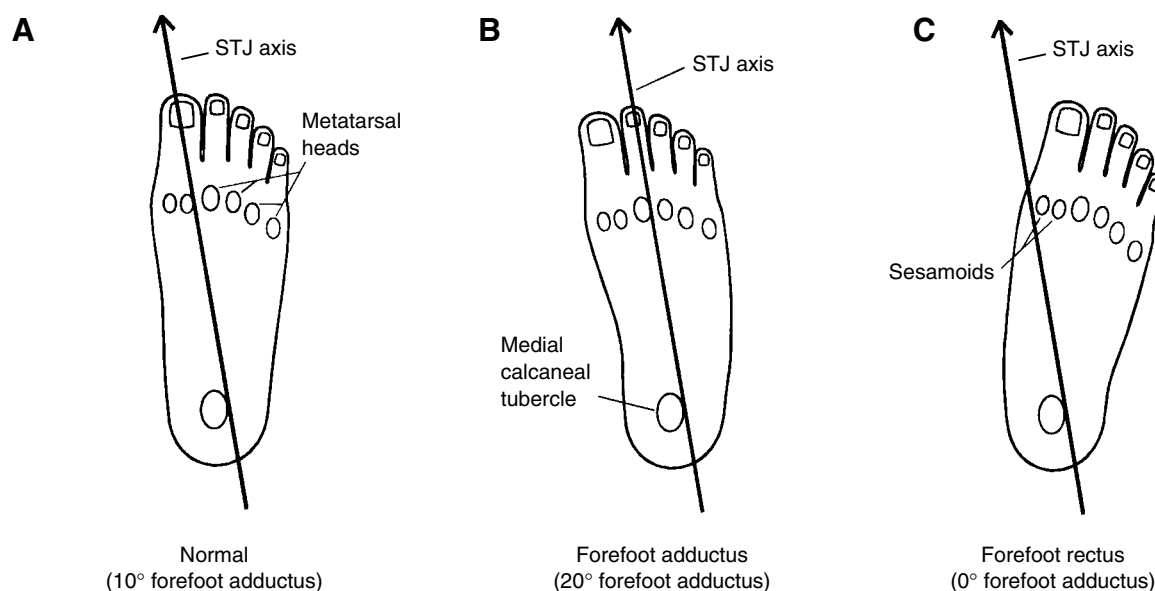


Figure 21. In Foot A, there is 10° of forefoot adductus and the subtalar joint (STJ) axis is positioned just lateral to the medial calcaneal tubercle and over the first intermetatarsal space of the forefoot. In Foot B, 10° of forefoot adductus has been added to Foot A so that 20° of forefoot adductus results. The medial shift in the forefoot in relation to the subtalar joint axis in Foot B results in a net increase in subtalar joint supination moment. In Foot C, the forefoot adductus of Foot A has been changed to a forefoot rectus (0° forefoot adductus). The lateral shift in the forefoot in relation to the subtalar joint axis in Foot C results in a net increase in subtalar joint pronation moment.

tion moment, and ground reaction force acting on the fifth metatarsal head now has a shorter moment arm to produce subtalar joint pronation moment. Because of this relative medial shift of the forefoot to the subtalar joint axis, which is caused by the 10° increase in forefoot adductus angle, ground reaction force acting on the plantar forefoot of Foot B now causes a net increase in subtalar joint supination moment, when compared with Foot A.

According to the same logic, the decrease in forefoot adductus angle in Foot C causes a relative lateral shift in the forefoot to the subtalar joint axis, when compared with Foot A. Ground reaction force acting on the forefoot of Foot C will cause increased subtalar joint pronation moment since the fifth metatarsal head now has a greater pronation moment arm and the first metatarsal head has switched from having a supination moment arm to a pronation moment arm. As a result of this relative lateral shift of the forefoot to the subtalar joint axis, which is caused by the 10° decrease in forefoot adductus angle, ground reaction force acting on the plantar forefoot of Foot C now causes a net increase in subtalar joint pronation moment, when compared with Foot A.

The author proposes that the characteristic clinical changes that occur in feet with structural variances in the transverse plane relationship of the

forefoot to the rearfoot are due to the relative medial or lateral shift of the forefoot to the subtalar joint axis and the mechanical effect this has on the balance of subtalar joint moments, which result not only from ground reaction force but also from muscular tensile forces and ligamentous tensile forces during weightbearing activities. Even though the spatial location of the subtalar joint axis remains constant to the rearfoot as long as the subtalar joint rotational position does not change, the changes in transverse plane structural relationship of the forefoot to the rearfoot significantly affects the balance of subtalar joint supination and pronation moments. In turn, any alteration in the balance of subtalar joint pronation and supination moments affects the rotational equilibrium across the subtalar joint axis, which will change the mechanical response of the foot to both externally and internally generated forces acting upon it.^{14, 34, 35, 49}

The above analysis of the effect of structural variances of transverse plane forefoot-to-rearfoot relationship also readily explains the biomechanical effects of rearfoot and/or forefoot surgeries that alter the transverse plane structural position of the forefoot relative to the rearfoot. A classic example of this is the Evans calcaneal osteotomy, in which the anterior calcaneus is structurally lengthened by means of an

osteotomy and bone graft (Fig. 22). Since the Evans calcaneal osteotomy structurally lengthens the lateral column of the foot, leaving the medial column the same length, the forefoot is directly forced into a more adducted structural position in relation to the rearfoot.⁵¹⁻⁵⁶

The increased structural forefoot adductus that the Evans procedure creates results in a more medial position of the forefoot relative to the subtalar joint axis that, in effect, increases the subtalar joint supination moment by a mechanism similar to that described above for a forefoot adductus foot type. The net result of the Evans procedure, therefore, is to increase the subtalar joint supination moments and decrease the subtalar joint pronation moments acting on the foot; this, in turn, helps eliminate the common symptoms seen in flexible pes valgus deformities that are caused by excessive subtalar joint pronation moments. The above analysis leads to the obvious conclusion that one of the possible practical benefits of the subtalar joint axis location/rotational equilibrium theory would be to allow for more accurate pre-operative prediction of the amount of transverse plane correction necessary in a surgery, such as the

Evans calcaneal osteotomy, to achieve optimal post-surgical results.

Conclusion

The subtalar joint axis location/rotational equilibrium theory of foot function attempts to explain and clarify the many experimental and clinical observations of the mechanical behavior of the foot that researchers and clinicians have made over the years. The theory also was developed to explain and clarify the author's experimental and clinical observations relating to the mechanical behavior of the foot.^{13-18, 20, 33-35, 40} In addition, the theory was developed to offer an additional theory of foot function that may improve on the traditional podiatric biomechanics theories, which are based largely on the works of Root et al.^{7, 32}

The central premise of the theory is that the spatial location of the subtalar joint axis in relation to the osseous components of the foot, which may be altered by both subtalar joint rotational position and foot structure, directly affects the magnitude and relative balance of pronation and supination moments acting across the subtalar joint axis during weightbearing

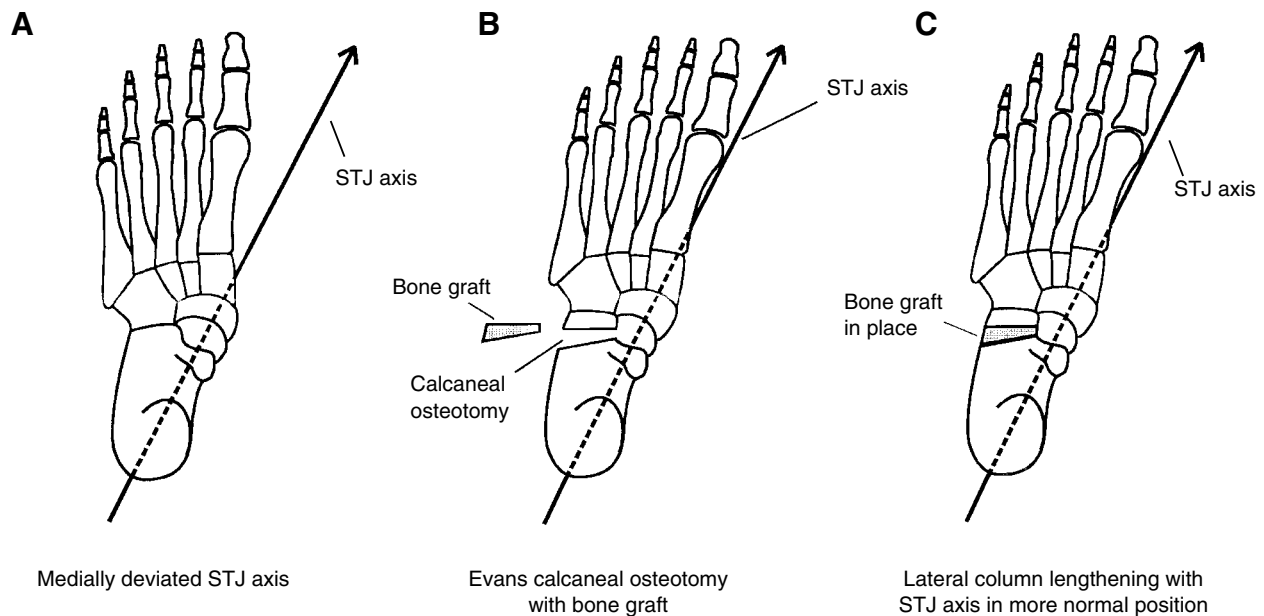


Figure 22. A, The plantar aspect of a right foot with a severely medially deviated subtalar joint axis (STJ). B and C, The mechanical effect of an Evans calcaneal osteotomy on a foot with a severely medially deviated subtalar joint axis is to lengthen the lateral column of the foot by interposing a bone graft into the anterior calcaneus so that the forefoot becomes structurally more adducted in relation to the rearfoot and the subtalar joint axis. The Evans calcaneal osteotomy therefore produces its biomechanical effect by effectively increasing the supination moment acting across the subtalar joint axis in much the same way that an increase in the forefoot adductus angle also increases the subtalar joint supination moment.

activities. In addition, alterations in the spatial location of the subtalar joint axis change the mechanical effect that both external forces (eg, ground reaction force) and internal forces (ie, ligamentous tensile forces, muscular tensile forces, and joint compression forces) have on the structural components of the foot and lower extremity. The net balance of subtalar joint pronation and supination moments then affects not only the rotational position of the subtalar joint but also the direction, angular velocity, and angular acceleration of movement of the foot about the subtalar joint axis, and the other pedal joint axes, during weightbearing activities.

It is vitally important to point out that the simplification of the foot into this one model of foot function does not explain all of the complex interactions between the external and internal forces that act on the multiple joint axes of rotation that exist within the human foot and lower extremity. Specifically, the joints of the midfoot, including the midtarsal joints, have been purposely omitted in order to simplify the discussion of the mechanical characteristics of the subtalar joint. When this was done, however, many important factors that affect the mechanics of the foot and that also are critical in determining the mechanical characteristics of the foot and lower extremity may have been omitted. Hopefully, the theory of foot function presented here will serve as a useful basis for the production in the future of a more complete theory of foot function that will, likewise, be based on scientific research and clinical observation.

The development of better theory to explain the experimental results of researchers and observations of clinicians is of paramount importance if a higher level of knowledge of the mechanical nature of the foot and lower extremity is desired. Better theory also allows more coherent synthesis of new research and clinical findings and provides important direction for future research. Finally, and possibly most critically, better theory allows for a more complete understanding of the complex interactions of the foot and lower extremity with their surrounding environment so that more effective methods of treatment of painful conditions of the foot and lower extremity may be developed.

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