Functional foot orthoses

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INTRODUCTION

If we take the International Standards Organization (ISO) definition of an orthosis as:

An externally applied device used to modify the structural or functional characteristics of the neuro-musculo-skeletal system.

then there are a wide range of devices which are foot orthoses. This range would include footwear with adaptions, 'simple' insoles and pads and the rigid foot orthoses produced from casts of the foot. It is the latter of these on which this article concentrates as it is these orthoses which suffer from a general lack of understanding of their principles and applications. This is not to say that the simpler insoles are always used to their best effect, to which many practitioners will readily attest, but it is because the claims made for the rigid foot orthoses seem to be rather extensive.

These orthoses were developed in the late 1950s and early 1960s, largely by a trial and error process, by a podiatrist in California, USA, Merton Root. His work, in association with other key colleagues, led to the Root functional foot orthosis which has been further developed over the years into a number of different designs. However, the basis behind all of them is the assessment and prescription techniques developed by Root and his colleagues.2,3

This article will review the biomechanical basis for foot orthoses and explain the processes by which dramatic functional improvements in the foot and proximal structures can be achieved.

FUNCTIONAL ANATOMY

A very brief review of the functional anatomy of the foot is given here, but for further detailed information the reader is directed to Michaud.4 The joints of the foot are all triplanar in nature, that is their motion gives rise to significant rotations in all three principal body planes and an appreciation of this is important when assessing the foot and describing its function (Fig. 1). The ankle joint, also known as the talocrural joint, has an average axis at about 8° to the transverse plane and 20–30° to the frontal plane.4 This axis allows for mainly dorsiflexion/plantarflexion together with a
small, but significant, amount of talar abduction with ankle dorsiflexion. However, Inman et al. have noted deviations of up to 23° from the transverse plane and in such situations the added range of talar adduction/abduction helps in absorbing the rotational motions of the leg.

The subtalar joint (STJ) is located between the talus and calcaneus with an axis which lies about 42° to the transverse plane and 16° to the sagittal plane. This orientation of the axis allows for significant amounts of eversion/inversion in the frontal plane and adduction/abduction in the transverse plane. Variations in axis alignment are well known and will thus vary the proportions of the triplanar components of motion. For example, if the axis lies at 45° to the transverse plane there will be 1° of hindfoot motion for every degree of tibial rotation. If this axis now lies at an increased angle of say 60°, for every 1° of tibial rotation there will be less than one-third degree of hindfoot motion. The location of the axis of the subtalar joint is clinically significant in that a high axis is thought to be responsible for chronic injury to structures distal to the STJ and a low axis for injury to structures distal to the STJ.

The concept of subtalar neutral positioning is important to understand as it forms the key reference point for much of the assessment and casting for rigid foot orthoses. This was considered to be the point in full STJ motion where the range of inversion is equal to double the range of eversion. It is generally accepted that the STJ is in neutral when equal amounts of the talus head are prominent or palpable on both the medial and lateral aspects of the navicular. This is established clinically by holding the foot firmly and moving the STJ through its full range of motion whilst palpating the head of the talus. When the medial and lateral prominences are felt to be equal the STJ is thought to be in neutral. This can be checked by establishing if the superior and inferior curves of the lateral malleolus are symmetrical. Other techniques exist which are based upon changes in moving the STJ through its full range of motion whilst varying the proportions of the triplanar components of motion. For example, if the axis lies at 45° to the transverse plane there will be 1° of hindfoot motion for every degree of tibial rotation. If this axis now lies at an increased angle of say 60°, for every 1° of tibial rotation there will be less than one-third degree of hindfoot motion.

The midtarsal joint (MTJ), sometimes called Chopart's joint, consists of the combined articulations between the talonavicular and calcaneocuboid joints. These function about two axes, longitudinal and oblique. The longitudinal axis of the MTJ produces significant amounts of inversion/eversion during supination/pronation with little other motion. The oblique axis produces significant motion in both the sagittal plane and, of particular importance, the transverse plane.

It has been suggested that MTJ pronation occurs in two phases. Phase I follows the usual pattern which ends when STJ pronation reaches its maximum. In Phase II, further medial midfoot motion occurs without further calcaneal eversion. This causes leg rotation, as the calcaneus rotates on its tubercles, and allows the navicular and cuboid to abduct. This explains the often observed continued leg rotation beyond the point of maximum STJ pronation.

The first ray is a functional unit consisting of the first metatarsal and the medial cuneiform. The axis of this joint is almost parallel to the transverse plane so, although its motion is strictly triplanar, the amount of transverse plane motion is small. Principally, as the first ray dorsiflexes it inverts and vice versa.

The key to understanding the function of rigid foot orthoses is the inter-relationship between the weight bearing foot motion and motion of the leg and body above it. The foot reacts to proximal intersegmental rotational and angular relationships to bring its plantar surface down to the ground, within the limits of foot motion. Conversely, a change in the motion within the foot can cause the proximal body to adopt an abnormal position resulting in limitation in motion or discomfort. Sometimes these changes can be subtle and on other occasions they are obvious. For example, in the case of genu valgum during standing, body weight will fall a long way medial to the STJ. If the foot is now observed when standing with the STJ in neutral, sometimes called the neutral calcaneal stance position or NCSP, it will be everted if the degree of genu valgum exceeds the combined degree of STJ varus and tibial varum.

It is not sufficient just to understand static foot/leg relationships but a full appreciation of the complex motions and their effects during gait is also required. Some of these have been mentioned briefly. As this is a vast topic only the basics will be presented here and the interested reader is directed to Michaud et al7.

MOTIONS DURING IDEAL GAIT

The gait cycle is divided into stance and swing phases lasting about 60% and 40% of the total cycle time respectively (Fig. 2). Most of what affects foot orthotic prescription centres on the stance phase. At heel strike the hip is flexed to about 30°, the knee is almost fully extended, the ankle is slightly dorsiflexed, the STJ is slightly supinated and the MTJ is fully pronated about its oblique axis and supinated about its longitudinal axis. As the foot is loaded the STJ starts to pronate and continues as weight is transferred to the front of the foot. The MTJ position locks the forefoot in an inverted position ready to accept weight. As the fifth metatarsal head starts to load, a combination of ground reaction forces and relaxing tibialis anterior allows a smooth transfer of load from lateral to medial sides accompanied by pronation about the longitudinal axis of the MTJ. The oblique axis of the MTJ remains pronated (Fig. 3).

By midstance the leg is externally rotating and the STJ is supinating so that by the end of this phase it is
Fig. 2—Detail of the major components of a single gait cycle—defined as the period between successive ipsilateral heel strikes. R—Right; HS—Heel strike; SLS—Single leg stance; L—Left; TO—Toe off; DLS—Double leg stance; FFL—Forefoot loading.

Fig. 3—The triplanar motions of the STJ and both axes of the MTJ during one gait cycle (adapted from Pratt et al.).

in neutral. This coincides with the longitudinal axis of the MTJ reaching full pronation and the foot is converting from a flexible adaptor and shock absorber into a rigid lever ready to accept the demands of the propulsive phase of stance. The forefoot is 'locked' on the hindfoot by the superior border of the cuboid coming into contact with the dorsal border of the overhanging calcaneus and held there by ligamentous restraint. This so-called neutral position is replicated during the biomechanical examination which will be discussed later.

During the propulsive phase of stance the STJ continues to supinate and the peronei lift the lateral border of the foot to shift the load medially. This causes supination about the oblique axis of the MTJ to occur. These motions are assisted by the continuing external rotation of the leg and by the action of the plantar intrinsic muscles (the windlass effect). Just before toe-off the STJ starts to pronate from its supinated position. Because of the medially directed forefoot loading, the first ray, which is shorter than the second, has to plantarflex actively to provide much of the propulsion for walking to continue. This transfer of load to the first metatarsal head is associated with an elevation of the lateral column to allow for the change in metatarsal axis orientation from the oblique axis (heads 2–5) to the transverse axis (heads 1–2).

In swing phase the STJ continues to pronate from its supinated position until at midswing it is pronated. It then moves into neutral and re-supinates just prior to heel strike. Motion about the two MTJ axes reverses during swing, passing through their neutral positions at about midswing. The forefoot then becomes supinated about the longitudinal axis and pronated about the oblique axis in preparation for heel strike.

BIOMECHANICAL EXAMINATION

Functional foot orthoses are used to correct or compensate for biomechanical abnormality at points throughout the weight bearing chain. Thus, to be able to assess exactly what position is required for foot casting and orthotic prescription, the inter-relationship between the foot and the ground and between the foot and its proximal segments is essential. For this to be gained requires a thorough measurement of the foot
and legs statically and dynamically. The essence of what is being obtained is a description of the triplanar relationships and ranges of motion in the whole lower limb. Restriction in motion or abnormal relationships will lead to some kind of compensation by some element in the chain. It is often the problems caused by the compensation which is the initial reason for referral rather than for the actual cause of the situation.

To reduce the amount of re-positioning of the subject, the examination is usually broken down into prone, supine, standing and dynamic sections. Prone examination is started by bisecting the calcaneus with the foot in its neutral position (STJ in neutral and both MTJs fully pronated). This is done by drawing a line between the medial and lateral calcaneal condyles and then drawing a line at 90° to this at the mid point of the first line. The distal third of the lower leg is then bisected longitudinally to give two reference lines. With the foot held in its neutral position these two lines would ideally be parallel to each other. However, in most cases there is a deviation from this ideal which is recorded in degrees of varus or valgus, the subtalar angle (Fig. 4). The forefoot angle is then recorded, again with the foot in neutral. Ideally, the plane of the forefoot would be at 90° to the calcaneal bisector but again there is usually a deviation which is recorded in degrees of valgus or varus, the midtarsal angle. It is important that the STJ is in neutral during this as it will give a false indication of the forefoot to hindfoot relationship, giving a false forefoot varus with STJ supination and forefoot valgus with STJ pronation.

With the forefoot still in neutral the alignment of the metatarsals can be recorded and the range of first ray motion measured. Flexing the knees to 90° and maximally internally and externally rotating the legs can show ranges and asymmetries in hip rotation. With the knees straight, hip extension and knee flexion can be assessed. The presence of plantar callus can also be readily recorded before moving on to the supine examination.

In supine the range of motion of the hallux can be measured, the forefoot inversion about the longitudinal MTJ axis can be observed (quantification is impossible) and the motion at the ankle joint measured. A common error in this latter measurement is to allow the STJ to pronate whilst dorsiflexing the foot. This results in the dorsiflexion component of STJ pronation adding to the actual ankle motion to give a falsely higher value for ankle dorsiflexion. Leg length can be measured by one of several methods and then the amount of tibial torsion measured. This is best done by rotating the leg until the femoral condyles lie parallel to the couch. A goniometer is then used to measure the angle between the transmalleolar line and a line parallel to the couch in line with the femoral condyles. Finally, muscle strengths can be measured in the usual manner.

The standing examination is vital as it provides the angular information to allow the prescription of the orthosis to be made. Qualitative tests include the assessment of arch height differences between weight bearing and non-weight bearing and the relative amounts of leg rotation associated with inversion and eversion of the forefoot. As noted earlier, when performing this, STJ axis orientation can produce different proportions of internal and external rotation. When standing with the STJ in neutral action, ideally the calcaneal bisector would be at 90° to the ground but usually this is not the case so any deviation is recorded as the degree of inversion or eversion. The effect of any measured leg length discrepancy can be assessed in the usual way. The final measurement here is to record the amount of tibial varum using the leg bisector already drawn. This should be carried out with the feet at their usual angle and base of gait. To do this it is usually sufficient to get the subject to walk on the spot for a few seconds then stop when instructed by the examiner. If this fails it is possible to stop the subject at some point during the dynamic evaluation and carry out the measurement.

The dynamic assessment is usually just carried out visually and serves as a double-check to confirm the assessments and measurements made. Although this is a qualitative examination it is often the most difficult to do as motions sometimes occur rather too fast for easy observation. Practice is the key here. Aids such as a video camera and recorder can be used to help identify aspects of the gait but this is still a qualitative assessment.

From these measurements, the angles of the hindfoot and forefoot are calculated as shown in Figure 4. From these the angles for the angulation of

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Fig. 4—The measurements of the tibial angle (t), STJ angle (s) and MTJ angle (m) are obtained during the biomechanical examination. By combining these, the two angles used for posting purposes, r and f, are obtained: \[ r = t + s \] and \[ f = r + m. \]

Note: angles are summed when of the same sense (both varus or both valgus) and subtracted if of different senses.
the hindfoot and forefoot sections of the orthosis can be derived. This angulation is called posting and can be extrinsic, that applied as a wedge of additional material after the main shell has been formed, or intrinsic, applied as a wedge or addition to the cast prior to forming the shell. Before an orthosis can be made, however, the foot needs to be cast so as to capture the relationship required based upon the assessment and measurements.

As a result of all of these measurements, the angles for posting are quoted to an accuracy of 0.5°, which is considered to be essential to give the optimum control of the foot and limit compensation mechanisms.

**CASTING TECHNIQUES AND ORTHOTIC MANUFACTURE**

There are many ways in which a suitable cast may be taken with some variations being more a matter of personal preference than determined by the requirements of the orthosis. There are five non-weight bearing techniques, which are mostly used, and several other semi-weight bearing methods.\(^4\)\(^5\)

The foot needs to be casted in a non-compensated position so that orthotically the ground can, in effect, be brought up to the plantar surface and support the position. Because of the limitations in space the basic neutral position suspension technique will be described in detail and the reader is directed to Anthony\(^3\) for detail of the other variations. They all aim to achieve the same end result but represent adaptions to suit certain circumstances.

For this casting technique the patient is supine with their foot at mid-chest height. The clinicians arm, wrist, hand and fingers are held straight, as in a salute, and the thumb placed in the sulcus of the fourth and fifth toes (Fig. 5). With this grip maintained the STJ is moved through its range of motion and the neutral position established. With this position maintained, the foot is lifted slightly from the couch and a dorsiflexion force applied to the MTJ to fully pronate it about both axes. The ankle is only dorsiflexed to resistance, which is not necessarily to 90°. Once familiarized with this position, 20 cm wide plaster of Paris bandage strip is prepared. Two lengths are needed for each foot, one extending from distal to the first metatarsal head around the heel to distal to the fifth metatarsal head, the other overlapping the first one but wrapped around the toes. The first length is wetted and then wrapped around the foot so that it extends to mid-malleolar height and overlaps on the plantar surface of the foot (Fig. 6). The second piece is wetted and wrapped around the front of the foot to align with the dorsal border of the first piece and then overlapped on the plantar foot surface. Any extra material is pushed into the sulcus of the toes and the whole plantar surface stroked from one end to the other to exclude any air trapped under the bandage - this forms a slipper cast. The foot is re-positioned as described above and held until the plaster has set. It is removed by pulling off at the heel and sliding distally and then has to be assessed to ensure that it has captured the position required. If not it would have to be re-taken. Before sending off the cast, for manufacture of the orthosis, the calcaneal bisector line is drawn on the outside of the cast as a reference.

Weight bearing techniques, used when a neutral position is undesirable or not achievable, include either full or partial weight bearing impressions taken with polystyrene foam or in putty.\(^5\)\(^9\) In each case the aim is still to match the position in the impression with the position determined by the assessment. From any of the methods a negative impression of the plantar surface of the foot is obtained and a positive model is formed from these by filling with plaster of Paris slurry. It is vital to position the cast or foam/putty impression so that the top surface of the filled positive is at 90° to the calcaneal bisector, or at any other specified angle as given by the clinician. Angles for intrinsic posts will be on the prescription sheet and have to be built into the cast by using the top surface
Fig. 7—The vacuum press used to form the foot orthoses. One press is shown with its vacuum applied which forms the plastic over the plantar surface of the cast. The other press is shown open with a cast and plastic sheet which has just been formed.

Fig. 8—Foot orthoses showing two possible variations in design from the many available (courtesy of the Orthotics and Disability Research Centre, Derby UK).

as a reference plane. Other additions are also required such as those to allow for expansion of the soft tissues on weight bearing or for the lowering of the medial longitudinal arch. With so many variations and adaptations the interested reader can obtain detailed information in other publications.

Once the cast has been prepared, which can take well over an hour, the shell of the orthosis can be formed over the plantar surface. The usual technique is to heat a sheet of the material, such as acrylic, polypropylene, polyethylene, carbon fibre and vacuum form it directly to the cast (Fig. 7). Once cooled the orthosis can be trimmed, extrinsic posts applied using the top of the positive cast as a reference plane, edges cleaned, covers or other additions applied and the orthosis is then ready to supply (Fig. 8).

EXAMPLES OF TREATMENT
Forefoot valgus (or evertus)

This is a fixed congenital osseous deformity in which the forefoot plane is everted relative to the calcaneal bisector with the foot in its neutral position (Fig. 9A).
When fully compensated the forefoot will invert to the ground during midstance which can have one of two results. Firstly, what usually occurs is that the talonavicular joint may supinate, principally involving inversion. This is particularly so if the STJ is abnormally pronated during midstance. The compensation may take the form of supination about the longitudinal axis of the MTJ only, usually called a flexible forefoot valgus (Fig. 9B). The consequences of this compensation include lateral instability of the foot on uneven surfaces, dislocation-type hallux abductus and hallux-abductovalgus, mild contracture of the lesser digits, callus under the second and third metatarsal heads, tailor’s bunion and postural fatigue. In the presence of limitation or prevention of the necessary compensation motions a rigid forefoot valgus is seen (Fig. 10). This tends to produce a calcaneal varus, a varus shift of the tibia and rapid external rotation of the whole limb. The main pathologies observed here can include severe chronic ankle strains, sagittal plane retraction of all digits retro-calcaneal exostoses and bursitis, ilio-tibial band friction syndrome at the hip and knee, sesamoiditis, lateral knee strain and keratoma beneath the first and fifth metatarsal heads.

In both cases the treatment is aimed at holding the forefoot in its non-compensated position and thus removing the need for any compensatory mechanisms and relieving symptoms. With high degrees of forefoot valgus simple posting will not work and more complicated forms are needed such as split posting or triaxial posting.

Forefoot varus (or invertus)

The aetiologies of the congenital variation of this condition include a plantarflexed fifth metatarsal (flexible or rigid), plantarflexed cuboid, plantarflexed fourth metatarsal and congenital metatarsus primus...
The Foot

A foot in its neutral position showing a forefoot varus deformity and (B) The compensated position when a rigid deformity is present.

elevatus (Fig. 11A). Acquired forefoot invertus can be caused by acquired metatarsus primus elevatus and acquired plantarflexed fifth metatarsal. When this is compensated for the calcaneus moves into valgus and the STJ pronates and associated MTJ pronation about the oblique axis (Fig. 11B). This compensation produces abnormal rotations in the leg which can lead to many soft tissue and osseous problems in the knees (particularly), hips and lumbar spine.

The treatment is again aimed at removing compensation and relieving symptoms, in this case primarily by the prevention of abnormal STJ pronation. This is best done by supporting the foot in a neutral position whilst posting the forefoot to control the forefoot supinatus which is secondary to the hindfoot position.

It is clear that the correct treatment for many consequences of poor foot position relies on a full biomechanical assessment and a complete understanding of the relationships between the foot and the rest of the body. The author has seen many people who present knee and back pains which are entirely treatable with appropriate foot orthoses. This is not to say that all knee and back problems are related to foot abnormalities as this is clearly false. But many problems go unresolved because the wrong area of the body is being treated.

**DISCUSSION**

It is easy to see that the techniques described above rely on two basic skills: the ability to (a) bisect a limb segment accurately and (b) reliably determine the STJ neutral position. There are a number of problems associated with these as they are both prone to errors which may be greater than the accuracy with which the measurements are required for any clinical value. As such there have been some studies carried out to examine the ability of clinicians to perform the latter of these fundamental tasks. There is little published on the former of these tasks but there are arguments to cast doubt upon its absolute accuracy.

It is well known that the skin of the body moves as the limb is moved and this can easily be illustrated by examining your own skin near a joint during motion. This movement is measurable in mm and so any line or point on the skin will also move. Thus, the value of such a point or line as a reference for accurate measurement of motion must be in doubt. In addition to the movement errors associated with skin lines, the ability of the clinician to bisect a limb segment, with soft tissues between the skin and the skeleton, is questionable. An unreported study carried out in the Orthotics and Disability Research Centre, UK, showed that the most experienced clinicians could not bisect (by eye) the lower third of the leg to an accuracy better than about 3°; the less able clinicians were worse than this. It was possible to increase the accuracy to about 1.5° if the width of the limb was accurately measured with calipers at a number of locations and then these values used to mark the mid line. However, this took far too long to perform so many of the clinicians said it was impractical in the clinic.
If the lines are unreliable then the measurements taken from them will likewise be suspect, and it is these derived angles that have been more often recorded and used to determine the accuracy of the whole procedure. Griffith, in a large study using nine clinicians, examined the inter- and intra-observer errors associated with the measurements of ankle joint dorsiflexion, STJ inversion, eversion, range of motion and neutral (in three ways) and the angle of the hallux. Concentrating on the STJ measurements, they all required that a bisector be drawn first and then used to find the amount of inversion and eversion. From these the total range and neutral position could be calculated. The second way used to find STJ neutral was by the palpation method already described. The third way was to position the subject in their angle and base of gait, to palpate the talar head and adjust the prominences until equal by internally and externally rotating the leg.

The findings of this study showed that the accuracies were:

1. Calculated neutral position - an average of 2.63°, varus with a standard deviation (SD) of 4.32°.
2. Measured neutral position - an average of 6.02°, varus with an SD of 3.06°.

This shows that all techniques produced a varus position when compared with the radiographically determined neutral position, with the 'calculated' approach the most accurate but the 'measured' technique with the least variability. There are many reasons for this inaccuracy which are not related to the bisectors being in error. For example, the positioning and alignment of goniometers with the limb is critical for accuracy. Added to this is the fact that the STJ is significantly triplanar in action and positioning of the single axis goniometer with respect to the joint is bound to produce some discrepancies in measurement. This can be improved upon by using a flexible goniometer, although errors are still unacceptably high. When all of these factors are taken into account it is surprising that the accuracy of the final prescription is as high. The poor reliability of these measurements is nevertheless a cause for concern for all practitioners engaged in biomechanical measurements of the lower limb. These sentiments are echoed by Freeman who compared measurements of both relaxed and neutral calcaneal stance positions. Kidd not only similarly questioned the measurements and bisectors as accurate but also the validity of the 1/3: 2/3 ratio as a viable technique.

Despite these concerns there are many practitioners working in this area who can provide equally convincing evidence for the repeatability and accuracy of the various techniques. A study by Cook et al examined 138 subjects and measured the neutral position of the STJ in three ways; palpation of the talus, equalising the proximal and distal curves of the lateral malleolus and the observation of the skin over the sinus tarsi. They found a 95% correlation between the three methods but assumed that a +1° error was clinically acceptable, which not all clinicians would agree with.

Phillips et al used bisectors of the calcaneus and lower third of the leg to produce the planar deviations for various STJ orientations. Despite their rigorous mathematical analysis no allowance was made for the possibility that the measurements used in the equations produced were themselves open to the kinds of errors detailed above.

The triplanar motion of the STJ complicates the essentially two dimensional assessment techniques usually used. This matter was addressed by Engberg et al in an in vitro study of nine cadaveric lower legs and feet. They found that the monitoring of the inversion/eversion and abduction/adduction orientations of the talocalcaneal/talocrural complex is more valuable in predicting pronation and supination positions than by using inversion/eversion alone.

Despite the obvious difficulties with the measurement accuracy, a matter which is still very much in discussion, the philosophy and rigour of the approach do produce significant successes in treatment of problems both in the foot and, often more importantly, proximally. It takes time to fully appreciate the techniques and understand the protocol but the outcome of such an understanding can be very rewarding for both the clinician and the patient.

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