

Test apparatus for the measurement of the flexibility of ankle-foot orthoses in planes other than the loaded plane

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Abstract

Previous publications have reported on the flexibility of ankle-foot orthoses (AFO) only in the same plane as the applied load. This paper reports on a test apparatus developed to detect the flexibility of an AFO in 5 degrees of freedom when subjected to a plantar/dorsiflexion moment, a medial/lateral moment or a torque. A moment applied to an AFO in one plane induces angulation and translation in all planes.

Introduction

This work stems from an interest in relating the results of clinical evaluations of AFOs by Raschke (1997) to defined mechanical behaviours of the prescribed ankle joints.

It was observed that AFO cross-coupled deformation effects (motion in planes other than the applied plane) may be influential upon the clinical outcome. Raschke (1997) noted that by selecting a pair of ankle joints with different stiffness characteristics, the orthotic prescription may be more appropriate in matching the patient's requirements. One of the authors has observed that reinforcing an AFO with extremely stiff carbon fibre may produce a superior effect to a typical thermoplastic AFO as far as improved pain relief is concerned. This may be due to a reduction in cross-coupled deformation effects.

Rubin and Dixon (1973), Condie and Meadows (1977), Clark and Lunsford (1978) and Miyazaki *et al.* (1993) have reported on the

dorsal/plantar flexibility of AFOs when subjected to dorsi/plantarflexion moments. Chowanec (1983) reported that when an AFO was subjected to an inversion or eversion moment, load cells detected an apparent dorsi/plantarflexion moment. Chowanec commented that this was more noticeable with an eversion moment but that applying a dorsi/plantarflexion moment did not create significant cross-coupled effects. Ward (1987) refined to the test rig developed by Chowanec but did not investigate cross-coupled effects. Golay *et al.* (1989) studied the effect of malleolar prominence on the flexibility of polypropylene AFOs in dorsiflexion. Lunsford *et al.* (1994) reported on the dorsal/plantar flexibility of AFOs subjected to cyclic dorsi/plantarflexion moments and commented on the effect of the variation in wall thickness of manually draped AFOs. Sumiya *et al.* (1996) reported on the variation of dorsal/plantar flexibility of AFOs with different trimlines when subjected to dorsi/plantarflexion moments. Yamamoto *et al.* (1993) studied the dorsal/plantar flexibility of AFOs when subjected to dorsal/plantarflexion moments and also the inversion/eversion flexibility of AFOs when subjected to inversion/eversion moments.

This paper reports on mechanical measurement system to monitor 5 degrees of freedom and thereby quantify cross-coupled deformation in AFOs.

The motion of a solid body in a space may be identified as the combined effect of three linear (translation) and three rotational (angulation) degrees of freedom in any three-dimensional coordinate system. The normal ankle joint system, consisting of several identifiable axes, provides mobility of one "solid" body, the foot, in relation to another solid body, the lower leg.

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Table 1. Translatory and angular motion in each plane.

	Translation movement	Angulation movement
Sagittal plane	Anterior/Posterior (Proximal/Distal)	Plantar/dorsiflexion
Frontal plane	Medial/Lateral (Proximal/Distal)	Inversion/Eversion
Transversal plane	Anterior/Posterior Medial/Lateral	Internal/External Rotation

In anatomy and in prosthetic and orthotic analysis, Anatomic Reference Planes (ARP) are used instead of co-ordinate systems, referring translations and rotations to movements in these planes. In this application, the AFO ankle joint axis was positioned in the frontal plane and the AFO soleplate defined the transverse (horizontal) plane. The six degrees of freedom are expressed in ARP terms in Table 1.

As a plane is two-dimensional, each plane exhibits two translatory degrees of freedom.

Method

The axis of the ankle joint was identified by the orthotist while wrap casting the patient. A "master" plaster model was used to ensure that the axes of the selected ankle joints of all the AFOs were positioned identically. A long pin was attached to the master mould to ensure that this axis was subsequently transferred to all future plaster models and AFOs. The axis of the AFO ankle joint was aligned in the frontal plane. The plantar surface of the plaster model, i.e. the foot base of the plastic AFO, was flattened. A rigid plate, compatible with the inner sole of the AFO, was drilled with three holes (Fig. 1). These three holes correspond to those previously drilled and tapped on the base of the apparatus using a numerically controlled machine. The rigid plate was positioned accurately over the inner sole of the AFOs so that the three holes could be identified and drilled through the plastic AFOs (Fig. 1). The flat foot base of each tested AFO could then be bolted to the base plate of the apparatus in a reproducible way. Allowing for the most unlikely combination of clearance between the bolts and the holes a maximum rotational positioning error of the AFO of 0.1° may occur. This inaccuracy would have a

negligible effect on the cross-coupled deformations.

A rigid central metal structure "buried" in a calf model, was used to apply loads and monitor movements. The square cross-sectional column was partially covered by a rigid polyurethane foam dummy formed from the "master" shank mould. Prior to pouring the foam, the central column was positioned vertically above the pre-determined ankle axis. Distally, the central metal structure incorporates four extended members. These four extended members have been drilled and tapped to accommodate four pins or outriggers. Loads may be applied distally to the central column in the anterior, posterior, medial or lateral directions via the four outriggers.



Fig. 1. AFO and the rigid plate.



Fig. 2. Location of medial and posterior plates.

After draping the AFOs over identical plaster cast models, the AFOs were fitted sequentially to the dummy shank. Each AFO was positioned on the foam dummy and located via upper and lower Velcro straps. A long threaded pin with a hot tip was screwed through the accessible distal anterior hole so that the hot tip protruded posteriorly through the AFO, proximal to the ankle level. The hot tipped pin was removed. The distal anterior and posterior outriggers were screwed to the rigid central structure. A similar procedure was adopted after locating the medial hole through the AFO. A hot tipped pin was screwed in the lateral direction through the foam covered metal structure until it protruded laterally through the AFO. This long hot tipped pin was removed. Medial and lateral outriggers were screwed to the metal structure so that they extended beyond the AFO.

Proximally, at approximately "knee height" above the foamed calf, the central metal structure was drilled, tapped and long threaded bolts to outriggers were fitted posteriorly and medially.

The proximal and distal outriggers on the medial aspects of the calf were used to locate a flat aluminium plate external to the AFO as shown in Figure 2.

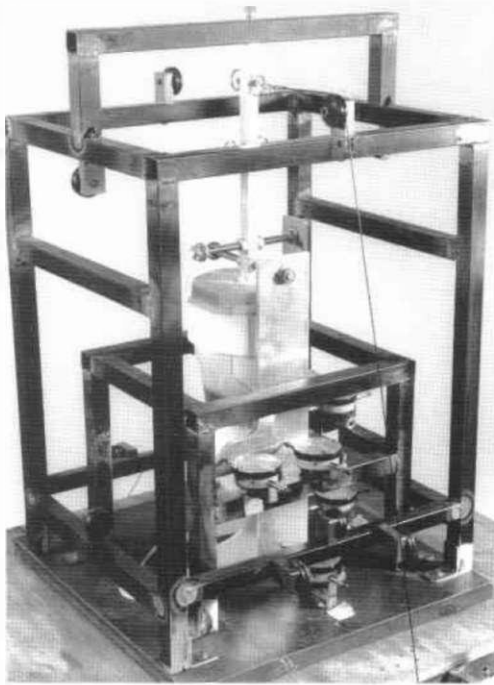
This medial plate effectively defined the sagittal plane when no load was applied to the AFO. Similarly, the proximal and distal outriggers on the posterior aspect of the calf were used to locate a flat aluminium plate external to the AFO. This posterior plate defined the frontal or coronal plane when the AFO was unloaded.

The test apparatus was constructed to enable moments to be applied to the AFO and the resulting movements to be recorded. Proximal loading hooks were attached to the central column at mid-thigh level. A single cable attached to two locations on the "calf model" and passing over pulleys mounted on the outer framework enabled moments (or pairs of forces) to be applied to the AFO. The single cable also passed over a swivel pulley arrangement mounted on the under surface of the base of the apparatus so that loads could be applied through the cable tension generated via the suspended masses, as shown in Figure 3a. This is also illustrated schematically in Figure 3b. The inner framework was used to position dial gauges which monitored corresponding motion.

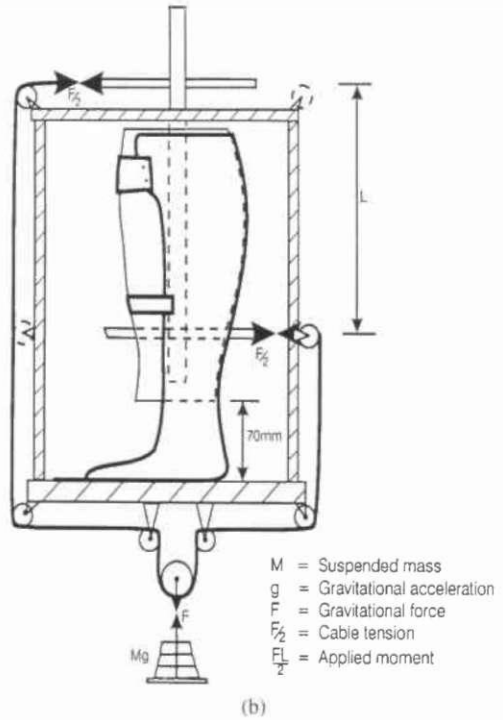
The following test procedure was followed. The selected AFO was fitted to the dummy shank and foot section clamped to the base plate of the test apparatus. Incremental and decremental moments were applied and the motion of the medial and posterior plates relative to the inner frame of the test apparatus was noted. The moments applied in all three planes were representative of moments recorded during gait. The motion of both plates was recorded using six 25mm range dial gauges (accuracy .01mm), as shown in Figure 4. Both the medial and posterior plates were in contact with three dial gauges.

Translations and angular motions were calculated from recordings from pairs of these gauges. For example, plantar and dorsiflexion could be calculated from sagittal plane recordings of the upper and lower dial gauges that contact the posterior plate. Rotation in the transverse plane could be calculated from recordings of the upper pair gauges in contact with either the posterior or medial plate. As the six gauges were read sequentially, instantaneous recordings were not possible. Hence the measuring method was sensitive to creep of the plastic AFOs.

This paper presents the flexibility results of a polypropylene AFO that does not incorporate an



(a)



(b)

Fig. 3. The test for apparatus.

ankle joint. However, the AFO was bolted to the base plate of the test apparatus so that the plane

of the ankle axis, defined at the casting stage, coincided with the frontal plane and also with the upper and lower dial gauges in contact with the medial plate. Other types of AFOs could be bolted to the rig in the same way.

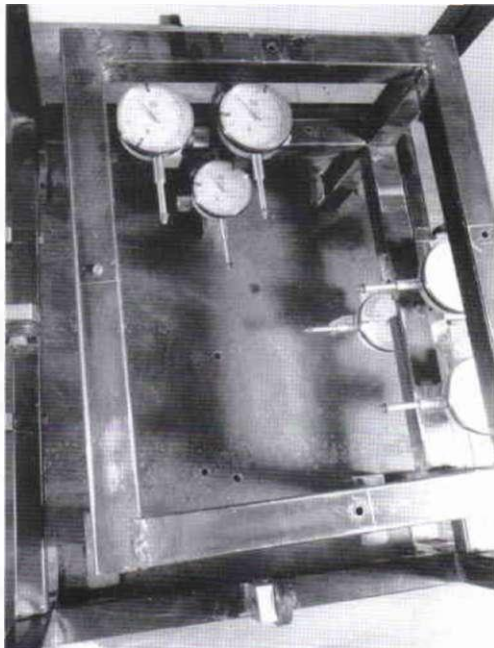


Fig. 4. Position of dial gauges

The gauge readings were transferred to spreadsheets where subsequent calculations presented the results as graphs. For example, the angulations and horizontal translation at the anatomic ankle joint level in the sagittal plane may

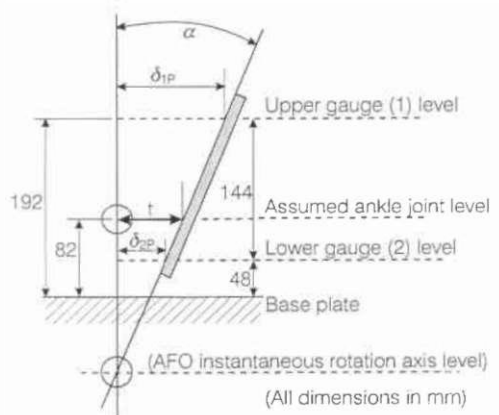


Fig. 5. Geometric configurations of AFO under test.

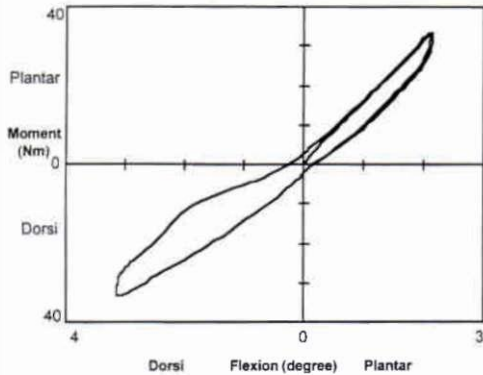
be calculated from the data presented in Figure 5. The anterior or posterior movements of the upper and lower dial gauges in contact with the posterior plate record the motion in the sagittal plane.

$$\alpha = \tan^{-1} (\delta_{IP} - \delta_{2P}) / 144$$

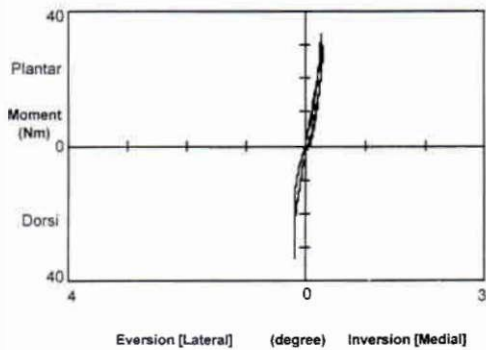
$$t = \delta_{IP} - (192 - 82) (\delta_{IP} - \delta_{2P}) / 144$$

Using the displacements noted from the pair of vertical gauges in contact with the medial plate similar equations enable the horizontal translations and angulations in the frontal plane to be determined.

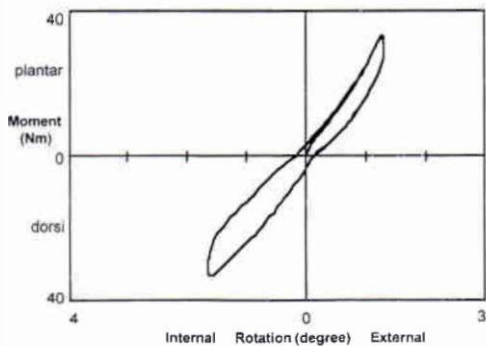
In summary, angular motion about all axes can be measured together with translations in



(a)

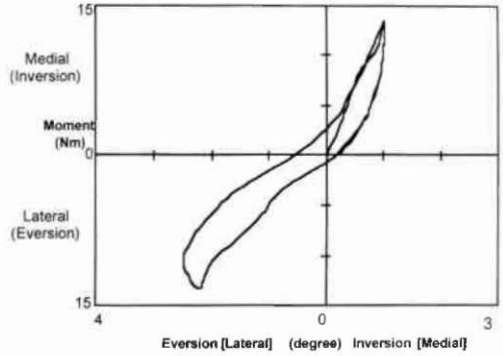


(b)

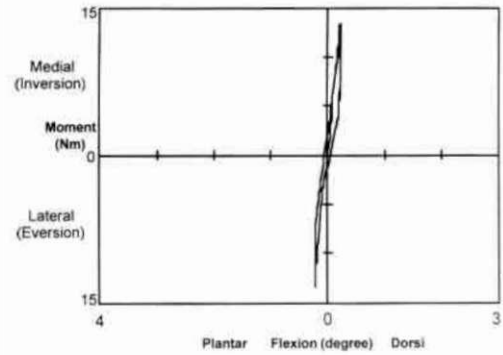


(c)

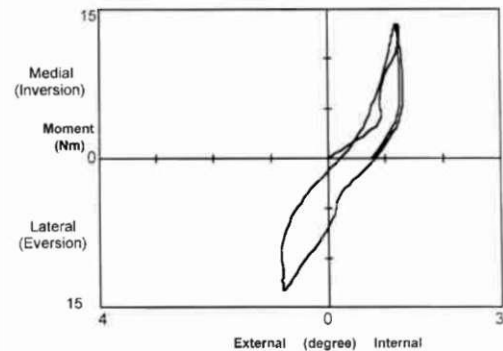
Fig. 6. Angulation due to plantar/dorsiflexion moments. (a) sagittal; (b) frontal; (c) transverse.



(a)



(b)



(c)

Fig. 7. Angulation due to inversion/eversion moments. (a) frontal; (b) sagittal; (c) transverse.

the transverse plane.

Results

The test apparatus was used to determine the flexibility characteristics of a single AFO subjected to moments applied in the sagittal,

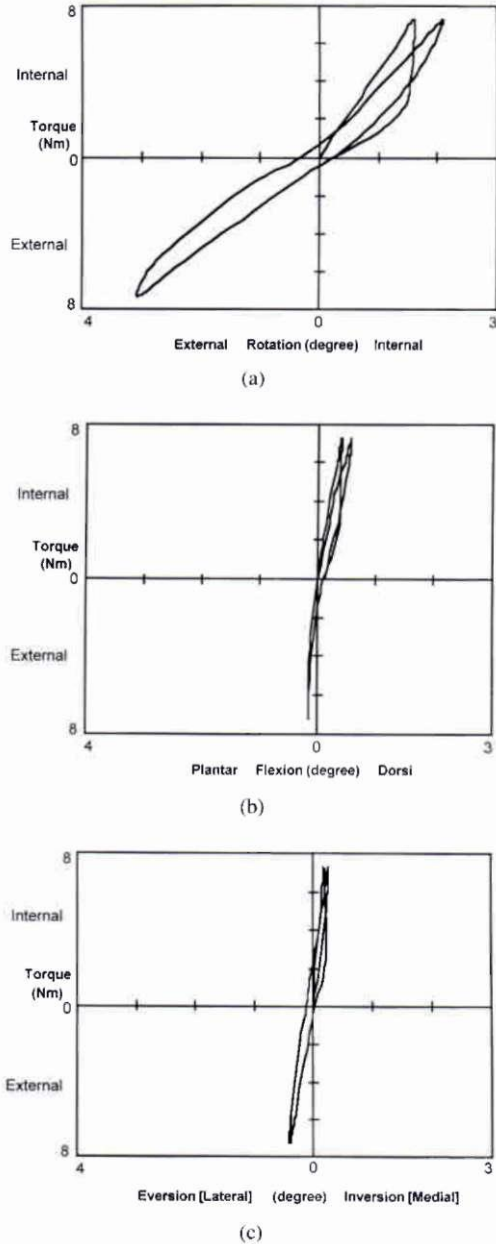


Fig. 8. Translation due to internal/external torques. (a) transverse; (b) sagittal; (c) frontal.

frontal and transverse planes. The “calf model” provided support for the calf section of the AFO but the AFO has no restriction from a leg (or flail leg) for the 70mm axial length above the soleplate of the AFO. For each selected load application, the corresponding angulations are presented in all three planes shown in Figures 6, 7 and 8. The corresponding translations in the transverse plane are presented in Figures 9, 10 and 11. These results relate to a “stiff” polypropylene AFO incorporating no orthotic ankle joint.

Repeatability, after removal and re-installation was studied and Figure 12 displays the similarity in the results of two identical tests performed on different days.

The presented graphs illustrate ways to compare the flexibility of AFOs.

Discussion

In an AFO, the function of the joints, the deformations of the soft tissue coupling between

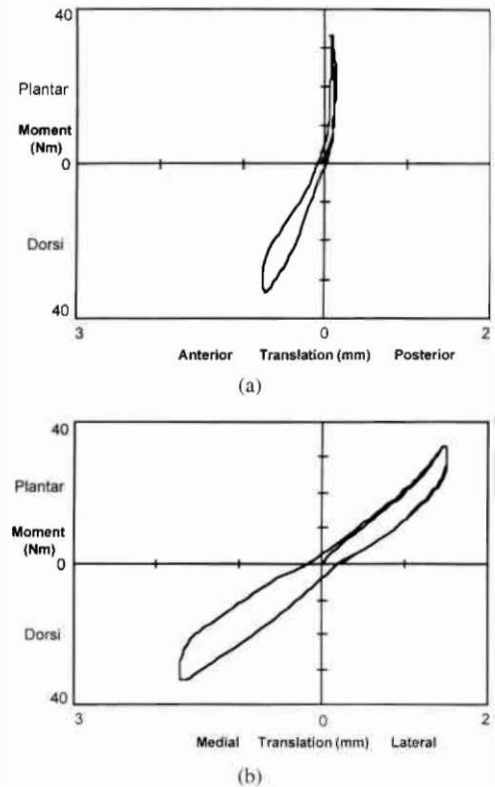


Fig. 9. Translation due to plantar/dorsiflexion moments (a) anterior/posterior; (b) medial/lateral.

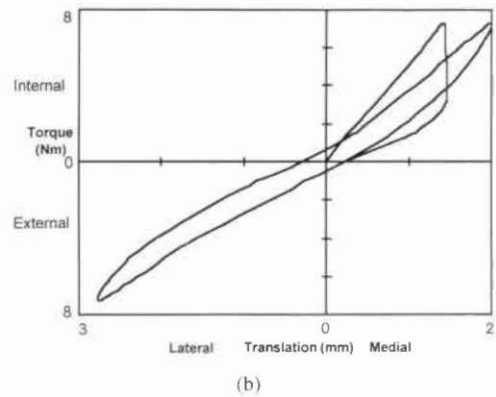
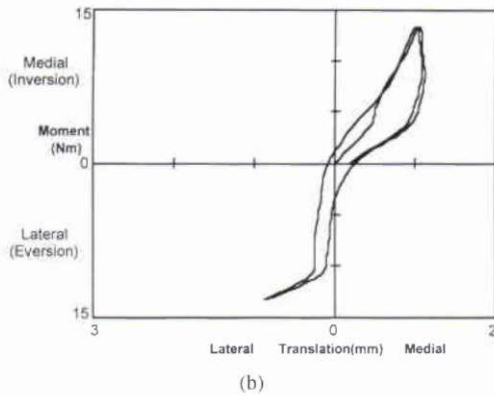
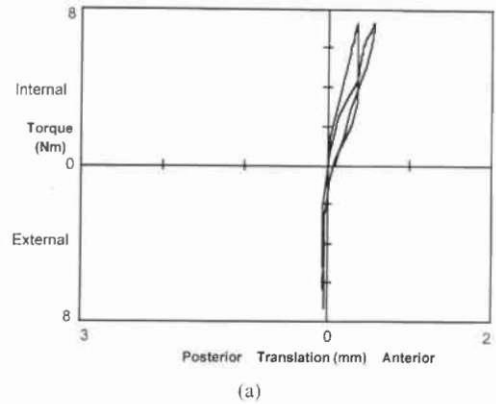
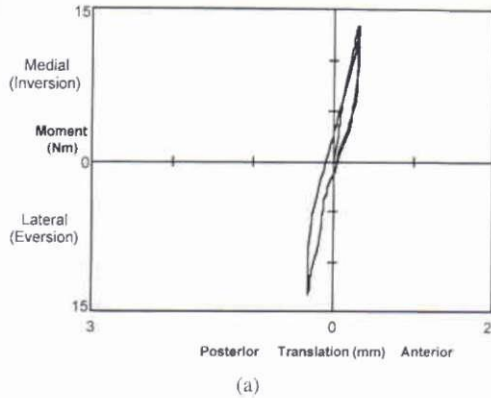


Fig. 10 Translations due to inversion/eversion moments
(a) anterior/posterior; (b) medial/lateral.

Fig. 11. Translation due to internal/external torques
(a) anterior/posterior; (b) medial/lateral.

the orthoses and the skeleton, and the structural deformations of the orthoses interact and must all be taken into account.

This study is limited to the orthotic ankle joint as fitted, including the structural properties of the AFO in the vicinity of the joint, but eliminating the orthoses/tissue interface. This approach also makes no allowance for compliant feet or shoes. It is considered that attempting to introduce all these factors would introduce too many variables and too many effects to quantify. Since this test apparatus will be used to compare the flexibility of a range of AFOs incorporating different ankle joints this approach was considered valid. This limits the study to investigating the AFO's flexibility over an approximate 70mm axial length of AFO from the top of the soleplate clamp to the distal surface of the foam calf.

A "stiff" polypropylene AFO has been used in this paper to demonstrate the capability of the

test apparatus.

In Figures 6 and 7 the (a) graphs illustrate load/deflection characteristics similar to previous researchers. The presented results do

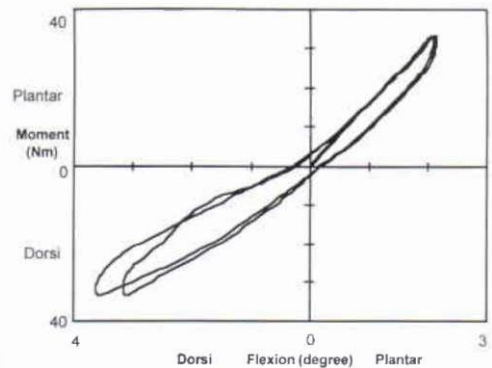


Fig. 12. Repeatability of sagittal angulation due to plantar/dorsiflexion moments.

not correlate exactly with previous studies due to variations in the loading apparatus and the contact area of the AFO with the base plate of the test apparatus and the enclosed "calf model". The other graphs in Figures 6, 7 and 8 illustrate the extent of angular cross-coupled deformation displayed by this particular AFO.

Figure 6 graph (c) illustrates that when subjected to dorsiflexion moments the AFO brim rotated internally relative to the soleplate. Likewise applied plantarflexion moments were accompanied by an external rotation of the AFO brim relative to the soleplate. The magnitudes of the cross-coupled rotations were approximately half that of the magnitude of the plantar/dorsiflexions. Figure 6 graph (b) illustrates that cross-coupled deformations in the frontal plane were significantly less but did follow a similar pattern.

Figure 7 graph (c) illustrates that when subjected to eversion (lateral bending) moments the AFO brim rotated externally relative to the soleplate. Applied inversion (medial bending) moments were accompanied by less internal rotation of the AFO brim. The magnitudes of the rotations were similar to the degree of eversion/inversion produced by the loading condition. Figure 7 graph (b) illustrates that cross-coupled deformations in the sagittal plane were significantly less but did follow a similar pattern. Figure 8 graphs (b) and (c) illustrate that when subjected to external/internal torques the cross-coupled deformations in the sagittal and frontal plane were significantly less as also were the magnitudes of the applied torques which as previously indicated were representative of those encountered during gait.

Figures 9, 10 and 11 illustrate that when subjected to moments in any of the 3 planes mediolateral translation of the AFO was the most prominent translation. When subjected to dorsiflexion moments as in Figure 9 graph (a) the magnitude of the anterior translation at ankle joint level was greater than that of the posterior translation when subjected to plantarflexion moments. Figure 9 graph (b) displays large mediolateral translations with applied plantar/dorsiflexion moments. When the AFO was subjected to eversion (lateral bending) moments as in Figure 10 graph (b) the magnitude of the lateral translation at ankle joint level was greater than the magnitude of the medial translation when the AFO was subjected

to inversion moments. Figure 10 graph (a) illustrates corresponding anteroposterior translations when the AFO was subjected to inversion/eversion moments. When the AFO was subjected to internal torques as in Figure 11 graph (a) the magnitude of the anterior translation at ankle joint level was greater than the posterior translation which resulted when the AFO was subjected to external torques. Figure 11 graph (b) illustrates larger corresponding mediolateral translations when the AFO was subjected to internal/external torques.

The asymmetric trimlines of the medial and lateral foot section of the soleplate of the AFO would influence the cross-coupled deformation displayed. The polypropylene AFO was manually draped and vacuum formed. There would be some resulting inconsistency in wall thickness of the AFO which would influence some cross-coupled deformation effects. Examination of asymmetric trimlines and variation in wall thickness will be investigated and reported in future studies.

In this test apparatus the motion of the AFO has been studied with a moment being applied in a single plane. In clinical practice the AFO may be subjected to combinations of all 3 moments at any instant. These combinations of moments may influence cross-coupled deformation effects.

Measurement of the sixth degree of freedom, the proximal/distal translation, is not possible with this test rig, unless a further reference plate and further gauges were added. If the calf is pivoting about its long axis, which may differ from the instantaneous AFO axis, related proximal/distal translation will occur between the calf and the AFO. The recorded gauge movements allow estimation of the instantaneous AFO axis, to predict this relative translation (not presented in this paper).

Conclusions

This test apparatus provides a protocol for applying moments in three planes and recording reproducible angulations and translations with 5 degrees of freedom.

When subjected to moments in the sagittal or frontal plane, rotation is the prominent cross-coupled deformation. When subjected to torques there is no prominent cross-coupled deformation.

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