Plantarflexion Resistance of Selected Ankle-Foot-Orthoses

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Abstract

Although ankle-foot-orthoses are widely used in the treatment of neuromuscular pathologies, prescribers and clinicians have only a limited amount of objective data available to distinguish one variant from another. This study investigated the feasibility of using the mechanical resistance provided at ten degrees of dorsiflexion to distinguish between various AFO designs. A simple apparatus was developed to precisely measure average dorsiflexion resistance in a low cost, repeatable manner that simulates the clinical effect of an AFO during upright ambulation. Results indicate that this single measure provides an objective method to group prefabricated and custom-made AFOs according to their ability to support the flaccid foot during gait. Those prefabricated orthoses that provide dorsiflexion torque similar to that offered by custom-made orthoses are likely to be more suitable for ambulatory applications than those that offer only minimal support.

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Introduction

Ankle-Foot-Orthoses [AFOs] are one of the most commonly prescribed lower limb orthoses, due in large part to their versatility in providing selected biomechanical controls to augment impaired functions. They are also generally well tolerated by those who wear them and are therefore often associated with a positive clinical outcome.

Despite their widespread clinical application, only a limited amount of objective data has been published regarding the control offered by specific AFO designs. This study was conducted to objectively document, in a simple manner, the resistance to plantarflexion of a variety of commonly prescribed AFOs. This data may prove useful in verifying the effectiveness of such orthoses when used to facilitate ambulation for individuals with neuromuscular impairments, and in developing prescription criteria for their clinical application.

Materials and Methods

To insure that the orthoses tested were representative of actual devices that might be provided in a clinical setting, a volunteer subject was recruited who is a normal 59-year-old male 6’3” tall and weighing 245 pounds. A negative impression was taken of his right lower leg in the conventional manner, using fiberglass casting tape wrapped over a single layer of cotton stockinet. His foot was placed in a neutral position on a casting plate to simulate the footbed of a conventional shoe. Routine circumferential and linear measurements of the casted limb were also recorded.

The negative impression was filled with plaster to create a positive model that was then rectified in accordance with standard industry practice. All casting artifacts and stockinet marks were removed and the malleolar regions were built up with plaster patches to create slight relief areas over these bony prominences.

The final model, which may be considered representative of a typical large adult male lower leg, was then duplicated in rigid polyurethane foam over a plywood core and reinforced externally with a polyester resin vacuum-bag lamination over a single layer of nylon stockinet. The laminated model was then used to create the test apparatus, which is similar to that described by Golay et al[1].

Tested orthoses

The original plaster positive model was then used to fabricate 8 different custom-made AFOs of varying biomechanical designs, as summarized in Table One. Three of the custom orthoses were the minimal contact sidebar and band type while five were total contact thermoplastic orthoses. All were constructed in accordance with industry standard fabrication methods using readily available components and materials that are routinely incorporated in typically prescribed orthoses.

Ten prefabricated AFOs were also fitted to the positive model. The prefabricated orthoses selected represent a range of commonly prescribed devices. The tested orthoses are summarized in Table One.

TABLE ONE: Characteristics of the tested orthoses

Sample Number	Manufacturer	Material Used	Ankle Control	Source for Joints
1	Custom made	Aluminum & leather	Klenzak joint, spring loaded	USMC[a] #211-140-802
2	Custom made	Aluminum & leather	Klenzak joint, with solid rod	USMC #211-140-802
3	Custom made	Aluminum & leather	Thrust bearing Phelps joint, 90 degree stop	USMC #19017
4	Custom made	4 mm thermoplastic polypropylene-polyethylene copolymer	Solid ankle trimline	Not applicable
5	Custom made	4 mm thermoplastic polypropylene-polyethylene copolymer	Posterior leaf spring trimline	Not applicable

[a] USMC
180 North San Gabriel Blvd.
Pasadena, CA 91107-3488

6	Custom made	4 mm thermoplastic polypropylene-polyethylene copolymer	Tamarack #742-L-85 ankle joints [dorsiflexion assist]	Becker[b]
7	Custom made	4 mm thermoplastic polypropylene-polyethylene copolymer	Becker 760-L Oklahoma Ankle Joints; Precision O&P Elite Line PSA-100-A adjustable dorsiflexion spring assist	Becker Precision O&P[c]
8	Custom made	4 mm thermoplastic polypropylene-polyethylene copolymer	Becker 760-L Oklahoma Ankle Joints; Precision O&P Elite Line PAS-100-A adjustable plantar flexion stop	Becker Precision O&P
9	Orthomerica[d] OA-3547-01	3 mm polypropylene homopolymer plastic	Trimline at ankle midline [limited motion]	Not applicable
10	Select Medical Products[e] #001203	Low temperature Kydex thermoplastic	Not adjustable	Not applicable

[b] Becker Orthopedic
635 Executive Dr.
Troy, MI 48083-4576

[c] Precision Orthotic & Prosthetic Components Inc.
P.O. Box 24556
Tempe, Arizona 85285-4556

[d] Orthomerica
505 31st St.
Newport Beach, CA 92663-3805

[e] Select Medical Products

11	Flexboot-01FB2 Flexboot Ortho[f]	Low temperature Kydex thermoplastic	Not adjustable	Not applicable
12	New Age Oscar Orthosis Corrective Systems[g]	Low temperature Kydex thermoplastic	Not adjustable	Not applicable
13	Multi-Podus-10MP Restorative Care of America[h]	Low temperature Kydex thermoplastic	Not adjustable	Not applicable
14	EZ-Boot #10-320 Orthotic Rehab[i]	Unspecified thermoplastic	Not adjustable	Not applicable

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P.O. Box 459
Pinellas Park, FL 33790-0459

[f] Flex-Boot Ortho
9380 NC Hwy 8
Lexington, NC 27292

[g] Orthosis Corrective Systems
6554 44th St. N.
Pinellas Park, FL 33781

[h] Restorative Care of America
11236 47th St. North
Clearwater, FL 34622

[i] Orthotic Rehab
1209 Tech Blvd., Suite 202
Tampa, FL 33619

15	PRAFO®-650 Anatomical Concepts, Inc.[j]	Injection-molded polypropylene, 1/8” anodized aluminum upright	Standard aluminum posterior bar	Not applicable
16	PRAFO®-650HD Anatomical Concepts, Inc.	Injection-molded polypropylene, 3/16” anodized aluminum upright	Heavy duty aluminum posterior bar	Not applicable
17	PRAFO®-650APU Anatomical Concepts, Inc.	Injection-molded polypropylene, 1/8” extruded aluminum upright	Adjustable aluminum posterior bar	Not applicable
18	PRAFO®-650SS Anatomical Concepts, Inc.	Injection-molded polypropylene, 1/8” spring steel upright	Spring steel posterior bar	Not applicable

All orthoses were fitted and adjusted to the test model by an experienced orthotist who is certified by the American Board for Certification in Prosthetics and Orthotics. The prefabricated devices were adjusted in accordance with the manufacturer’s written instructions and guidelines.

[j] Anatomical Concepts, Inc.
493 Bev Rd., Building #4
Boardman, OH 44512-6451

Test Apparatus

The test apparatus was constructed by placing a single axis hinge in the transmalleolar region of the reinforced wooden core foam model of the subject's lower leg. Sufficient material was removed so the model could bend freely from 20 degrees of dorsiflexion to 20 degrees of plantarflexion, thus simulating normal sagittal plane ankle motion in this range.

The shank of the articulated leg model was mounted rigidly to the back of the test stand so that the foot segment could move freely, as shown in Figure 1. The various orthoses provided the resistance to plantarflexion motion. This was measured by placing a stainless steel band across the dorsum of the model in the region corresponding to the metatarsal heads, located 25.4 cm [10 inches] anterior to the ankle joint for this individual.

A "Mark 10" digital force gauge with certified calibration[k] was connected from the steel band to a screw drive, which was used to apply a distraction force that would cause the model to plantarflex. A liquid-filled angle measurement device was attached solidly to the plantar surface of the foot segment so that it read "0.0" degrees when the midline of

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[k] Mark 10 Digital Force Gauge
Model MG-100
Mark-10 Corporation
458 West John Street
Hicksville, NY 11801

the foot segment was at a right angle to the midline of the shank segment. As the foot segment was plantarflexed, the measured angle increased up to 20 degrees, which was the maximum movement allowed by the test apparatus.

Testing

To eliminate any measurement artifacts due to compression of soft interfaces, all materials lining the orthoses were removed and the calf section was rigidly bolted to the shank portion of the model. The screw jack was then used to deflect the foot portion of the model in 1 degree increments, from 0 to 10 degrees of plantarflexion, similar to the method of Sumiya. The resistance supplied by each orthosis was recorded for a total of ten trials. Figure 2 summarizes the average resistance provided by each orthosis at 10 degrees of plantarflexion.

A second set of measurements was performed on all orthoses that could be altered from a neutral position to one that held the foot segment in 10 degrees of dorsiflexion. This was accomplished by adjusting the stops, bending the uprights, or thermal remolding of the orthosis. Figure 3 summarized the average resistance generated at 10 degrees of plantarflexion for those orthoses that could be tested in this manner.

Results

As might be expected, the resistance provided by the orthoses increased as the foot segment was pulled in the direction of plantarflexion, whether the starting point was from 10 degrees of dorsiflexion or from the neutral [zero degree] position. Furthermore, those orthoses that could be adjusted to a more acute dorsiflexion angle all demonstrated greater resistance to plantarflexion motion than when adjusted to a neutral position.

Although the range of resistances measured was large, the orthoses could be classified into three relatively distinct groups based on this parameter. Since the magnitude of the resistance to plantarflexion will directly affect the amount of toe clearance in midswing for individuals with pretibial muscle group deficiencies, this grouping may have clinical significance.

Discussion

Previous authors have shown that the sagittal plane stiffness of the tested AFOs varies widely[2],[3] and that the resistance provided significantly affects pathologic gait.[4] It has also been shown that, for a given individual with a gait disorder, the range of acceptable resistances is fairly narrow.[5] This recent objective data, supports the concept of providing functional orthoses based on the patient's biomechanical deficits, as originally termed "biotechnical matching" by Lehneis.[6]

No definitive method for measuring load deflection characteristics of orthoses has been established[7], although there is general consensus in the literature that sagittal plane stiffness is of particular clinical importance. The proliferation of custom designs and prefabricated variants in recent years has made it increasingly difficult to judge the effectiveness of a particular AFO prior to completion of the fitting. For this reason, we investigated the use of a simple digital tensiometer to objectively quantify the plantarflexion resistance supplied at the forefoot for a variety of common orthoses, as suggested by Rubin and Dixon in 1973.[8]

Paralysis or paresis of the pretibial muscles can result from traumatic injuries as well as a variety of neuromuscular disorders. The resulting inability to maintain toe clearance during swing phase is probably one of the most common reasons for the prescription of lower limb orthoses. Impairment of the pretibial muscles also compromises the patient's ability to control the rate of descent of the foot during loading response and typically results in a characteristic "foot slap" gait.

A broad range of orthoses may be used to treat these biomechanical losses. The clinician must select a design that provides sufficient plantarflexion resistance to effectively decelerate the foot in early stance as well as maintain at least a neutral ankle-foot attitude in swing phase. However, if the orthosis provides too much resistance to plantarflexion, ankle motion will be inhibited throughout loading response and, as a result, the normal shock absorbing mechanism is disrupted and knee stability is reduced. So, the challenge is to apply sufficient resistance to eliminate the gait pathology without introducing additional aberrations.

In this study, the tested orthoses fell into three distinct groupings based on the average static resistance to plantarflexion. The first grouping can be termed the "plantarflexion stop" or PFS orthoses as they all provided at least 20 pounds of resistance when set initially in a neutral position. Clinical observation has confirmed that these devices significantly limit plantarflexion motion and their use is recommended only when such a reduction in the range of motion at the ankle is desired. The PFS orthoses were all custom made devices with the exception of the prefabricated solid ankle plastic AFO [#9] and the heavy duty PRAFO® [#17]. When adjusted to an initial alignment in 10 degrees of dorsiflexion, these orthoses all provided at least 45 pounds of resistance in the measured position.

The second grouping of orthoses provided 10-16 pounds of resistance in neutral and 20-25 pounds of resistance from an initial angle of 10 degrees dorsiflexion. These devices would effectively dampen plantarflexion during loading response without unduly restricting ankle motion, thereby restoring some of the normal shock absorption that results from the interaction between knee and ankle movements in early stance. They would also maintain good toe clearance throughout swing phase. This grouping could be termed the "plantarflexion resistance" or PFR orthoses, and they are preferable to the more rigid devices in the first group unless there are specific reasons to restrict this ankle motion. The PFR group included many of the custom made orthoses and all but one of the PRAFO®s.

The third group provided no more than five pounds of resistance from a neutral position and included all the tested prefabricated recumbent splints. This group may be termed the "non ambulatory" or NA devices since clinical experience has shown that such minimal resistances are insufficient to assure toe clearance or to significantly decelerate the foot in early stance. However, these devices may be quite suitable to maintain the foot in a neutral position when the patient is recumbent since the force of gravity pulling the foot into plantarflexion is minimized in that posture.

It should be noted that this study looked only at one aspect of AFO function: resistance to movement toward plantarflexion. This data provides no information about resistance to dorsiflexion, or resistances in other planes, and should therefore be interpreted with caution. Klasson et al have documented clearly that plastic AFOs provide resistance in all planes even when prescribed primarily for single plane control.[9]

Golay et al used a similar measurement strategy to ours but looked exclusively at dorsiflexion resistance.[10] They showed that for custom made polypropylene AFOs, such variables as the final wall thickness of the plastic and the degree of malleolar build-ups significantly affected the resistance to dorsiflexion provided. Sumiya et al reported that for the flexible plastic AFOs tested, the overall resistance to both plantarflexion and dorsiflexion increased almost proportionally to the width of the posterior portion of the device.[11] Singerman et al recently published a more comprehensive look at four AFO types and noted that changes to the trimlines intended primarily to alter the resistance inevitably altered the effective axis of rotation of the device as well.[12]

Conclusion

This study found that commonly prescribed contemporary AFO designs could be grouped according to the maximum static resistance provided when deflected to 10 degrees of plantarflexion. The designs that would stop plantarflexion movement all provided the greatest magnitude of measured resistance and were predominantly custom made devices. The group that provided intermediate levels of resistance but also allowed a significant range of ankle motion included custom made devices and all except the heavy-duty PRAFO® designs. The group that provided only minimal resistance was all non-adjustable prefabricated splints best suited for non-ambulatory applications.

Prescribing physicians, orthotic clinicians, and reimbursement authorities may be able to use such objective data to help distinguish between orthoses that are superficially similar in appearance but offer distinctly different biomechanical advantages. In principle, it may be possible for the future to use the results from instrumented analysis of individual pathologic gait patterns to specify the desired amount of plantarflexion resistance for their orthosis so it is no longer necessary to determine this by subjective means during iterative clinical walking trials. Measurement and publication of a much broader array of data about the resistances and motion provided by lower limb orthoses may be helpful in increasing objectivity in the prescription and design of such devices.

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Tables, Figures, and Legends

Figure 1:

The model from an impression of an adult male lower leg with a single axis hinge at malleolar level, permitting free movement from 20 degrees of plantarflexion to 20 degrees of dorsiflexion, is anchored rigidly to the vertical stand. Test orthoses were attached rigidly to the calf segment and static dorsiflexion resistance was measured at the metatarsal heads, to simulate the clinical effect of walking with an AFO intended to compensate for dorsiflexion weakness. Digital goniometer [A] measured deflection angle while digital tensiometer recorded the static force applied at the metatarsal head region.

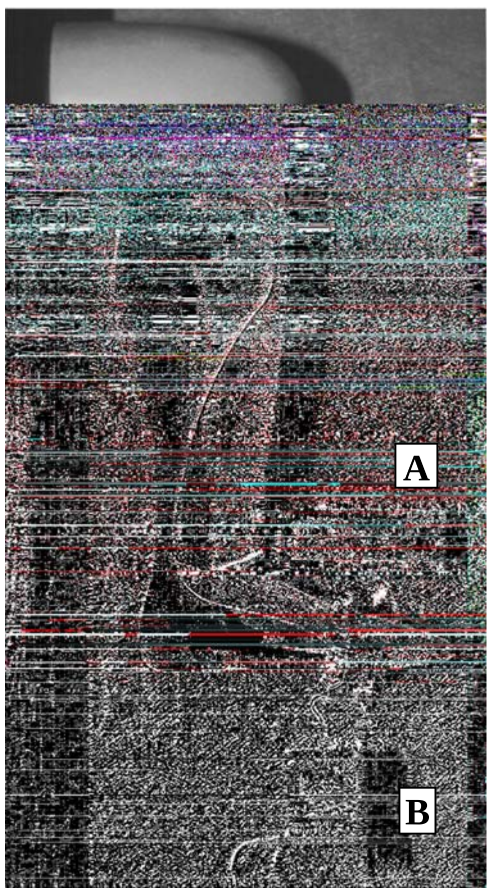
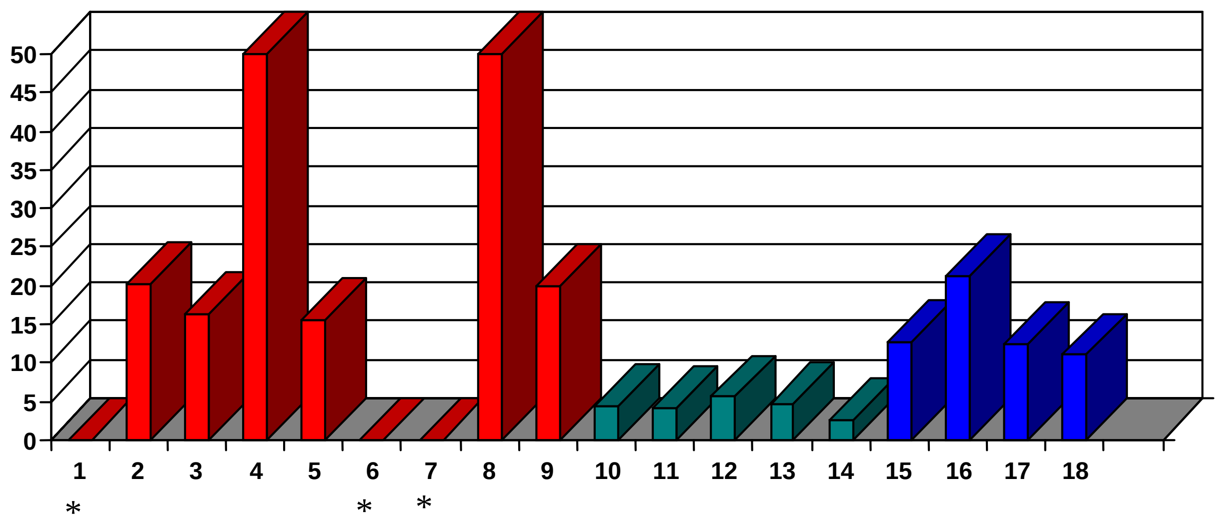


Figure 2:

Average static resistance measured at 10 degrees of plantarflexion, for orthoses that were initially set in neutral plantarflexion-dorsiflexion. The left column shows the resistance in pounds.



1. Klenzak, with spring (not tested at 90 degrees)
2. Klenzak, with solid pin
3. Phelps
4. Custom AFO, with solid ankle
5. Custom AFO, with posterior leaf spring trimline
6. Custom AFO, with model #742-L-85 Tamarack (not tested at 90 degrees)
7. Custom AFO, with Oklahoma joints, PSA-100 dorsiflexion assist (not tested at 90 degrees)
8. Custom AFO, with Oklahoma joints, PAS-100 plantarflexion stop
9. Prefabricated AFO, custom fitted, 1/8 polypropylene, semi-rigid trimline
10. Recumbent splint, Select Medical Products
11. Recumbent splint, Flexboot - 01FB2
12. Recumbent splint, New Age Oscar
13. Recumbent splint, Multi-Podus - 10MP
14. Recumbent splint, EZ-Boot #10320
15. PRAFO® (Standard)
16. PRAFO® (Heavy duty)
17. PRAFO® (APU)
18. PRAFO® (Stainless steel)

* Note: Orthoses 1, 6 and 7 could not be tested from a position of 90 degrees since they are preset in 10 degrees of dorsiflexion.

Figure 3:

Average static resistance measured at 10 degrees of plantarflexion, for orthoses that were initially set in 10 degrees of dorsiflexion. The left column shows the resistance in pounds.

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1. Klenzak, with spring
2. Klenzak, with solid pin
3. Phelps
4. Custom AFO, with solid ankle
6. Custom AFO, with model #742-L-85 Tamarack
7. Custom AFO, with Oklahoma joints, Elite line PSA-100 dorsiflexion assist
8. Custom AFO, with Oklahoma joints, Elite line PAS-100 plantarflexion stop

15. PRAFO® (Standard)
16. PRAFO® (Heavy Duty)
17. PRAFO® (APU)
18. PRAFO® (Stainless steel)

*Note: Orthoses 5 & 9-14 could not be tested in this configuration as they were fabricated in a neutral attitude.

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