Effect of a Tone-Inhibiting Dynamic Ankle-Foot Orthosis on the Foot- Loading Pattern of a Hemiplegic Adult:A Preliminary Study

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Introduction

Foot-loading patterns are one of the most direct measures of dynamic foot alignment during stance. By examining foot-loading patterns, clinicians can determine the sequence of contact points along the foot as weight is accepted. For example, a loading pattern involving initial contact of the forefoot to the floor may give the clinician an objective indication of spasticity or ankle-joint range-of-motion limitations. This information would then better enable the clinician to make appropriate decisions about the best course of treatment.

Despite the usefulness of information about foot-loading patterns, the few published studies documenting neurologic patients' foot-loading patterns involve only the static examination of weightbearing when the foot is standing. In one such study it was noted that hemiplegic subjects bore significantly less weight through the involved leg, with less weight acceptance through the heel compared to age-matched normal control subjects (1). The foot-ground pressure pattern (FGP) used in this study measures the pattern of weightbearing when the subject is standing quietly; it does not give information about how the foot is loaded as the subject progresses through stance phase.

Ryerson discusses three patterns of foot loading in hemiplegic subjects as the patient progresses through stance (2). These different patterns are the result of the patient's level of muscle tone as well as the range of motion available at the talocrural and subtalar joints (3). While knowledge of these three patterns of foot loading is clinically useful, they have not been experimentally validated, and therapists working to alter these loading patterns do not have objective ways to measure improvement.

Further research in the area of foot-loading patterns in neurologic patients is needed. Currently, no studies document the effect of various orthotic devices on these patients' foot-loading patterns. Data from such research may help validate the effectiveness of commonly used orthotic management procedures used by clinicians in treating these patients.

Tone-inhibiting orthoses are widely pre scribed in neurorehabilitation. One of thc most clinically popular tone-inhibiting orthoses is the dynamic ankle-foot orthosis (DAFO), a "very thin, flexible supramalleolar orthosis with a custom-contoured sole-plate to include support and stabilization to the dynamic arches of the foot" (4). The DAFO was designed based on the concept that the most important aspect of tone-inhibiting orthotics is obtaining neutral alignment of the ankle and foot (5). This device provides a supportive total contact exoskeleton that maintains neutral forefoot and subtalar joints while allowing graded amounts of ankle eversion, inversion, plantarfiexion and dorsifiexion.

The DAFO is widely used, particularly in the pediatric population, and has several unique features. First, it allows graded foot motion within the orthosis so normal balance reactions involving proximal musculature can occur. Second, by providing support of the foot's natural arches, weight is more equally distributed throughout the foot. Thus, stimulation of foot reflexes better approximates normal function (6-8). Third, DAFOs provide secure medial-lateral stability and midline positioning, resulting in improved grading of ankle plantar- and dorsiflexion. This stabilization has proven so effective, many clinicians have noted a decrease in abnormal plantarfiexion in patients wearing DAFOs. In one case, a 15-year-old spastic diplegic patient with a resistant heel-cord contracture gained 15 degrees of passive dorsiflexion with knee extension as a result of wearing DAFOs for three months (4).

The clinical effects of management with DAFOs are very promising. In one study, a four-year-old boy with spastic diplegia showed significant increases in the duration and efficiency of balanced standing when wearing DAFOs as compared to his performance without these orthoses (5). In another study, the effects of DAFOs were reported on a 69-year-old male who was 18 months post-CVA, who had no voluntary movement at the foot or ankle, and who demonstrated forceful hyperextension of the knee when wearing a conventional AFO (9). Within one month of receiving his DAFO, the patient demonstrated active toe extension and showed a 10-degree increase in knee flexion during toe-off. The author of this study attributed these improvements to the controlled mobility afforded by the DAFO. The effects of DAFOs on the temporal variables of gait were reported in a single-subject study by Diamond (10). The subject, a hemiplegic adult, showed significant increases in velocity, step length and stance time when wearing a DAFO as compared to his performance when barefoot. Although all of these studies are single-subject designs, the author of one such study defended this methodology by stating: "The single-subject design is particularly appropriate for evaluating treatment effectiveness in neurologic patients because of the organic and behavioral variability of this disorder" (5).

The purpose of this study was to examine the effect of the DAFO on the foot-loading patterns of a hemiplegic adult. The authors believed the application of the DAFO would result in a significantly better foot-loading pattern compared to that generated when wearing a shoe alone.

Method

Design, Fitting and Fabrication of the DAFO

Before making the plaster mold of the foot and ankle, a footplate supporting the natural arches of the foot (i.e., the peroneal, metatarsal, medial longitudinal and toe crease arches) is constructed. Hylton and Cusick have described footplate fabrication techniques (11,12).

Nylon stockinette is applied to the foot and lower leg, and the bony areas of the foot and ankle are marked with indelible pencil. The plaster foot plate is then applied to the plantar aspect of the foot. To obtain an optimal plaster impression, the ankle must be placed in slight dorsiflexion with the subtalar joint in neutral position. A cutting tube is placed anteriorly and fast-setting plaster is applied, incorporating the footplate. Carefully mold around the calcaneous to keep the subtalar joint in a neutral position.

The plaster mold usually requires minimal modifications except for smoothing. Relief for bony prominences may be provided if these are extremely prominent. One-eighth-inch of Aliplast(r) and orthopedic-grade polypropylene are vacuum-formed over the cast and stretched thin (13). A padded circular calf strap and anterior strap above the ankle are attached to the orthosis after trimlines have been cut and smoothed. Figure 1 illustrates the completed DAFO.

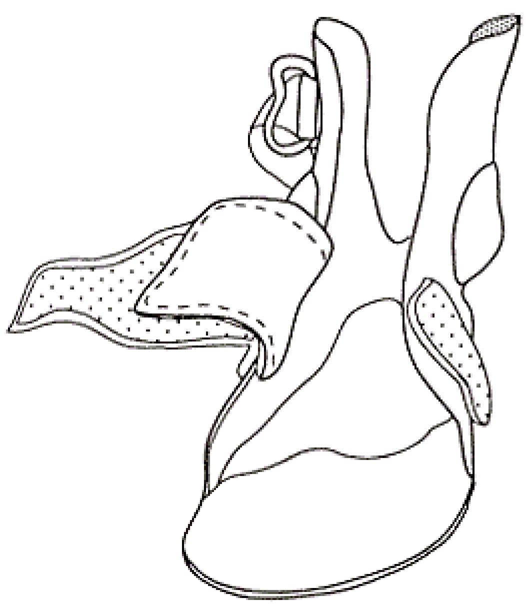

Figure 1. Dynamic ankle-foot orthosis.

Subject

The subject was a 55-year-old male who had suffered a left side cerebral vascular accident two years previously, resulting in right hemiplegia. The subject was an independent ambulator who wore a rigid polypropylene ankle-foot orthosis set at zero degrees of ankle dorsiflexion, which he felt was too restricting.

The subject was evaluated by a registered physical therapist (KM). He demonstrated minimal active knee fiexion and full extension in the right lower extremity in standing, but he had no active ankle dorsiflexion. Moderate extensor spasticity was present in the right lower extremity, resulting in calcaneal varus and forefoot supination at heelstrike (2). Moderate genu recurvatum was also present during stance.

The subject initially displayed a 15-degree ankle plantar flexion contracture, but this was managed by a four-week course of serial casting until 10 degrees of passive dorsiflexion was obtained. The subject was then evaluated by a certified orthotist

(DM) and a plaster impression was taken for the DAFO. The subject gave written informed consent to participate in the study, which was approved by the Northern Arizona University Human Subjects Institutional Review Board.

Procedure

An A-B-B-A single-subject design was used for the study. This design allows the comparison of the baseline (A) condition (barefoot) with the treatment (B) condition (orthosis). This design also allows the comparison of pre- and post-treatment baselines (Al and A2, respectively), making it possible to determine the presence of a carryover effect.

Foot-loading data was collected using the EMED-SF(r) plantar pressure analysis system (14). The EMED-SF uses a pressure-sensitive mat embedded with 1 ,300 sensors which detect pressures as low as one newton/cm_2. The pressure mat is embedded in the center of a wooden walkway two feet wide, 20 feet long and one inch high. The EMED-SF is connected to a computer that provides an analysis of the progression of foot loading as well as a graphic representation of the areas and extent of plantar pressure during the stance phase of gait.

Data was collected in two sessions. The first session involved 10 walking trials across the EMED-SF pressure platform with the subject wearing his shoes. This was the first baseline condition (A1), noted as "shoe-only, condition one" (SO-1). Immediately following the SO-1 condition, the subject was fitted with the DAFO. The subject then walked with the DAFO until he felt assured of his safety and comfort. He then performed 10 walking trials across the EMED-SF pressure platform. This was the first treatment condition (B1), noted as DAFO-1. Subject fatigue was carefully monitored during all trials, and brief rest periods were given as needed.

Following the completion of the SO-I and DAFO-1 trials, the subject was instructed to wear the DAFO during all waking hours for the next 14 days and to walk as much as possible. The subject was also asked to track the amount of time spent standing and walking each day.

The second data collection session occurred 14 days later. The subject reported wearing the DAFO 16 hours a day, spending about four hours a day standing and/or walking. The subject then performed 10 walking trials wearing the DAFO. This was the second treatment condition (B2), noted as DAFO-2. It was immediately followed by 10 return-to-baseline walking trials (A2), noted as "shoe-only, condition two" (SO-2).

Data Analysis

Three dependent variables related to foot-loading patterns were examined. These included:

- *Total Foot Force* (TFF,) as measured in newtons (one Newton = 4.42 lbs). TFF is the maximum amount of weight borne through the foot as it comes in contact with the pressure plate during a single stance period.
- *Total foot area* (TFA) as measured in square centimeters. That is, the maximum area of the foot's plantar surface in contact with the pressure plate during a single stance period.
- *Total foot contact time* (TEC) as measured in milliseconds. TFC is the total amount of time spent on the foot in contact with the pressure plate as it progresses through a single stance period.

The EMED-SE data analysis system allows a discrete examination of specific sections of the foot. For the purposes of this study, the foot was divided into thirds to enable the exploration of these variables as they pertained to the hindfoot, midfoot and forefoot.

Data analysis was performed using the split middle technique to determine statistical differences among the four conditions (15). The .05 level of significance was used.

Results

The mean and the standard error of the mean (SEM) for each variable under the four conditions is represented in Table 1 , which also shows a summary of the effect of the DAFO on TFA, TFC and TFF during stance. Total foot area in contact with the pressure plate and total force generated through the foot were both significantly increased as a result of wearing the DAFO. Total stance duration was significantly decreased as a result of wearing the DAFO. These changes were noted between the SO-1 and DAFO-1 conditions, suggesting application of the DAFO had an immediate effect.

Effect of DAFO on total area (in cm^2) under foot during stance

	SO_1 (A_1)	$DAFO_1$ (B_1)	$DAFO_2$ (B_2)	SO_2 (A_2)
mean	190	208	206	183
SEM	2.48	0.77	1.29	1.62

SO_1–$DAFO_1$: S; $DAFO_1$–$DAFO_2$: NS; $DAFO_2$–SO_2: S
$DAFO_1$–SO_2: S
SO_1–SO_2: S

s = $p < .05$

Effect of DAFO on total stance duration (in milliseconds)

	SO_1 (A_1)	$DAFO_1$ (B_1)	$DAFO_2$ (B_2)	SO_2 (A_2)
mean	1592	1323	1252	1537
SEM	32.38	40.41	26.34	25.03

SO_1–$DAFO_1$: S; $DAFO_1$–$DAFO_2$: S; $DAFO_2$–SO_2: S
$DAFO_1$–SO_2: S
SO_1–SO_2: S

s = $p < .05$

Effect of DAFO on total force under foot during stance

	SO_1 (A_1)	$DAFO_1$ (B_1)	$DAFO_2$ (B_2)	SO_2 (A_2)
mean	1241	1574	1758	1345
SEM	32.69	23.94	26.82	17.02

SO_1–$DAFO_1$: S; $DAFO_1$–$DAFO_2$: S; $DAFO_2$–SO_2: S
$DAFO_1$–SO_2: S
SO_1–SO_2: S

s = $p < .05$

Table 1.

For each of the three variables, significant differences between the SO-1 and SO-2 conditions occurred, suggesting a possible carryover effect due to wearing the DAFO for 14 days. For total stance duration and total force, there were significant differences between DAFO-1 and DAFO-2, indicating that continuous wear of the DAFO results in increasing improvements over time.

Discussion

The study indicates that use of a DAFO may result in greater stability through the foot during stance as noted by the increases in TFA and TFF generated when this orthosis was worn. The increased TFA seen in this study may be related to the tone-inhibiting features of the DAFO design, namely, contoured total contact support of the foot's natural arches. These features may hold the foot more securely in the orthosis, perhaps preventing spasticity-induced foot postures, which result in less complete contact of the plantar surface with the ground. EMG analysis would be helpful in future DAFO studies to determine if support of the natural foot arches promotes firing of proximal lower extremity muscles for optimal foot loading (such as the anterior tibialis and the peroneals).

The increase in TFF, seen as a result of wearing the DAFO, may be due to the enhanced stability afforded by the increase in TEA. Support of the foot's natural arches may provide more uniform sensory input throughout the entire foot, resulting in a greater sense of postural security. This security could in turn manifest itself in the subject's ability to bear more weight through the hemiplegic leg when wearing the DAFO.

The results of this study indicate that wearing the DAFO decreases TFC. This finding may be related to a greater efficiency of gait, resulting from a smoother forward progression of pressure through the foot. This progression of foot loading (which is analogous to the center of pressure) as it occurred at the hindfoot, midfoot and forefoot is shown for the SO-1 and DAFO-2 conditions in Figure 2 and Figure 3 , respectively. In the SO-1 condition, initial contact of the foot with the pressure plate occurred at the lateral midfoot, at the base of the fifth metatarsal. Weight was then shifted backward toward the anterior hindfoot; however, there was no weight acceptance onto the hindfoot. This pattern may have been due to poor foot support within the shoe, resulting in spasticity-related foot posturing into supination, which was maintained at initial contact. Figure 2 shows a cluster of X's at the midfoot, indicating the subject spent a considerable portion of stance bearing weight through this area, possibly to maintain maximal stability. Finally, weight was shifted forward, progressing through the midfoot and forefoot, culminating in a toe drag. This loading pattern required a mean of 1,592 milliseconds.

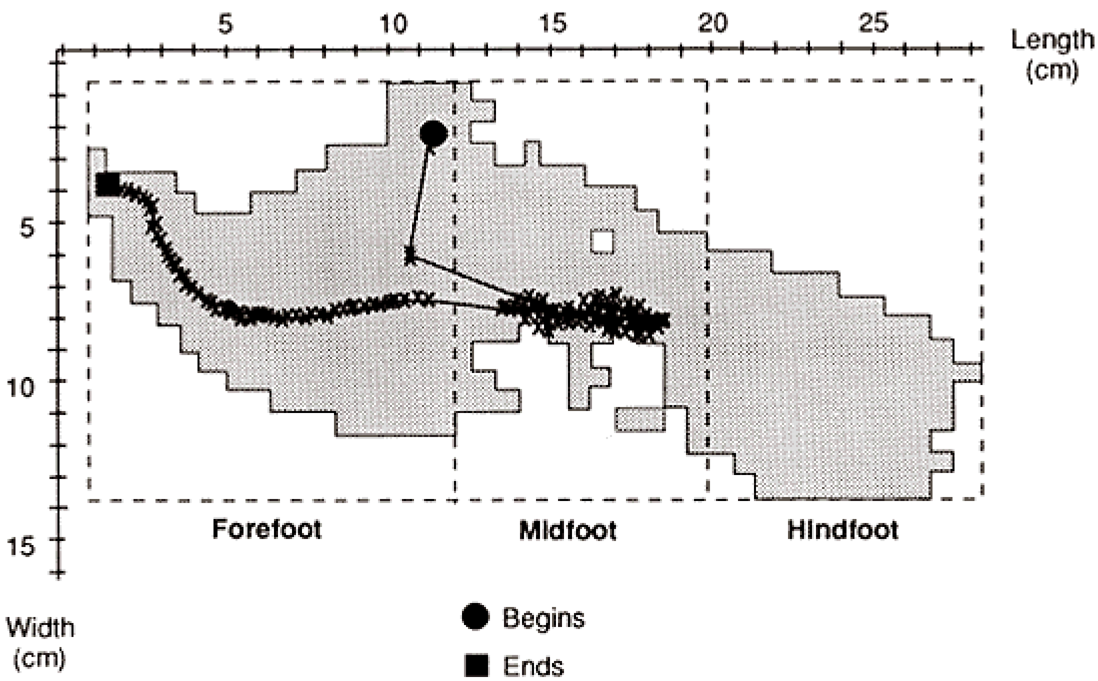

Figure 2. Sequence of foot loading during the SO-1 condition.

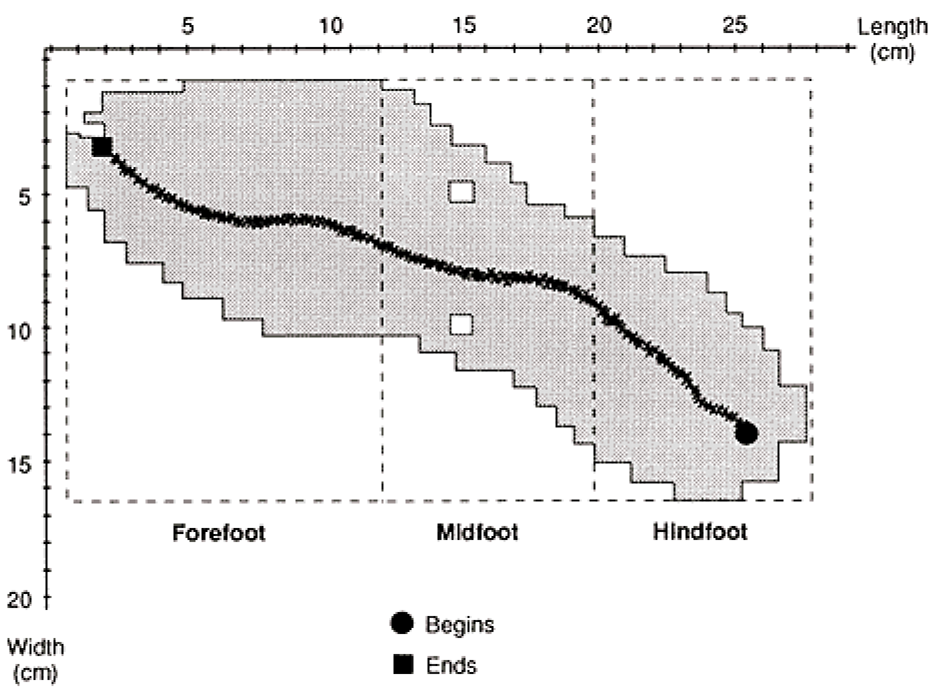

Figure 3. Progression of foot loading during the SO-2 condition.

In contrast, the progression of foot loading in the DAFO-2 condition (shown in Figure 3) indicates initial contact of the foot with the pressure plate occurred at the posterior hindfoot and progressed forward through the midfoot and forefoot, bisecting the foot. In the hindfoot area, the X's are more spread out, suggesting that acceptance of weight progressed through the hindfoot in a smooth manner. In the midfoot and forefoot, the X's are closer together, although relatively evenly spaced. This pattern of X's indicates that while the subject spent the majority of the stance period bearing weight through these areas, the forward progression of weight acceptance was relatively smooth. This loading pattern required a mean of 1,252 milliseconds.

The heel-to-toe loading pattern seen in Figure 3 may be due to the flexibility of the DAFO, which allows graded movement to occur at the ankle in the frontal and sagittal planes, providing unrestricted forward movement of the tibia over the foot. Such movement would allow a natural heelstrike followed by a smooth forward progression through footflat, heel-off and toe-off.

The decrease in stance time seen in the hemiplegic leg may also be related to the faster overall gait velocity allowed by the DAFO. Future DAFO studies should measure gait velocity to examine relative stance duration between the hemiplegic and unaffected legs. It is possible that while the stance duration of the hemiplegic leg is decreased when wearing the DAFO, when compared to the stance duration of the uninvolved leg, this measure may be more proportional as gait velocity increases.

Finally, the results of this study indicate the improvements attained from wearing the DAFO for 14 days may be maintained when the subject returns to walking with the shoe only. It is possible that the combined features of foot arch support and the flexibility afforded by the DAFO result in activation of foot and ankle musculature, which is maintained as these muscles become stronger. In this study, the SO-2 condition was measured immediately after a 14-day trial of DAFO use, and no attempts were made to measure the duration of this carryover effect. It may be enlightening to conduct further studies exploring this factor.

Conclusion

The results of this study indicate that using DAFO for 14 days may result in a faster progression of the center of mass over the foot during stance. Greater foot stability may also result as noted by the increases in total foot force and area generated.

The positive findings of any single-subject study can certainly be met with optimism; however, additional studies are needed to validate findings. Obviously, replications of this study using larger subject groups would be valuable.

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