Effect of Shoes on Stiffness and Energy Efficiency of Ankle-Foot Orthosis: Bench Testing Analysis

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Understanding the mechanical properties of ankle-foot orthoses (AFOs) is important to maximize their benefit for those with movement disorders during gait. Though mechanical properties such as stiffness and/or energy efficiency of AFOs have been extensively studied, it remains unknown how and to what extent shoes influence their properties. The aim of this study was to investigate the effect of shoes on stiffness and energy efficiency of an AFO using a custom mechanical testing device. Stiffness and energy efficiency of the AFO were measured in the plantar flexion and dorsiflexion range, respectively, under AFO-alone and AFO-Shoe combination conditions. The results of this study demonstrated that the stiffness of the AFO-Shoe combination was significantly decreased compared to the AFO-alone condition, but no significant differences were found in energy efficiency. From the results, we recommend that shoes used with AFOs should be carefully selected not only based on their effect on alignment of the lower limb, but also their effects on overall mechanical properties of the AFO-Shoe combination. Further study is needed to clarify the effects of differences in shoe designs on AFO-Shoe combination mechanical properties.

Keywords: ankle foot orthoses, footwear, gait, moment, orthotics

Ankle-foot orthoses (AFOs) are widely used to assist the gait of individuals with ankle impairments due to neurological or musculoskeletal disorders. Their mechanical properties and effect on gait need to be well understood by clinicians, so that patients can receive maximum benefit from their orthoses. The mechanical properties of AFOs, such as stiffness (moment per degree) and energy efficiency (ratio of released energy to stored energy), have been characterized using various mechanical testing devices,1–3 and their effects on gait in individuals with neuromuscular diseases have been investigated.4–7 Varying stiffness of AFOs has been shown to affect kinematics and kinetics of lower limb joints during gait in individuals with cerebral palsy4 and stroke.5,6 A simulation study also showed that the energy cost of gait might be optimized by properly tuning AFO stiffness.8 However, the importance of adjusting AFO stiffness is still underestimated, and the majority of clinical studies do not explicitly report AFO stiffness. Energy efficiency indicates how much energy is returned or lost while an AFO is dorsiflexed or plantar flexed during gait. This efficiency might affect gait during stance, but it requires further investigation.

AFOs are generally used in combination with shoes. Recent studies have focused on the effect of shoes on the alignment of the lower limb during gait.9,10 However, it seems that AFOs have been tested independent of shoes, and the effect of shoes on the mechanical properties of AFOs has not been generally reported.11 The sole of a shoe may function as a cushion due to its elasticity and affect the overall stiffness and energy efficiency of the AFO-Shoe combination. Therefore, the aim of this study was to investigate the effect of shoes on stiffness and energy efficiency of AFOs using a custom mechanical testing device.

Methods

A custom motorized mechanical testing device was used to quantify stiffness and energy efficiency of the AFO.2 This device was equipped with an inline uniaxial torque sensor (TRT-500, measurement range: 500 in-lb or 56.5 N·m, Transducer Tech Inc., USA) and an optical encoder (Dahamer Motion Inc., USA) to test the moment-angle characteristics of the AFO within a torque range of ± 30 N·m (Figure 1A). The AFO was mounted to the device by clamping the AFO footplate to the flat articulating platform of the testing device using a clamp and attaching the tibial section of the AFO to a plaster surrogate leg using the AFO tibial fastener strap. Both motor speed and direction of rotation were controlled by a motor drive. Data acquisition was done using an NI PCI-6221 M Series DAQ, while a graphical user interface (GUI) that can set rotational speed and maximum torque and display moment-angle curves was developed using LabVIEW (National Instrument Inc., USA).

Thirteen AFOs with bilateral articulated ankle joints (Triple Action™, Becker, USA) fabricated from polypropylene homopolymer (3/16”) were tested in this study.12 Each AFO was custom fabricated using different positive plaster casts taken from 13 adults (age: 52 [17] years old, height: 1.74 [0.11] m, body mass: 81 [19] kg, mean [SD]) in the institutional review board (University of Utah: IRB_00062924) approved study. Thus, the size and shape of each AFO was unique (height: 383 [26] mm, footplate length: 254 [17] mm, thickness at proximal end of shank: 4.0 [0.1] m). The
AFOs were tested with the ankle joints locked (ie, movement to plantar flexion and dorsiflexion was mechanically blocked) at neutral position (ie, 0 degree). The AFOs were tested under (1) AFO alone and (2) AFO with shoe (New Balance 928, New Balance Inc., USA) (AFO-Shoe combination) conditions. Solid ankle-cushion heel (SACH) prosthetic feet were used to fill the room inside the shoe in the AFO-Shoe combination and clamp the orthoses to the testing device’s articulating platform (Figure 1B). The prosthetic feet were sized as was appropriate for the AFOs. Neither the prosthetic feet nor the plaster surrogate legs were physically connected to the ankle joints. The rotational center of the joints of the AFOs was aligned to the rotational center of the motor shaft of the testing device. Once the AFO or AFO-Shoe combination was fixed to the mechanical testing device via the surrogate leg and the articulating platform, the orthosis was automatically plantar flexed and dorsiflexed until it reached 30 N·m in either direction at a rotational speed of 6°/s for 60 seconds. The motor of the testing device was designed to switch direction once it reached the torque limit (ie, ± 30 N·m). The test was repeated 3 times per AFO. The resistive moment and corresponding angular positions of the AFO or AFO-Shoe were measured with the torque sensor and the encoder at the sampling frequency of 1000 Hz.

The moment and angular position data were digitally filtered using a fourth-order zero-lag low-pass Butterworth filter with a cutoff frequency at 5 Hz. The effect of gravity on the footplate of the device was subtracted from the original moment data. The moment-angle data were plotted as hysteresis loops. The following parameters were calculated based on a previous study from the hysteresis loops averaged across cycles and trials for each AFO. Stiffness was obtained via curve fitting the moment-angle curve using linear regression: (1) dorsiflexion stiffness (N·m/°) = slope of the moment-angle curve above 0 N·m in the dorsiflexion resistance range (DF-ROM) (Figure 2A); (2) plantar flexion stiffness (N·m/°) = slope of the moment-angle curve below 0 N·m in the plantar flexion resistance range (PF-ROM) (Figure 2B); (3) stored and released energy below 0 N·m in the plantar flexion resistance range (J) (in order to calculate the energy in joule [J], area under the moment-angle curve was divided by 57.3 because 1 radian is equal to 57.3°; Figure 3A, B); (4) stored and released energy above 0 N·m in the dorsiflexion resistance range (J; Figure 3C, D); and (5) energy efficiency (%) = ratio of released energy to stored energy in plantar

![Figure 1](image1.png) — (A) Mechanical testing device and (B) AFO-Shoe combination mounted on the device.

![Figure 2](image2.png) — Definition of dorsiflexion stiffness and plantar flexion stiffness of an ankle foot orthosis.
Results

Both dorsiflexion and plantarflexion stiffness revealed significant decreases for the AFO-Shoe combination in comparison to the AFO-alone condition (Table 1). Dorsiflexion stiffness was significantly \( p = .0022 \) decreased by 13\% from 6.3 (1.2) N·m\(^{\circ}\) to 5.5 (1.2) N·m\(^{\circ}\), while plantarflexion stiffness was significantly \( p = .0052 \) decreased by 15\% from 6.6 (1.1) N·m\(^{\circ}\) to 5.6 (1.3) N·m\(^{\circ}\).

Stiffness of the AFO-Shoe combination was significantly greater than the AFO alone, but no significant differences were found in energy efficiency between the 2 conditions.

Discussion

This is the first study that investigated the effect of shoes on stiffness and energy efficiency of an AFO. Results revealed that stiffness of the AFO-Shoe combination was significantly smaller than the AFO alone, but no significant differences were found in energy efficiency. This study therefore suggests that shoes used with AFOs should be carefully selected based on not only their effect on alignment of the lower limb, but also their effects on overall mechanical properties of the AFO-Shoe combination.

Stiffness of the AFO-Shoe combination should be reported rather than the AFO alone in future studies that investigate the effects of AFOs’ stiffness on kinematics and kinetics of gait.

The sole of the shoe is compressed by the AFO during plantar flexion and dorsiflexion, and this reduces the effective stiffness of the AFO. The mean plantar flexion and dorsiflexion stiffness of the AFOs tested in this study was 6.6 N·m\(^{\circ}\) and 6.3 N·m\(^{\circ}\), respectively. The stiffness was similar to a previous study that found 6.35 N·m\(^{\circ}\) as an average for 10 AFOs prescribed for individuals with stroke or multiple sclerosis.\(^{13}\) Plantar flexion of an AFO generally occurs during initial contact, while dorsiflexion occurs during midstance in gait. If the effect of shoes on AFO stiffness is underestimated or neglected, timing of foot flat after initial contact may be altered in individuals with foot drop. Excessive knee flexion may also occur during midstance in individuals with weak knee extensors even if the stiffness of the AFO alone is sufficient.

Hardness of the outsole of the shoe used in this study was measured to be approximately 70 shore A (ie, medium hard). The compressibility of the outsole is however significantly influenced by the geometry of the midsole, shape of the rocker, and other elements in shoe design. Therefore the effects of hardness and shoe sole design on the stiffness of the AFO-Shoe combination should be explored in future studies.

The energy efficiency of the AFO-Shoe combination did not change because it increased about the same percentage of stored and released energy in comparison to the AFO alone. In the plantar flexion resistance range (below 0 N·m), 27\% increases for the stored energy and 30\% increases for the released energy were comparison to the AFO-alone condition (Table 1).

Table 1 Comparison of Mechanical Parameters of the AFO Between the AFO-Alone and the AFO-Shoe Combination Conditions, Mean (SD)

<table>
<thead>
<tr>
<th></th>
<th>K-DF (N·m(^{\circ}))</th>
<th>K-PF (N·m(^{\circ}))</th>
<th>ES-DF (J)</th>
<th>ER-DF (J)</th>
<th>ES-PF (J)</th>
<th>ER-PF (J)</th>
<th>EE-DF (%)</th>
<th>EE-PF (%)</th>
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<tr>
<td>AFO</td>
<td>6.3 (1.2)†</td>
<td>6.6 (1.1)†</td>
<td>1.36 (0.29)</td>
<td>0.77 (0.12)*</td>
<td>1.24 (0.24)†</td>
<td>0.69 (0.09)†</td>
<td>57.9 (10.0)</td>
<td>57.5 (10.9)</td>
</tr>
<tr>
<td>AFO-Shoe</td>
<td>5.5 (1.2)</td>
<td>5.6 (1.3)</td>
<td>1.48 (0.31)</td>
<td>0.85 (0.14)</td>
<td>1.58 (0.46)</td>
<td>0.90 (0.16)</td>
<td>57.9 (6.4)</td>
<td>58.9 (9.3)</td>
</tr>
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Abbreviations: AFO = ankle-foot orthoses; K-DF = dorsiflexion stiffness; K-PF = plantar flexion stiffness; ES-DF = energy stored in the dorsiflexion resistance range; ER-DF = energy released in the dorsiflexion resistance range; ES-PF = energy stored in the plantar flexion resistance range; ER-PF = energy released in the plantar flexion resistance range; EE-DF = energy efficiency in the dorsiflexion range; EE-PF = energy efficiency in the plantar flexion range.

Note. An asterisk (*) indicates significant difference at \( p < .05 \) from the AFO-Shoe combination condition, while a cross (†) indicates significant difference at \( p < .01 \) from the AFO-Shoe combination condition.
revealed, while in the dorsiflexion resistance range (above 0 Nm), 9% increases for the stored energy and 10% increases for the released energy were demonstrated. The shoes therefore contributed to increases for both stored and released energy. And, this increase in stored and released energy appeared to be mainly attributed to increases in the range of motion (PF-ROM and DF-ROM) in the AFO-Shoe combination. Increases in released energy with shoes indicate increases in energy return; therefore, selection of shoes could possibly influence energy cost during gait.8

This study has some limitations. First, there may be a potential misalignment between the rotational shaft of the device and the center of the AFO joint. The testing device imposes a fixed center of rotation on the AFOs. In reality, this center is unlikely to be fixed due to the complex connections between the leg, shoe, and AFO, as well as the center of the anatomical ankle joint. Therefore, it might be more realistic to allow an unconstrained rotation eliminating the inevitable shear forces caused by the experimental constraint of the current testing device. Second, the surrogate leg was made of plaster and did not have an outer layer that mimics soft tissues of a human leg. Use of a real human leg may be ideal; however, it is difficult to control individual differences, such as soft tissue, which may affect AFO-human leg interface. Third, the AFO was secured to the surrogate leg using a fastener strap. Tightness and tension might not have been consistent across the tested AFOs. Fourth, the loading capacity was limited as the motor and gearbox of the testing device was designed to offer up to a continuous torque of 30 Nm in either direction. Finally, only 1 single type of shoe was tested in this study. Various shoes with different sole hardness should be tested to explore their effect on stiffness and energy storage/return. This may be valuable to maximize the benefits from the AFO-Shoe combination during gait.

In conclusion, this study demonstrated that stiffness of the AFO-Shoe combination was significantly decreased compared to the AFO-alone condition, but no significant differences were found in energy efficiency. Therefore, based on the results of this study, we suggest that shoes used with AFOs should be carefully selected not only based on their effect on alignment of the lower limb, but also their effects on overall mechanical properties of the AFO-Shoe combination.

Acknowledgments

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Conflict of Interest Disclosure

Kobayashi T and Orendurff MS were employees of Orthocare Innovations. LeCursi N works for Becker Orthopedic, manufacturer of an AFO joint (Triple Action™) used in this study.

References


