

Sensitivity Analysis of Loading Conditions on Mechanical Stiffness Measurements of a Passive Dynamic Ankle Foot Orthoses

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INTRODUCTION

Passive Dynamic Ankle Foot Orthoses (PD-AFO) are spring-like braces prescribed for patients with various gait impairments, including children with cerebral palsy, and patients recovering from stroke.

Using a novel automated fabrication method, McLucas et al. developed a PD-AFO consisting of footplate, strut, and cuff components (Figure 1). These AFOs can serve several functions: 1) help prevent foot drop during first rocker phase of gait, 2) store elastic energy during the second rocker phase as the subject's shank applies a force to the cuff surface, 3) release the stored energy to aid in forward propulsion during the third rocker phase.

The rate and magnitude of elastic energy storage supplied by the PD-AFO are influenced by the mechanical stiffness properties. Ultimately, the mechanical properties may predict the effectiveness of the orthotic during gait. Therefore, developing an accurate and reliable method for experimental stiffness measurements will be essential for adequate PD-AFO prescription.

Traditional assessment of AFO stiffness involves a linear approximation of the ratio of the externally applied moment to the angular deformation. Previous evaluations have been performed by various methods of external loading applications. These include a manual loading via custom-made apparatus [2], an automated loading about all three planes by a robotic device [3], and a loading by a muscle training device while a person's limb was fitted into an AFO [4]. Yet, there are no definitive methods for the most accurate and reliable methods.

The accuracy and reliability of stiffness estimates may depend on the ability to replicate loading conditions when a subject walks with the AFO. It is

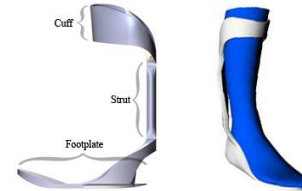


Figure 1: The PD-AFO components consist of footplate, strut, and cuff.

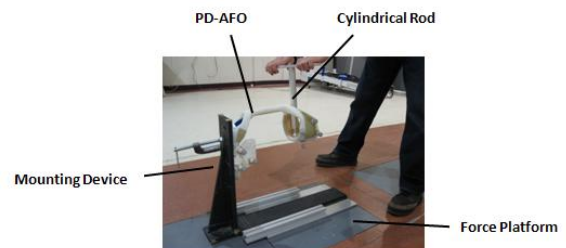


Figure 2: The footplate of AFO is mounted onto a vertical base plate. The entire mounting device is above a force platform. A cylindrical rod with a spherical tip is used to apply a force to the cuff surface, deforming the AFO into dorsiflexion.

unknown whether certain loading techniques can influence the AFO stiffness.

The purpose of this study was to examine the sensitivity of different loading angles on the reliability of stiffness measurements. Specifically, the study analyzed the effects of altering the angle of force applied to the cuff on estimates of PD-AFO stiffness.

METHODS

A PD-AFO described by McLucas et al. was used for the stiffness analysis. The footplate of the AFO was mounted to a vertical base plate that was placed over a force platform (Figure 2). A custom-made cylindrical rod with a spherical end tip was used to manually apply a slow continuous force to the inner surface of the cuff, deforming the AFO into dorsiflexion. Retroreflective markers were placed on the cuff and the footplate, and the movement of the markers was measured using a motion capturing

system. Under the assumption of rigid body segments, a three-dimensional angular deformation of footplate relative to cuff was measured using a Cardan X-Y-Z sequence (X-axis represents the flexion-extension axis). By subtracting the initial weight of the AFO and the mounting device, the ground reaction force signified the reaction force supplied by the AFO. The AFO moment about the X-axis was estimated using inverse dynamics under the assumption of static equilibrium. The stiffness was calculated by the slope of the linear fit of the sagittal plane components of the moment versus angular deformation (from 0 to 10 degrees) graph (Figure 3). A total of 17 trials were performed. For each trial, the load angle (angle of the force applied relative to the cuff segment) was varied to alter the amount of shear forces in the sagittal plane. The average load angle for each trial was calculated by measuring the angle of the ground reaction force relative to the cuff surface in the sagittal plane for the duration of the trial. The load angle is indicative of the magnitude of shear forces relative to the normal force. The load angle is 90 degrees when the applied force is purely normal to the cuff segment. An increase in shear forces directed away from the ankle joint center will result in an increase of the load angle, while an increase in shear forces directed towards the ankle joint center will result in a decrease of load angle.

RESULTS AND DISCUSSION

The experimental stiffness values of PD-AFOs are sensitive to the load angles. The AFO stiffness was as high as 3.20 Nm/deg, and was as low as 2.41 Nm/deg, depending on the load angles (Figure 4). The presence of shear forces directed towards the ankle joint center decreased the AFO stiffness, while shear forces directed away from the ankle joint center increased the stiffness.

Using the linear regression model shown on Figure 4, the stiffness when the load angle is 90 degrees can be estimated as 2.71 Nm/deg. For every one degree of deviation from 90 degrees, there is a 1.0% error in the AFO stiffness.

CONCLUSIONS

Our results indicate that altering the load angle on the cuff can modify the experimentally derived AFO stiffness. These results give valuable insights

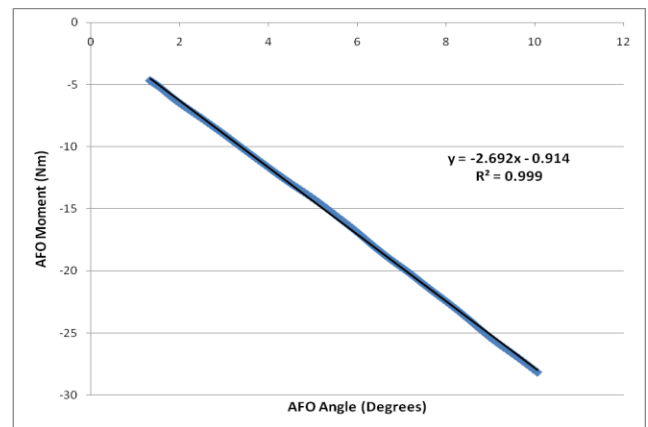


Figure 3: The stiffness of AFO is calculated by finding the linear best fit of the Moment vs Angle curve. Negative moment signifies a plantarflexion moment. Analysis was restricted to the sagittal plane.

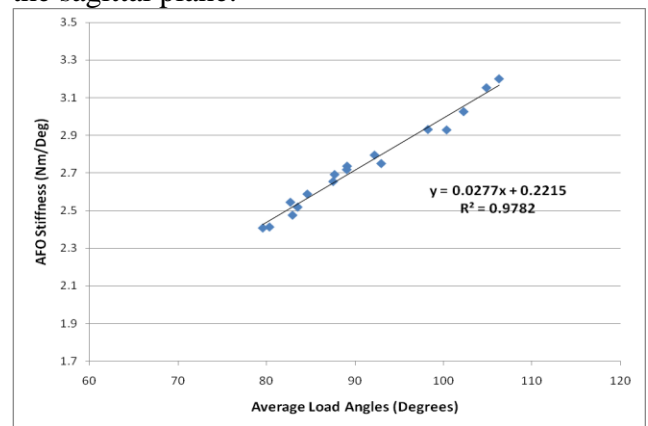


Figure 4: The effects of Load Angles on AFO Stiffness. As the Load Angle is increased (the force is directed more distally away from the Ankle Joint Center), the magnitude of stiffness increases.

into designing a device for accurate and reliable stiffness measurements of PD-AFOs. Our goal is to devise an experimental method that replicates congruent loads and congruent deformations induced while a person walks with the AFO, such that the experimental stiffness values equate the stiffness supplied by the AFO during gait.

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