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Brief report

# The effect of ankle–foot orthosis plantarflexion stiffness on ankle and knee joint kinematics and kinetics during first and second rockers of gait in individuals with stroke

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ABSTRACT

*Background:* Stiffness of an ankle–foot orthosis plays an important role in improving gait in patients with a history of stroke. To address this, the aim of this case series study was to determine the effect of increasing plantarflexion stiffness of an ankle–foot orthosis on the sagittal ankle and knee joint angle and moment during the first and second rockers of gait.

*Methods:* Gait data were collected in 5 subjects with stroke at a self-selected walking speed under two plantarflexion stiffness conditions (0.4 Nm/° and 1.3 Nm/°) using a stiffness-adjustable experimental ankle–foot orthosis on a Bertec split-belt fully instrumented treadmill in a 3-dimensional motion analysis laboratory.

*Findings:* By increasing the plantarflexion stiffness of the ankle–foot orthosis, peak plantarflexion angle of the ankle was reduced and peak dorsiflexion moment was generally increased in the first rocker as hypothesized. Two subjects demonstrated increases in both peak knee flexion angle and peak knee extension moment in the second rocker as hypothesized. The two subjects exhibited minimum contractility during active plantarflexion, while the other three subjects could actively plantarflex their ankle joint.

*Interpretation:* It was suggested that those with the decreased ability to actively plantarflex their ankle could not overcome excessive plantarflexion stiffness at initial contact of gait, and as a result exhibited compensation strategies at the knee joint. Providing excessively stiff ankle–foot orthoses might put added stress on the extensor muscles of the knee joint, potentially creating fatigue and future pathologies in some patients with stroke.



## 1. Introduction

An ankle–foot orthosis (AFO) is frequently provided as a form of orthotic intervention to minimize the challenges of walking in patients with stroke (de Wit et al., 2004; Gok et al., 2003; Tyson and Thornton, 2001). Furthermore, mechanical characteristics, such as the stiffness of an AFO, play an important role in assisting with gait (Bregman et al., 2011; Kobayashi et al., 2011b; Yamamoto et al., 1993). AFO plantarflexion stiffness resists movement of the ankle joint toward a plantarflexion direction, while dorsiflexion stiffness resists movement toward a dorsiflexion direction (Kobayashi et al., 2011a). Non-articulated AFOs, such as solid or posterior leaf spring AFOs, do not allow separate tuning of plantarflexion and dorsiflexion stiffness, while some articulated AFOs, such as AFOs with an oil-damper joint, allow tuning of plantarflexion stiffness without affecting dorsiflexion stiffness (Yamamoto et al., 2011).

For patients with foot-drop, appropriately tuned plantarflexion stiffness of an AFO could improve the first and second rockers during the stance phase and toe clearance during the swing phase of gait (Yamamoto et al., 2011). Previous research suggests that excessive plantarflexion stiffness could affect knee joint kinematics in patients with stroke (Kobayashi et al., 2013). However, this effect has not been systematically investigated with kinetic data. Providing excessively stiff AFO might put added stress on the extensor muscles of the knee joint, potentially creating fatigue and future pathologies. It is currently difficult for orthotists to prescribe an AFO that optimizes gait while minimizing stress on the knee joint. Therefore, the aim of this case series study was to determine the effect of increasing plantarflexion stiffness of an AFO on the sagittal ankle and knee joint angle and moment during the first and second rockers of gait. It was hypothesized that increases in plantarflexion stiffness of an AFO would induce 1) decreases in peak plantarflexion angle and increases in peak dorsiflexion moment at the ankle in the first rocker, and 2) increases in peak flexion angle and peak extension moment at the knee in the second rocker.

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## 2. Methods

### 2.1. Participant

Five subjects (2 females/3 males), with a history of stroke, participated in this study. Their mean age was 62 (9) years old and mean time since stroke incidence was 6 (2) years. Inclusion criteria of the study were 6-month post-stroke with hemiplegia as a result of stroke and ability to walk on a treadmill with the use of an AFO but without a walking aid. Exclusion criteria were confounding injury, musculoskeletal or cognitive problems that would limit the ability to walk on an instrumented treadmill. After informed consent was obtained for this Institutional Review Board approved study, the following clinical tests were performed on each subject: 1) Volitional contraction of ankle and knee joint musculature, 2) amount of manual passive plantarflexion and dorsiflexion range of motion (RoM) while the knee joint kept in extension, 3) the Timed-Up and Go Test (TUG) (Podsiadlo and Richardson, 1991), and 4) the Modified Ashworth Scale (MAS) (Bohannon and Smith, 1987).

### 2.2. Gait data collection and analysis

Following consent, a custom experimental AFO (Orthocare Innovations, Mountlake Terrace, WA, USA) was donned that allowed the adjustment of plantarflexion stiffness by varying the spring rate of 2 separate compression springs (Spring 1: 0.4 Nm/°; Spring 2: 1.3 Nm/°) (Fig. 1). Spring stiffness range was determined based on a preceding study (Yamamoto et al., 1993). The compression spring was situated in the posterior aspect of the AFO and was changed during different walking trials to alter the plantarflexion stiffness. No spring was placed in the anterior aspect, thus the AFO had no spring induced dorsiflexion stiffness. The shank to vertical angle of the AFO was adjusted in the range of 5 to 10° of dorsiflexion for each subject.

**Fig. 1.** Experimental setup using the custom experimental AFO, Bertec split-belt fully instrumented treadmill and Vicon 3-D motion analysis system.

Each subject was instrumented with reflective markers based on a modified Cleveland Clinic Marker Set defining 8 segments. Due to space restrictions and the tight fit of the AFO, markers were placed directly on the AFO to define the ankle joint center and for tracking the shank segment. Each subject walked at a self-selected walking speed (0.11 m/s to 0.22 m/s) on a Bertec split-belt fully instrumented treadmill (Bertec Corporation, Columbus, OH, USA) for two separate trials using two different spring conditions (Fig. 1). The subject was secured in a harness. The same speed was set on the treadmill for both stiffness conditions in each subject. The order of spring stiffness was randomized for the walking trials. During walking, data were acquired using a Vicon 10-camera motion analysis system (Vicon Motion Systems, Oxford, UK) and the instrumented treadmill at a rate of 200 Hz for 5 successful steps. Data were recorded and synchronized using Vicon Nexus (Vicon Motion Systems, Oxford, UK) and post-processed using Visual3D (CMotion, Germantown, MD, USA). Marker and force platform data were filtered using a low pass, zero-phase shift Butterworth filter at 6 Hz and 20 Hz, respectively (Winter, 2005).

From the post-processed data, 1) peak ankle plantarflexion angle and peak ankle dorsiflexion moment in the first rocker and 2) peak knee flexion angle and peak knee extension moment in the second rocker were extracted for the 5 successful steps of each trial. The mean of the 5 steps was calculated for each gait variable in each stiffness condition and expressed as descriptive statistics.

## 3. Results

### 3.1. Clinical assessment outcomes

Clinical assessment outcomes are summarized in Table 1. Subjects 2 and 4 exhibited minimum contractility during active plantarflexion, while subjects 1 and 5 had active dorsiflexion. The passive ankle range of motion was within 40° of plantarflexion and 10° of dorsiflexion across the subjects. All subjects could actively flex and extend their knee.

### 3.2. Effect of AFO plantarflexion stiffness on the ankle

Effect of AFO plantarflexion stiffness on the ankle is summarized in Fig. 2(A) and (B). Dorsiflexion angles and plantarflexion moments were defined as positive. By increasing plantarflexion stiffness of the AFO, the peak plantarflexion angle was reduced and the peak dorsiflexion moment was increased at the ankle across the subjects in general.

### 3.3. Effect of AFO plantarflexion stiffness on the knee

Effect of AFO plantarflexion stiffness on the knee is summarized in Fig. 2(C) and (D). Knee flexion angles and knee extension moments were defined as positive. By increasing plantarflexion stiffness of the AFO, subjects 2 and 4 demonstrated increases in peak knee flexion angle and peak knee extension moment as hypothesized. Subject 1

**Table 1**
Clinical assessment outcomes in each subject.

| Subject | TUG | MAS | Ankle PF | Ankle DF | Ankle PF RoM (°) | Ankle DF RoM (°) | Knee Ext | Knee Flex |
|---|---|---|---|---|---|---|---|---|
| 1 | 12.4 | 1+ | + | + | 35 | 5 | + | + |
| 2 | 16.6 | 3 | Min | Min | 15 | 5 | + | + |
| 3 | 17.6 | 2 | + | – | 35 | 10 | + | + |
| 4 | 10.4 | 1 | Min | – | 35 | 10 | + | + |
| 5 | 28.5 | 1+ | + | + | 40 | 5 | + | + |

Abbreviations: Ankle PF/DF: Ability to actively plantarflex/dorsiflex the ankle, Ankle PF/DF RoM: Passive range of motion in plantarflexion/dorsiflexion of the ankle (knee in extension), Knee Ext/Flex: Ability to actively extend/flex the knee, Min: minimum contractility, MAS: Modified Ashworth Scale, TUG: Timed-Up and Go Test.

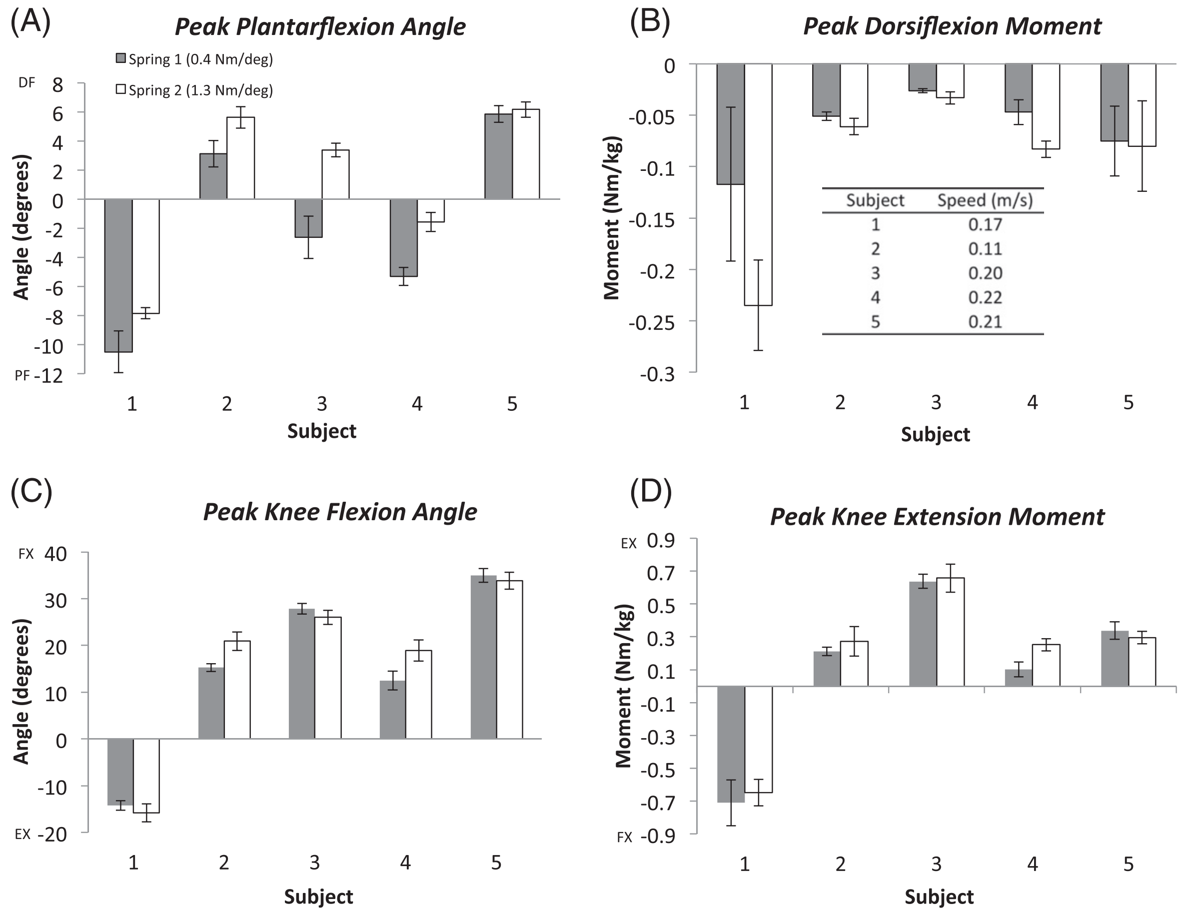


**Fig. 2.** Kinetic and kinematic outcomes [mean (standard deviations)] at knee and ankle joints in each subject. (A) Peak plantarflexion angle in the first rocker, (B) peak dorsiflexion moment in the first rocker, (C) peak knee flexion angle in the second rocker, (D) peak knee extension moment in the second rocker. Dorsiflexion angles and plantarflexion moments were defined as positive for the ankle joint, while knee flexion angles and knee extension moments were defined as positive for the knee joint. A self-selected walking speed set on the treadmill in each subject is presented as a table inside this figure. Abbreviations: DF, dorsiflexion; EX, extension; FX, flexion; PF, plantarflexion.

walked with a hyperextended knee pattern and demonstrated decreases in peak flexion moment.

## 4. Discussion

This study investigated the effects of plantarflexion stiffness of an AFO on ankle and knee joint kinematics and kinetics during the first and second rockers of stance in 5 subjects with stroke who showed varying levels of active and passive ankle range of motion. The subjects generally reduced the peak plantarflexion angles when using Spring 2 (1.3 Nm/°) compared to Spring 1 (0.4 Nm/°) (Fig. 2A). This result is consistent with the preceding study (Kobayashi et al., 2011a). The subjects also generally demonstrated increases in dorsiflexion moment with Spring 2. The spring of the AFO complements the function of dorsiflexors in patients with stroke. Dorsiflexion moment is thus the summation of moment from the dorsiflexors of the subject and moment from the spring of the AFO. With increases in plantarflexion stiffness of the AFO, the dorsiflexion moment is expected to increase (Fig. 2B).

As we hypothesized, two subjects (2 and 4) showed an increase in knee flexion angle and knee extension moment while walking in the AFO with increased plantarflexion stiffness. Potential clinical characteristics that may affect AFO prescription include: period after stroke, range of motion, muscle strength and spasticity of lower-limb joints, sensory disorders, higher brain function disorder and cognitive disorders. Examination of the clinical parameters revealed that subjects 2 and 4 exhibited minimum contractility to plantarflex the ankle, while the other three subjects could actively plantarflex (Table 1). With greater dorsiflexion moments contributed by Spring 2, subjects 2 and 4 appeared to have increased difficulty in plantarflexing their ankle at initial contact, forcing the tibia to rotate in the sagittal plane and causing more knee flexion. To counteract this movement, they also displayed increased knee extension moments (Fig. 2D). Subject 1 reduced a peak knee flexion moment with Spring 2, suggesting a potential benefit of increased plantarflexion stiffness of an AFO on knee hyperextension.

Those with decreased ability to actively plantarflex their ankle may have difficulty overcoming plantarflexion stiffness at initial contact, and as a result exhibit compensation strategies at the knee joint. This is clinically important because prescription of excessively stiff AFOs could put added stress on the extensor muscles of the knee joint, potentially creating fatigue and future pathologies at the knee in some patients with stroke. Knee position may also be affected by knee muscle strength, knee contracture, or shank to vertical angle of the AFO. No direct relationship was observed among TUG, MAS, RoM and the gait parameters. Limitations of this study include a small sample size, external factors such as the bulkiness of the experimental AFO and walking on a treadmill that limited a self-selected walking speed, and errors associated with inverse dynamics calculations (Cappozzo et al., 1996). A full lower extremity physical exam should be performed in future study.

## 5. Conclusions

Plantarflexion stiffness of an AFO should be customized for each individual to maximize the potential of the AFO to assist gait, while minimizing the risk of excessive stress on the knee joint in patients with a history of stroke. A future research should investigate the effect of AFO stiffness on gait and how clinical assessment outcomes prior to AFO prescription can be fully utilized to assist in individually designing an AFO in a larger scale study.

## Conflict of interest statement

Kobayashi T, Lincoln LS, and Orendurff MS are employees of Orthocare Innovations and designed the custom experimental AFO used in this study.

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