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Contribution of ankle-foot orthosis moment in regulating ankle and knee motions during gait in individuals post-stroke

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Abstract

Background—Ankle-foot orthosis moment resisting plantarflexion has systematic effects on ankle and knee joint motion in individuals post-stroke. However, it is not known how much ankle-foot orthosis moment is generated to regulate their motion. The aim of this study was to quantify the contribution of an articulated ankle-foot orthosis moment to regulate ankle and knee joint motion during gait in individuals post-stroke.

Methods—Gait data were collected from 10 individuals post-stroke using a Bertec split-belt instrumented treadmill and a Vicon 3-dimensional motion analysis system. Each participant wore an articulated ankle-foot orthosis whose moment resisting plantarflexion was adjustable at four levels. Ankle-foot orthosis moment while walking was calculated under the four levels based on angle-moment relationship of the ankle-foot orthosis around the ankle joint measured by bench testing. The ankle-foot orthosis moment and the joint angular position (ankle and knee) relationship in a gait cycle was plotted to quantify the ankle-foot orthosis moment needed to regulate the joint motion.

Findings—Ankle and knee joint motion were regulated according to the amount of ankle-foot orthosis moment during gait. The ankle-foot orthosis maintained the ankle angular position in dorsiflexion and knee angular position in flexion throughout a gait cycle when it generated

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Conflict of interest statement

Kobayashi T and Orendurff MS were employees of Orthocare Innovations and designed the articulated AFO used in this study.

moment from −0.029 (0.011) to −0.062 (0.019) Nm/kg (moment resisting plantarflexion was defined as negative).

Interpretations—Quantifying the contribution of ankle-foot orthosis moment needed to regulate lower limb joints within a specific range of motion could provide valuable criteria to design an ankle-foot orthosis for individuals post-stroke.

Keywords

AFO; gait; hemiplegia; orthotics; stiffness

1. Introduction

An ankle-foot orthosis (AFO) generates moments to regulate movement of the lower limb joints. AFOs that passively generate moments are generally used in clinical settings although AFOs that actively generate moments have been developed (Sawicki and Ferris, 2008). The AFO moment resisting plantarflexion complements the internal dorsiflexor moments, while AFO moment resisting dorsiflexion complements the internal plantarflexor moments of the anatomical ankle joint. In previous research, an articulated AFO that generated moments resisting plantarflexion was shown to have systematic effects on the kinematics and kinetics of ankle and knee joints in individuals post-stroke (Kobayashi et al., 2015). However, the contribution of the AFO moment to net ankle moment measured by a force platform was not quantified. The net ankle moment is comprised of anatomical ankle moment (human contribution) and AFO moment (AFO contribution). Therefore, it is still unclear how much contribution is needed from the AFO moment to regulate ankle and knee joint motion during gait in these individuals. Quantification of the AFO moment during gait can be performed indirectly by analyzing mechanical property of an AFO on the bench (Kerkum et al., 2015; Yamamoto et al., 1993) or directly by mounting a load cell on a joint (Kobayashi et al., 2016; Yamamoto et al., 2013). Clarifying the AFO moment needed to regulate lower limb joint movement to assist gait in individuals post-stroke could provide valuable AFO design criteria. The aim of this study was to quantify the contribution of the articulated AFO moment to regulate ankle and knee joint motion during gait in individuals post-stroke.

2. Methods

2.1. Participants

Ten individuals post-stroke participated [2 females/8 males, age: 56(11) years old, body mass: 99 (17) kg, body height: 1.76(0.11) m]. All subjects were at least 6-month post-stroke and had unilateral limb involvement (6 right/4 left). They could walk safely on an instrumented treadmill with the use of an AFO but without a walking aid. Detailed clinical characteristics of this group of participants can be found elsewhere (Kobayashi et al., 2015).

2.2. Gait analysis

After informed consent was obtained for this Institutional Review Board approved study (University of Utah, IRB_00062924), gait analysis was performed. This was accomplished by placing reflective markers on the head, trunk and limbs based on a modified Cleveland

Clinic Marker Set defining 8 segments [2 feet, 2 shanks, 2 thighs, 1 pelvis, and 1 HAT (head, arm, and trunk)]. The markers were placed directly on the AFO, and a rigid cluster (four markers) was secured to the upright of the AFO and used for dynamic tracking. Each subject was secured in a safety harness and asked to walk on a split-belt instrumented treadmill (Bertec corporation, Columbus, OH, USA) wearing the AFO with an articulated ankle joint (Figure 1A). The treadmill was set at comfortable self-selected walking speed (0.15 – 0.27 m/s) and participants walked with the AFO set at four different spring levels: S1, S2, S3 and S4 (Figure 1). Same speed was set on the treadmill for all trials in each participant.

The articulated ankle joint of the AFO was designed to provide moment resisting plantarflexion using a steel spring at different spring rates. The spring did not generate moment resisting dorsiflexion. No steel spring resistance was set on the AFO under the S1 moment level and this represented a baseline condition. In addition, the initial angle and heel height of the AFO were kept constant for all trials in each participant.

Participants were given a short acclimatization period to practice walking on the treadmill before each data collection. Gait data were collected using a Vicon Nexus 10-camera motion analysis system (Vicon Motion Systems, Oxford, UK) and the Bertec instrumented treadmill at a rate of 200Hz for 5 successful steps of the affected limb wearing the AFO. Seated rests were provided if necessary during data collection.

2.3. Data analysis

Visual3D (CMotion, Germantown, USA) was used for post-processing of the gait data. A low pass, zero-phase shift Butterworth filter at 6 Hz and 20 Hz was used to filter marker and force platform data, respectively. The ankle and knee joint angles and moments of 5 steps of the affected limb were averaged and normalized to a gait cycle for each spring level in each participant.

The mechanical property of the AFO under each spring level was quantified on the bench using a custom device (Gao et al., 2011) (Figure 1B). The moment and angular position data were collected at 100Hz with an angular velocity of 3°/s. A fourth-order zero-lag low pass Butterworth filter with a cutoff frequency of 5Hz was used to filter the data. The mean of the loading and unloading curve of the hysteresis loop (i.e. the angle and moment relationship of the AFO around the ankle joint) (Figure 1 B&C) was used to calculate the AFO moment during gait based on the ankle angular positions in a gait cycle (Kobayashi et al., 2015). The AFO moment was normalized to body mass (Nm/kg) in each participant. The AFO moment resisting plantarflexion and plantarflexion angles were defined as negative in this study. The AFO moment in a gait cycle was subsequently averaged for the ten participants under the four spring levels (Figure 1D). The mean net ankle moment, mean AFO moment and mean anatomical ankle moment in a gait cycle were plotted for each spring level (Figure 2). Finally, in order to clarify the contribution of the AFO moment generated to regulate ankle and knee joint motion, the mean AFO moment was plotted against the mean ankle angular position (Figure 3A) and mean knee angular position (Figure 3B) in a gait cycle as a scattered graph under the four spring levels in the ten participants.

2.4 Statistical analysis

One-way repeated measures ANOVA was conducted to compare the peak AFO moment, ankle and knee angular positions at initial contact among the spring conditions (S1–S4). Adjustments were made if a violation of sphericity was found (Huynh-Feldt adjustment if the sphericity estimate >0.75, Greenhouse-Geisser otherwise). Post-hoc multiple comparisons with Bonferroni adjustment were conducted if ANOVAs showed significant differences in the spring conditions. Partial eta squared (η^2_p) was reported as measures of effect size. Statistical analyses were conducted in SPSS v.19.0 (IBM Corp. Armonk, USA) and statistical significance level was set at $\alpha = 0.05$.

3. Results

3.1. AFO moment in a gait cycle

The mean AFO moment generated during a gait cycle under the four spring levels in the ten participants is presented in Figure 1D. The AFO moment showed a systematic change according to the spring levels (S1 to S4) set on the AFO. The range of mean AFO moment was −0.006 (0.001) to −0.011 (0.002) Nm/kg for S1, −0.020 (0.007) to −0.039 (0.007) Nm/kg for S2, −0.023 (0.010) to −0.053 (0.017) Nm/kg for S3 and −0.029 (0.011) to −0.062 (0.019) Nm/kg for S4 (Figure 1D). The significant differences in the spring conditions were found in the peak AFO moment ($F[1.204, 10.834])=66.354$, $P<0.001$, $\eta^2_p=0.881$). Post-hoc multiple comparisons showed significant increases of the peak AFO moment in S2 ($P<0.001$), S3 ($P<0.001$) and S4 ($P<0.001$) compared to S1 (Table 1).

3.2. Contribution of AFO moment to net ankle moment

The mean AFO moment, mean anatomical ankle moment and mean net ankle moment of the ten participants were plotted across a gait cycle for the four spring levels (Figure 2).

3.3. AFO moment to regulate ankle angular position

The relationship between the mean AFO moment and the mean ankle angular position in a gait cycle is shown in Figure 3A. The significant differences in the spring conditions were found in the ankle angular position at initial contact ($F[3, 27])=40.125$, $P<0.001$, $\eta^2_p=0.817$). Post-hoc multiple comparisons showed significant increases in the contribution of AFO moment in S3 ($P<0.001$) and S4 ($P<0.001$) compared to S1, which shifted the ankle angular position at initial contact of a gait cycle toward dorsiflexion (Table 1).

3.4 AFO moment to regulate knee angular position

The relationship between the mean AFO moment and the mean knee angular position in a gait cycle is shown in Figure 3B. The significant differences in the spring conditions was found in the knee angular position at initial contact ($F[3, 27])=13.678$, $P<0.001$, $\eta^2_p=0.603$). Post-hoc multiple comparisons showed significant increases in the contribution of AFO moment in S3 ($P<0.05$) and S4 ($P<0.005$) compared to S1, which shifted the knee angular position at initial contact of a gait cycle toward flexion (Table 1).

4. Discussion

This study quantified the AFO moment and clarified its contribution to regulate ankle and knee joint motion during gait in individuals post-stroke. Furthermore, results showed that ankle and knee joint motion were regulated according to the amount of AFO moment during gait. The mean ankle angular position was shifted toward dorsiflexion and the mean knee angular position was shifted toward flexion at initial contact due to increases in AFO moment resisting plantarflexion (Figure 3). These results confirm the findings of previous studies (Fatone et al., 2009; Kobayashi et al., 2013). The AFO maintained the mean ankle angular position in dorsiflexion and mean knee angular position in flexion throughout a gait cycle under S4, in which the AFO generated moment from −0.029 (0.011) to −0.062 (0.019) Nm/kg (Figure 3). Quantifying the contribution of AFO moment needed to regulate lower limb joints within a specific range of motion would provide valuable criteria to design an AFO for an individual post-stroke.

Increase of AFO moment resisting plantarflexion from S1 to S4 showed more defined net dorsiflexor moment, which suggests improvement in heel rocker at initial contact (Figure 2). The AFO moment showed its peak at early stance, and it was smaller during swing phase. This outcome confirms that the AFO moment resisting plantarflexion should be tuned at initial contact in individuals post-stroke (Yamamoto et al., 1993). However, the AFO moment resisting plantarflexion also impedes plantarflexion at the end of stance phase (Figure 3A). This is expected to limit push-off that is important to propel the body forward. This tradeoff relationship (*i.e.* heel strike versus push-off) needs to be investigated in order to explore how much AFO moment is necessary to optimize gait of individuals post-stroke. This work investigated only the AFO moment resisting plantarflexion. Further work is also necessary to explore the effect of AFO moment resisting dorsiflexion in regulating lower limb joint movement. Finally, movement of the ankle-foot complex inside the AFO was not quantified. The angle of the AFO joint and anatomical ankle joint may not perfectly match.

5. Conclusions

This study quantified the amount of moment generated from an articulated AFO to regulate ankle and knee joint motion. In the future, orthotists may design an AFO based on quantified AFO moment that is necessary for individuals post-stroke.

Acknowledgments

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Highlights

- An ankle-foot orthosis affects ankle and knee motion during gait in individuals post-stroke.
- Bench testing and gait analysis were performed to measure ankle-foot orthosis's moment.
- The amount of the orthotic moment necessary to regulate the ankle and knee motion was quantified.
- These data are valuable in designing an ankle-foot orthosis for individuals post-stroke.

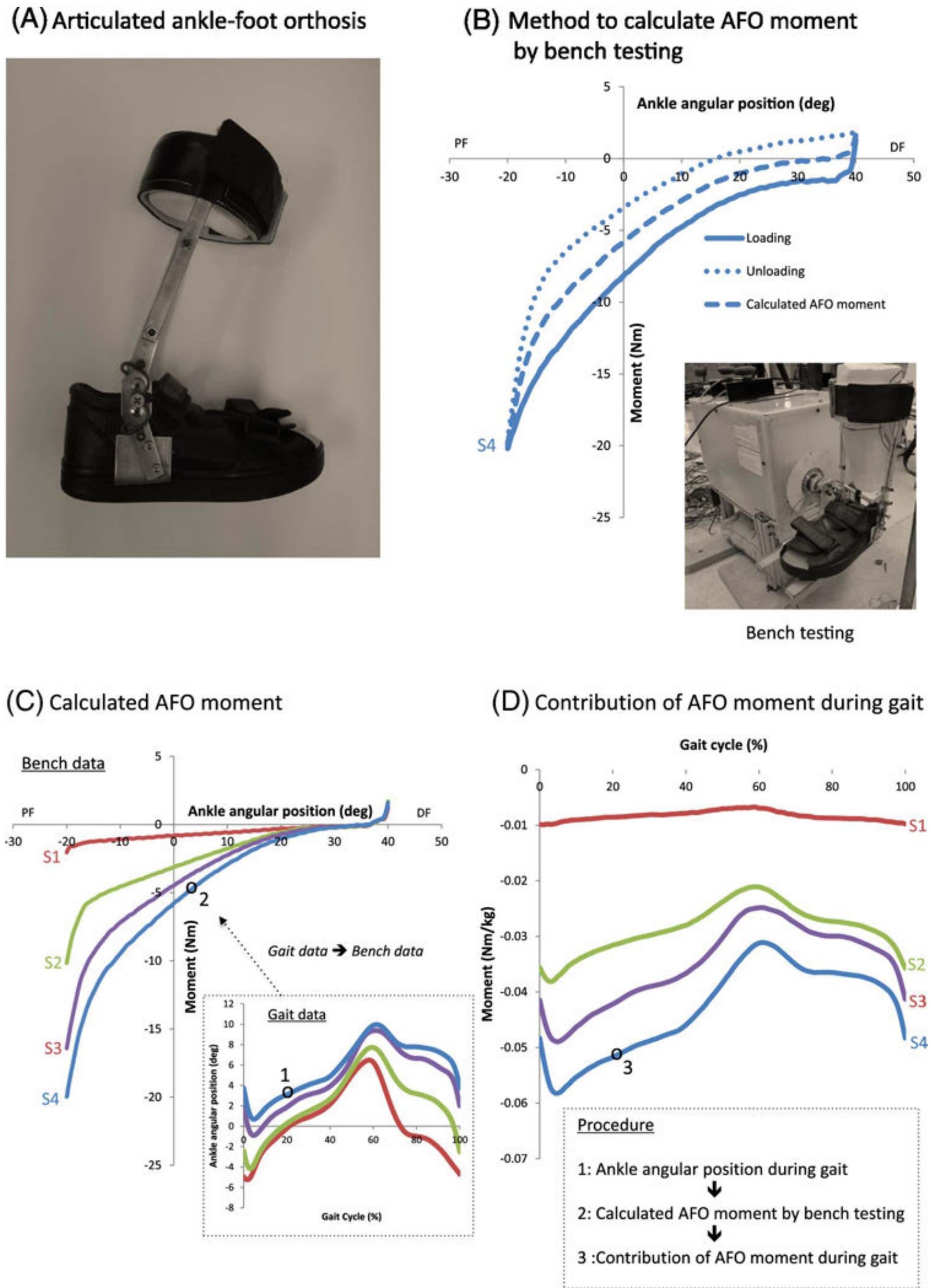

Figure 1.

(A) An articulated ankle-foot orthosis used in the study. (B) Method to calculate AFO moment from a hysteresis loop obtained through bench testing of the articulated AFO. This hysteresis loop was measured under S4 condition. Dorsiflexion (DF) is defined as positive, while plantarflexion (PF) is defined as negative. (C) Relationship between the calculated AFO moment and ankle angular position (bench data) and mean ankle angular positions in a gait cycle (gait data) under S1, S2, S3 and S4 conditions. A circle (o) indicates ankle angular position and calculated AFO moment at 20% of a gait cycle under S4 condition. (D) Mean

AFO moment throughout a gait cycle under S1, S2, S3 and S4 conditions in the ten participants. A circle (o) indicates AFO moment at 20% of a gait cycle under S4 condition. AFO moment resisting plantarflexion is defined as negative and plantarflexion is defined as negative at ankle.

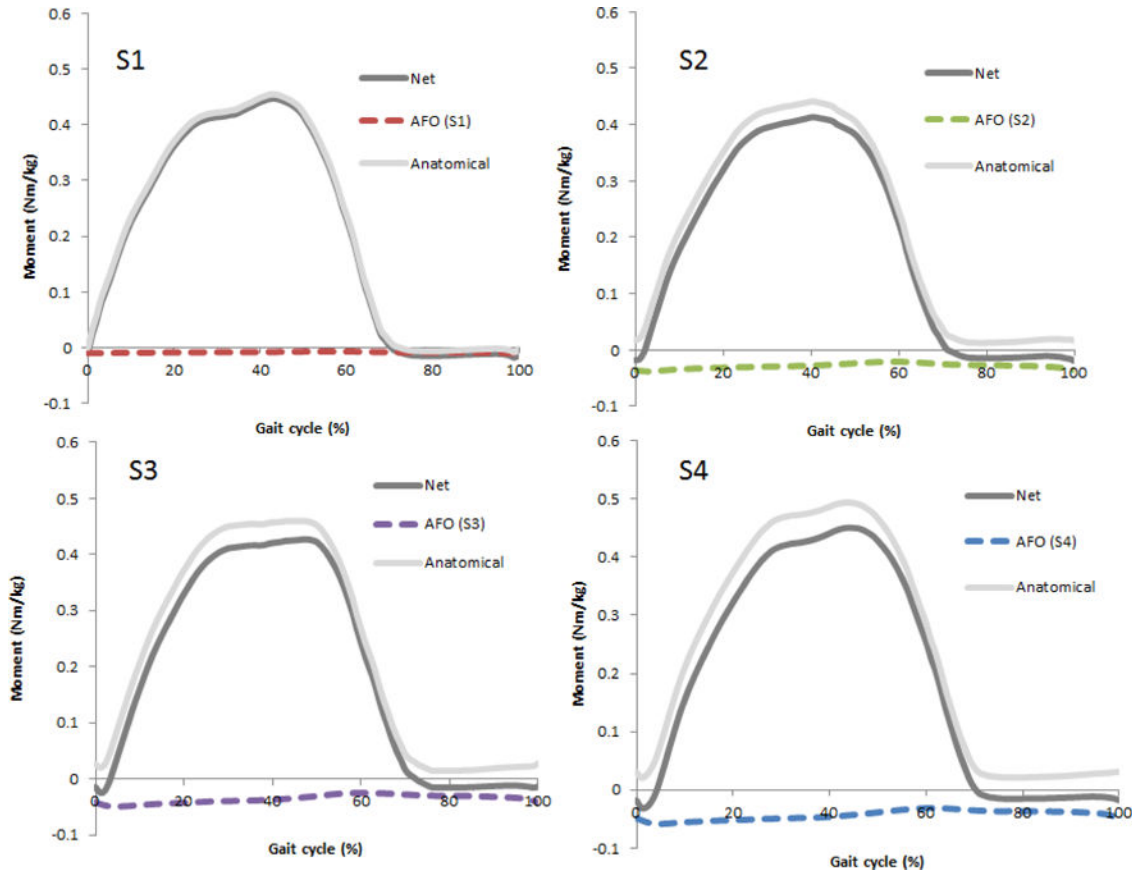

Figure 2.

Mean net ankle moment (Net), mean AFO moment (AFO) and mean anatomical ankle moment (Anatomical) throughout a gait cycle under S1, S2, S3 and S4 conditions in the ten participants. AFO moment resisting plantarflexion is defined as negative and internal plantarflexor moment is defined as positive.

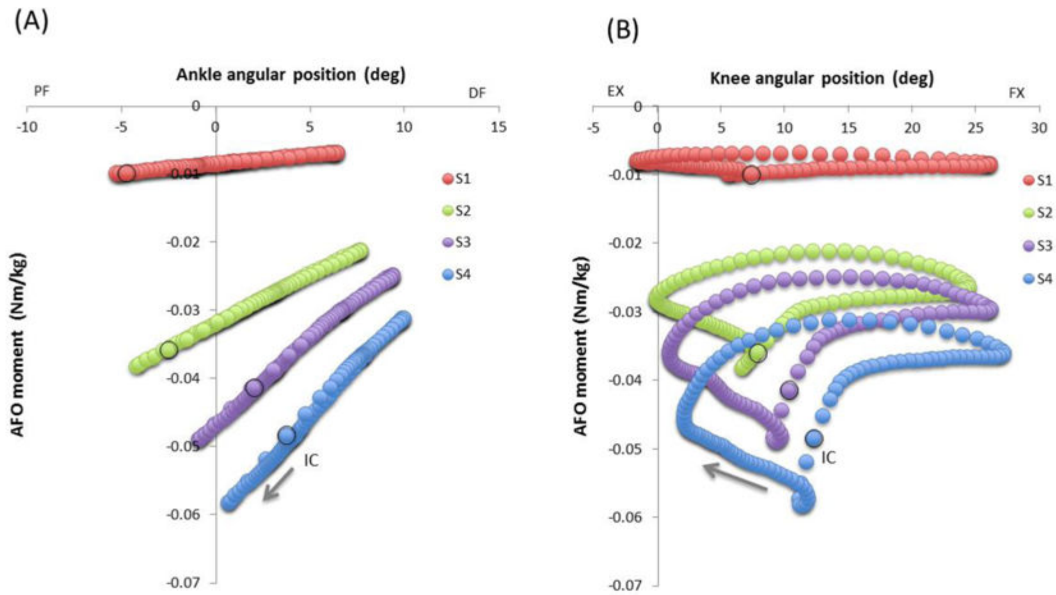

Figure 3.

(A) Relationship between mean AFO moment and mean ankle angular position in a gait cycle under S1, S2, S3 and S4 conditions in the ten participants. (B) Relationship between mean AFO moment and mean knee angular position in a gait cycle under S1, S2, S3 and S4 conditions in the ten participants. AFO moment resisting plantarflexion was defined as negative, plantarflexion was defined as negative at ankle and flexion was defined as positive at knee. Initial contact (IC) is indicated with a circle (○). The arrow indicates the direction of the loop from 0% to 100% of a gait cycle.

Table 1

Peak AFO moment during gait and ankle and knee angular positions at initial contact for each spring level.

	Peak AFO moment (Nm/kg)	Ankle angle at IC (deg)	Knee angle at IC (deg)
S1	−0.011 (0.002)	−4.97 (4.64)	7.20 (5.52)
S2	−0.039 (0.007)*	−2.43 (3.59)	7.79 (5.88)
S3	−0.053 (0.017)*,†	1.92 (4.65)*,†	10.43 (5.98)*
S4	−0.062 (0.019)*,†,#	3.74 (3.69)*,†	12.27 (5.10)*,†

Abbreviations: AFO, ankle-foot orthosis; IC, initial contact

An asterisk (*) indicates significant differences from S1 condition, a cross (†) indicates significant differences from S2 condition, and a hash key (#) indicates significant differences from S3 condition. The statistical significance level was set at $\alpha = 0.05$. AFO moment resisting plantarflexion was defined as negative, plantarflexion was defined as negative at ankle and flexion was defined as positive at knee.