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Reduction of genu recurvatum through adjustment of plantarflexion resistance of an articulated ankle-foot orthosis in individuals post stroke

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Abstract

Background—Genu recurvatum (knee hyperextension) is a common issue for individuals post stroke. Ankle-foot orthoses are used to improve genu recurvatum, but evidence is limited concerning their effectiveness. Therefore, the aim of this study was to investigate the effect of changing the plantarflexion resistance of an articulated ankle-foot orthosis on genu recurvatum in patients post stroke.

Methods—Gait analysis was performed on 6 individuals post stroke with genu recurvatum using an articulated ankle-foot orthosis whose plantarflexion resistance was adjustable at four levels. Gait data were collected using a Bertec split-belt instrumented treadmill in a 3-dimensional motion analysis laboratory. Gait parameters were extracted and plotted for each subject under the four plantarflexion resistance conditions of the ankle-foot orthosis. Gait parameters included: a) peak ankle plantarflexion angle, b) peak ankle dorsiflexion moment, c) peak knee extension angle and d) peak knee flexion moment. A non-parametric Friedman test was performed followed by a *post-hoc* Wilcoxon Signed-Rank test for statistical analyses.

Findings—All the gait parameters demonstrated statistically significant differences among the four resistance conditions of the AFO. Increasing the amount of plantarflexion resistance of the

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Conflict of interest statement

Kobayashi T, Orendurff MS and Daly WK are/were employees of Orthocare Innovations and designed the articulated AFO used in this study.

ankle-foot orthosis generally reduced genu recurvatum in all subjects. However, individual analyses showed that the responses to the changes in the plantarflexion resistance of the AFO were not necessarily linear, and appear unique to each subject.

Interpretations—The plantarflexion resistance of an articulated AFO should be adjusted to improve genu recurvatum in patients post stroke. Future studies should investigate what clinical factors would influence the individual differences.

Keywords

AFO; gait; hemiplegia; hyperextension; orthotics; stiffness

1. Introduction

Individuals recovering from a stroke often develop abnormal joint kinematics and kinetics. On the involved side, the knee typically demonstrates either a flexed pattern or a hyperextended pattern (genu recurvatum) (Mulroy et al., 2003). Genu recurvatum is a common problem among patients post stroke, and can cause functional mobility limitations and additional joint pathology due to progressive knee hyperextension (Cooper et al., 2012).

A potential cause of genu recurvatum includes but not limited to weakness / spasticity of the knee extensors, weakness of the knee flexors and/or contracture / spasticity of ankle plantarflexors (Bleyenheuft et al., 2010). To address these potential causes of genu recurvatum, orthoses such as knee-ankle-foot orthoses (KAFOs) (Boudarham et al., 2013), knee orthoses (Portnoy et al., 2015) and ankle-foot orthoses (AFOs) (Jagadamma et al., 2010) have been utilized. AFOs are primarily used to prevent foot drop of the ankle, but an appropriately adjusted non-articulated AFO-footwear combination (Jagadamma et al., 2010) and an articulated AFO with plantarflexion stop (Fatone et al., 2009) were suggested to reduce genu recurvatum in patients post stroke.

Previous studies suggest that the amount of plantarflexion resistance of articulated AFOs affect knee joint kinetics and kinematics in a heterogeneous group of individuals post stroke: a mixture of individuals with or without genu recurvatum (Kobayashi et al., 2015). However, examining the groups with genu recurvatum separately and individually may be important to develop a better understanding. Therefore, the aim of this study was to focus on the patients post stroke with genu recurvatum and to investigate their individual responses to changes in plantarflexion resistance of an articulated AFO on knee joint kinematics and kinetics. It was hypothesized that an increase in plantarflexion resistance of the AFO would reduce genu recurvatum.

2. Methods

2.1. Participants

Six male individuals post stroke with genu recurvatum participated in this study (Table 1). All subjects had unilateral limb involvement (3 right/3 left). Their mean (SD: standard deviation) body height was 1.74 (0.07) m and mean body mass was 100 (16) kg. The mean age was 52 (11) years old and mean time since stroke incidence was 7 (4) years. The inclusion criteria of this study were listed as follows: 1) hyperextension of the knee during mid-stance while walking 2) ability to walk safely on an instrumented treadmill using an AFO without a walking aid, and 3) at least 6-month post-stroke with hemiplegia. A knee hyperextension was defined as a knee extension that goes beyond 0° in stance phase on the affected limb (Lamontagne et al., 2001).

2.2. Clinical assessment

After informed consent was obtained for this Institutional Review Board approved study, the following clinical tests were performed on each subject to assess their mobility, spasticity, and muscle weakness: 1) Timed-Up and Go test (TUG), 2) Modified Ashworth Scale (MAS) of the affected ankle, and 3) Manual Muscle Testing (MMT) of ankle and knee joints.

2.3. Gait analysis

An articulated AFO with plantarflexion resistance-adjustable joints was used (Kobayashi et al., 2015) (Figure 1A). The plantarflexion resistance of the AFO was altered by exchanging a steel spring, resulting in 4 different spring rates (S1, S2, S3 and S4). The plantarflexion resistance of the AFO for springs S1–S4 ranged from 1.98 to 8.29 Nm at 0°, 2.12 to 12.61 Nm at 10°, and from 2.41 to 20.35 Nm at 20° of plantarflexion measured by a custom device (Gao et al., 2011) (Figure 1B).

After the AFO was fit to each subject, reflective markers were placed on their limbs, head and trunk 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 dynamic tracking was accomplished using a rigid cluster on the upright above ankle joint (Kobayashi et al., 2015). The initial angle (i.e. an angular position at which a plantarflexion resistance is initiated) and heel height of the AFO were kept constant for all gait trials across the subjects (Figures 1A).

Each subject walked at a self-selected walking speed wearing a safety harness on a Bertec split-belt instrumented treadmill (Bertec corporation, Columbus, OH, USA) (Table 2). Gait data were collected under 4 spring conditions with randomized order (S1, S2, S3 and S4). For each subject, the identical speed was set on the treadmill for all trials with the different AFO spring conditions. Gait data were acquired using a Vicon 10-camera motion analysis system (Vicon Motion Systems, Oxford, UK) and the instrumented treadmill at a rate of 200Hz for 5 successful steps of the leg with the AFO. Before each data collection, the subject was given an acclimatization period to walk on the treadmill, and seated rest was provided when necessary.

2.4. Data processing

Post-processing of the data was performed 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. The ankle and knee joint moments were normalized to body mass (Nm/kg). The ankle and knee joint angles and moments of 5 steps of the leg with the AFO were averaged and normalized to a gait cycle for each spring condition in each subject. The following gait parameters were extracted from the leg with the AFO in each subject (Figure 2): (a) peak ankle plantarflexion angle, (b) (internal) peak ankle dorsiflexion moment, (c) peak knee extension angle and (d) (internal) peak knee flexion moment in the second rocker of stance. The joint moments are described as "internal" moments throughout this study. These gait parameters were selected from early to mid-stance because they are closely related to hyperextension of the knee.

2.4. Statistical analysis

Due to the small sample size (n=6), a non-parametric Friedman test was performed to detect general difference among the different spring rates. A *post-hoc* Wilcoxon Signed-Rank test was subsequently performed for multiple comparisons for each parameter. To minimize the alpha error, we only performed the paired statistical comparisons between S1 and the three other spring conditions (3 comparisons). A statistical significance was set to an alpha=0.05.

3. Results

3.1. Clinical assessment outcomes

The outcome of each clinical assessment for this cohort of 6 subjects was as follows (Table 2): 1) The TUG ranged from 10.62 to 20.18 seconds and its mean (SD) was 15.26 (3.22) seconds; 2) The MAS ranged from 2 to 3; 3) The MMT of the ankle plantarflexors ranged from 1 to 4, the MMT of the ankle dorsiflexors ranged from 0 to 4, the MMT of the knee extensors ranged from 3+ to 5, and the MMT of the knee flexors ranged from 2+ to 5.

3.2. Ankle joint angles and moments

The mean ankle joint angles and moments under S1 and S4 conditions as well as normal gait data (Winter, 1991) is shown in Figure 2A&B. The range and mean (SD) of the peak plantarflexion angle and the peak dorsiflexion moment of the 6 subjects under each spring condition is presented in Table 3. The Friedman test showed statistical differences and the post-hoc tests results are presented in Table 3. Individual analyses showed that the peak plantarflexion angle was reduced and the peak dorsiflexion was increased, in general, by increasing the plantarflexion resistance of the AFO (Figure 3A&B).

3.3. Knee joint angles and moments

The mean knee joint angles and moments under S1 and S4 conditions as well as normal gait data (Winter, 1991) is shown in Figure 2A&B. The range and mean (SD) of the peak knee extension angle and the peak knee flexion moment of the 6 subjects under each spring condition is presented in Table 3. The Friedman test showed statistical differences and the post-hoc tests results are presented in Table 3. Individual analyses showed that both the peak knee extension angle and the peak knee flexion moment were generally reduced by increasing the plantarflexion resistance of the AFO (Figure 3C&D).

4. Discussion

This study investigated the individual responses to changes in plantarflexion resistance of an articulated AFO on knee joint kinematics and kinetics in patients post stroke with genu recurvatum. Genu recurvatum was generally reduced in all subjects by increasing the amount of plantarflexion resistance of the articulated AFO. The ankle and knee joint angle and moment parameters showed statistically significant differences among the spring conditions of the AFO (Table 3). However, individual analyses showed that the responses to the changes in the plantarflexion resistance of the AFO were not necessarily linear and unique to each subject (Figure 3). These results suggested that genu recurvatum could be improved by individually adjusting the amount of plantarflexion resistance of an articulated AFO in patients post stroke. The direct relationship between the clinical assessment outcomes (Table 2) and the individual responses (Figure 3) were not clear in this study. Additional studies with more participants is needed to explore this relationship.

Previous studies that compared orthotic to non-orthotic conditions showed that use of an articulated AFO with plantarflexion stop would reduce mean peak knee flexion moment from −0.4 Nm/kg to −0.3 Nm/kg in a group of 7 subjects (Fatone et al., 2009) and use of a knee-ankle-foot orthosis (KAFO) would reduce it from −0.54 Nm/kg to −0.27 Nm/kg in a group of 11 subjects (Boudarham et al., 2013). These studies suggested that the AFO and KAFO could reduce genu recurvatum. In this study, the mean peak knee flexion moment was reduced from −0.628 Nm/kg to −0.398 Nm/kg ($P<0.05$) by increasing the amount of plantarflexion resistance of the articulated AFO (Figure 3D). Reduction of peak knee flexion moment was generally accompanied with decrease in peak knee extension angle in all subjects (Figure 2C&D).

5. Conclusions

This study suggested that an articulated AFO with appropriately adjusted plantarflexion resistance could serve effectively to improve genu recurvatum in individuals post stroke. However, orthotists need to be aware that individual responses to changes in the plantarflexion resistance of the AFO on knee joint kinematics and kinetics may not be linear and are unique to each patient.

Acknowledgments

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Highlights

- Genu recurvatum (knee hyperextension) is common in patients post stroke.
- Plantarflexion resistance of ankle-foot orthosis affects genu recurvatum.
- Individual responses to changes in plantarflexion resistance are unique.
- Plantarflexion resistance should be adjusted to improve genu recurvatum.

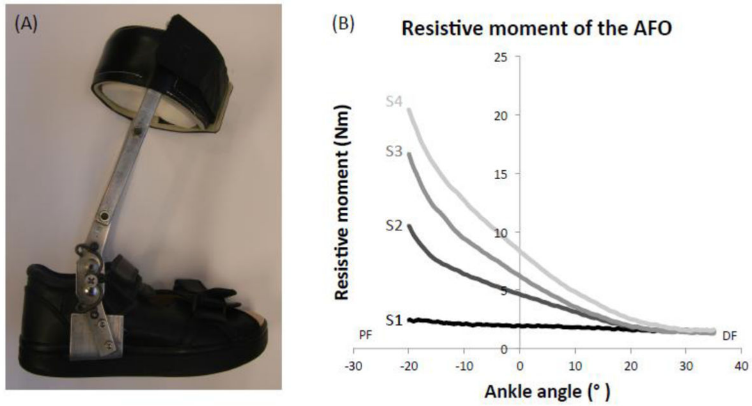


Figure 1.
(A) The articulated ankle-foot orthosis (AFO) used in this study, (B) Plantarflexion resistance characteristics of the AFO under 4 spring conditions (S1, S2, S3 and S4) (Kobayashi et al., 2015).

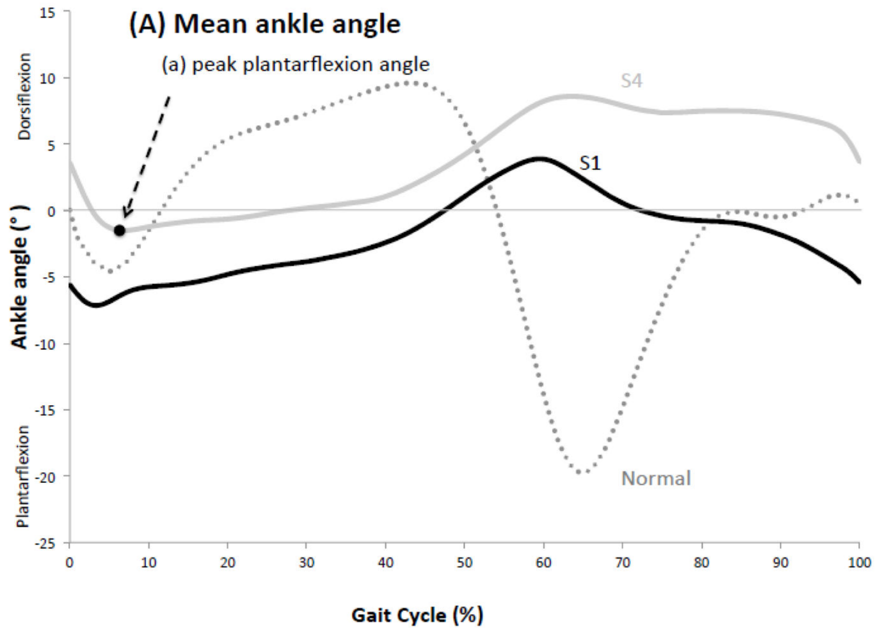
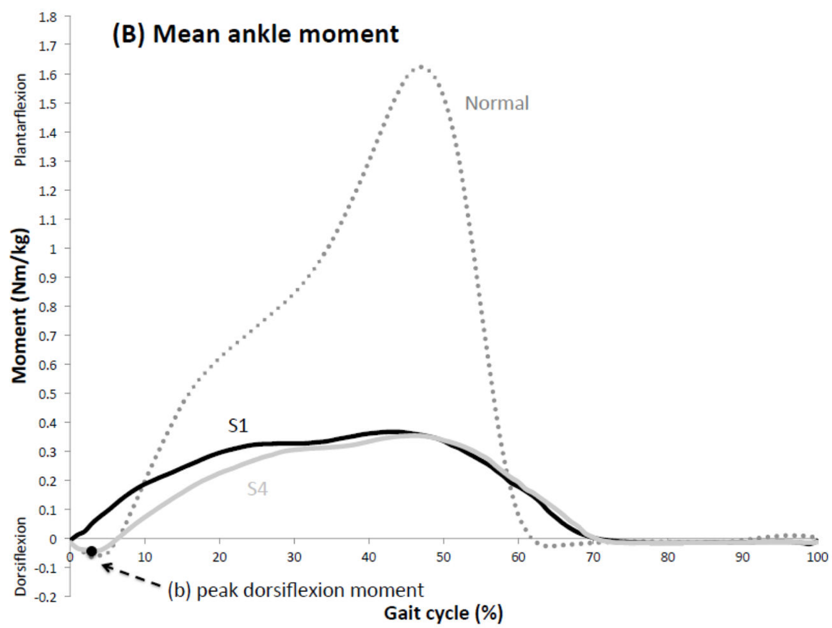


Figure 2A



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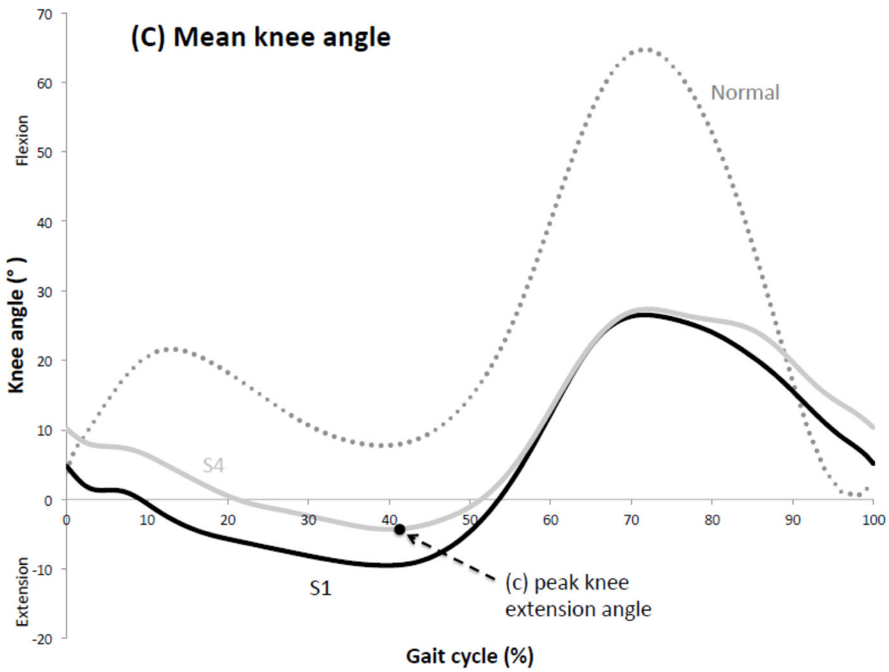

Figure 2C

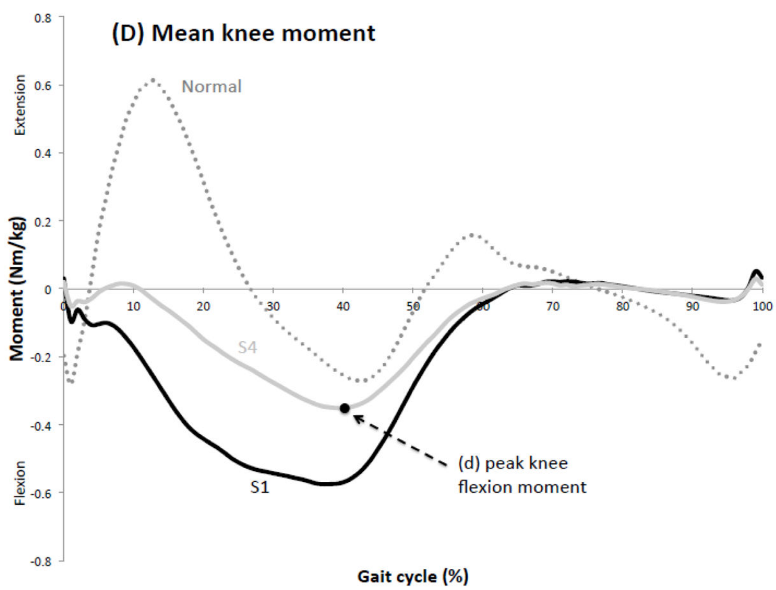

Figure 2D

Figure 2.

The effect of plantarflexion resistance of the articulated ankle-foot orthosis under spring condition S1 and S4 on the (A) mean ankle joint angles, (B) mean ankle joint moments, (C) mean knee angles and (D) mean knee moment. Normal gait data were adopted from Winter. 1991. The results from spring conditions S2 and S3 fell within the range of S1and S4;

therefore, only the results from S1 and S4 are presented in the graphs for clarity. Actual data of ankle and knee angle and moment parameters under each spring condition can be found in Table 3. 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.

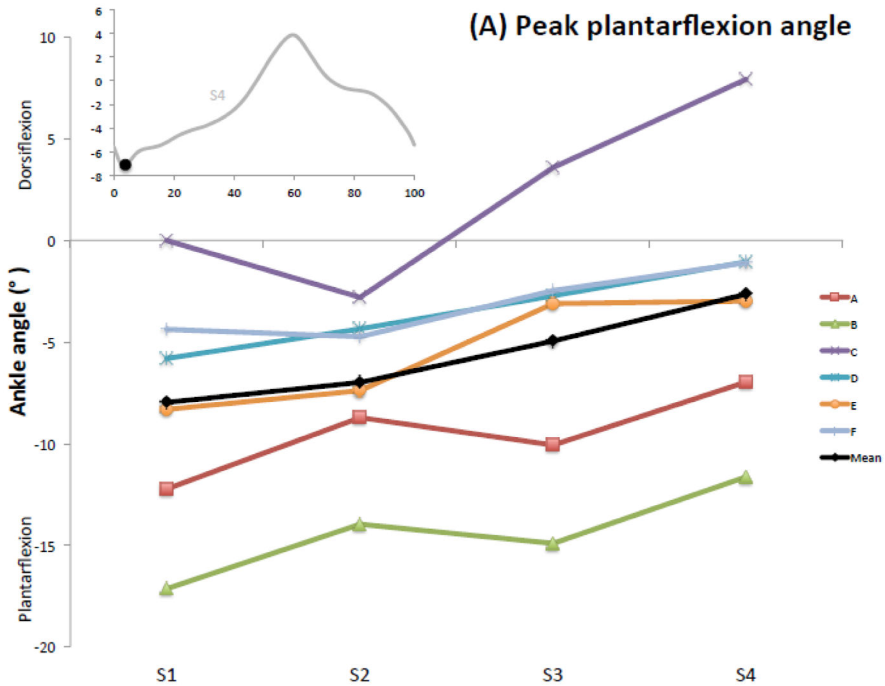

Figure 3A

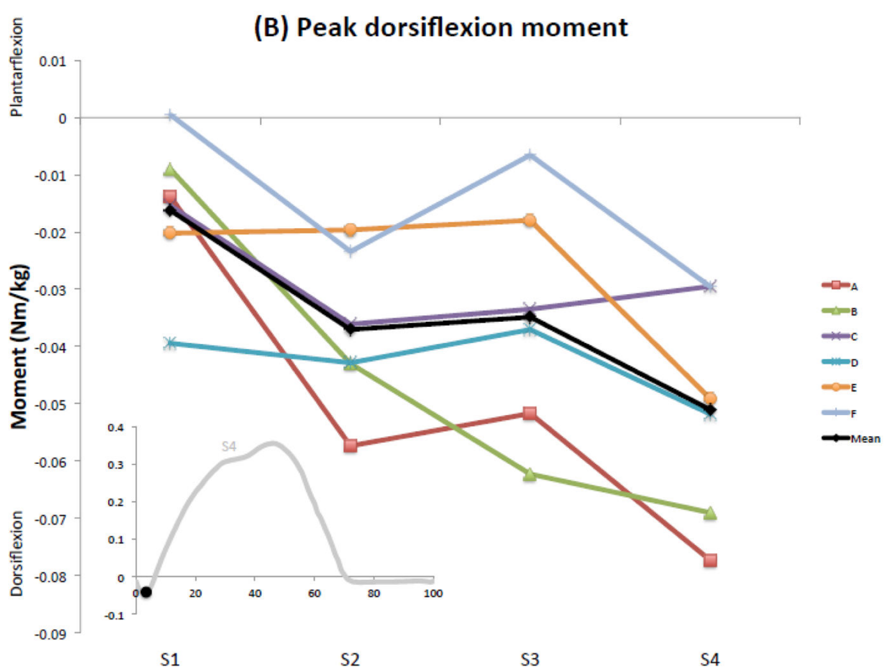

Figure 3B

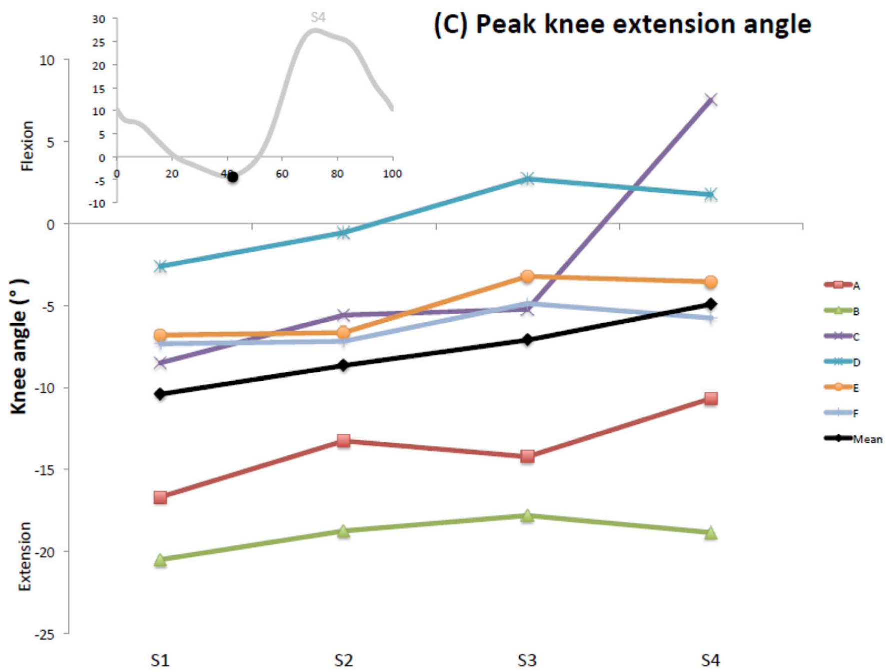

Figure 3C

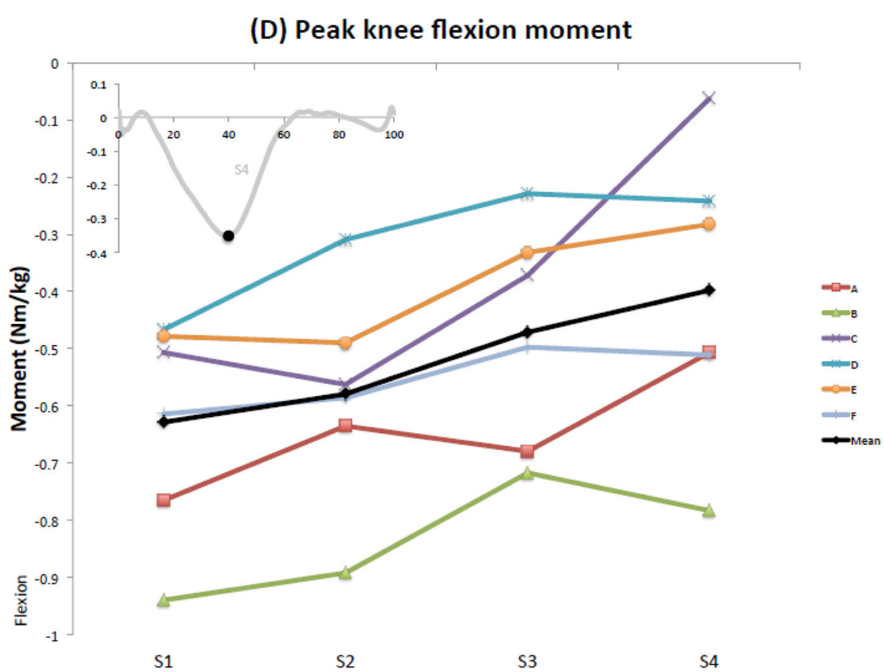

Figure 3D

Figure 3.

Individual responses to the changes of the plantarflexion resistance of the AFO from spring condition S1 to S4 in (A) peak plantarflexion angle, (B) peak dorsiflexion moment, (C) peak knee extension angle, and (D) peak knee flexion moment. 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.

Table 1

Demographic data of the subjects

Subject	Height (m)	Weight (Kg)	Gender	Age (year-old)	Affected side	Period after stroke (year)
A	1.70	93	M	48	L	1
B	1.90	120	M	38	L	3
C	1.69	111	M	64	R	4
D	1.72	108	M	64	R	11
E	1.72	80	M	57	R	10
F	1.72	85	M	41	L	10

Abbreviations: M, male; L, left; R, right

Table 2

Outcomes of clinical assessment and self-selected treadmill speed.

Subject	Ankle MAS	Ankle MMT PF	Ankle MMT DF	Knee MMT EX	Knee MMT FX	TUG (S)	Self-selected treadmill speed (m/s)
A	3	2−	1	5	4	15.7	0.24
B	3	4	2+	5	3+	20.2	0.15
C	2	4	4	4	4	14.6	0.21
D	2	3+	0	4	4	13.5	0.25
E	3	3+	3+	5	5	10.6	0.27
F	3	1	0	3+	2+	16.9	0.15

Abbreviations: MAS, Modified Ashworth Scale; MMT, Manual Muscle Testing, DF, dorsiflexors, PF, plantarflexors, EX, extensors, FX, flexors, TUG, Timed-Up and Go test

Table 3

The range and mean (SD) of ankle and knee joint angle and moment parameters under four spring conditions (S1, S2, S3 and S4) of the ankle-foot orthosis.

Ankle	**Peak plantarflexion angle**		**Peak dorsiflexion moment**	
	Range (°)	**Mean (SD) (°)**	**Range (Nm/kg)**	**Mean (SD) (Nm/kg)**
S1	[−17.15, 0.00]	−7.98 (6.01)	[−0.039, −0.001]	−0.016 (0.013)
S2	[−13.96, −2.81]	−7.00 (4.03)	[−0.057, −0.020]	−0.037 (0.014)
S3	[−14.91, 3.60]	−4.95 (6.53)*	[−0.062, −0.007]	−0.035 (0.021)
S4	[−11.63, 7.94]	−2.63 (6.58)*	[−0.077, −0.029]	−0.051 (0.020)*
Knee	**Peak knee extension angle**		**Peak knee flexion moment**	
	Range (°)	Mean (SD) (°)	Range (Nm/kg)	Mean (SD) (Nm/kg)
S1	[−20.51, −2.62]	−10.41 (6.75)	[−0.939, −0.466]	−0.628 (0.189)
S2	[−18.75, −0.57]	−8.67 (6.39)*	[−0.892, −0.309]	−0.579 (0.191)
S3	[−17.80, 2.71]	−7.11 (7.55)*	[−0.717, −0.229]	−0.471 (0.200)*
S4	[−18.85, 7.54]	−4.92 (9.27)*	[−0.783, −0.062]	−0.398 (0.225)*

An asterisk (*) indicates significant difference at $P < 0.05$ from S1 with the *post-hoc* Wilcoxon Singed rank test.

Abbreviations: SD, standard deviation