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Short communication

Effects of articulated ankle–foot orthosis dorsiflexion range of motion on lower-limb joint kinematics during gait in individuals post-stroke

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ABSTRACT

Adjusting the range of motion (ROM) and spring stiffness of ankle–foot orthoses (AFOs) for individuals post-stroke enables customized functionality and targeted support during specific phases of the gait cycle. Modifications to dorsiflexion ROM or spring stiffness theoretically influences the second and third rockers of gait. Understanding these effects is crucial for optimizing gait in individuals post-stroke. This study investigated the impact of dorsiflexion ROM adjustments in multi-function articulated AFOs on ankle, knee, and hip kinematics during gait in individuals post-stroke. Nine participants were tested across six AFO settings, including three dorsiflexion ROM levels (0°, 5°, 10°) with two spring stiffness levels (low stiffness = 200 N/mm, high stiffness = 515 N/mm) of the Triple Action ankle joint. Kinematic data were collected using a 3D motion capture system, and joint angle parameters were analyzed throughout the gait cycle. The results showed that increasing dorsiflexion ROM significantly increased the maximum dorsiflexion angle of the ankle and decreased the maximum extension angle of the knee, with no significant effects on hip joint kinematics or walking speed. Increased ankle dorsiflexion facilitates tibial progression during the second rocker of gait, enhancing walking efficiency. However, the decrease in knee extension angle or increase in knee flexion angle may pose challenges to knee stability. This study suggests that dorsiflexion ROM of articulated AFOs should be tailored: individuals with stable knee joints may benefit from increased dorsiflexion ROM to optimize the second rocker, while those with unstable knees may require reduced dorsiflexion ROM to enhance stability.

1. Introduction

Individuals post-stroke often experience unilateral motor impairments that significantly affect their daily activities (Chen et al., 2005). Ankle-foot orthoses (AFOs) are commonly used to support gait in this population (Daryabor et al., 2022). Adjusting the range of motion (ROM) for dorsiflexion and plantarflexion in articulated AFOs is a key clinical strategy to customize their functionality (Totah et al., 2019). Tuning the ROM and spring stiffness of a multi-function articulated AFO can provide targeted support during specific phases of the gait cycle (Kobayashi et al., 2017). For example, in cases of foot slap or rapid knee flexion during early stance, increasing the plantarflexion ROM or reducing plantarflexion spring stiffness may help alleviate these gait deviations. Conversely, if knee hyperextension occurs during early stance, reducing plantarflexion ROM or increasing plantarflexion spring stiffness may mitigate this issue (Kobayashi et al., 2015).

Adjusting plantarflexion ROM or spring stiffness optimizes the first rocker of the gait cycle (Daryabor et al., 2018), while modifications to dorsiflexion ROM or spring stiffness could theoretically affect the second and third rockers. During gait, the first rocker converts the potential energy into forward kinetic energy through the body's downward motion, transferring it to the second and third rockers (Perry & Burnfield, 2010). These mechanisms are crucial for maintaining gait stability and facilitating forward progression. Additionally, adjustments to dorsiflexion ROM or spring stiffness not only directly influence ankle motion but also indirectly affect knee joint stability during stance. Therefore, understanding the effects of dorsiflexion ROM and spring stiffness adjustments of an AFO on post-stroke gait is critical for optimizing gait performance and stability.

Though effects of an articulated AFO's mechanical properties on the first rocker of gait have been well investigated in previous studies (Kobayashi et al., 2015; Yamamoto et al., 2018), their effects on the

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second and third rockers of gait remain unknown. This study aimed to investigate the effects of different dorsiflexion ROM settings and their interaction with dorsiflexion spring stiffness settings in multi-function articulated AFOs on ankle, knee, and hip joint kinematics in individuals post-stroke, under two dorsiflexion spring stiffness conditions. We hypothesized that increasing the dorsiflexion ROM would increase the maximum dorsiflexion angle of the ankle and reduce the maximum extension angle of the knee during stance while walking. Additionally, as the effects of dorsiflexion ROM on hip joint kinematics may be limited (Rimaud et al., 2024; Yamamoto et al., 2022), we hypothesized that increasing the dorsiflexion ROM would not significantly affect the maximum hip joint extension and flexion angle. Finally, we hypothesized that there would be interaction effects between the dorsiflexion ROM and spring stiffness settings.

2. Methods

2.1. Participants

Nine individuals post-stroke (five females and four males) were recruited from the community to participate in this study. Among them, six had ischemic strokes and three had hemorrhagic strokes. Five participants had right hemiplegia, while four had left hemiplegia. The participants had an average age of 56 (8) years, an average height of 163 (4) cm, an average weight of 61 (7) kg, and an average time since stroke of 7 (5) years. Mean and standard deviations (SD) are shown as mean (SD). Six participants used a non-articulated AFO, one participant used an articulated AFO, and two participants did not use an AFO in their daily life. The outcomes of the muscle strength grading: Medical Research Council (MRC) Manual Muscle Testing scale (Hip extensor/flexor, Knee extensor/flexor, Ankle dorsiflexor/plantarflexor), the manual passive ROM of ankle dorsiflexion with the knee at 90° of flexion in the affected limb, and Berg Balance Scale (BBS) score are summarized in Table 1 (Naqvi & Sherman, 2023). The inclusion criteria were as follows: 1) age 18 years or older; 2) a history of stroke for at least six months with hemiplegia; and 3) ability to safely and proficiently use an AFO for walking. Exclusion criteria were: 1) presence of significant ankle joint contractures (i.e., manual passive ROM of dorsiflexion is limited to 5° less than the neutral position); 2) symptoms of idiopathic dizziness within the past six months; 3) previous treatment with botulinum toxin; 4) more than one cerebrovascular event; and 5) any additional lower limb injuries, musculoskeletal issues, or cognitive impairments unrelated to hemiplegia. The study was approved by the Human Subjects Ethics Sub-Committee of The Hong Kong Polytechnic University (approval number: HSEARS20230919004). Informed consent was obtained from all participants before their involvement in the study.

2.2. Experimental procedure

Kinematic data were collected using a 3D motion capture system (MX-T 160, Vicon, Oxford Metrics, UK) equipped with eight infrared cameras operating at a sampling rate of 200 Hz. Sixteen reflective markers were placed on participants according to the lower-limb plug-in gait model. The Plug-in Gait model is Vicon's implementation of the Conventional Gait Model, which has been widely used and provides reliable body kinematic and kinetic modelling (Kainz et al., 2017; Stief et al., 2013). The markers were placed on the left and right ASIS (anterior superior iliac spine), PSIS (posterior superior iliac spine), Thigh, Knee, Tibia, Ankle, Heel, and Toe. All participants wore standardized shoes during the trials. A Becker Gait Evaluation Orthosis (GEO) AFO (Becker Orthopedic, Troy, MI, USA) was fitted to the affected limb of each participant. The foot plate and posterior calf shell of the GEO AFO are prefabricated from carbon composite, with a total weight of the AFO approximately 630 g. The plantarflexion ROM and spring stiffness as well as alignment of the multi-function articulated joint (Triple Action® Ankle joint) of the GEO AFO were optimized for each participant based on Steps 1 to 4 of an algorithm described in a previous study (LeCursi et al., 2024) and the participant's subjective feedback (Fig. 1 **(a)**). The algorithm consisted of 5 steps: Step 1: Bench adjustment, Step 2: Static alignment, Step 3: Swing phase alignment, Step 4: Early stance phase adjustment, and Step 5: Late stance phase adjustment.

The study tested three different dorsiflexion ROM settings (0°, 5°, and 10°) of the Triple Action joint of the GEO AFO under two different dorsiflexion spring stiffness levels (low stiffness = 200 N/mm; high stiffness = 515 N/mm) (Fig. 1 **(b)**). The AFO's joint dorsiflexion stiffness is 0.44 Nm/deg with the low-stiffness spring, while it is 1.13 Nm/deg with the high-stiffness spring. The stiffness levels were selected based on previous studies as well as clinical practice (Kobayashi et al., 2018). The dorsiflexion ROM of the AFO is inversely correlated with the threshold resistance (pre-loading) of the springs. Therefore, increasing the ROM reduces the spring's threshold resistance, while decreasing the ROM increases it (Fig. 1 **(a)**). Before data collection, participants were instructed to practice walking on a 10-meter walkway to familiarize themselves with the experimental protocol. For each experimental condition, participants were required to walk on the walkway at their self-selected speed for at least three successful trials while wearing the AFO under each AFO setting (Fig. 1 **(b)**). Adequate rest was provided between trials to prevent fatigue from affecting the results.

2.3. Data collection and analyses

All data were processed using Vicon Nexus software (Vicon Motion System, Oxford, UK), and the marker trajectories were filtered with the

Table 1
Muscle strength grading (MRC manual muscle testing scale) of hip, knee, and ankle joints and manual passive ROM of ankle dorsiflexion in the affected limb, and Berg Balance Scale score.

Participant	Hip flexor	Hip extensor	Knee flexor	Knee extensor	Dorsiflexor	Plantarflexor	Ankle DF ROM (°)	BBS score
1	5	4	5	5	4	0	0	47
2	4	4	5	5	3	3	−5	44
3	4	4	4	4	2	4	5	54
4	5	4	3	4	3	3	0	52
5	5	2	2	4	2	2	15	45
6	5	5	5	5	4	5	10	55
7	3	3	3	5	3	3	5	44
8	5	3	4	5	3	4	5	44
9	5	5	5	5	2	5	10	48

Abbreviations: MRC: Medical Research Council; DF: dorsiflexion; ROM: range of motion; BBS: Berg Balance Scale.
Note: The manual passive range of motion was tested with the knee at 90 degrees of knee flexion.

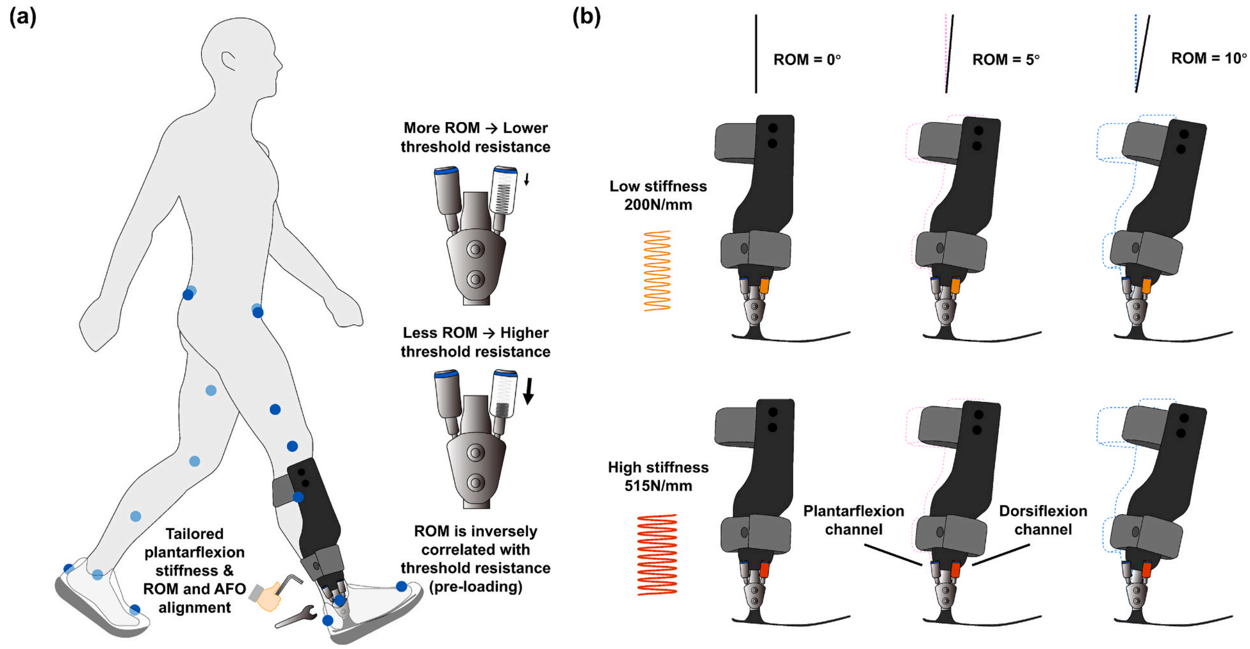

Fig. 1. Experimental setup. (a) The lower-limb plug-in gait model was used, with 16 reflective markers securely attached to the corresponding anatomical landmarks. The plantarflexion spring stiffness, ROM (range of motion), and AFO (ankle–foot orthosis) alignment were customized and adjusted for each participant. The ROM and threshold resistance (pre-loading) on the spring are inversely correlated. When the spring is pre-compressed, threshold resistance increases while ROM decreases (due to the reduced available range of motion of the spring), and vice versa. (b) The experimental conditions consisted of six different AFO settings, combining three dorsiflexion ROM levels (0°, 5°, and 10°) and two dorsiflexion spring stiffness levels (low stiffness spring = 200 N/mm; high stiffness spring = 515 N/mm).

Woltring filter. The gait cycle was defined based on the sagittal plane displacement of the heel marker. The middle three gait cycles of each trial were extracted for analysis for each AFO setting. Joint angles of the ankle, knee, and hip in the sagittal plane of the affected limb were averaged and normalized to 101 points across the gait cycle. The extracted parameters included: Max Plantarflexion, the maximum plantarflexion angle during the first 30 % of the gait cycle; Max Dorsiflexion, the maximum dorsiflexion angle during 40 %-60 % of the gait cycle; Max Knee Flexion 1, the maximum knee flexion angle during the first 20 % of the gait cycle; Max Knee Extension, the maximum knee extension angle during 20 %-50 % of the gait cycle; Max Knee Flexion 2, the maximum knee flexion angle during 50 %-90 % of the gait cycle; Max Hip Extension, the maximum hip extension angle during 30 %-60 % of the gait cycle; and Max Hip Flexion, the maximum hip flexion angle during the final 20 % of the gait cycle. Walking speed was also measured based on the trajectory of the marker at the lateral anterior superior iliac spine for each AFO setting.

2.4. Statistical analysis

Two-way repeated-measures ANOVA was conducted to examine the main effects of dorsiflexion ROM settings (0°, 5°, and 10°) and spring stiffness settings (low stiffness spring = 200 N/mm, high stiffness spring = 515 N/mm) on ankle, knee, and hip joint angles. Sphericity was assessed using Mauchly test, and the Greenhouse-Geisser correction was implemented when sphericity was violated. If a main effect of ROM or stiffness was significant, post-hoc analyses were conducted for three pairwise comparisons using Fisher's Least Significant Difference (LSD) Test. All statistical analyses were performed using SPSS software (IBM SPSS Statistics 26, SPSS Inc., Chicago, IL). A p-value of < 0.05 was considered statistically significant.

3. Results

The main effects of ROM were demonstrated for Max Dorsiflexion (main effect of ROM: $p < 0.001$) and Max Knee Extension (main effect of ROM: $p = 0.017$) (Table 2). Post-hoc analysis revealed that as dorsiflexion ROM increased, Max Dorsiflexion (DF) significantly increased (0°DF–5°DF: $p < 0.001$; 0°DF–10°DF: $p < 0.001$; 5°DF–10°DF: $p = 0.002$). In addition, as dorsiflexion ROM increased (0°DF vs. 5°DF and 0°DF vs. 10°DF), Max Knee Extension significantly decreased (a decrease in negative values); however, there was no significant difference between 5°DF and 10°DF (0°DF–5°DF: $p = 0.028$; 0°DF–10°DF: $p = 0.018$; 5°DF–10°DF: $p = 0.064$). No main effects were observed for interaction or stiffness for any parameter. Similarly, no main effects of ROM were found for Max Plantarflexion, Max Knee Flexion 1, Max Knee Flexion 2, Max Hip Extension, Max Hip Flexion, or walking speed. Fig. 2 shows the ankle, knee, and hip joint angles during the gait cycle under different experimental conditions.

4. Discussion

This study compared the effects of different dorsiflexion ROM settings (0°, 5°, 10°) of the multi-function articulated AFO on the kinematics of the ankle, knee, and hip joints in individuals post-stoke under two dorsiflexion spring stiffness conditions (low stiffness and high stiffness). The study's hypotheses were supported: as dorsiflexion ROM increased, the maximum dorsiflexion angle of the ankle during walking also increased, while the maximum extension angle of the knee decreased. Congruently, the hip joint angles and walking speed were not significantly different among the conditions. However, no interaction effects were found between the dorsiflexion ROM and stiffness settings.

An increase in the maximum dorsiflexion angle of the ankle

Table 2
Lower-limb joint kinematic parameters and walking speed under different range of motion and spring stiffness settings of the ankle–foot orthosis.

Parameters	Spring	0DF	5DF	10DF	Main effect of ROM (p-value)	Main effect of Stiffness (p-value)	Interaction effect (p-value)	Post-hoc Test 0DF-5DF	Post-hoc Test 0DF-10DF	Post-hoc Test 5DF-10DF
Max Plantarflexion (°)	**Low Stiffness**	0.80 ± 2.54	0.50 ± 2.80	0.60 ± 3.01	0.228	0.290	0.531	—	—	—
	High Stiffness	0.17 ± 3.44	−0.59 ± 3.83	−0.02 ± 3.65						
Max Dorsiflexion (°)	**Low Stiffness**	11.45 ± 2.21	14.28 ± 1.34	15.43 ± 2.05	**<0.001***	0.541	0.146	**<0.001***	**<0.001***	**0.002***
	High Stiffness	12.77 ± 5.28	14.47 ± 4.94	16.64 ± 4.90						
Max Knee Flexion 1 (°)	**Low Stiffness**	5.78 ± 5.44	6.89 ± 6.09	6.16 ± 6.64	0.414	0.885	0.315	—	—	—
	High Stiffness	6.26 ± 6.68	6.14 ± 8.13	6.82 ± 7.44						
Max Knee Extension (°)	**Low Stiffness**	−7.17 ± 5.16	−3.73 ± 5.20	−3.86 ± 5.69	**0.017***	0.479	0.314	**0.028***	**0.018***	0.064
	High Stiffness	−4.45 ± 7.66	−3.80 ± 7.41	−2.35 ± 7.88						
Max Knee Flexion 2 (°)	**Low Stiffness**	17.38 ± 12.87	18.80 ± 12.77	18.31 ± 13.96	0.214	0.809	0.358	—	—	—
	High Stiffness	17.91 ± 12.52	18.32 ± 14.53	19.56 ± 13.67						
Max Hip Extension (°)	**Low Stiffness**	−12.61 ± 7.27	−12.46 ± 7.33	−13.17 ± 7.36	0.068	0.126	0.691	—	—	—
	High Stiffness	−10.27 ± 7.55	−10.81 ± 7.17	−11.50 ± 7.30						
Max Hip Flexion (°)	**Low Stiffness**	17.66 ± 9.53	18.44 ± 9.47	17.61 ± 9.62	0.682	0.066	0.748	—	—	—
	High Stiffness	18.67 ± 8.99	18.95 ± 9.84	18.99 ± 8.69						
Walking speed (m/s)	**Low Stiffness**	0.45 ± 0.13	0.49 ± 0.14	0.49 ± 0.15	0.273	0.084	0.085	—	—	—
	High Stiffness	0.44 ± 0.13	0.45 ± 0.15	0.47 ± 0.14						

Abbreviations: 0DF: 0 degrees dorsiflexion range of motion (ROM); 5DF: 5 degrees dorsiflexion ROM; 10DF: 10 degrees dorsiflexion ROM.
Note: Low stiffness spring = 200 N/mm, High stiffness spring = 515 N/mm.

facilitates tibial progression during the second rocker of gait, thereby enhancing walking efficiency (Perry & Burnfield, 2010). Adjusting the dorsiflexion ROM provides effective control over the duration of the second rocker. However, it is important to note that dorsiflexion ROM also influences the knee joint. As dorsiflexion ROM increases, the maximum knee extension angle decreases, which may impair knee stability. Hyperextension of the knee during gait is a characteristic feature of hemiparetic gait (Kobayashi et al., 2016; Von Schroeder et al., 1995), and an overextended knee can contribute to gait stability. Therefore, reducing the knee extension or increasing knee flexion by increasing dorsiflexion ROM could compromise walking stability.

The dorsiflexion spring and ROM restrictions act as a functional substitute for the plantarflexor muscles, working in coordination with the hip extensors to control rapid forward tibial progression and prevent potential rapid knee flexion (Cooper et al., 2012). Increasing dorsiflexion ROM could help minimize ligamentous injuries and pain in the knee joint in individuals post-stroke and facilitate more natural gait (Tani et al., 2016). Individuals post-stroke with stable knee joints may benefit from increased dorsiflexion ROM adjustments enhancing the second rocker of gait. In contrast, those with unstable knee joints may benefit from reduced dorsiflexion ROM adjustments to improve knee stability.

It is important to note that ROM of an articulated AFO is influenced by several factors: 1) ROM limit set at the joint, 2) structural deformation of the AFO between the footplate and shell, 3) movement of the AFO inside the footwear, 4) interactions at the interface between the limb and

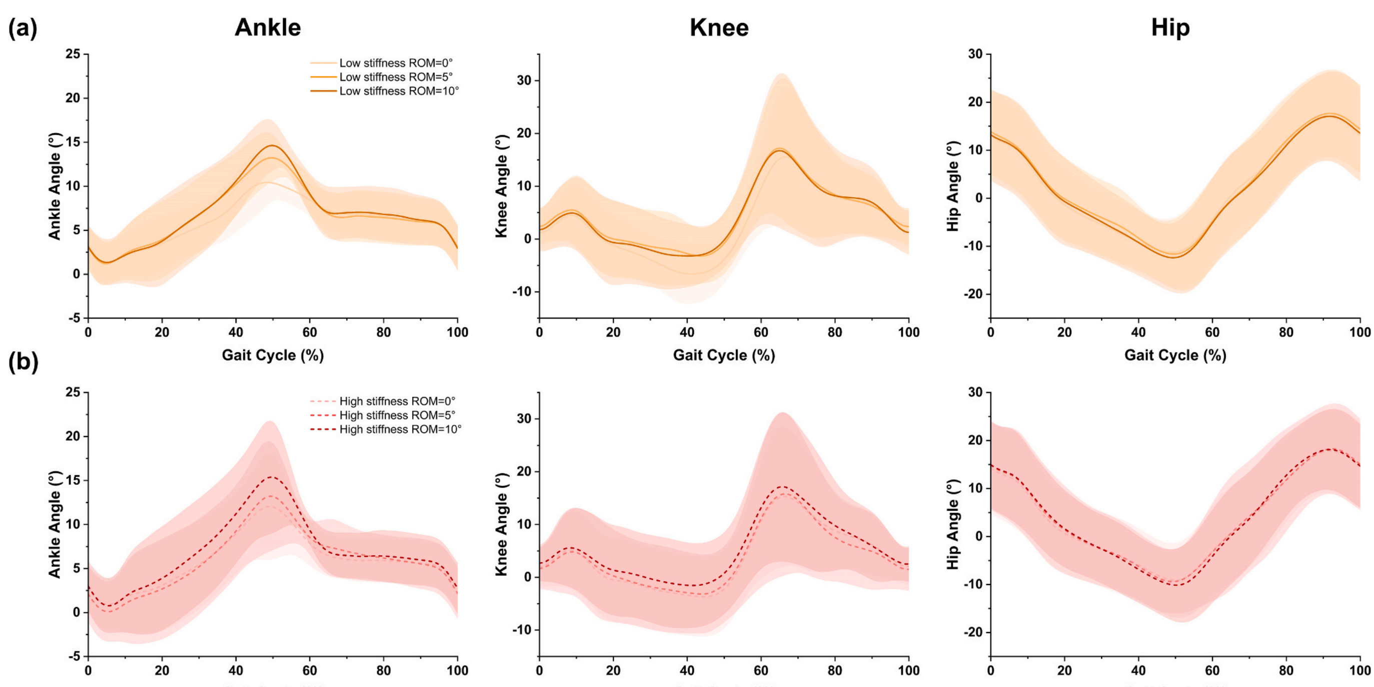

Fig. 2. Joint angles of the ankle, knee, and hip during the gait cycle. (a) AFO (ankle–foot orthosis) with low stiffness spring (200 N/mm): the solid line represents the mean angle, and the shaded area indicates the standard deviation. (b) AFO with high stiffness spring (515 N/mm): the dashed line represents the mean angle, and the shaded area indicates the standard deviation.

the AFO, and 5) joint play. As a result, setting the dorsiflexion ROM to 0 degrees still allows for some dorsiflexion movement of the ankle joint during gait (Fig. 2). The difference in dorsiflexion ROM between 5 and 10 degrees is smaller than between 0 and 5 degrees in the low spring stiffness condition, which may be related to limited dorsiflexion ROM in some participants (Table 2).

This study had several limitations. First, only the effects of dorsiflexion ROM adjustments on kinematics in individuals post-stroke were examined, and kinetic analysis was not included. While evaluation of kinetic data is important, it is challenging for individuals post-stroke to consistently strike force plates accurately under various AFO conditions while walking. Therefore, future studies could use an instrumented treadmill to investigate their joint kinetics. Second, this study only explored two dorsiflexion spring stiffness settings and did not examine a broader range of spring stiffness. Future studies should investigate the effects of multiple spring stiffness levels under the same ROM conditions. Third, motion artifacts due to skin markers, along with the fact that some markers were not placed directly on a barefoot surface, may have influenced the kinematic data. Fourth, this study had small sample size (n = 9), and a larger scale study is warranted to generalize the effects of AFO's ROM and stiffness on gait in individuals post-stroke.

In conclusion, this study demonstrated that the dorsiflexion ROM of an articulated AFO affects ankle joint and knee joint kinematics during gait in individuals post-stroke. Therefore, the dorsiflexion ROM of the AFO should be tuned based on individual needs, particularly to maintain knee joint stability during gait.

CRediT authorship contribution statement

Yufan He: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Mark W.P. Koh:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Chloe L.Y. Wong:** Writing – review & editing, Methodology, Investigation. **Fan Gao:** Writing – review & editing, Methodology, Investigation. **Toshiki Kobayashi:** Writing – review & editing, Visualization, Project administration, Methodology, Investigation, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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