Ogura *et al.*
Journal of NeuroEngineering and Rehabilitation (2024) 21:150
https://doi.org/10.1186/s12984-024-01432-8

Journal of NeuroEngineering
and Rehabilitation

RESEARCH **Open Access**

Effects of ankle joint degree of freedom of knee–ankle–foot orthoses on loading patterns and triceps surae muscle activity on the paretic side in individuals with subacute severe hemiplegia: a retrospective study

Ayumu Ogura[1], Yuta Chujo[2*], Naoto Mano[1,3], Kimihiko Mori[2], Takayuki Konishi[1], Takayuki kuwabara[1,3], Masanori Wakida[2] and Kimitaka Hase[1]

Abstract

Background Individuals with subacute severe hemiplegia often undergo alternate gait training to overcome challenges in achieving walking independence. However, the ankle joint setting in a knee–ankle–foot orthosis (KAFO) depends on trunk function or paralysis stage for alternate gait training with a KAFO. The optimal degree of ankle joint freedom in a KAFO and the specific ankle joint conditions for effective rehabilitation remain unclear. Therefore, this study aimed to investigate the effects of different degrees of freedom of the ankle joint on center-of-pressure (CoP) parameters and muscle activity on the paretic side using a KAFO and to investigate the recommended setting of ankle joint angle in a KAFO depending on physical function.

Methods This study included 14 participants with subacute stroke (67.4 ± 13.3 years). The CoP parameters and muscle activity of the gastrocnemius lateralis (GCL) and soleus muscles were compared using a linear mixed model (LMM) under two ankle joint conditions in the KAFO: fixed at 0° and free ankle dorsiflexion. We confirmed the relationship between changes in CoP parameters or muscle activity under different conditions and physical functional characteristics such as the Fugl–Meyer Assessment of Lower Extremity Synergy Score (FMAs) and Trunk Impairment Scale (TIS) using LMM.

Results Anterior–posterior displacement of CoP (AP_CoP) ($p = 0.011$) and muscle activity of the GCL ($p = 0.043$) increased in the free condition of ankle dorsiflexion compared with that in the fixed condition. The FMAs ($p = 0.004$) and TIS ($p = 0.008$) demonstrated a positive relationship with AP_CoP. A positive relationship was also found between TIS and the percentage of medial forefoot loading time in the CoP ($p < 0.001$).

Conclusions For individuals with severe subacute hemiplegia, the ankle dorsiflexion induction in the KAFO, which did not impede the forward tilt of the shank, promotes anterior movement in the CoP and muscle activity of the GCL. This study suggests that adjusting the dorsiflexion mobility of the ankle joint in the KAFO according to improvement in physical function promotes loading of the CoP to the medial forefoot.

---

*Correspondence:
Yuta Chujo
chujoyut@makino.kmu.ac.jp
Full list of author information is available at the end of the article

Keywords Biomechanical phenomena, Electromyography, Gait, Lower extremity, Orthotic devices, Stroke rehabilitation

Background

Many individuals develop a gait disorder after a stroke. Despite recent advancements in rehabilitation science, 40% of individuals with hemiplegia who initially have difficulty in walking do not achieve walking independence, even 3 months after stroke onset [1]. Early and high-intensity gait training for individuals with subacute stroke has been reported to promote walking independence at 6 months after gait training [2]. Rehabilitation for individuals with hemiplegia aims to induce plastic changes in the central nervous system by inhibiting compensation from the nonparetic limb and increasing the frequency of using paretic limb. Orthotic treatment plays a vital role in facilitating repetitive movement of the paretic limb with a reduced degree of freedom. Currently, previous studies have reported the effectiveness of gait training on overground surfaces using a knee–ankle–foot orthosis (KAFO) for individuals with subacute severe hemiparesis [3, 4].

Generating a gait rhythm with sensory input is important as a gait strategy for individuals with subacute severe hemiparesis and those having difficulty in achieving walking independence. The transition from stance to swing is controlled by muscle spindles in the hip flexor muscles and group Ib afferents from the Golgi tendon organs in the ankle extensor muscles [5]. Alternate gait training is provided to induce ankle dorsiflexion and hip extension in gait, which a KAFO assists. Abe et al. demonstrated that alternate gait training overground with a KAFO in the subacute phase led to earlier improvements in Functional Independence Measure gait scores [4], suggesting providing information on hip extension under load may induce increased muscle activity in the lower limbs on the paretic side. However, muscle activity in the lower limb on the paretic side during alternate gait training with a KAFO has not yet been confirmed.

Additionally, the center-of-pressure (CoP) on the paretic side is an important indicator of gait ability in hemiplegia. Choi et al. reported that greater anterior–posterior displacement of the CoP (AP_CoP) in the subacute phase improved walking independence in individuals with hemiplegia [6]. In addition, Echigoya et al. reported a positive relationship between Fugl–Meyer Assessment scores and walking speed [7]. Therefore, AP_CoP serves as a marker of functional impairment and activity limitation. Development of strategies to promote an increase in the AP_CoP may lead to the acquisition of independent walking ability in individuals with subacute stroke. However, few studies have focused on CoP during assisted gait using a KAFO in individuals with subacute stroke. A previous study reported that the CoP path moved from the heel to the medial forefoot and hallux in healthy participants [8]. Thus, we believe that medial forefoot loading is crucial for gait in individuals with stroke, as well as for increased AP_CoP.

Limiting the degree of freedom in the ankle joint with an ankle–foot orthosis for individuals with chronic hemiplegia has been shown to increase the ankle dorsiflexion angle during the stance phase [9] and to decrease braking forces during the initial double support, resulting in improved gait speed [10]. However, Mulroy et al. reported that, compared to the free ankle dorsiflexion condition, limitation of the ankle dorsiflexion angle results in decreased muscle activity of the soleus (SOL) during the stance phase in individuals with chronic stroke [11]. Therefore, adjusting the degree of freedom in the ankle joint according to the degree of functional recovery is crucial. In addition, improvements in gait ability in individuals with subacute stroke have been associated with physical function, which reduces limb motor function and trunk control [12, 13]. However, the specific ankle joint conditions for a KAFO according to physical function remain unclear.

First, this study aimed to examine the effects of different degrees of freedom in the ankle joint on CoP parameters and muscle activity on the paretic side using a KAFO for individuals with severe hemiplegia. Second, we aimed to determine the relationship between CoP parameters, muscle activity, and physical function according to different settings of ankle joint angles in a KAFO. We hypothesized that CoP parameters and muscle activity in the triceps surae would improve under ankle dorsiflexion induction in a KAFO, as it does not impede the forward tilt of the shank during terminal stance. Moreover, adjusting ankle joint function based on individual physical function may be necessary, as previous studies suggest that motor impairment and trunk control impairment after stroke are closely associated with poor mobility performance and gait instability [14, 15].

Methods

Study design

We performed a retrospective analysis using data collected from individuals with hemiplegia in the subacute phase. These data were collected from

November 1, 2019, to August 1, 2022, at a university hospital for routine medical care to confirm the degree of functional recovery. Information obtained on day of assessment, sex, and age were extracted from medical records. This study was approved by the Ethics Committee of Kansai Medical University and conducted in accordance with the Declaration of Helsinki (#2022150). Informed consent was obtained through an opt-out process.

The study recorded gait measurements using CoP parameters and muscle activity during gait for each participant. Physical function was assessed using the Fugl–Meyer Assessment of Lower Extremity Synergy Score (FMAs) and the Trunk Impairment Scale (TIS) [16]. Gait measurements and physical function, such as the FMAs and TIS, were assessed once per week, and the measurements were repeated throughout hospitalization.

Participants

This study enrolled 14 individuals (age: 67.4 ± 13.3 years; paretic side right: 7) with hemiplegia in the subacute phase for a total of 31 trials. The inclusion criteria were as follows: (1) orthopedic pathologies or history that would interfere with legs during walking; (2) difficulty in walking independently, requiring a KAFO due to severe knee instability; and (3) independence in activities of daily living before stroke onset. The exclusion criteria were as follows: (1) communication difficulty in individuals with severe consciousness impairment; (2) presence of bilateral paralysis; and (3) unsuitability for a KAFO due to severe spasticity and musculoskeletal disorders.

Procedure

The participants repeatedly walked at a self-selected speed with a KAFO, assisted by a physical therapist, on a 10 m-long overground walkway: 1 m for acceleration, followed by 8 m for gait measurement, and 1 m for deceleration. Gait measurements were performed until at least 10 gait cycles could be completed, excluding obvious outliers such as significant noise. A physical therapist provided assistance for the trunk from behind, and a thigh belt was used to minimize the swing of the paretic limb and its contact position at heel contact. Alternating large hip flexion and extension exercises were conducted as part of alternate gait training in all trials. Two designated physical therapists with 7 and 5 years of clinical experience, respectively, were assigned to minimize assistance errors during evaluation. Outside of gait measurement days, gait training with a KAFO was provided by each therapist for at least 20 min, approximately 5 days per week, using the same assistance as that during the gait measurement while monitoring vital signs.

Our goal was to confirm the effects of different degrees of freedom in the ankle joint on CoP parameters and muscle activity on the paretic side using a KAFO. The knee joint was fixed in the extension position using a ring-lock hinge joint, and the ankle joint degree of freedom was adjusted using a double Klenzak ankle joint. Two ankle joint conditions were established: a fixed condition with 0° of dorsiflexion and plantarflexion and a free condition with 0° of plantarflexion and a range of motion from 0° to 20° of dorsiflexion. Plantarflex motion can lead to forefoot contact at heel contact, resulting in pelvic retraction during the stance phase and potentially causing circumduction of the lower limb during the swing phase. Therefore, we fixed the plantarflexion angle of the ankle joint at 0° in all the trials.

Pedobarography data were collected using the Pedar®-x (Novel GmbH, Munich, Germany; sampling rate: 100 Hz), which is an objective and quantifiable pressure distribution measuring system for monitoring the magnitude and timing of plantar loading [17]. This system comprises a portable data collection device worn on the participant's buttocks and elastic sensor insoles inserted directly beneath the soles of the feet (Fig. 1). The insoles were selected to fit the individual's foot size before measurement.

Muscle activity during gait was recorded using surface electromyography (EMG) signals, and foot switch data were recorded using the Noraxon Clinical DTS system (Scottsdale, AZ, USA; sampling rate: 1,500 Hz). EMG activity was recorded from the gastrocnemius lateralis (GCL) and SOL on the paretic side using superficial bipolar Ag–AgCl electrodes (Blue sensor; Medicotest, Inc., Olstykke, Denmark) with an inter-electrode spacing of 2 cm. The skin was cleaned using an alcohol swab to minimize impedance, and the electrodes were placed according to the recommendations for obtaining EMG signals for the noninvasive assessment of muscles [18].

Data collection

For each trial, CoP parameters and muscle activity were extracted from the recorded data. The origin was designated as the most posterior and medial point, and the X (M–L) and Y (A–P) coordinates for the CoP were derived for each foot during the stance phase [19]. We calculated the displacement of the X axis, which is defined as the mediolateral displacement of the CoP (ML_CoP); displacement of the Y axis, which is defined as the AP_CoP; and loading force (maximum and average values) during the stance phase. Pedobarography data were divided into four plantar regions (heel, hindfoot, medial forefoot, and lateral forefoot). The percentage of loading time was calculated by determining the load percentage of stance time for each region using

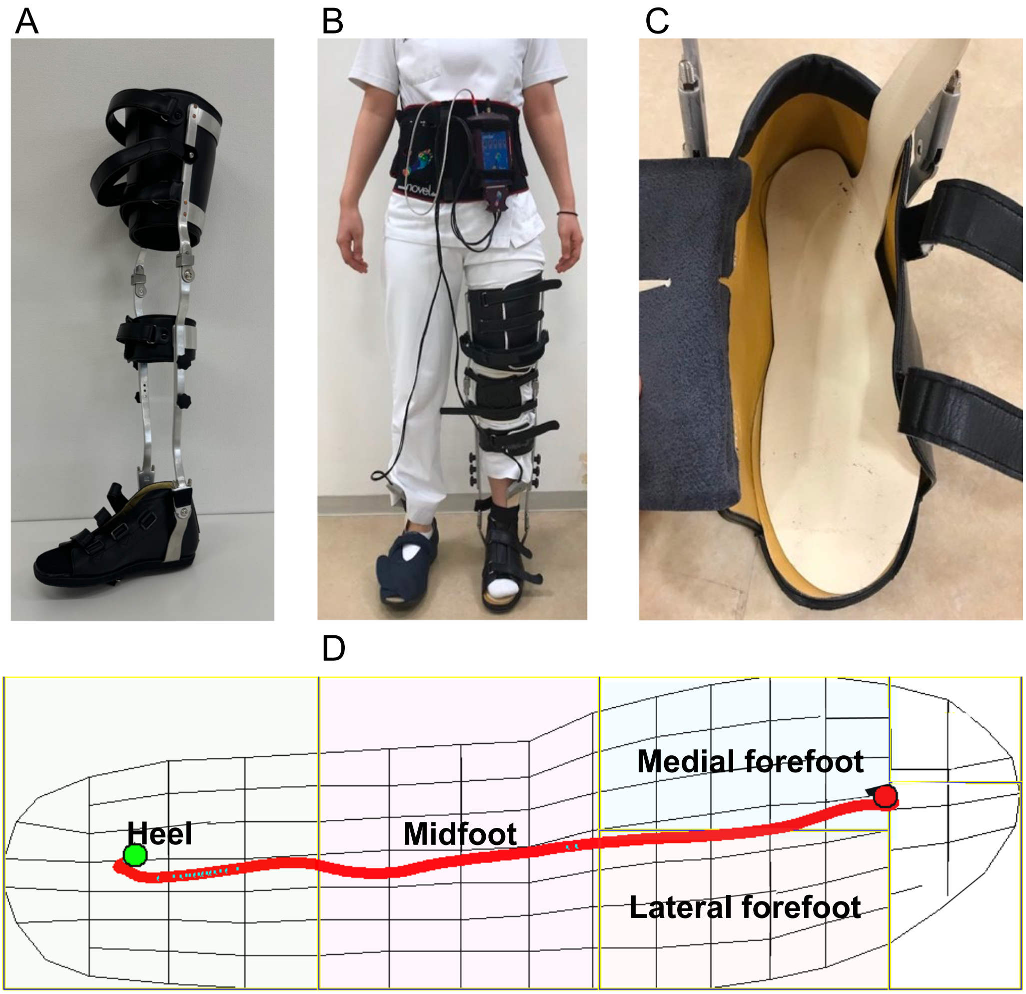

Fig. 1 Knee-ankle–foot orthosis and plantar pressure measurement system. **A** Knee-ankle–foot-orthosis (KAFO) used in this study. **B** Overview of the KAFO used in this study. The orthosis is customized to fit the individual's lower extremity anatomy, which is designed to provide optimal support and freedom of movement. **C** Setup method for the plantar pressure measurement system. **D** Segmentation of specific foot areas (e.g., heel, midfoot, medial forefoot, lateral forefoot) for analysis of plantar pressure data

Multimask Evaluation (Novel Electronics, Inc., Munich, Germany). Heel contact was defined as the point at which the sensor measured a force greater than zero, and toe-off was defined as the initial point at which all forces on the plantar surface of the foot became equal to zero in reference to a previous study [10]. A gait cycle was unilaterally defined as the time between heel contact of the same leg.

EMG signals were band-pass filtered with cutoff frequencies in the range of 10–500 Hz using a zero-lag second-order Butterworth filter and were then demeaned, rectified, and low-pass filtered using a zero-lag second-order Butterworth filter with a cutoff frequency of 20 Hz. EMG data were adapted over stable 10 gait cycles, and the signal-averaging technique was used for calculation. The average amplitude of muscle activity for the first and second halves of stance phases in both the fixed and free conditions were calculated for each participant. Next, the average amplitude of muscle activity was calculated over 10 gait cycles in the fixed condition. Finally, the average amplitude of each stance phase in both the fixed and free conditions was normalized to the average amplitude of gait cycle for the fixed condition (normalized gait cycle EMG: %GCEMG). These data were calculated using custom software in MATLAB R2017a (Mathworks, Inc., Natick, MA).

Statistical analyses

In our study, gait assessments were performed once a week, and measurements were repeated throughout the patient's hospital stay under consistent conditions. The individual differences in motor function among participants and the number of days after stroke onset could have introduced random effects on CoP parameters and muscle activity. Therefore, we used a linear mixed model that accommodated repeated measurements and missing values. The normality of residuals was evaluated after fitting every model, as described previously [20, 21].

First, to compare the effects of different ankle joint conditions on CoP parameters and muscle activity, CoP parameters and muscle activity were considered as dependent variables. The ankle joint condition was considered as a fixed effect, whereas factors such as participant, assistance condition, days since stroke onset, FMAs, and TIS were considered as random effects. Second, to confirm whether CoP parameters and muscle activity were influenced by physical function, we examined the relationship between physical functional characteristics and changes in CoP parameters or muscle activity under two conditions. The degree of change was calculated as described below, by subtracting the value in the free condition from that in the fixed condition for each parameter. Changes in CoP parameters or muscle activity were considered as dependent variables. The fixed effects were FMAs or TIS, whereas the random effects included participant, assistance condition, and days since stroke onset. Statistical significance was assumed at $p < 0.05$, and effect sizes for ankle joint condition comparisons were calculated using Cohen's d. All statistical analyses were performed using R software version 3.6.1 (R Foundation for Statistical Computing, Vienna, Austria).

Results

Participant characteristics

The participant demographics, clinical data, and breakdown of each trial are shown in Table 1. The average first measurement date was 16.6 ± 7.4 days after stroke onset, the first measured FMAs was 6.8 ± 5.5 points, and the first TIS was 4.5 ± 4.2 points. Among the 14 participants, 5 could only complete one measurement because of early transfer to another hospital or delayed start of gait training due to their general condition. All participants scored 0 points in the Functional Ambulation Category.

Change in each parameter due to ankle joint difference

Center-of-pressure

The results of the two comparison conditions, namely the AP_CoP, ML_CoP, loading force, and percentage of load time, are presented in Table 2. The AP_CoP was significantly higher in the free condition than in the fixed condition ($p = 0.011$). However, no significant differences were observed between the two conditions for the other CoP parameters.

Muscle activation

The results of the two competition conditions for muscle activity are shown in Table 2. No significant differences were observed in the muscle activity of the GCL for the first half of stance phases ($p = 0.316$), or that of the SOL for the first and second halves of stance phases ($p = 0.316$, $p = 0.077$) between the two conditions. In contrast, the muscle activity of the GCL

Table 1 Demographic characteristics of participants

ID	Paretic side	Age (years)	Sex	Weight (kg)	Date of first measurement (day)	Initial FMAs	Initial TIS	Breakdown of each trial
1	Left	68	Female	51	35	4	0	5
2	Right	81	Female	36.5	26	20	12	1
3	Right	84	Female	44.8	10	5	4	2
4	Left	61	Female	42.5	13	0	0	4
5	Right	65	Female	45.4	6	0	8	4
6	Left	55	Male	56.9	9	6	10	1
7	Right	79	Female	49.1	16	8	0	2
8	Left	80	Male	54.3	18	14	0	1
9	Left	59	Male	77.3	20	9	6	2
10	Left	54	Male	56.7	22	7	8	2
11	Right	85	Female	62.2	15	9	7	1
12	Right	76	Female	78.4	16	10	2	1
13	Left	51	Female	47.8	15	0	0	3
14	Right	46	Male	79.6	12	4	6	2

FMAs, Fugl–Meyer Assessment of Lower Extremity Synergy Score; TIS: Trunk Impairment Scale

Table 2 Comparison of the two conditions in CoP path, loading force, and percentage of loading time

Gait parameters	Fixed*, n = 31	Free*, n = 31	Mean difference	95% CI	Effect size†	p-value
CoP path						
AP_CoP (mm)	**34 [16, 52]**	**41 [18, 89]**	**10.8**	**2.6, 19.1**	**0.79**	**0.011**
ML_CoP (mm)	8 [6, 13]	10 [7, 21]	1.9	− 0.81, 4.7	0.42	0.159
Loading force						
Maximum loading (N)	215 [140, 288]	206 [148, 277]	− 24	− 56.9, 8.9	− 0.43	0.149
Average loading (N)	144 [104, 183]	141 [101, 194]	− 12.4	− 34.4, 9.5	− 0.34	0.26
Percentage of loading time						
Heel (%)	81 [46, 97]	71 [42, 98]	0.71	− 4.0, 5.5	0.08	0.764
Hind foot (%)	9 [0, 33]	16 [0, 32]	0.02	− 5.8, 5.9	0.002	0.993
Medial forefoot (%)	0 [0, 0]	0 [0, 7]	2.6	− 1.3, 6.5	0.37	0.196
Lateral forefoot (%)	0 [0, 0]	0 [0, 0]	− 1.1	− 4.7, 2.5	− 0.18	0.537
Muscle activity						
First GCL (%GCEMG)	152 [131, 172]	161 [130, 187]	5	− 4.9, 14.9	0.26	0.316
Second GCL (%GCEMG)	**81 [72, 94]**	**83 [70, 96]**	**6.4**	**0.1, 12.6**	**0.54**	**0.043**
First SOL (%GCEMG)	165 [149, 177]	165 [154, 182]	4.9	− 4.8, 14.6	0.68	0.316
Second SOL (%GCEMG)	88 [79, 112]	87 [74, 142]	6.8	− 0.7, 14.5	0.47	0.077

CI, confidence interval; CoP, center-of-pressure; AP, anteroposterior; ML, mediolateral; GCL, gastrocnemius lateralis; SOL, soleus

In one participant, positive estimates indicated larger values for each parameter under free conditions. Bold p-values indicate a significant difference between the fixed and free conditions. The sample size represents the number of trials

* Median [interquartile range], † Cohen's d

for the second half of stance phases was significantly increased in the free condition compared with that in the fixed condition (p = 0.043). A typical example of an individual between the fixed and free conditions is shown in Fig. 2.

Relationship between physical function and changes in CoP parameters or muscle activity under free and fixed conditions

The relationship between physical function and changes in CoP parameters or muscle activity is shown in Table 3.

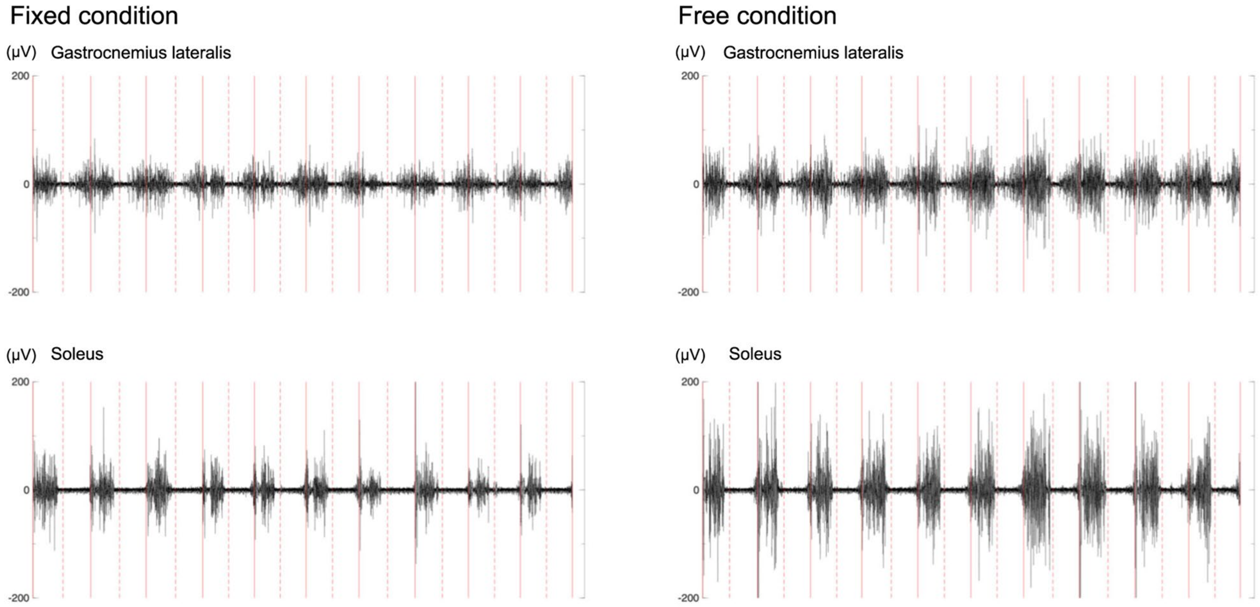

Fig. 2 Typical electromyography (EMG) amplitudes during the gait cycle between the fixed and free conditions of ankle-knee-foot orthosis (KAFO). The solid red line indicates initial contacts, and the dashed red line indicates toe off

Positive coefficients indicate that the better the physical function, the greater the gait parameter value under the free condition. The FMAs was positively correlated with changes in the AP_CoP (p = 0.004), and the TIS was positively correlated with changes in the AP_CoP (p = 0.008). In addition, the TIS was positively correlated with changes in the percentage of medial forefoot loading time in the CoP (p < 0.001). Figure 3 shows a typical example of an individual. The AP_CoP and percentage of medial forefoot loading time decreased in the fixed condition compared with those in the free condition for participant 9 (FMAs: 9 points, TIS: 6 points). Conversely, the AP_CoP and percentage of medial forefoot loading time increased in the fixed condition compared with those in the free condition for participant 4 (FMAs: 0 points, TIS: 0 points). Individuals with lower FMAs and TIS had an increased AP_CoP and percentage of medial forefoot loading time in the fixed condition.

Discussion

This study investigated the effects of different degrees of freedom of the ankle joint in a KAFO on CoP parameters and muscle activity of the lower limb on the paretic side. In addition, we examined the relationship between changes in each parameter and physical function. The results revealed that the AP_CoP and muscle activity in the GCL increased in the free ankle dorsiflexion. Furthermore, the FMAs and TIS were positively correlated with the AP_CoP. A positive relationship was also found between the TIS and percentage of medial forefoot loading time in the CoP. Moreover, individuals with lower FMAs and TIS exhibited a decrease in the AP_CoP in the free condition compared with that in the fixed condition.

KAFO-induced ankle dorsiflexion increased the AP_CoP and muscle activity in the GCL during the second half of the stance phase. Assisted gait training using a KAFO is conducted for automatic gait control adaptive processes in individuals with subacute stroke [22]. This approach facilitates the anterior path of the CoP, promotes loading on the medial forefoot, and enhances muscle activity in the lower extensor group. Alternate leg movements, coupled with afferent input from load receptors, have been reported to induce locomotor-like muscle activity in individuals with a spinal cord injury [23]. Alternative gait training for individuals with subacute severe hemiplegia has been reported to improve gait function via proprioceptive receptor input [4]. In this study, the knee joint fixation effect of the KAFO enabled the formation of an inverted pendulum motion, as large hip flexion and extension exercises were conducted during gait measurement. In general, participants were induced to do more dorsiflexion at the ankle joint when the KAFO was the free ankle dorsiflexion, as it does not impede the forward tilt of the shank during terminal stance. The dorsiflexion of the ankle joint using KAFO

Table 3 Relationship between physical function and changes in CoP parameters or muscle activity

Gait parameters	FMAs			TIS		
	Estimated value	95% CI	p-value	Estimated value	95% CI	p-value
CoP path						
AP_CoP (mm)	**2.3**	**0.8, 3.8**	**0.004**	**2.9**	**0.9, 5.0**	**0.008**
ML_CoP (mm)	0.2	– 0.3, 0.8	0.357	0.4	– 0.3, 1.1	0.281
Loading force						
Maximum loading (N)	3.1	– 2.8, 9.0	0.277	3.1	– 4.6, 10.8	0.402
Average loading (N)	0.8	– 3.2, 4.8	0.673	0.6	– 4.6, 5.8	0.806
Percentage of loading time						
Heel (%)	– 0.9	– 1.9, 0.1	0.072	– 1.1	– 2.4, – 0.1	0.079
Hind foot (%)	0.1	– 1.3, 1.5	0.869	– 0.3	– 2.1, 1.4	0.662
Medial forefoot (%)	0.6	– 0.01, 1.2	0.052	**1.1**	**0.5, 1.7**	**< 0.001**
Lateral forefoot (%)	– 0.03	– 0.7, 0.6	0.917	0.1	– 0.7, 1.0	0.675
Muscle activity						
First GCL (%GCEMG)	– 1.2	– 3.2, 0.7	0.217	– 1.4	– 3.9, 1.1	0.259
Second GCL (%GCEMG)	0.5	– 0.8, 1.9	0.408	0.6	– 1.0, 2.4	0.446
First SOL (%GCEMG)	– 0.6	– 2.8, 1.6	0.59	– 1.3	– 4.2, 1.4	0.322
Second SOL (%GCEMG)	0.05	– 1.8, 1.9	0.961	0.6	– 1.7, 2.9	0.606

FMAs, Fugl–Meyer Assessment of Lower Extremity Synergy Score; TIS: Trunk Impairment Scale; CI: confidence interval; CoP, center-of-pressure; AP, anteroposterior; ML, mediolateral; GCL, gastrocnemius lateralis; SOL, soleus

Bold p-values indicate significant relationships. Positive values indicate a positive relationship between physical function and CoP parameters or muscle activity

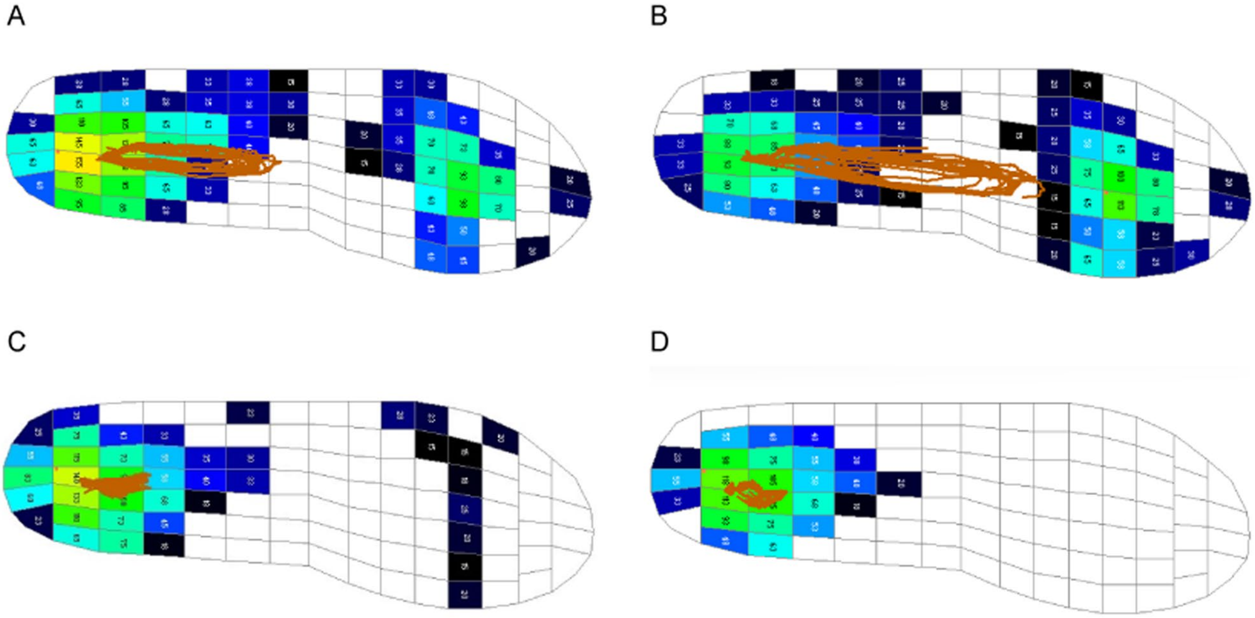

Fig. 3 Typical difference between the two conditions in the anterior–posterior displacement of center-of-pressure (AP_CoP) and percentage of the medial forefoot loading time according to the Fugl–Meyer Assessment of Lower Extremity Synergy Score (FMAs) and Trunk Impairment Scale (TIS). The color of each area indicates increasing pressure in the following order: white (unloaded area), black, blue, light blue, green, yellow, and red. The brown line indicates the CoP trajectory. Fixed condition (**A**) and free condition (**B**) for the first trial of participant 9 (individual with left hemiplegia, FMAs: 9 points, TIS: 6 points), and fixed condition (**C**) and free condition (**D**) for the first trial of participant 4 (individual with left hemiplegia, FMAs: 0 points, TIS: 0 points)

induced extension of the AP_CoP. The possibility remains that the increased internal ankle plantarflexion moment corresponds to the external ankle dorsiflexion moment due to increasing pressure in the forefoot, which might influence muscle activity in the GCL. In addition, forced ankle plantar flexor movement has been confirmed to decrease muscle activity in the triceps surae during terminal stance [24]. Therefore, it is important to induce ankle dorsiflexion movement during the stance phase and activate Golgi tendon afferents, which serve as load receptors for the ankle dorsiflexor muscles. In particular, muscle activity in the gastrocnemius during the terminal stance phase is suggested to promote the forward path of the AP_CoP and contribute to the propulsive force in the forward direction [25]. Thus, this study proposes the need to induce muscle activity in the gastrocnemius by promoting forefoot loading through ankle dorsiflexion mobility in the KAFO during assisted gait training for individuals with subacute severe hemiplegia.

In our study, individuals with higher FMAs and TIS showed an increase in the AP_CoP under free conditions. In addition, the TIS demonstrated a positive relationship with the percentage of medial forefoot loading time in the CoP. In a previous study, the higher AP_CoP reflected more trunk progression and better gait performance [6]. Individuals with good trunk function might show increased step length on the nonparetic side or trailing limb angle expansion on the paretic side by maintaining an upright trunk position during the terminal stance phase on the paretic side. However, individuals who exhibited a decrease in the AP_CoP and percentage of loading time on the medial forefoot, which are indicators of forefoot loading under free conditions, exhibited reduced physical function. In the early stance phase on the paretic side, the braking force should be controlled while shifting the center of gravity forward and upward to form an inverted pendulum motion. However, individuals with low trunk function may experience increased braking force and restricted forward movement [26] of the CoP due to the posterior tilt of the pelvis and anterior tilt of the trunk during assisted gait. Future research is required to fully understand the mechanisms underlying the physical function associated with CoP parameters and muscle activity for individuals with severe hemiplegia during gait using a KAFO.

Taken together, these findings suggest that allowing unrestricted dorsiflexion of the ankle joint with KAFO may facilitate functional reconstruction of the paretic lower limb; however, the ankle joint condition may be adjusted according to physical function of individuals. Individuals with lower trunk function and severe paralysis, such as difficulty in static sitting and conjugate movements, may require additional training to improve trunk function and lower limb paralysis in addition to gait training with KAFO. Adjusting the KAFO ankle joint condition according to physical function may serve as a treatment strategy for achieving early walking independence.

This study has some limitations. First, as a retrospective study, it is subject to potential bias, challenges of establishing causality, and inability to account for all potential confounding variables. Second, the amount of physical assistance may influence our results. Although the study was limited to two physiotherapists for gait measurement to minimize assistance errors, the amount of physical assistance was not always consistent. Third, kinematic parameters such as hip extension angle, which is considered to influence muscle activity and forefoot loading, were not measured. Finally, the effects of higher brain dysfunction were not considered. Genthon et al. reported that unilateral spatial neglect affected load asymmetry [27]. Therefore, future studies should investigate the relationship between higher brain dysfunction and CoP parameters, as well as muscle activity.

Conclusions

This study demonstrated that both the AP_CoP and muscle activity in the GCL increased in the free condition of the ankle joint with a KAFO. Furthermore, in individuals requiring a KAFO during gait, those with a high level of physical function who have had severe hemiplegia may benefit from promoting forefoot loading under ankle dorsiflexion induction. In contrast, individuals with a low level of physical function may benefit from promoting forefoot loading under limited ankle dorsiflexion. These findings indicate that the degree of freedom in the ankle joint should be adjusted according to improvements in trunk function or paralysis stage, and orthotic conditions should be set to promote forefoot loading to facilitate functional recovery of gait performance.

Abbreviations

CoP	Center-of-pressure
KAFO	Knee–ankle–foot orthosis
GCL	Gastrocnemius lateralis
FMAs	Fugl–Meyer Assessment of Lower Extremity Synergy Score
TIS	Trunk Impairment Scale
AP_CoP	Anterior–posterior displacement of the CoP
ML_CoP	Mediolateral displacement of the CoP
EMG	Electromyography
SOL	Soleus
CI	Confidence interval

Acknowledgements

This work was supported by "the Strategic Project for Proofreading and Submission Support of International Academic Papers" by Kansai Medical University.

Author contributions

AO and YC conceived and designed the study. AO and NM acquired the data. AO, YC, TK, TK and NM analyzed and interpreted the data. AO, YC, KM, MW and KH wrote the manuscript. All authors reviewed and approved the fnal manuscript.

Funding

This work was partially supported by the JSPS KAKENHI (grant numbers 23K19909 and 23K16560).

Availability of data and materials

The datasets used and/or analyzed during this study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate

This study was approved by the Ethics Committee of Kansai Medical University (approval number 022150).

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

Author details

[1]Department of Physical Medicine and Rehabilitation, Kansai Medical University Hospital, 2-3-1 Shinmachi, Hirakata, Osaka 573-1010, Japan. [2]Faculty of Rehabilitation, Kansai Medical University, 18-89 Uyamahigashimachi, Hirakata, Osaka 573-1136, Japan. [3]Department of Physical Medicine and Rehabilitation, Kansai Medical University, 2-5-1 Shinmachi, Hirakata, Osaka 573-1191, Japan.

Received: 28 March 2024 Accepted: 24 July 2024

References

1. Preston E, Ada L, Dean CM, Stanton R, Waddington G. What is the probability of patients who are nonambulatory after stroke regaining independent walking? A systematic review. Int J Stroke. 2011;6:531–40.
2. Pohl M, Werner C, Holzgraefe M, Kroczek G, Mehrholz J, Wingendorf I, et al. Repetitive locomotor training and physiotherapy improve walking and basic activities of daily living after stroke: a single-blind, randomized multicentre trial (DEutsche GAngtrainerStudie, DEGAS). Clin Rehabil. 2007;21:17–27.
3. Sato K, Inoue T, Maeda K, Shimizu A, Murotani K, Ueshima J, et al. Early wearing of knee-ankle-foot orthosis improves functional prognosis in patients after stroke. J Stroke Cerebrovasc Dis. 2022;31:106261.
4. Abe H, Nishiyama K, Yamamoto Y, Okanuka T, Yonezawa Y, Matsumoto K. Impact of alternate gait training using knee–ankle–foot orthoses with oil damper ankle hinge in patients with subacute severe hemiplegia. Brain Sci. 2021;11:1430.
5. Pearson KG. Role of sensory feedback in the control of stance duration in walking cats. Brain Res Rev. 2008;57:222–7.
6. Choi H, Kim WS. Anterior-posterior displacement of center of pressure measured by insole foot pressure measurement system in subacute recovery stage of post-stroke hemiplegia. Technol Health Care. 2018;26:649–57.

7. Echigoya K, Okada K, Wakasa M, Saito A, Kimoto M, Suto A. Changes to foot pressure pattern in post-stroke individuals who have started to walk independently during the convalescent phase. Gait Posture. 2021;90:307–12.
8. Chiu MC, Wu HC, Chang LY, Wu MH. Center of pressure progression characteristics under the plantar region for elderly adults. Gait Posture. 2013;37:408–12.
9. Tyson SF, Sadeghi-Demneh E, Nester CJ. A systematic review and meta-analysis of the effect of an ankle-foot orthosis on gait biomechanics after stroke. Clin Rehabil. 2013;27:879–91.
10. Nolan KJ, Yarossi M. Preservation of the first rocker is related to increases in gait speed in individuals with hemiplegia and AFO. Clin Biomech. 2011;26:655–60.
11. Mulroy SJ, Eberly VJ, Gronely JK, Weiss W, Newsam CJ. Effect of AFO design on walking after stroke: impact of ankle plantar flexion contracture. Prosthet Orthot Int. 2010;34:277–92.
12. Craig LE, Wu O, Bernhardt J, Langhorne P. Predictors of poststroke mobility: systematic review. Int J Stroke. 2011;6:321–7.
13. Smith MC, Barber PA, Stinear CM. The TWIST algorithm predicts time to walking independently after stroke. Neurorehabil Neural Repair. 2017;31:955–64.
14. Arene N, Hidler J. Understanding motor impairment in the paretic lower limb after a stroke: a review of the literature. Top Stroke Rehabil. 2009;16:346–56.
15. Isho T, Usuda S. Association of trunk control with mobility performance and accelerometry-based gait characteristics in hemiparetic patients with subacute stroke. Gait Posture. 2016;44:89–93.
16. Verheyden G, Nieuwboer A, Mertin J, Preger R, Kiekens C, De Weerdt W. The Trunk Impairment Scale: a new tool to measure motor impairment of the trunk after stroke. Clin Rehabil. 2004;18:326–34.
17. Ramanathan AK, Kiran P, Arnold GP, Wang W, Abboud RJ. Repeatability of the Pedar-X in-shoe pressure measuring system. Foot Ankle Surg. 2010;16:70–3.
18. Hermens HJ, Freriks B, Disselhorst-Klug C, Rau G. Development of recommendations for SEMG sensors and sensor placement procedures. J Electromyogr Kinesiol. 2000;10:361–74.
19. Mizelle C, Rodgers M, Forrester L. Bilateral foot center of pressure measures predict hemiparetic gait velocity. Gait Posture. 2006;24:356–63.
20. Dean JC, Bowden MG, Kelly AL, Kautz SA. Altered post-stroke propulsion is related to paretic swing phase kinematics. Clin Biomech. 2020;72:24–30.
21. Swaminathan K, Porciuncula F, Park S, Kannan H, Erard J, Wendel N, et al. Ankle-targeted exosuit resistance increases paretic propulsion in people post-stroke. J Neuroeng Rehabil. 2023;20:85.
22. Beyaert C, Vasa R, Frykberg GE. Gait post-stroke: pathophysiology and rehabilitation strategies. Neurophysiol Clin. 2015;45:335–55.
23. Kawashima N, Nozaki D, Abe MO, Akai M, Nakazawa K. Alternate leg movement amplifies locomotor-like muscle activity in spinal cord injured persons. J Neurophysiol. 2005;93:777–85.
24. Bo NJ. Motoneuronal drive during human walking. Brain Res Rev. 2002;40:192–201.
25. Francis CA, Lenz AL, Lenhart RL, Thelen DG. The modulation of forward propulsion, vertical support, and center of pressure by the plantarflexors during human walking. Gait Posture. 2013;38:993–7.
26. Tamaya VC, Wim S, Herssens N, Van de Walle P, Willem DH, Steven T, et al. Trunk biomechanics during walking after sub-acute stroke and its relation to lower limb impairments. Clin Biomech. 2020;75:105013.
27. Genthon N, Rougier P, Gissot AS, Froger J, Pélissier J, Pérennou D. Contribution of each lower limb to upright standing in stroke patients. Stroke. 2008;39:1793–9.

Publisher's Note