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Static Ankle-foot Orthosis Improves Static Balance and Gait Functions in Hemiplegic Patients after Stroke

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Abstract—**The purpose was to examine the effects of static anterior and posterior ankle-foot orthoses (AAFOs & PAFOs) using with regular shoes on improving static and gait function in patients recovering from stroke. Static and dynamic balance control were measured under four conditions: barefeet, wearing regular shoes only, and wearing regular shoes with AAFOs or PAFOs. The results indicated that wearing regular shoes markedly increased the center of pressure (CoP) sway ($p < 0.05$) in static standing conditions. Both AAFOs and PAFOs decreased CoP sway and increased bilateral limb loading symmetry compared to barefoot and wearing shoes alone ($p < 0.05$). PAFOs decreased CoP sway more than AAFOs ($p > 0.05$) and also boosted medial-lateral weight shifting more effectively ($p < 0.05$). Both types of AFOs increased walking efficiency but influenced the roll-over shape of the CoP adversely during level walking. The conclusions are that both AAFOs and PAFOs improved static and dynamic balance control when they were used with regular shoes and PAFOs appeared to be more efficient than AAFOs. Shoes worn daily with AFOs is a key consideration influencing balance control in stroke patients. However, AFOs with static design impeded the function of the three rocker systems of the foot during ambulation.**

I. Introduction

Ankle-foot control mechanism is one of the most important components for balance control while standing and walking. An estimated 20% of stroke survivors have difficulties in controlling their ankle-foot complex adequately, which causes deficits in standing balance and gait functions.[1] When standing, stroke patients usually load more over their non-paretic limb than the paretic one. Therefore, increased central commands for balance control is needed; this causes increased center of pressure (CoP) sway.[2] Furthermore, CoP sway was found to be more pronounced in medial-lateral (ML) than anterior-posterior (AP) direction in stroke survivors due to impaired bilateral limb-loading-unloading mechanism. During level walking, stroke patients with ankle-foot control problems often demonstrate inadequate ankle dorsiflexion during the midswing phase, inappropriate weight acceptance with the lateral border of the foot dropping during the terminal swing and insufficient push-off during the late stance; in combination, these deficits lead to a slow walking speed and short step length.[3] Balance control deficits have been reported to be associated with an increased risk of falls and a decrease in functional independence,[4] which could lead to re-hospitalizations due to fractures or increased needs for medical or family care. Therefore, reestablishing balance control during standing and walking is a priority during rehabilitation phase of stroke patients.

The conventional approach to address problems associated with inadequate balance control caused by impaired ankle-foot control is the application of a traditional ankle-foot orthosis (AFO) with a posterior shelf that extends from the mid-calf to the metatarsal area of the foot. The device is a static design, which ensures that the ankle is stabilized at 90° of dorsiflexion and the foot is positioned with 0° rotation around the sagittal axis. Use of the posterior AFO (PAFO) aims to rebuild ankle-foot stability in both the AP and ML dimensions and is hypothesized to improve balance control during standing and walking.[5] Some investigators agreed that PAFOs improve static standing balance by either reducing CoP sway or increasing bilateral limb loading symmetry,[5] but others have argued that these effects were only effective for patients in the acute post-stroke stage.[5] Researchers also suggested the CoP sway while standing was less with the PAFO than without the device.[6] The effects of PAFOs on gait parameters was addressed by several studies and the results revealed fasten walking speed, and generate a more intense cadence, longer stride and better gait symmetry.[5] Some researchers have suggested that PAFOs, although promoting toe clearance at the initial and terminal stances while walking, might inhibit sensory feedback from the heel needed for integrated ankle-foot control for balance maintenance and thus might hinder the active and passive ankle-foot control mechanism dynamic CoP progression during walking. [2]

Bivalve anterior AFOs (AAFOs), first designed by Wu et al., have an anterior shelf along the dorsal surface of the tibia that extends to the metatarsal area and a transverse bar runs across the volar surface of the metatarsal head at the midfoot [7,8]. The intention of AAFOs design, the same as PAFOs, was to improve ankle-foot stability and gait patterns. The bivalve design was hypothesized to be able to provide stronger mechanical forces than single shelf PAFOs in resisting strong inverse torque over the midfoot as a result of muscle spasticity. Furthermore, the sensory feedback from the sole and the heel of the foot necessary for integrated balance control during standing and walking is preserved with AAFOs. AAFOs is less time consuming in fabrication than PAFOs. Therefore, physicians preferred AAFOs than PAFOs for stroke patients. However, the effects of AAFOs on bilateral weight bearing symmetry and CoP sway was not

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conclusive. [7] No study compared the effects between AAFOs and PAFOs on standing balance and gait functions.

Regular shoes was found to affect gait in humans comparing with walking barefeet. AFOs are usually worn with shoes, [8] but the integrated effects of shoes and AFOs has only been examined by one paper. The results showed that both PAFOs and regular shoes increased step length, walking velocity and cadence and shoes can contribute to the effects of PAFOs on gait parameters. How AFOs affect standing and walking balance control when worn in shoes has never been investigated.

The purpose of this study was to examine the effect of static anterior and posterior ankle-foot orthoses (AAFOs & PAFOs) using with regular shoes on improving static balance and gait function in patients recovering from stroke. In addition to frequent used parameters defining standing and walking balance control such as CoP sway and gait parameter, the roll-over pattern of CoP was measured to demonstrate how static AFOs design affects ankle-foot mechanism during walking. The results of this study would be important references for clinicians advising the daily use of AFOs for post-stroke patients to improve daily living safety.

II. Methods

A. Subjects

Fifteen patients that suffered stroke with residual hemiparesis were recruited. The demographic data of the participats is showed at Table 1.

TABLE I. DEMOGRAPHIC, BASELINE BALANCE AND MUSCULAR CONDITION DATA FOR THE STUDY PARTICIPANTS ABLE TYPE STYLES

Source	Data
Number of participants (n)	15
Sex (male : female)	11 : 4
Age range (year)	38~71
Body weight range (kg)	46.5~73
Body height range (cm)	152~169
Duration since onset range (month)	1~20
Side of paresis (right : left)	11 : 4
Berg Balance Scale static score range	12~24
Berg Balance Scale dynamic score range	16~30
Modified Ashworth Score (ankle dorsiflexor) range	0~2
Modified Ashworth Score (plantar flexor) range	0~3
Lower limb Brunnstrom Stage range	3~4

Note: The data with * sign indicated "average ± SD (range)".

B. Procedures and Instruments

Participants who fulfilled the inclusion criteria were scheduled for measurements after providing written informed consent. All data were recorded or tested by registered occupational therapists that were blinded to the research objectives. Low-temperature thermosplastic AAFOs and PAFOs were then custom-molded by a single licensed occupational therapist. The manufacture of all AFOs followed standardized clinical procedures.

The measurement of standing balance and gait function was arranged after one week of adaptation to AFOs for daily use. Standing balance was measured when the patients were instructed to stand on a 0.5-meter long pressure mat (Footscan, Belgium, sampling rate: 100 Hz), while looking straight ahead and resting their arms in a neutral position along the side of the body; the standing posture was maintained as still as possible for 30 seconds. Balance at two standing posture was measured: shoulder-width standing and tandem standing with the affected limb posteriorly. Gait parameters and CoP roll-over patterns were measured when the subjects were walking at a self-selected and comfortable pace along a 10-meter walkway with the pressure mat in the middle. Four foot-switches were attached outside the soles of shoes at the heel, great toe, and 1st and 5th metatarsal heads to define the gait cycle for parameter calculations. The CoP roll-over pattern was exported from the 3-D data processer of the pressure mat for qualitative analysis. A third task, which required the subjects to shift their body weight as far as possible anteriorly, posteriorly, medially, and laterally with both feet set shoulder-width apart, was used to measure the effect of AFOs on stability limits during voluntary weight shifting in the AP and ML directions. All the tasks were performed under four experimental conditions: barefoot, wearing shoes only, wearing shoes and AAFOs, or wearing shoes and PAFOs. The shoes used in this study were made by soft fabrics at shoe upper and with rubber sole. All measurement conditions were randomized to eliminate possible order effects.

C. Data Processing

The parameters in this study (CoP total path excursion, and maximum CoP displacement in the anterior-posterior and medio-lateral directions bilateral weight bearing difference (BWBD) was calculated by customized written program with the data output by the instrument (Rsscan pressure measurement system).

Gait parameters, including walking speed (WS), cadence and step length (SL), were defined by a desk-top workstation based on the data derived from four foot-switches. The average performance over three walking trials was analyzed. Characteristics of CoP roll-over shapes (Figure1) during walking were extracted and qualitatively analyzed to demonstrate the effects of AFOs on control of the ankle-foot complex during walking. The CoP roll-over shape under the supporting feet was frequently used to indicate the function of ankle-foot mechanism during stance phase of a gait cycle,[38-40] and were shown to be sensitive to therapeutic interventions aimed at improving ankle-foot control mechanism.[38,40]

D. Statistical Analysis

Descriptive analysis was used to describe the demographic characteristics of all patients. Repeated measure two-way analysis of variance (ANOVA; standing postures and experimental conditions) was used to examine the effects of experimental conditions on standing balance control. When the interaction effects between stance posture (SP) and footwear conditions (FW) were significant, the simple main effects of FW were analyzed via one-way ANOVA. When the interactions between effects were not significant and the main effects of FW were significant, pair-wise comparisons were used to show the difference between any two footwear conditions. Repeated measures one-way ANOVA was used to investigate the effects of footwear conditions on stability limitations and walking performance. Post-hoc paired *t*-tests were used to examine the difference between any two footwear conditions. A commercialized statistical software package was used for all statistical analysis and the level of statistical significance was set at $p < 0.05$.

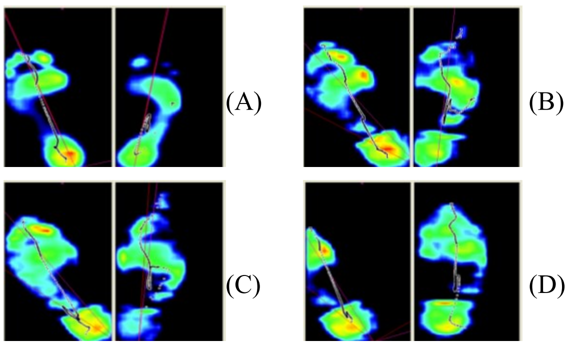

Figure 1. CoP Roll-over pattern under individual foot of a stroke patient with right-sided hemiparesis in four test conditions: (A) barefoot walking, (B) walking with shoes only, (C) walking with shoes + AAFOs, and (D) walking with shoes + PAFOs.

III. RESULTS

A. Static standing balance control

There is no interaction between standing postures and foot-wear conditions on static standing balance control, indicating that stance postures and foot-wear conditions affect static standing balance control independently(Table 2,SP x FW CoP TPE, $p = 0.388$; SP x FW for BWBD: $p = 0.538$). The main effects of foot –ware condition on CoPTPE was significant (Table 2, $p = 0.002$) and on BWBDS is near significant (Table 2 p = 0.097). In order to showed pure foot-ware effects, paired t-tests for each stand posture was conducted and the results showed that CoPTPE increased significantly when wearing shoes only Subsequent analysis of the effects of footwear conditions in each standing posture shows that affect CoP TPE significantly. Post-hoc paired *t*-tests demonstrates that CoPTPE increases significantly in conditions of wearing only shoes compared with conditions of barefoot ($p = 0.001$). When wearing shoes and PAFOs and/or AAFOs, the CoPTE decreased significantly (AAFOs, $p = 0.005$; PAFOs, $p = 0.037$). However, the effects of PAFOs and AAFOs on CoPTPE did not differ ($p = 0.571$) with the tendency that shoes +AAFOs condition tends to induce a larger CoPTPE than shoes + PAFOs condition did.

FW conditions did not affect BWBD while standing ($p = 0.097$). Paired *t*-testing showed that only PAFOs significantly reversed the adverse effects of stroke and shoes on BWBD ($p = 0.016$, $p = 0.045$) but the effects of PAFOs and AAFOs on BWBD did not differ significantly ($p = 0.327$). The descriptive data further demonstrated that the shoes in this study reduced the load on the paretic limb more than barefoot conditions, while both PAFOs and AAFOs increased the load on the paretic limb. Furthermore, the PAFO tended to facilitate more symmetrical limb loading by increasing the paretic limb loading compared with the AAFO.

TABLE II. REPEATED MEASURES TWO-WAY ANALYSIS OF VARIANCE FOR COP MEASURES OF STATIC STANDING BALANCE.

Source	SS	DF	MS	*F*	*p*
CoP total traveling path excursion (TPE)					
FW	94.574	3	31.525	6.044	0.002**
SP	728.302	1	728.302	21.459	0.000**
FW × SP	10.067	3	3.356	1.032	0.388
Bilateral limb weight bearing difference (BWBD)					
FW	1419.679	3	473.226	2.243	0.097
SP	7011.474	1	7011.474	5.255	0.038*
FW × SP	538.867	2	179.622	0.734	0.538

* $p < 0.05$; Abbreviations: FW = footwear conditions; SP = stance postures; × = interactions.

B. Dynamic balance control during voluntary weight shifting

The data showed that FW conditions significantly influenced the ML stability limitation (Table III, MML, $p = 0.003$) but did not affect the stability limitation in the AP direction. The post-hoc paired *t*-test showed that PAFOs significantly increased MML ($p = 0.008$, 0.014, respectively), compared to barefoot and shoes only conditions. Furthermore, the effects of PAFOs and AAFOs on MML was significantly different ($p = 0.015$), which indicated that PAFOs were more effective in increasing MML than AAFOs.

TABLE III. REPEATED MEASURES ONE-WAY ANALYSIS OF VARIANCE FOR MEASURES OF DYNAMIC STANDING STABILITY AND AMBULATION.

Source	SS	DF	MS	*F*	*p*
MAP	0.148	3	0.049	0.075	0.973
MML	43.529	3	14.510	5.396	0.003**
WS	0.079	3	0.026	11.516	0.000**
Cadence	220.638	3	73.546	8.288	0.000**
SL	0.017	3	0.006	14.796	0.000**

Abbreviation notation: MAP: maximum CoP displacement in the anterior-posterior direction, MM: maximum CoP displacement in the medio-lateral direction, WS: walking speed, SL: step length.

C. Gait functions

The results showed that walking performance under the four FW conditions were significantly different (Table III; WS, cadence, and SL, $p < 0.001$). The post-hoc paired *t*-test analysis showed that both PAFOs and AAFOs consistently and significantly influenced the WS, cadence, and SL ($p < 0.05$). The descriptive data demonstrated that both PAFOs and AAFOs effectively increased walking efficacy of stroke patients in comparison with the other two conditions, but the effects between PAFOs and AAFOs did not differ significantly ($p = 0.426$, 0.275, 0.159, respectively).

D. CoP roll-over pattern while walking

Figure 1 illustrated the CoP roll-over shape of a typical patient with right-sided hemiplegia. When the patient walked barefoot, the CoP began at the heel but stopped at the midfoot. When the patients were wearing shoes only, the CoP roll-over pattern was notably different from barefoot walking as a result of the increased contact of the forefoot, but decreased heel contact, with the ground. Furthermore, PAFOs and AAFOs increased the duration of contact between the sole and the ground, and the PAFOs aligned the CoP with the foot axis while the AAFOs shifted the CoP laterally from the foot axis. Regardless of whether PAFOs or AAFOs were used with shoes, the progression of the CoP was markedly inhibited compared with the straight forward progression pattern observed in non-paretic limb.

IV. Discussions

The first finding that both PAFOs and AAFOs increased static standing balance by reducing CoP sway and increasing the loading under the paretic limb was consistent with previous studies [5] but contradicted with others.[7] The studies that favored the effects of AFOs on standing balance suggested that the static design of both PAFOs and AAFOs increased the passive stability of the ankle joint by limiting ankle movement in both the frontal and sagittal planes, possibly through a peripheral nerve ascending pathway triggered by proprioceptive inputs from the rigid ankle joint. Therefore, balance control that commences from the central nervous system (CNS) decreases, and CoP sway decreases as a consequence.

Our results further showed that shoes tended to increase CoP sway but PAFOs and AAFOs reversed this effect. The contradictory results of shoes on CoP sway during standing might be due to the different structure rigidity of the shoes used in this study and the study by Churchill et al.[9] However, our study failed to discriminate the effects of PAFOs and AAFOs on standing balance and rejected the hypothesis that AAFOs were superior to PAFOs in supporting the ankle-foot complex of stroke patients.[8] This could be due to the mild inverting muscle spasticity (Table 1), which mildly impairs ankle-foot control. The biomechanical advantages of AAFOs on inhibiting the inversion movement was not strong enough to discriminate between two designs in increasing standing balance. Finally, the shoes used in this study might have masked the efficacy of AFOs on standing balance. In future studies, patients with a sever inversion spasticity should be recruited to illustrate the effects of AAFOs in stabilizing the ankle-foot stability for standing stability. Furthermore, the effects of shoes with different degrees of firmness should be investigated to clarify the clinical recommendations regarding the choice of shoes to be worn with AFOs.

The results of this study further suggest that a static AFO design can help patients with postural control problems in dynamic tasks that require bilateral voluntary weight shifting [5] due to the effects of AFOs on increasing the stability of the impaired ankle-foot mechanism. The walking speed was, therefore, improved.[5] However, as suggested by several other studies[5,7], the static design of AFOs tended to prevent the re-establishment of ankle strategies when voluntary weight shifting is required for postural control. This occurs as a result of the limitation of the implementation of the heel-toe rocker motion during ambulation, which might explain the residual irregularity of the CoP trajectory found in this study (Figure 1).

The metatarsal bar under the forefoot area at the metatarsal head region in AAFOs, although it might increase the passive stability of the ankle-foot complex, could be the source of instability when AAFOs were used with shoes in this study. This might explain why stroke patients were more willing to shift the weight toward the paretic limb when wearing PAFOs than AAFOs. A lack of difference in gait parameters between both AFO designs might have been due to the fact that both AFOs provide similar ankle stability by keeping the ankle joint in a good alignment and giving external support. AAFOs appeared to induce a larger CoP deviation in the frontal plane than PAFOs, but both AFOs designs did not differ in terms of ankle motion restriction in the sagittal plane.

V. Conclusions

Both PAFOs and AAFOs improved the static standing stability and walking parameters for chronic stroke patients. PAFOs appeared to outperform AAFOs when used with shoes with a soft upper surface. CoP roll-over shapes revealed that static design AFOs could restrain ankle-foot rocker systems and thus impede the effects of AFOs on ambulation efficiently. Furthermore, shoes chosen to be used with static AFOs and the degrees of ankle spasticity may alter the functions of AFOs. Further research is required to clarify the effects of other frequently used footwear on the function of static AFOs. Specifically, rigidity analyses should be performed for the AFOs in three dimensions, as well as ground reaction force analyses during walking, to provide solid evidence regarding the influence of static plastic AFOs on dynamic postural control of patients after stroke.

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