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Improving Gait Stability in Stroke Hemiplegic Patients with a Plastic Ankle-Foot Orthosis

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Stroke is the leading cause of long-term disability, and many stroke patients have hemiparesis. Hemiparesis induces ankle-control disturbances and equinovarus deformity, leading to difficulty in walking and an increased risk for falling. Plastic ankle-foot orthosis (PAFO) is frequently prescribed to correct ankle joint alignment and increase walking speed and stride length during ambulation. While several studies have shown that PAFO improves gait parameters, such as stride length and walking speed, in hemiplegic patients, the effect of PAFO on gait stability remains unclear. We quantitatively assessed the effect of PAFO on gait stability in 16 hemiplegic stroke patients (mean age 55.9 ± 11.8 years; 5 female and 11 male subjects; and 11 hemorrhagic and 5 ischemic stroke) using an ink footprint record. Wearing PAFO significantly improved the stride length, step length on the unaffected and affected sides, step width, walking speed, step frequency and functional ambulation ability. The coefficient of variation (CV), as an index of stability of movement from trial to trial, provides a measure that defines motor skills for a given task. Unaffected-side step-length CV and step-width CV were significantly decreased, when using PAFO. Furthermore, the correlation was found only between unaffected-side step length and its CV. The decrease in CV indicates that PAFO improved gait stability. We concluded that in addition to providing a faster gait, PAFO improves gait stability during walking. Gait stability and gait efficiency need to be considered separately in evaluating the effects of ankle-foot orthosis on gait performance in hemiplegic patients.
——— gait analysis; ankle foot orthosis; gait stability; hemiplegia; coefficient of variation.
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Walking ability after stroke is often disrupted because of muscle weakness, spasticity, and impaired sensorimotor control. Yet regaining the ability to walk is a major goal during rehabilitation of stroke patients. Ankle-foot orthosis (AFO) is frequently prescribed for hemiplegic patients to correct ankle joint alignment, increase walking speed, and reduce energy expenditure during ambulation (Corcoran et al. 1970; Lehmann 1979; Lehmann et al. 1983; Mojica et al. 1988; Chen et al. 1999; Hesse et al. 1999; Tyson and Thornton 2001; Gok et al. 2003). Various AFO designs make use of metal as well as plastic materials. Because metal orthoses are heavy and have a poor cosmetic appearance, they have been gradually replaced by plastic AFO (PAFO) (Corcoran et al. 1970). Conventional PAFO, designed as a posterior leaf type, is fabricated by lamination or a vacuum-forming technique over a positive plaster model of the limb. PAFO is the most commonly prescribed AFO (about 70%) in Japan (Sumiya et al. 1993). Typically, AFO is used for patients with gait abnormalities such as foot drop during swing, mediolateral ankle instability, and insufficient push off during the stance phase of the gait cycle.

Results of previous studies have shown that AFO improves gait parameters such as stride length, cadence, and walking speed (Corcoran et al. 1970; Lehmann 1979; Lehmann et al. 1983; Mojica et al. 1988; Tyson and Thornton 2001; Gok et al. 2003). When Mojica and associates (1988) investigated the effects of PAFO on body sway in 8 hemiplegic post-stroke patients, they noted that when patients were not wearing a PAFO, the center of foot pressure moved toward the unaffected limb and body sway was excessive. With a PAFO, the center of foot pressure shifted to the mid-position and body sway decreased. Accordingly, PAFO clearly improves the static balance of standing hemiplegic patients (Mojica et al. 1988; Chen et al. 1999). However, the effect of PAFO on gait stability in hemiplegic patients has not been clarified.

Human ambulation is a repetitive rhythmic movement

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with considerable diversity. Ambulation pattern and movement constancy can be suboptimal in patients with motor impairment. Disturbances in gait pattern and its constancy can be assessed by the coefficient of variation (CV) of gait characteristics such as stride length, step length, and step width (Isaacs 1982; Gabell and Nayak 1984). Moreover, previous studies (Isaacs 1982; Gabell and Nayak 1984; Maruyama and Nagasaki 1992; Vieregge et al. 1997; Stolze et al. 2000; Brach et al. 2001) have proposed that variation in gait represents a measure of gait performance stability.

This study used a footprint method to quantitatively assess the effect of PAFO on gait stability in hemiplegic stroke patients.

Materials and Methods

Subjects

Sixteen hemiplegic patients who had been prescribed PAFO were recruited as subjects. Criteria for selection were (1) unilateral hemiparesis caused by cerebrovascular disease, (2) ability to walk at least 8 m, 4 times bare feet without external support except from a cane, (3) ability to follow simple verbal commands or instructions [functional independence measure (FIM; Fiedler and Granger 1996), comprehension score of 3 points or greater], (4) freedom from neglect phenomena, defined as a visuospatial perception score of 3 points according to the Stroke Impairment Assessment Set (SIAS) (Chino et al. 1994), and (5) no history of orthopedic problems related to the lower extremity. Table 1 shows the demographic and etiologic characteristics of the subjects.

Ethical approval was obtained from the ethics committee of Tohoku University Graduate School of Medicine. Informed consent was obtained from all participants.

The subjects were assessed for hemiparesis according to Brunnstrom's lower limb motor stage (Brunnstrom 1966), for kinesthesia according to the SIAS sensory scale (Chino et al. 1994), and for ankle dorsiflexion based on the passive range of motion. The subjects were prescribed one of the following PAFOs: Shoehorn-type PAFO (9 subjects), Gillette double-flexure joint AFO (Becker Orthopedic, Troy, MI, USA) (6 subjects), or the Tamarack flexure joint AFO (Becker Orthopedic) (1 subject; Table 2). The PAFO was made to order for several patients.

The shoehorn-type PAFO is a posterior leaf-type orthosis that resists all movement allowing no planter flexion or dorsiflexion. The Gillette and Tamarack hinged PAFOs have lateral hinges at the ankle joint. Hinged AFO was selected for patients with less impaired lower limb function.

Instruments

Paper walkways were used to assess spatial gait characteristics. A paper of 8 m length was divided into a 5-m walkway, with 1.5-m area left at each end to establish start and finish lines. Small stickers (2 cm × 2 cm, with felt adhesive backing soaked in ink) were attached to the subject's sole at the head of the metatarsus of the fifth toe (Fig. 1).

Procedure

Subjects ambulated 8 m on the paper walkway with ink patches on their foot soles, which left behind a footprint record. The first and last 1.5 m of the walk was not used because of changes in walking speed that occur when a person starts and stops walking.

Subjects were asked to walk with or without PAFO at their most comfortable (i.e., self-selected) speed along the 8-m walkway. When walking, the subjects used ambulation aids as shown in Table 2. The order of testing (with and without a PAFO) was randomized. Testing was repeated twice for two conditions, i.e., barefoot and wearing a PAFO, and mean values for the stride length, step length, symmetry, and step width were calculated for each trial. Measurements of spatial parameters were made by one of two authors (NS, KS) kept unaware of the subject's gait status and who had not participated in ambulation

Table 1. Demographic and etiologic characteristics of the hemiparetic subjects.

Subject	Gender	Age (years)	Diagnosis	Affected limb	Height (cm)	Weight (kg)	Interval from onset (months)
1	M	62	INF	R	163	46	5.3
2	M	29	ICH	R	183	99	2.6
3	M	55	ICH	L	168	66	4
4	M	73	INF	L	160	54	4.4
5	M	45	ICH	R	172	57	10.4
6	M	55	ICH	R	170	61	50.4
7	F	48	INF	R	150	55	5.3
8	F	57	ICH	L	149	54	15.7
9	F	70	INF	L	147	45	32.6
10	M	47	INF	R	165	65	2
11	M	52	ICH	R	167	72	5.8
12	M	79	ICH	R	160	60	55.4
13	M	55	ICH	L	165	67	28.7
14	F	55	ICH	L	155	71	111.8
15	M	56	ICH	R	168	80	113.8
16	F	58	ICH	R	152	52	49.5

F, female; ICH, intracerebral hemorrhage; INF, infarction; L, left; M, male; R, right.

Table 2. Clinical characteristics of the hemiparetic subjects.

Subject	Ambulation aids	PAFO	BRS (L/E)	FAC (barefoot)	Position sense	ROM (degrees)
1	SPC, AFO	Hinge[a]	IV	3	3	20
2	SPC, AFO	Hinge[a]	IV	3	3	20
3	SPC, AFO	SHB	IV	3	3	5
4	SPC, AFO	SHB	IV	3	3	10
5	SPC, AFO	SHB	IV	3	0	0
6	SPC, AFO	Hinge[a]	IV	3	3	0
7	SPC, AFO	SHB	III	3	3	15
8	SPC, AFO	Hinge[a]	IV	4	3	15
9	SPC, AFO	SHB	IV	4	3	10
10	SPC, AFO	Hinge[a]	IV	3	3	20
11	SPC, AFO	Hinge[a]	IV	3	2	20
12	SPC, AFO	SHB	III	4	3	20
13	SPC, AFO	Hinge[b]	III	4	0	15
14	AFO	SHB	IV	4	3	20
15	AFO	SHB	III	4	0	0
16	AFO	SHB	III	4	3	15

BRS, Brunnstrom recovery stage; FAC, functional ambulation category; L/E, lower extremity; PAFO, plastic ankle-foot orthosis; ROM , range of motion for ankle dorsiflexion with the knee flexed 90°. (The angle between the fibular shaft and the fifth metatarsal bone was measured. The right angle between the fibular shaft and the fifth metatarsal bone was defined as 0° of dorsiflexion); SHB, shoehorn brace; SPC, single-point cane; [a], Gillette double flexure joint; [b], Tamarack flexure joint.

Position sense was assessed in the great toe according to the Stroke Impairment Assessment Set. When no position change was detected by the patient after the maximum possible motion, a score of 0 was given. A score of 1 indicated that the patient recognized movement of the digit but not the direction, even at maximal excursion. When the patient correctly perceived the direction of a moderate excursion, the score was 2. A score of 3 indicated that the patient could correctly identify the direction of a slight movement.

testing.

Measurements

Gait parameters

The 5-m walk was timed using a stopwatch, and the steps were counted. These were converted into units of walking speed (m/min) and cadence (the numbers of steps per unit time, steps/min). Stride length for the right leg was measured as the linear distance between successive ipsilateral ink marks. Step length was measured as the linear distance between contralateral ink marks. Step width was measured as the transverse linear distance between the borders of two consecutive footprints (Fig. 2).

The functional ambulation category (FAC) (Holden et al. 1984; Holden et al. 1986) is an ordinal scale used to assess functional ambulation ability. The physical therapist who treated or tested subjects in this study determined the FAC values of the subjects.

Statistical Analysis

Step-length symmetry was evaluated by dividing the values for unaffected-side step length by those for affected-side step length. Furthermore, symmetry ratios for the two conditions were compared in terms of the absolute value of the difference from 1. CV, used to represent the variation in each spatial parameter (stride length, step length, and step width), was calculated as a percentage by dividing the standard deviation (SD) by the mean value and multiplying the result by 100.

Each parameter was compared between gait measurements with and without a PAFO, using a paired *t*-test or the Wilcoxon's signed-rank test. FAC ratings with and without a PAFO were compared using the Wilcoxon's signed-rank test. CV values of parameters exhibiting a significant difference between the two conditions were examined for correlation with individual gait parameters using Pearson's correlation coefficient or Spearman's rank correlation. SPSS for Windows version 11.0J (SPSS, Chicago) was used for the analysis and a P value of < 0.05 was considered statistically significant.

Results

For one patient (no. 1), only the second trial measurement was used for analysis because he almost fell when ambulating without a PAFO during the first trial. Comparisons of mean values for each gait parameter between conditions with and without a PAFO are presented in Table 3.

Gait parameters

Significant increases were found in walking speed (126.5%, $P < 0.01$), cadence (109.7%, $P < 0.05$), stride length (115.5%, $P < 0.01$), and step length of the unaffected (119.8%, $P < 0.01$) and affected sides (111.8%, $P < 0.05$) when walking with a PAFO compared to walking without a PAFO. Step width was increased significantly when wearing a PAFO ($P < 0.05$), but by only 3%. The variance in

Fig. 1. Timed ambulation and ink footprint record.

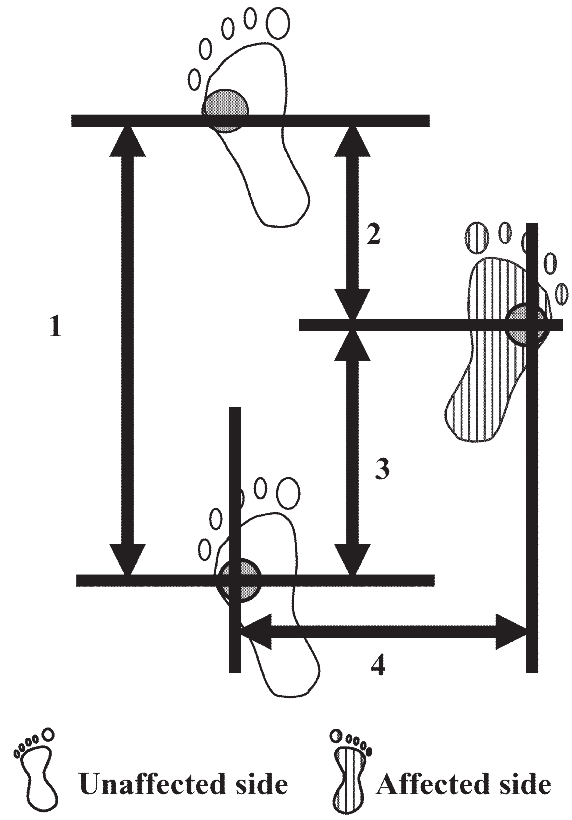

Fig. 2. Measurement of spatial parameters from ink footprints on a paper walkway in patients with right hemiparesis. 1, stride length; 2, unaffected-side step length; 3, affected-side step length; 4, step width.

Table 3. Comparison of gait parameters assessed with and without a PAFO.

	Without PAFO	With PAFO	*P* value
Stride length (cm)*	56.9 ± 13.6	65.7 ± 13.6	0.0041
CV%	7.4 ± 2.5	6.4 ± 2.7	0.26
Unaffected side step length (cm)*	26.3 ± 8.2	31.5 ± 5.9	0.0011
CV%*	15.5 ± 8.0	9.5 ± 3.9	0.0019
Affected side step length (cm)*	30.4 ± 9.4	34.0 ± 10.0	0.044
CV%	10.5 ± 7.5	9.2 ± 4.4	0.45
Step width (cm)**	28.2 ± 5.0	29.8 ± 4.4	0.034
CV%**	7.7 ± 4.6	5.5 ± 1.8	0.0038
Velocity (m/min)*	18.1 ± 8.1	22.9 ± 6.8	0.0032
Cadence (step/min)*	66.8 ± 21.0	73.3 ± 15.8	0.015
Step-length symmetry ratio	0.36 ± 0.45	0.25 ± 0.23	0.11
Step-length symmetry ratio range	0.003 – 1.84	0.01 – 0.99	

CV, coefficient of variation; PAFO, plastic ankle foot orthosis. Values are mean ± S.D.
*Significant at $P < 0.05$ by paired *t*-test. **Significant at $P < 0.05$ by Wilcoxon's signed-rank test.

Table 4. Correlation of unaffected-side step-length CV and step-width CV with gait parameters.

	Unaffected-side step-length CV[a]		Step-width CV[b]	
	Without PAFO	With PAFO	Without PAFO	With PAFO
Velocity	–0.20	–0.25	0.27	0.09
Cadence	–0.07	0.1	0.15	0.27
Stride length	0.22	–0.18	0.37	0.24
Unaffected-side step length	–0.76**	–0.78**	0.21	0.24
Affected-side step length	–0.30	–0.47	0.33	0.33
Step width	–0.40	–0.04	–0.53*	–0.35

CV, coefficient of variation; PAFO, plastic ankle foot orthosis; [a], Pearson's correlation coefficient; [b], Spearman's rank-order correlation coefficient. Step-width CV did not follow a normal distribution.
*$P < 0.05$; **$P < 0.01$.

Table 5. Comparison of FAC in hemiplegic patients with and without PAFOs.

FAC	Subject number (%)	
	Without PAFO	With PAFO
0	0 (0)	0 (0)
1	0 (0)	0 (0)
2	0 (0)	0 (0)
3	9 (56.3)	1 (63)
4	7 (43.8)	5 (31.3)
5	0 (0)	10 (62.5)

A significant improvement in FAC ($P < 0.001$) was found by Wilcoxon's signed-rank test. FAC, functional ambulation category; PAFO, plastic ankle foot orthosis.

step-length symmetry decreased when wearing a PAFO. Step-length symmetry ratios of 10 subjects (no. 1, 3, 5, 6, 7, 8, 9, 13, 15, and 16) increased to 1, while those of others (no. 2, 4, 10, 11, 12, and 14) decreased from 1. Overall, the step-length symmetry ratio was decreased (69.4%), but the difference was not significant ($P = 0.11$).

CV of spatial parameters

Unaffected-side step-length CV and step-width CV decreased significantly while wearing a PAFO ($P < 0.01$ each). However, affected-side step-length CV and stride-length CV did not differ between the two conditions ($P = 0.4$, Table 3).

Relationship between spatial-parameter CV and gait parameters

There was a significant difference between the use and nonuse of PAFO when we examined unaffected-side step-length CV and step-width CV, and this correlated with walking speed, cadence, and spatial parameters. Results showed a significant correlation between step-length CV of the unaffected side and step length of the unaffected side, both with ($r = –0.76$) and without a PAFO ($r = –0.78$). A significant relationship was observed between step-width CV and step width while walking without a PAFO ($r = –0.53$, Table 4).

FAC

Wearing a PAFO improved FAC ($P < 0.001$, Table 5); the number of participants who required considerable supervision (FAC 3) decreased from 9 (56.3%) to 1 (6.3%), while the number of participants who were able to ambulate independently on a level surface but required supervision or physical assistance for stairs, inclines, or nonlevel surfaces (FAC 4) decreased from 7 (43.8%) to 5 (31.3%). The number of participants who were able to ambulate independently on both nonlevel and level surfaces, stairs, as well as inclines (FAC 5) increased from none to 10 (63%).

Discussion

The simple walkway method used in the present study is suitable for clinical situations and previous studies have demonstrated its reliability, accuracy, and validity (Boenig 1977; Holden et al. 1984; Rigas 1984; Holden et al. 1986; Tyson and Thornton 2001). The longer do subjects walk, the higher became the reliability of measuring spatial parameters. However, walking a longer distances is difficult for patients with disabilities. Consequently, a 5-m walkway is usually used for patients with severe hemiplegia (Tyson and Thornton 2001). Moreover, preparation for a long-distance walkway is difficult in a clinical setting. Holden et al. (1984; 1986) reported that the reliability of gait parameters measured using a 20-foot (< 7 m) paper walkway was sufficient. Brach et al. (2001) used a 4-m walkway for hemiparetic patients to compare spatial parameter CVs among different conditions at various speeds. Using a 5-m paper walkway, Tyson and Thornton (2001) reported that spatial walking parameters for hemiplegic patients were better with an AFO than without it. Our study used a 5-m paper walkway, considering the demonstrated reliability of measurement and practicality in a clinical situation. We believe that this is a valid method for examining the effects of PAFO in hemiplegic patients.

The CVs of gait parameters are interpreted as indicating constancy or stability of movement from trial to trial; they therefore provide a measure of motor skill for a given task (Maruyama and Nagasaki 1992). Temporal (e.g., stride time) and spatial (e.g., stride length) parameters are used to examine variation in human gait. Gait stability has been assessed efficiently using the variability measure not only in elderly subjects (Gabell and Nayak 1984; Stolze et al. 2000), but also in physically disabled post-stroke patients (Zverev et al. 2002) and patients with Parkinson's disease (Vieregge et al. 1997). In fact, Gabell and Nayak (1984) reported that in both older and younger groups, the gait-patterning mechanism (step length and stride time) is more consistent than the balance-control mechanism (step width and double-support time) and that increased variability in gait is not necessarily a normal concomitant of old age. Furthermore, step length variability is greater in hospitalized patients with a history of falls than in those with no such history (Isaacs 1982). Therefore, the variability measure can be used as an index of gait performance stability (Maruyama and Nagasaki 1992).

In the present analysis, step-length CV of the unaffected side and step-width CV were decreased when wearing a PAFO. However, affected-side step-length CV was not decreased, suggesting that PAFO improved stability during the affected-side stance phase.

Step width was increased by wearing a PAFO. A larger step width could reflect increased postural gait impairment. In this study, the step width increase was as small as 1 cm (without PAFO, 28.2 ± 5.0 cm; with PAFO, 29.1 ± 4.4 cm). We interpret that the step-width increased because of the widening of toe out angles due to wearing a PAFO and not because of gait instability.

Previous studies (Lehmann 1979; Lehmann et al. 1983; Mojica et al. 1988; Chen et al. 1999; Tyson and Thornton 2001; Gok et al. 2003) have shown that wearing of PAFO increases walking speed, cadence, and stride length and improves FAC of subjects. These findings were confirmed in the present study. In addition, this report describes increases in the unaffected-side step length, affected-side step length, and step width when wearing a PAFO. There are a few studies that have focused on the effects of PAFO on step length in hemiplegic patients. Burdett et al. (1988) indicated that step length increases on the affected side while wearing PAFO when compared with that without a brace; however, the unaffected-side step length does not increase. This discrepancy between studies by Burdett et al. (1988) and ours may be because of differences in subject's impairments. However, this cannot be confirmed since they have not provided any details about patient's impairments in their study. Moreover, we found that the change in the step length symmetry ratio was inconsistent; ratios of some subjects rose to 1, while those of others fell from 1. We therefore concluded that a PAFO does not necessarily improve gait symmetry. Thus, these findings may suggest that assessment of step length rather than stride length reflects the effect of wearing PAFO in hemiplegic patients.

Gait stability improvement using a PAFO was assumed based on increased walking speed, cadence, and stride length. However, some gait parameters might not directly represent gait stability during walking. In this study, a good correlation was found only between unaffected-side step length and its CV.

Hesse et al. (1999) reported that the use of orthoses reduces double-stance duration and increases single-support duration upon the hemiparetic leg. Furthermore, the brace provides a feeling of security, reducing the patient's inclination to shift weight quickly to the nonparetic limb. Therefore, we concluded that in addition to improving gait stability during walking, PAFO also provides a more efficient gait. Gait stability and gait efficiency need to be considered separately when evaluating the effects of PAFO on gait performance in hemiparetic patients.

Our study has several limitations. First, we did not include patients who were unable to walk without a PAFO. Hemiplegic patients often have difficulty in ambulation even after being prescribed an orthosis. Second, all subjects improved over the 2 weeks following prescription of the PAFO, so results might have been influenced by the individual adaptations of the subjects to their PAFO. Consequently, the immediate effects of a PAFO on gait stability are not clear. Additional studies should investigate the time course of gait characteristics after initiating PAFO use. Third, we used CV parameters to indicate gait stability. For example, if movement of body parts becomes steady by the simple mechanism of an orthosis, the CV will become smaller. Thus, CV parameters might have reflected not only gait stability, but also other gait characteristics. Fourth, no "gold standard" exists for measuring gait stability. We need to determine the parameters that best reflect gait stability, considering temporal CV, acceleration, and the like.

In conclusion, the use of PAFO leads to a more dynamic and stable gait in hemiparetic patients. Gait stability can be assessed quantitatively using the distance parameter CV. We believe that the methods used in this study can contribute to prescribing appropriate PAFO for stroke patients in a clinical environment.

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