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Original Article

The use of a holistic figure in gait analysis: a preliminary study on the effect of ankle-foot orthosis

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ABSTRACT

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Objective: To examine the practical usefulness of a simplified three-dimensional treadmill gait analysis with a Lissajous overview picture (LOP), a holistic figure of marker trajectories, to present the effect of ankle-foot orthoses (AFO) on hemiparetic gait.

Methods: Seven patients with hemiparesis who were able to walk without an orthosis or gait assistive device were included in this study. Patients were measured with a simplified three-dimensional treadmill gait analysis system as they walked with and without an orthosis in a rehabilitation center of a university medical center. Gait was analyzed using the LOP, and quantitative comparisons were made to evaluate the changes in joint angles and joint position displacements during the swing phase.

Results: Using the orthosis decreased ankle plantar flexion during the swing phase ($p = 0.028$) and significantly reduced compensatory patterns, including hip elevation, knee elevation, and circumduction (p = 0.028, 0.018, and 0.028, respectively).

Conclusions: The quantitative assessment by a simplified gait analysis system clarified the effect of AFO on reducing the compensatory movement in a hemiparetic gait. The use of LOP helps to understand the holistic effect of AFO and to analyze the individual patterns of gait disturbance.

Key words: orthosis, hemiparesis, gait, rehabilitation.

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Introduction

Restoration of gait ability is a major objective in the rehabilitation of patients with hemiparesis. Despite intensive gait training, gait abnormalities may persist throughout the chronic stage [1]. The resultant hemiparetic gait pattern is a combination of deviations and the compensatory strategies determined by the remaining function [2]. These gait pattern deviations vary largely across individuals in both the stance and swing phases [3]. Orthotics are frequently used to minimize gait deviations, improve alignment, and improve walking for patients with hemiparesis depending on the level of gait ability [4]. An ankle-foot orthosis (AFO) is the most frequently used orthosis in hemiparesis rehabilitation. An AFO, which can be articulated or nonarticulated, provides resistance to plantar flexion for the improvement of effective gait biomechanics controlling the ankle complex. An AFO is generally prescribed to achieve lateral stability of the ankle in the stance phase and facilitate adequate toe clearance during swing, which facilitates safe ambulation. Safe ambulation is achieved by decreasing the fall risk through improving balance as well as improving gait efficiency by increasing the walking speed associated with increased stride length [5−14].

Several previous studies have demonstrated the remote effects of an AFO. There is some indication that AFOs can influence the knee joint indirectly by decreasing pathologic moments across the knee. The restriction of plantar flexion mobility by the AFO causes a significantly higher knee flexion moment during the loading response when the foot approaches the floor [15], and controlling the inclination of the tibia in mid to late stance may transfer forward momentum to facilitate knee extension in the terminal stance [16]. Gatti et al. revealed that an AFO can significantly improve the peak knee flexion angle during midswing, which will facilitate toe clearance [9]. Additionally, the reduction of compensatory movements, such as hip hiking, with the use of an AFO has also been reported [17]. Symmetry of gait improved with the use of an AFO when compared with walking without an orthosis [18, 19]. These indirect effects may contribute to a reduction in energy cost during ambulation [20]. Therefore, an evaluation of the holistic as well as the local influences of an orthotic should be considered.

For understanding the holistic change in gait patterns, Ohtsuka et al. reported the development of the Lissajous overview picture (LOP) illustrating a holistic figure of marker trajectories [21]. The holistic view of the gait with the LOP allows the depiction of both the movement patterns of each limb segment and the whole picture of the gait. This provides the capability to observe the primary effect and the remote effect of secondary gait abnormalities within one figure.

In this study, we evaluated the effect of an AFO for a hemiparetic gait, using the holistic figure, LOP, and individual quantification of the marker movement. The evaluation was done with a simple gait analysis system, using fewer joint markers than compared to previous gait analysis studies. The feasibility of this clinical-oriented gait analysis system is discussed.

Methods

1. Subjects

Seven subjects with hemiparesis enrolled in the rehabilitation program from October 2014 to April 2015 at the Rehabilitation Center of Fujita Health University Hospital participated in this study. Selection criteria included the ability to walk independently on a treadmill without an orthosis or handrail, ability to follow simple verbal commands or instructions, and daily use of an orthosis. Patients with significant orthopedic, neuromuscular, or neurological pathologies or a history that would interfere with walking or limit the range of leg motion were excluded from the study. Demographic and clinical characteristics were obtained from medical records. The participants were evaluated on a range of neurological motor impairments with the stroke impairment assessment set (SIAS). In evaluating the lower extremity, three items including hip flexion, knee extension, and foot tap were tested, and each item was rated from 0 (severely impaired) to 5 (normal) for expressing motor function of lower extremities (maximum score 15) [22]. Ethical approval was obtained from the medical committee board of the University Hospital. All subjects gave informed consent before participating.

2. Procedure

A cross-sectional study was carried out in the gait analysis laboratory of the rehabilitation department. The three-dimensional gait analysis (TDGA) was obtained using a KinemaTracer® three-dimensional treadmill gait analysis system (Kissei Comtec Co., Ltd., Matsumoto, Japan) and a computer for recording and data analysis. The KinemaTracer® consists of four charge-coupled device cameras installed around a treadmill and one computer controlling system. The reliability of this system for motion analysis was verified in a previous study [23]. All subjects practiced walking on the treadmill until they were familiar with the exercise prior to test initiation. Ten colored markers were placed bilaterally on the acromions, hip joints, knee joints, lateral malleoli, and fifth metatarsal heads during the treadmill walking test, and each subject was instructed to walk without an orthosis, then with an orthosis, during the same session at a comfortable self-selected speed. They were not allowed to use the handrails or any kind of assistive devices. Walking was recorded by video at a frame rate of 60fps, and duration of measuring time was 20 s. All gait data were collected in one session. The duration of all processes in the gait analysis was 20 min.

3. Outcome measures and statistics

Two physiatrists who were blinded to the AFO and non-AFO status provided data analyses. Two kinematic variables were assessed in the swing phase on the paretic side. The first element was composed of the vertical displacement of the acromion, hip, knee, ankle, and toe markers and the lateral displacement of the ankle marker. These outcome measurements were used to quantify compensatory strategies, for example, hip hiking and circumduction. The second element documented the angle changes of the hip, knee, and ankle joints between the mid-stance and mid-swing phase of the gait cycle, calculated with the formula $X=A-B$, where A is the value at mid-swing, when the lateral malleolus of the swing limb passes that of the stance limb in the direction of progression, and B is the value at mid-stance, when the lateral malleolus of the opposite limb passes the stance phase limb.

In addition, the results of the TDGA generated the movement pattern depicted from the trajectories of 10 markers and the virtual center of gravity simultaneously, i.e., the LOP (Figure 1). The Lissajous figure was expressed in three planes: horizontal, sagittal, and frontal. It was adjusted for the difference in height among subjects. At each marker, the raw data of three axes in each gait cycle were extracted, analyzed, and averaged. Patients' demographic variables were analyzed using descriptive statistics. Because of the small sample size, nonparametric statistics were applied. The Wilcoxon-signed ranks test was used to test gait parameters with and without the use of an orthosis. All statistical analyses were computed using SPSS 19.0 (SPSS Inc., Chicago, IL). A p value of less than 0.05 was considered

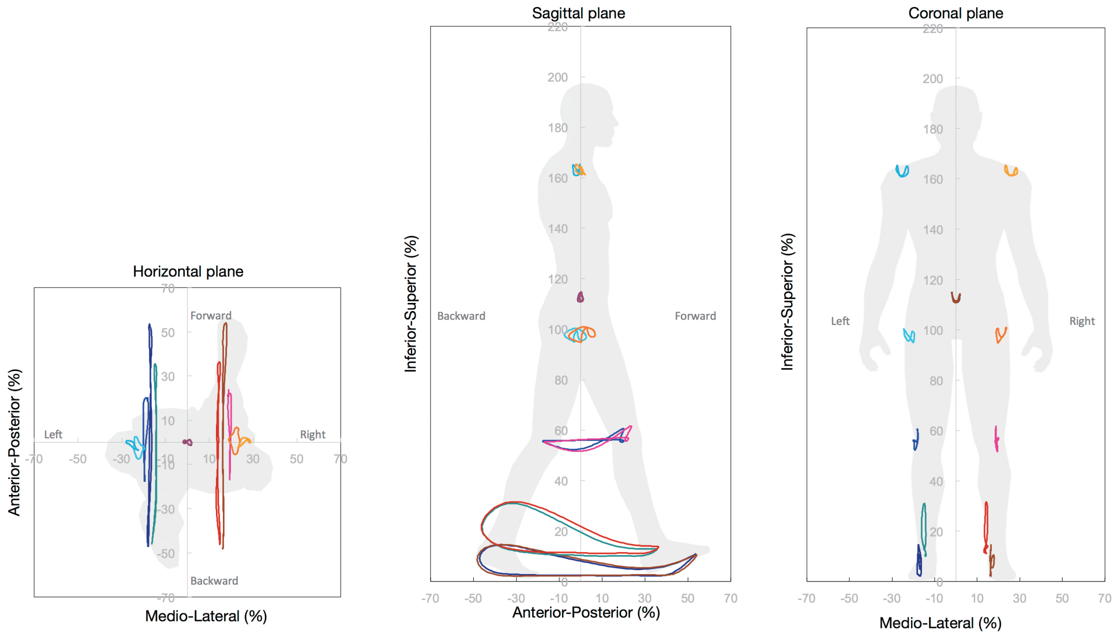

Figure 1. Representative LOP of one healthy subject (40 years old, male, treadmill speed 5 km/h) from the gait analysis database of the hospital.

Table 1. Patient demographic characteristics.

No.	Gender	Age (years)	Diagnosis	TAO (days)	SIAS-LE /15	Affected side	Treadmill speed (km/h)	Type of AFO	Height (cm)	Weight (kg)
1	M	18	ICH	81	8	L	2.3	APS-AFO	169	53
2	F	38	ICH	2260	8	L	2.5	C-AFO	168	58
3	M	68	ICH	2977	8	R	0.8	APS-AFO	170	57
4	M	74	Brain tumor	876	11	L	2.4	APS-AFO	162	65
5	M	41	ICH	32	12	L	1.7	C-AFO	164	68
6	M	53	ICH	47	12	R	2.8	APS-AFO	162	63
7	M	33	ICH	200	10	R	4.2	APS-AFO	176	68.5

Abbreviations: APS-AFO, adjustable posterior strut AFO; C-AFO, conventional plastic AFO; F, female; ICH, intracerebral hemorrhage; M, male; No., number; TAO, time after onset.

statistically significant.

Results

The mean age of the patients was 46.5 ± 19.8 years (range 18−74 years). Table 1 summarizes the demographic characteristics of the seven subjects who completed the study.

Figure 2 shows a representative LOP acquired from one patient (subject 5). The LOPs in the coronal plane of all subjects are shown in Figure 3 and illustrate the holistic changes in gait patterns in each patient. The reduction of hip hiking, knee elevation, and lateral displacement of the ankle are generally shown as the change in the trajectory of each marker from using the AFO.

Quantification of the displacement of each marker from the stance to swing phases is summarized in Figure 4. These results reveal that the elevation of the hip, knee, and lateral displacement of the ankle were significantly diminished when using an AFO ($p = 0.028$, p=0.018, p=0.028, respectively). No significant changes were observed in the elevation of the acromion and toe markers of a paretic limb in the comparison between with and without the AFO.

Changes in joint angles between swing and stance phases are shown in Figure 5. Ankle plantar flexion was significantly reduced with the AFO (p=0.028). No significant difference was observed at the hip and knee joints.

Discussion

An LOP, which is a holistic figure of marker

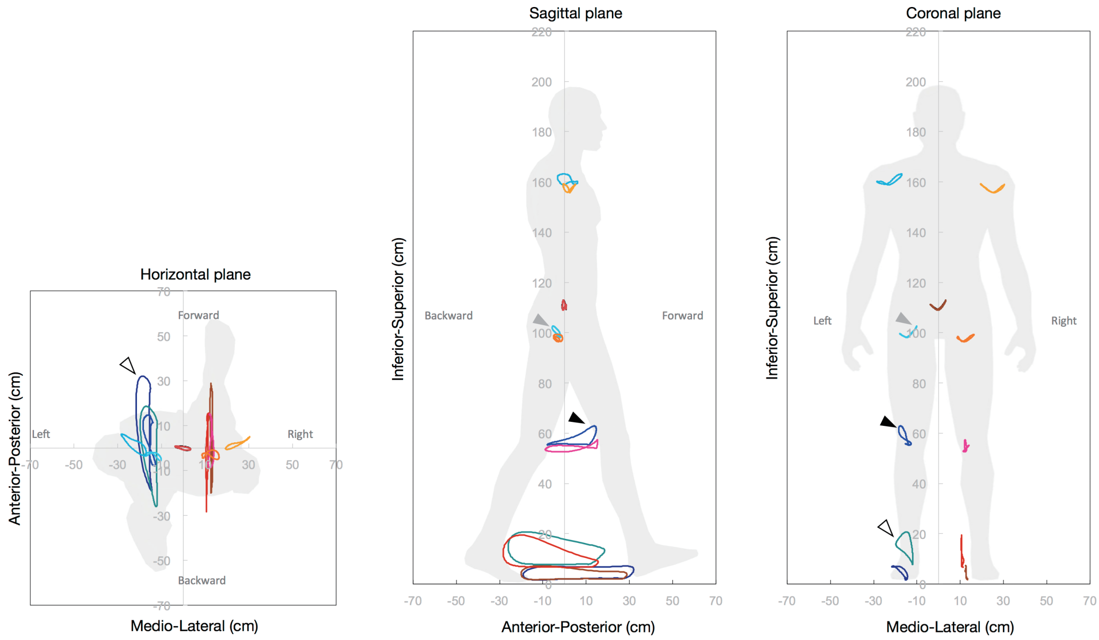

Figure 2. LOP demonstrating the gait pattern of one hemiparesis patient (subject 5) (white arrow, circumduction; black arrow, knee elevation; gray arrow, hip hiking).

Subject 1	Subject 2	Subject 3	Subject 4	Subject 5	Subject 6	Subject 7
L	L	R	L	L	R	R

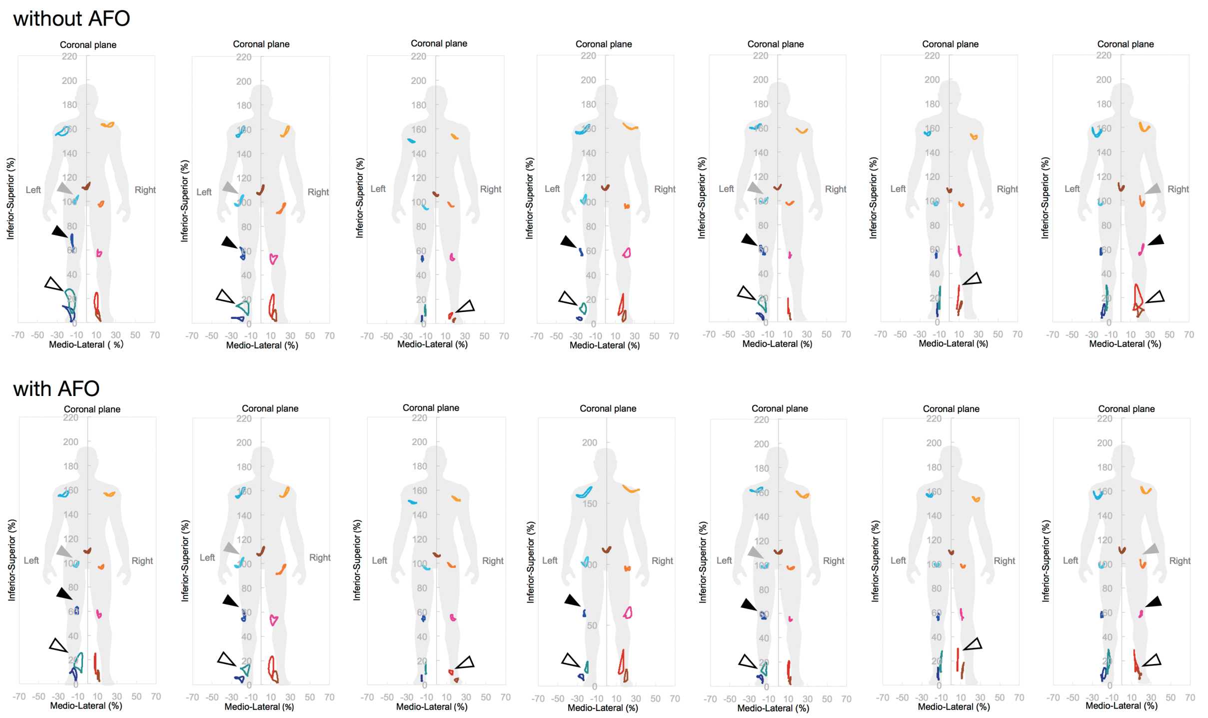

Figure 3. Lissajous figures of seven patients with hemiparesis comparing walking with and without an AFO on three planes (horizontal, sagittal, and coronal). The comparison of figures with and without an AFO shows the change in hip elevation (gray arrow), knee elevation (black arrow), and the lateral displacement of the ankle (white arrow). The arrows illustrate where the actual data differed by ≥ 0.5 cm between with and without the AFO.

trajectories, helps to focus on the individual problems of each patient. The quantitative comparison showed that the use of an orthosis can have a positive direct effect at the ankle by promoting ankle dorsiflexion during the swing phase and consequently diminish compensatory maneuvers by minimizing hip elevation,

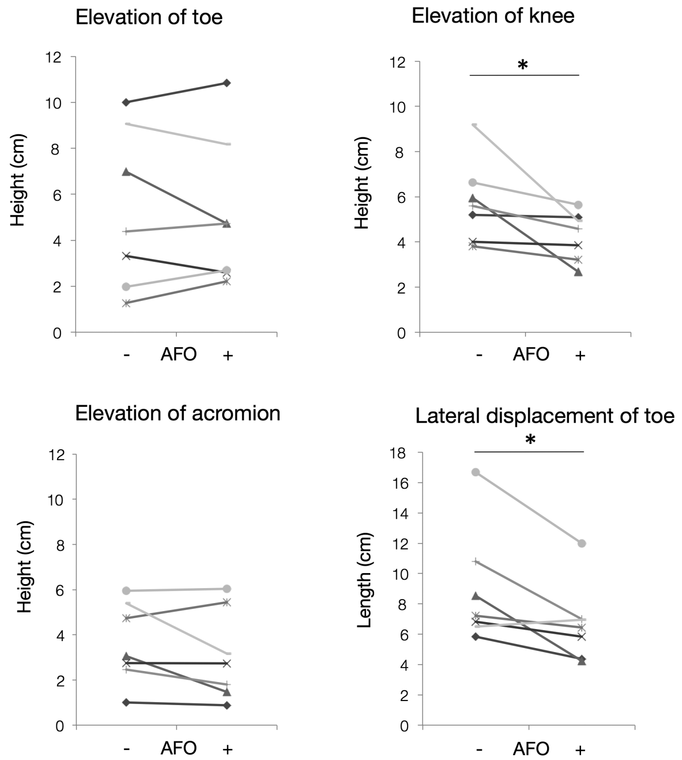

Figure 4. Comparison of joint position displacement of a paretic limb with and without an AFO. The hip elevation, knee elevation, and lateral displacement of the ankle (circumduction) were significantly reduced when using an AFO ($^{*}p$ = 0.028, 0.018, and 0.028, respectively).

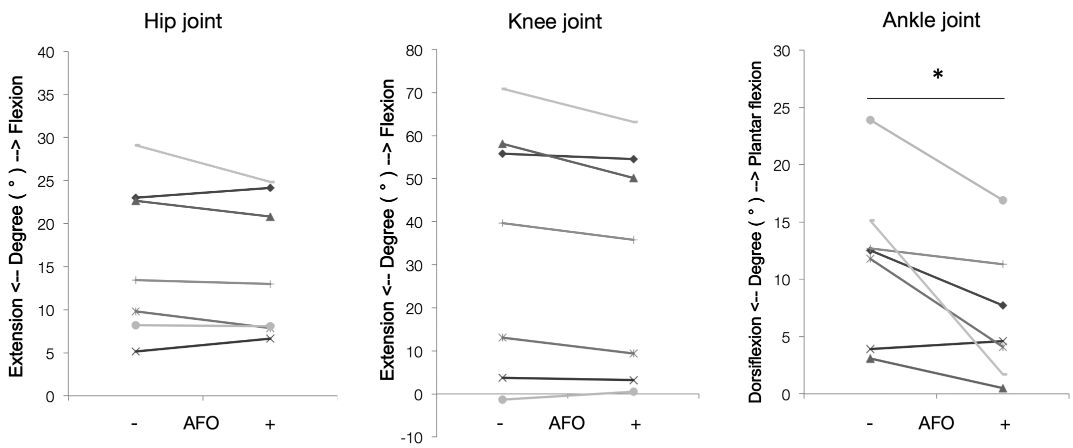

Figure 5. Comparison of the joint angle change of the involved limb of seven subjects, demonstrating the significant decrease in ankle plantar flexion ($^{*}p$ = 0.028).

knee elevation, and lateral displacement of the foot (circumduction), as shown in previous studies [24]. This potentially increases gait efficiency and reduces energy expenditure and may explain why many patients with hemiparesis continue using an AFO despite being able to walk without it in their daily life.

Elevation of the toe was not significantly increased by wearing the AFO compared to without it, which was in contrast with prior results. It is likely that the participants had adequate walking ability, since they could walk without a gait-assistive device or an orthosis. Despite this apparent lack of favorable effects of the AFO on increasing toe clearance to reduce fall risk, it can be presumed that the AFO helped to diminish the required energy, resulting in an increase in gait efficiency. To clarify the critical effect of an AFO to enable patients with hemiparesis to improve toe clearance or the stability of a paretic limb, comparisons in patients with more severe hemiparesis may be needed. No significant difference was observed in the acromion elevation between with and without the AFO. This possibly indicates that the improved leg shortening by use of an AFO was not so large as to affect trunk movement. As compensatory trunk movement is usually seen in patients with severe paresis, the effect of an AFO on trunk movement should be confirmed in patients with more severe paresis.

The comparison of an abnormal gait pattern using the LOP with and without an AFO leads to a comprehensive understanding of ambulation and resultant gait impairments and compensatory strategies as well as prevention of overlooking by visual observation. These benefits are not only applicable to gait professionals but also to medical practitioners who can intuitively interpret and understand the results of interventions, such as the effect of an orthotic as shown in this study, or any other gait training. The use of the Lissajous figure allows us to visualize the entire gait cycle and facilitates identification of abnormalities within a holistic view, contributing to improved interventions in the field of rehabilitation. Additionally, the duration of gait analysis in this study was only 20 minutes, which facilitates an efficient examination of the gait. This method is thus simple and highly practical to use in the clinical setting. Another consideration is the distinction between the uses of a treadmill compared with the overground gait. A number of studies have reported similar kinematics and kinetics between treadmill and overground walking [25−29]. Hence, treadmill-based analysis can be generalized to overground walking and can be used for movement analysis in clinical practice.

Study limitations

There are several limitations to this study. First, this study limited the participants to those who use an AFO in their daily life although they could walk without it, and thus the sample size was small and the analysis of the AFO effect may have been underpowered. However, a direct comparison of the effect of the AFO was achieved in one session for the same subject, which minimized the variability of acquired changes. The measurement of joint angles using the simplified marker set must be treated with caution and should be confirmed, although the changes of the ankle joint angles between the swing and stance phases reflected the use of an AFO in this study. Despite these weaknesses, the present findings demonstrate that this simplified TDGA is able to detect changes with the use of an AFO and suggest that the LOP of a simplified TDGA may be useful for comprehensive understanding of abnormal gait patterns. Future studies with larger samples are required to fully evaluate the AFO effects on a hemiparetic gait.

Conclusions

The quantitative assessment by a simplified gait analysis system clarified the effect of an AFO on reducing the compensatory movement in a hemiparetic gait. The use of the LOP showed the holistic effect of an AFO and may lead to a better intuitive understanding of the change in gait patterns. Further investigation of the feasibility of using gait analysis in the clinical setting for understanding the effect of clinical interventions is needed.

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