Original article

Association between improved trunk stability and walking capacity using ankle-foot orthosis in hemiparetic patients with stroke: evidence from three-dimensional gait analysis

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Keywords: *ankle-foot orthosis; gait; postural stability; walking speed; stroke*

Background Restoration of both normal movement of the pelvis and centre of mass is a primary goal of walking rehabilitation in post-stroke patients because these movements are essential components of effective gait. The aim of this study is to quantitatively analyze the effect of ankle-foot orthosis on walking ability, and to investigate the correlation between improvements in trunk motion and walking capacity.

Methods Walking speed, centre of mass displacement, and pelvic movements were examined in 20 post-stroke hemiparetic patients with and without ankle-foot orthosis using three-dimensional motion analysis.

Results Using ankle-foot orthosis improved walking speed, pelvic rotation and tilt, and lateral and vertical displacements of the centre of mass (P <0.01). Moreover, the gait asymmetry index was significantly decreased (P <0.01), and the Functional Ambulation Categories score improved significantly when patients used an ankle-foot orthosis (P <0.05). There was significant correlation between improvements in the walking capacity and the displacement of the centre of mass in both vertical and lateral directions (P <0.01).

Conclusions Using ankle-foot orthosis improves the walking capacity by improving the stability and concordant of the trunk in hemiplegic patients. The improvement in the walking capacity from using an ankle-foot orthosis may be attributed to its prevention of foot drop and compensation for the instability of the ankle joint.

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Approximately 60% of the stroke survivors reportedly have limited walking abilities,[1] usually displaying hemiplegic gait patterns or requiring the use of various walking aids. Therefore, regaining the ability to walk is a major task in regaining the ability to do activities of daily living (ADL) in post-stroke hemiplegic patients.[2,3] In clinical practice, using an ankle-foot orthosis (AFO) can improve walking ability in post-stroke patients,[4,5] correcting foot-drop in the swing phase and improving stability of the medio-lateral ankle joint in the stance phase, thereby increasing maximum walking speed in post-stroke patients.[6,7]

The body centre of mass (CoM) and pelvis make a number of small, symmetrical movements in the three-dimensional plane with each gait cycle in normal gait, whereas in post-stroke patients the body CoM makes large lateral and little vertical displacements and the pelvis display the wide-ranging rotation and left-right tilt movements characteristic of hemiplegic gait.[8] In addition, hemiplegic stroke patients also lack hip extension and ankle dorsiflexion on the weak side, and exhibit asymmetry of motion of the joints of the lower limb.[9] Some studies have shown that the abnormal motion of the body CoM and pelvis severely hinders the restoration of the walking ability in post-stroke patients.[10,11] However, the use of AFO to improve postural stability and standing balance in hemiplegic patients remain controversial. Some studies have shown that AFO improves postural stability or balance in the static or dynamic state,[12,13] whereas others suggest no significant impact on the balance and gait.[14,15]

Based upon our and others' studies, we hypothesize that AFO may improve walking capacity in hemiplegic stroke patients by correcting the abnormal motions of the body CoM and the pelvis. To test this hypothesis, we employed three-dimensional kinematic analysis to quantitatively analyze the effect of AFO on trunk motion and walking speed during the gait cycle and investigate the correlation between AFO-induced improvements in trunk motion and walking capacity.

METHODS

Participants

The total study sample comprised 20 stroke patients

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with hemiparesis: 11 males and nine females; mean age, (55.3±5.9) years (range: 44–65 years); mean weight, (61.7±8.7) kg (range: 46.1–74.6 kg); mean height, (1.63±0.07) m (range: 1.52–1.76 m); all native speakers of Chinese. Participants were recruited from the hospital's Department of Rehabilitation Medicine. Participants were those with a single and first-ever unilateral ischemic (16 persons) or hemorrhagic (four persons) supratentorial stroke. Stroke was defined according to the World Health Organization criteria.[16] Diagnoses were ascertained with radiological tests (computed tomography or magnetic resonance imaging or both) and clinical evidence of unilateral lesion. Those with subarachnoid hemorrhage were excluded. The time from onset of stroke to examination was 5–15 weeks (mean: 9.7 weeks). Twelve patients presented with right hemiparesis and eight with left. Moreover, all patients were evaluated for clinical functions using standard tests, including the National Institutes of Health Stroke Scale (mean: 7.00±2.69), Brunnstrom stage (mean: 4.00±0.79), and Barthel index (mean: 49.00±16.16). Written informed consent was given by all participants, and the project was formally approved by an authorized ethics committee of the First Affiliated Hospital of Sun Yat-Sen University.

Patients were required to meet the following criteria for inclusion in the study: (1) first episode of unilateral stroke with hemiparesis, (2) ability to understand and follow simple verbal instructions, (3) ambulatory before stroke, (4) Brunnstrom's stage of motor recovery for the affected lower limb range of 3–5, and (5) ability to walk at least 10 m without assistance. Excluded were those with any of the following: (1) neurological problems other than stroke that would interfere with gait and balance control, (2) premorbid or co-morbid orthopedic problems related to the limb, (3) uncorrectable visual impairment, and (4) severe aphasia or cognitive deficit that prevented comprehension of the task.

AFO

Participants used a specially molded plastic AFO fitted to each patient. The dorsiflexion angle of the AFO was adjusted to 90°. All the patients had some time (30-minute sessions, twice a day, for 5 days) to practice walking with the AFO before the gait analysis to ensure proper fit and allow for necessary adjustments.

Experimental design

The effect of AFOs on gait stability and functional balance control was measured using two types of assessment: gait kinematic tests and functional tests. Both tests were performed with and without patients wearing an AFO on the paretic side. The order of testing with and without AFO was randomized using a cross-over design. This order was used for both tests, which were performed on separate days for approximately 2 hours (between 3 and 6 pm) within 1 week. Before the start of each test, participants were asked to rest well at noon. Moreover, participants were allowed to rest between trials to prevent fatigue, and were instructed to immediately report any adverse event during the study.

Kinematic parameters

Trunk motions (vertical and lateral displacement of the body CoM and rotation and obliquity movements of the pelvis) and gait asymmetry index (GAI) during walking were calculated as markers of gait stability.[11,12,17,18]

The body CoM is located just anterior to the second sacral vertebra, but the best visualization of the shift in CoM is done by tracking torso displacement. In the vertical direction, the average adult male has a total vertical displacement of approximately 5 cm at average walking speed. This occurs during the gait between the double leg stance (minimum height point in the gait cycle) and the mid-stance on each leg (maximum height point in the gait cycle). In the plane of movement, the CoM is alternately shifted from the right leg to the left. The maximum position of the CoM to the right occurs at the midpoint of the stance phase on the right lower leg, and to the left occurs at the midpoint of the stance phase on the left lower leg. Total medial-lateral displacement is approximately 4 cm during normal ambulation.

Because the pelvis is a relatively rigid structure, the movement of both iliac crests is considered the best marker of pelvic motion during gait. Movement of the pelvis in the three-dimensional plane is a combination of rotation, anterior-posterior tilt and left-right obliquity. During normal walking, the pelvis incurs total anterior and posterior tilt of approximately 4° in the sagittal plane, total rotation of approximately 4° in the horizontal plane, and left and right obliquity of approximately 10° in the frontal plane.

The GAI was calculated as a marker of gait stability and fall risk.[17,18] The asymmetry index was determined as follows: 100×((swing paretic-swing nonparetic)/(swing paretic+swing nonparetic).

When the asymmetry index is 0.0, the gait is perfectly symmetrical, meaning that the swing time is similar in both limbs. Conversely, high asymmetry indicates that weight bearing is unevenly distributed, an imbalance that may lead to an increased risk of falls.[18,19]

Maximum walking speed was used as an overall measure of walking ability as it is a significant, sensitive, valid, and reliable indicator of ability in hemiplegic patients.[20,21] Post-stroke patients with good walking capacity exhibit a greater velocity, while subjects with poor walking capacity exhibit a slower speed.

Gait analysis procedure

Anthropometric data including height, weight, and leg length and joint width of the knee and ankle were collected. Eighteen reflective markers were placed on the anatomical landmarks recommended with use of the Quatisys 3.0

(Quatisys Medical AB, Gothenburg, Sweden), including bilateral shoulder/anterior superior iliac spine/superior of patella/lateral knee joint lines/tuberosity of tibia/lateral malleolus/heel/between the second and third metatarsal bones markers and the single thorax 12/sacrum marker. The patient was asked to walk 10 m as fast as possible on a level floor with and without AFO, looking towards the line of progression, while data were being captured. Six infrared cameras with a sampling frequency of 50 Hz recorded the three-dimensional spatial location of each marker as the subject walked. The three-dimensional gait data were collected with the Quatisys system and processed using Quatisys 3.0 software (Quatisys Medical AB). The motion of the body segments during walking was reconstructed. The gait events of heel strike and toe-off were identified by the computer operator using the stop-frame feature and frame-by-frame inspection of the stick figure.

Functional tests

Several tests were performed to assess functional balance and walking. Again, all tests were performed with and without subjects using an AFO on the paretic side. The Berg Balance Scale (BBS) was used to evaluate 14 sitting and standing activities.[22] Each task was graded 0–4, with higher scores reflecting higher speed, more stability or less assistance required to complete the task. The functional ambulation categories (FAC) were used to evaluate the level of independence during walking.[23] Performance was graded at six levels of walking ability (from 0: requiring support from two people to 5: able to walk indoors and outdoors without supervision).

Data analysis

Statistical calculations were carried out with PASW Statistics 17.0 (SPSS, Inc., Chicago, IL, USA). Pairwise comparisons were done of gait parameters with and without AFO using the *t*-test (alpha set at 0.05). Ratios of trunk kinematic parameters were obtained by dividing motion scores without AFO by the individual variable when using AFO. These were used to describe the linear association between the improvement in walking speed (Y) and a set of exploratory variables, including the motion ratios of body CoM and pelvis (X_{1-n}). Factors associated with admission in univariate analysis (P <0.20) by Fisher exact test were included in a linear regression model, with subsequent backward stepwise elimination of variables no longer significant (P >0.10).

RESULTS

The vertical and lateral displacements of body CoM, with or without an AFO, were (3.83±1.76) cm/(2.38±1.09)) cm, and (5.89±2.30)/(8.95±3.28) cm, respectively. The vertical displacement of CoM was significantly decreased (t(1,38)=7.612, P <0.01), but the lateral displacement was significantly increased (t(1,38)=11.029, P <0.01) when patients used an AFO. The anterior-posterior tilt and left and right obliquity and rotation movements of the pelvis when using AFO or no: (4.25±2.28)°/(6.83±4.25)°, (5.12±1.83)°/(5.46±2.18)°, and (9.66±3.69)°/(12.28±4.52)°, respectively. Both the anterior-posterior tilt and rotation of the pelvis significantly improved when using AFO over without AFO (anterior–posterior tilt: t(1,38)=4.595, P <0.01, rotation: t(1,38)=11.360, P <0.01). However, there was no significant improvement in the left and right obliquity motion of the pelvis (t(1,38)=0.642, P >0.05). The mean maximum walking speed was significantly faster with AFO than without (35.96±12.72) m/min vs. (29.10±11.40) m/min, t(1,38)=11.495, P <0.01). The GAI was significantly decreased when using an AFO than no ((0.17±0.03) vs. (0.20±0.04), t(1,38)=5.950, P <0.01).

The mean BBS score did not significantly differ between with and without using an AFO (48.00±4.21) vs. (47.35 (4.36), t(1,38)=2.041, P >0.05). However, the mean FAC score improved significantly when using an AFO, (4.30±0.47 vs. 4.10±0.55, t(1,38)=2.179, P <0.05).

The mean ratio of AFO (−)/AFO (+) of each variable was calculated. In univariate analysis, several gait kinematic factors including the ratios of CoM vertical and lateral displacements and the pelvis rotation were associated with the maximum walking speed ratio of the decision to admit. In multivariable models, only two variables were independently associated with improved walking capacity, the vertical and lateral displacement ratios of the CoM (Table 1). Table 1 showed that the walking speed ratio was affected by the lateral and vertical displacements ratios of the body CoM (F(1,38)=8.46, P <0.01). Adjusted R^2 suggested that the two independent variables could explain 44% of the variation in walking speed. Vertical displacement had the greatest effect on walking speed according to the values of standardized coefficients.

DISCUSSION

In the present study, we examined the effects of AFO on gait characteristics and walking capacity in hemiplegic patients post-stroke. We found that AFO could compensate for the instability of trunk motion and increase maximum walking speed. Moreover, the improvement in walking capacity was associated with compensation for instability in body CoM motion.

This study employed three-dimensional gait analysis to evaluate the affect of AFO on walking capacity and gait stability. Consistent with previous studies, we found that post-stroke patients had slower walking speed and poorer gait stability than normal, and the use of an AFO could increase both walking speed and FAC in these patients.[8,24,25] When walking barefoot, stroke patients are unsteady during the stance phase on the affected limb and also have some difficulty clearing the floor because of foot drop during the swing phase. In addition, improvement in stroke patients' walking ability is closely associated with trunk stability.[9-11] For example, hemiparetic patients trained in balance and body CoM transference during both standing and walking show improved walking speed.[26,27] Furthermore, robotassisted gait training to minimize the vertical and horizontal trunk movement as well as pelvis rotation can facilitate greater improvements in walking ability in post-stroke patients.[28] Walking can be defined as a series of losses and recoveries of balance. The smooth controlled transition between loss and recovery of gait stability continues as long as forward displacement of the body is achieved. In stroke patients, unilateral hemispheric injury weakens the affected lateral muscles, producing dysregulation of posture, balance, and locomotion, resulting in instability in walking and gait.[29,30] Mojica et al[31] investigated the effects of high-temperature thermoplastic AFO on body away movement in eight hemiplegic post-stroke patients using a force measuring platform system. They found a significantly reduced degree of body away when patients used AFO. Consistently, we found that all patients walked better and their gait stability improved when they used AFO. Interestingly, the beneficial effects occurred at the start of the very first trials with an AFO and did not require a period of practice to be effective. It should be noted that standing and mobility balance did not improve, although AFO immediately helped both walking speed and gait stability, which is in agreement with a previous study.[15] Moreover, the paretic lower limb contributed little to dynamic balance in stroke patients when using AFO.[32] Apparently, improvement in walking capacity cannot be readily attributed to a greater contribution by the paretic lower limb to weight-bearing or dynamic balance control.

We further examined the correlation between improvement in trunk stability and walking capacity when using AFO. The disturbances in walking ability due to stroke reflect disorders of both the base of support and trunk stability during gait. The hemiplegia-induced abnormal posture often leads to an inadequate base of support, which in turn brings about instability of the whole body in stroke hemiplegic patients. Therefore, correcting the abnormal posture should improve patients' limited ambulation. However, whether AFO can correct abnormal posture remains unclear. For example, little change is observed in step length and width in post-stroke patients wearing AFO and no.[33] In addition, AFO does not lead to a greater contribution by the paretic lower limb to body stabilization.[34] On the other hand, Mojica et al[31] found that AFO did significantly improve body stability and walking capacity. However, their study did not show any correlation between a reduction in body sway and improvement in walking speed. In the present study, we consistently observed improvement in body stability and walking capacity. Interestingly, we found that increased walking speed was affected by exploratory variables, including the lateral and vertical displacement ratio of body CoM when wearing AFO, which differs from Mojica's observation. The discrepancy may be due to a difference in methodology. Mojica ctal recorded the amount of body away movement by measuring the centre of foot pressure during static standing,[31] whereas we quantitatively measured trunk motion using three-dimensional gait analysis systems during dynamic gait. Nevertheless, our data suggest that the improvements in walking capacity when using AFO may be associated with the effect of AFO on gait stability.

Table 1. The main statistics of the final model (n=20)

Indices	B	SE	Beta	95% CI Lower Bound	95% CI Upper Bound	P values
Vertical ratio	0.21	0.07	0.56	0.08	0.35	0.004
Lateral ratio	0.52	0.20	0.45	0.10	0.94	0.017
Constant	0.56	0.17	–	0.20	0.93	0.005

Adjusted R^2: 0.44; Model P value: 0.003; SE of the estimate: 0.06.

Our data suggest that AFO can improve walking capacity by improving the stability and concordance of trunk motion in hemiplegic patients post-stroke. The improvement in functional walking capacity afforded by the use of AFO may be attributed to its prevention of foot drop and compensation for ankle joint instability.

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