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Original Article

Influence of gait exercise using a walking-assist robot for swing-leg motion in hemiplegic stroke patients: a preliminary study focusing on the immediate effect

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ABSTRACT
Fujii R, Tamari M, Nonaka Y, Tamiya F, Hosokawa H, Tanaka S. Influence of gait exercise using a walking-assist robot for swing-leg motion in hemiplegic stroke patients: A preliminary study focusing on the immediate effect. Jpn J Compr Rehabil Sci 2022; 13: 49−55.
Objective: We analyzed the effect of gait training using a walking-assist robot that assists a subject's knee joint movement and leg swing to achieve toe clearance of the paralyzed-side lower limb during treadmill walking.
Methods: The subjects were 10 hemiplegic stroke patients in a rehabilitation ward. The intervention consisted of gait training using the Welwalk WW-1000 (Welwalk) robot for 40 min. Immediately before and after this intervention, a gait analysis of the patients' treadmill walking was performed by a three-dimensional motion capture system. Statistical analyses compared the foot-to-floor distance and the shortening of hip-toe length (SHTL) of the paralyzed side before and after the intervention, and examined the relationship between the change of lower-limb joint kinematics and toe clearance before and after the intervention.
Results: The post-intervention SHTL was significantly lower compared to before the intervention, and there was a significant negative correlation between the change in the SHTL and the knee flexion angle from before to after the intervention.
Conclusion: Gait exercise using the Welwalk could contribute to the acquisition of more normal leg-swing strategies.
Key words: gait exercise assist robot Welwalk, hemiplegic stroke patients, toe clearance, shortening of hip-toe length, gait exercise

Introduction

A sufficient amount of gait training and lower-limb training is important to improve the gait ability of stroke hemiplegic patients [1]. However, many hemiplegic stroke patients have poor cardiopulmonary function [2], low nutritional status [3], and/or low self-efficacy for walking [4], which often prevents them from undergoing sufficient gait training. Robot technology is expected to help solve such problems [5], and various rehabilitation robots have been clinically applied.

Effective gait training using a robot has been revealed to improve the gait independence of hemiplegic stroke patients with severe gait disorders [6, 7]. More recent studies have focused on the effects of robotic assistance on abnormal gait patterns in hemiplegic stroke patients. Katoh et al. analyzed the abnormal gait patterns in hemiplegic stroke patients who used a walking-assist robot that assists the knee flexion-extension movement and the leg swing on the paralyzed side at the appropriate timing, and their results suggested that kinematic disorders of the trunk and lower limb in the swing phase of the paralyzed leg could be improved with this assistance [8]. It thus seems possible that gait training with assistance from a gait-assist robot could be useful not only for individuals with severe gait disorders, but also as a treatment strategy to improve abnormal gait patterns in hemiplegic stroke patients who are able to

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walk.

One of the main problems of abnormal gait patterns of hemiplegic stroke patients is the decreased toe clearance during the swing phase [9]; it is a major cause of stumbling and falling [10], and its improvement is clinically important. The toe clearance is determined by shortening of the entire lower extremity produced by hip and knee joint flexion and ankle dorsiflexion movements [11]. Hemiplegic stroke patients have difficulty shortening their entire lower extremity due to insufficient knee flexion during the swing phase [12]. Such kinematic disorders lead to decreased toe clearance and to compensatory strategies (e.g., hip-hiking and circumduction gait) to supplement toe clearance, resulting in decreased gait efficiency [13]. We speculated that robotic assistance might be a useful intervention for this toe clearance problem. The main functions of a robot designed to help an individual walk—such as proper assistance of the knee joint movement by assisting the leg and assisting the swing by a weight-support device—could enable a patient to achieve appropriate lower limb swing. This function could contribute to securing toe clearance through movement of the hip-knee-ankle joint by expanding the knee joint flexion movement in response to the shortening of the entire inhibited lower limb. However, the details of how robotic assistance affects the toe clearance have not been clarified.

Therefore, we conducted the present preliminary study to analyze the effect of gait training using a walking-assist robot that assists knee joint movement and leg swing to achieve toe clearance. We hypothesized that gait training using a robot would improve toe clearance, and that this improvement would involve an increase in the knee joint flexion angle.

Methods

1. Patients

The study subjects were hemiplegic stroke patients who were in our recovery rehabilitation unit in Musashigaoka Hospital during the year from April 2019 to March 2020. The selection criteria were as follows: (1) the patient's attending physician had determined that gait training using the walking-assist robot would be feasible based on the criteria for using the robot, (2) the patient was able to walk independently on a treadmill (wearing a trunk harness and using handrails were permitted), (3) the patient had a Hasegawa's Dementia Scale-Revised (HDS-R) score >20 points (i.e., the patient had no cognitive decline and could thus understand the study's purpose), and (4) the patient had no bone or joint disease, nerve disease, respiratory disease or cardiovascular disease that could affect gait performance. A final total of 10 patients who met the selection criteria were included as shown in Figure 1. Their mean age was 71.5±13.2; five males and five females; six with right hemiplegia and four with left hemiplegia. The patients' characteristics are summarized in Table 1.

We explained the study in advance to the patients orally and in writing and obtained their written consent. The study obtained ethical approval from the Institutional Ethics Committee of Musashigaoka Hospital (R1-01) and was conducted in compliance with the Declaration of Helsinki.

2. Intervention

The walking-assist robot Welwalk WW-1000 (Welwalk, Toyota Motor Corp., Aichi, Japan) was used for the intervention. As shown in Figure 2, the Welwalk is a walking-assist robot that consists of a knee-ankle-foot robot, a low-floor treadmill, a safety suspension harness, a robot relief, a front monitor for the patient and a control panel for the therapist [7, 8].

In the intervention, the patient walked on the treadmill with the knee-ankle-foot robot attached to the paralyzed lower limb (Figure 2) [7, 8]. The Welwalk is characterized by its high feedback (visual feedback via a front monitor and auditory feedback via sound) and precise adjustability (lower-limb assist during the swing and stance phases, etc.), which enables gait training based on motor learning theory. A load sensor located on the sole of the knee-ankle-foot robot plus the knee flexion-extension angle during the subject's gait are used to identify the gait cycle, and the robot appropriately assists in the knee joint flexion

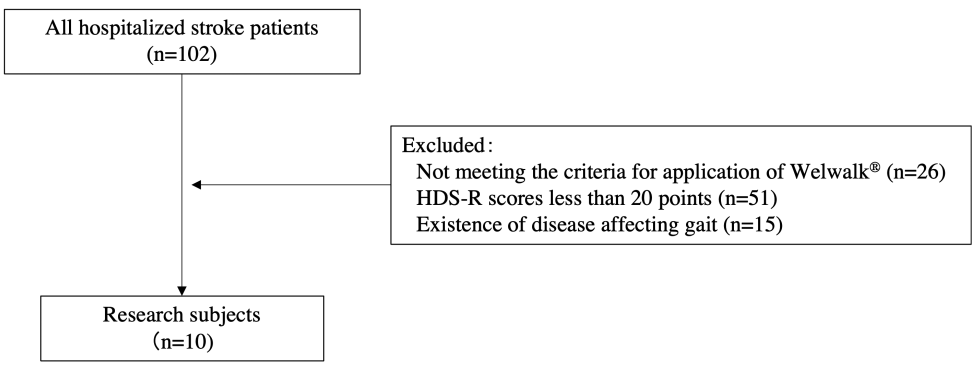

Figure 1. Flowchart of patient selection.

Table 1. Characteristics of the 10 patients with hemiplegic stroke.

Age, yrs	71.5±13.2
Male/female, *n*	5/5
Paralyzed side, *n*: right/left	6/4
Period since stroke onset, days	71.7±20.3
HDS-R scores	26.8±3.6
SIAS	
Hip-flexion test score	3.3±0.6
Knee-extension test score	3.0±0.9
Foot-pat test score	2.9±1.1
Total lower-limb motor function score	9.2±2.4
MAS	
Quadriceps, 0/1/1^+/2/3/4	3/4/1/2/0/0
Hamstrings, 0/1/1^+/2/3/4	3/3/2/2/0/0
Triceps surae, 0/1/1^+/2/3/4	1/5/2/2/0/0
10-m walk test, s	33.1±16.2
FIM walk score	4.6±0.7
FIM motor subscale score	56.8±15.5
FIM cognition subscale score	27.6±5.7
Using assist device, *n*: no use/T-cane/Quad-cane	0/6/4
Using lower-limb orthosis, *n*: no use/ankle-foot orthosis	0/10/0

Data are mean ± standard deviation (SD). FIM, Functional Independence Measure; HDS-R, Hasegawa's Dementia Scale-Revised; MAS, Modified Ashworth Scale; SIAS, Stroke impairment assessment set.

Figure 2. The gait exercise-assist robot Welwalk consists of a knee-ankle-foot robot, a low-floor treadmill, a safety suspension harness, a robot relief, a front monitor for the patient and a control panel for the therapist. In the present intervention, the patient walked on the treadmill with the knee-ankle-foot robot attached to the paralyzed lower limb. The figure is used with the permission of Toyota Motor Corp. (https://global.toyota/jp/download/35073671).

during the swing phase and the knee joint extension during the stance phase. In addition, the swing assist by the step assist enables proper lower-limb swing. These assist mechanisms enable gait training at the appropriate level of difficulty for a patient without compensatory strategies such as circumduction gait, hip-hiking, and lateral shift of the trunk, which are characteristics of hemiplegic stroke patients.

The gait training for each of the present patients using the Welwalk was performed by a physical therapist who had attended Welwalk leader training and was proficient in the use of the Welwalk, after the patient had complete three hours of a general rehabilitation program: range of motion exercises, muscle strengthening exercises, training of basic movement, training for activities of daily living (ADLs), etc. The amount of Welwalk assist was set as low as possible, i.e., to the amount that did not reduce compensatory strategies. Patients who could not hold the trunk in an upright position were allowed to use the trunk harness.

The robot's visual and auditory feedback functions were determined by the attending physician and physical therapist according to the patient's walking ability. The intervention was conducted for 40 min, incorporating rest periods as needed.

3. Outcomes

3.1 Patient characteristics

As summarized in Table 1, we assessed the patients' age, sex, paralyzed side, stroke onset, HDS-R score, the Stroke Impairment Assessment Set (SIAS) scores for lower-limb motor function (hip-flexion test, knee-extension test, foot-pat test, and the total score of these three tests), the Modified Ashworth Scale (MAS) for spasticity of quadriceps, hamstrings and triceps surae, the 10-m walk test, the Functional Independence Measure (FIM), the use of an assist device, and the use of a lower-limb orthosis.

3.2 Three-dimensional gait analysis

For the kinematic analysis of the effects of gait training using the Welwalk, we performed a gait analysis by using a three-dimensional motion capture system (KinemaTracer; Kissei Comtec, Nagano, Japan) that includes a four-charge-coupled-device camera. A treadmill walking task was measured at a sampling frequency of 60 Hz. The patients were instructed to walk at a comfortable speed on a treadmill (synchronous/asynchronous low-floor treadmill; Ohtake-Root Kogyo, Iwate, Japan). The patients were allowed to use a trunk harness and a handrail depending on their walking ability.

As shown in Figure 3, color markers (30-mm dia.)

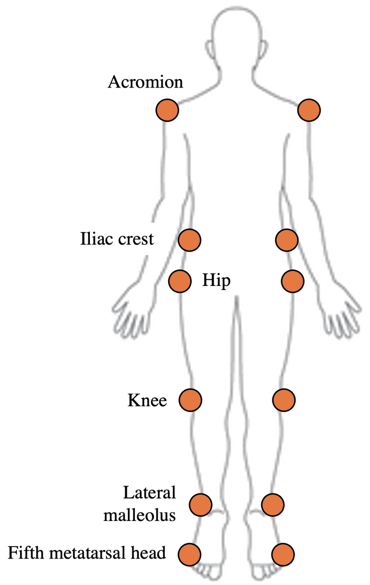

Figure 3. Positions of attaching the color markers to the patient bilaterally on the acromion, iliac crest, hip, knee, lateral malleolus and fifth metatarsal head to define the body segments.

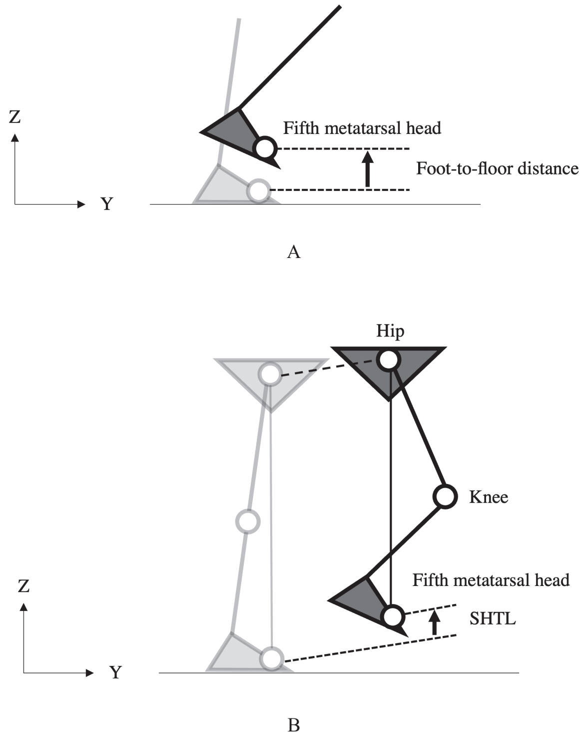

Figure 4. Details of the foot-to-floor distance and the shortening of hip-toe length (SHTL). In each panel, the left side (*gray*) represents the mid-stance point, and the right side (*black*) represents the mid-swing point. Circles indicate the color markers. Each index was determined by the difference between the lowest point of the fifth metatarsal head near mid-stance and the highest point near mid-swing (mid-swing — mid-stance). **A:** Foot-to-floor distance; the moving distance along the vertical axis of the fifth metatarsal head. **B:** SHTL; the direct distance between the hip and the fifth metatarsal head.

were placed bilaterally on the acromia, iliac crests, hip joints (one-third of the distance from the greater trochanter on a line joining the anterior superior iliac spine, and the greater trochanter), knee joints (midpoint of the anteroposterior diameter of the lateral femoral epicondyle), lateral malleolus and fifth metatarsal head, for a total of 12 locations. Based on the body segments obtained from each color marker, two distance values were calculated as indices of toe clearance: (1) the moving distance along the vertical axis of the fifth metatarsal head of the paralyzed leg during the swing phase (foot-to-floor distance; Figure 4A), and (2) the direct distance between the hip and the fifth metatarsal head of the paralyzed leg during the swing phase (i.e., the SHTL; Figure 4B) [14]. Each parameter was determined by the difference between the lowest point of the fifth metatarsal head near the mid-stance and the highest point near the mid-swing (mid-swing — mid-stance).

Regarding the difference between these two parameters, the foot-to-floor distance includes compensatory strategies such as circumduction gait and hip-hiking, whereas the SHTL is composed of hip flexion, knee flexion, and ankle dorsiflexion movements only, which are originally required during the swing phase of gait [14]. We also calculated time and distance factors (stance time, swing time, double-stance phase time, stride length and step length) and kinematic factors (hip flexion, knee flexion and ankle dorsiflexion angle of the paralyzed leg). For these joint angles, the change of flexion (dorsiflexion) angle was calculated based on the difference between the mid-stance and mid-swing (mid-swing — mid-stance) to correspond to the two indices of toe clearance (foot-to-floor distance and SHTL).

3.3 Assessment procedure

A series of patient characteristics was assessed first, and then the 3D gait analysis was performed; immediately after the analysis, the intervention was implemented. Immediately after the intervention was completed, the gait analysis was performed again. These assessments and interventions were conducted while confirming that the patient had recovered sufficient strength.

3.4 Statistical analyses

To examine the immediate effects of gait training using the Welwalk, we used Wilcoxon's signed rank test to compare the time and distance factors, kinematic factors, and indices of toe clearance of the paralyzed lower limb before and after the intervention. To investigate the relationship between the changes in toe clearance and lower limb kinematics, we used

Spearman's rank correlation coefficient to analyze the relationship between the amount of change in the indices of toe clearance (foot-to-floor distance and SHTL) and kinematic factors (hip flexion angle, knee flexion angle, and ankle dorsiflexion angle) in the paralyzed lower limb before and after the intervention (after intervention — before intervention).

The statistical analyses were performed using R software (ver. 4.0.0), and the level of significance was set at 5%.

Results

Table 2 lists the results of the changes in the gait parameters of the 10 patients with hemiplegic stroke from before to after the Welwalk intervention. Regarding the time and distance factors, there were significant increases in the patients' stride length and step length after the intervention ($p < 0.05$). There were no significant changes in the stance time ($p = 0.29$), swing time ($p = 0.13$), or double-stance phase time ($p = 0.77$). As a kinematic factor, the patients' knee flexion angle was significantly increased after the intervention ($p < 0.05$). One of the indices of toe clearance, SHTL, was significantly shortened after the intervention ($p < 0.05$). There were no significant changes in the hip flexion angle ($p = 0.69$), ankle dorsiflexion angle ($p = 0.45$), or foot-to-floor distance ($p = 0.32$).

Table 3 shows the results of the correlation analysis of changes in the two indices of toe clearance and lower-limb joint angles from before to after the intervention. We focused on the SHTL, which showed significant differences in the pre- and post-intervention comparison, and the results demonstrated a significant negative correlation between the change in the SHTL and the knee flexion angle before/after the intervention ($r = -0.70, p < 0.01$). However, no significant correlation was observed between the changes in the hip flexion angle ($r = 0.16$, $p = 0.56$) and ankle dorsiflexion angle ($r = 0.38$, $p = 0.24$).

Discussion

In this preliminary study, we analyzed the effects of gait training using a robot that assists the knee joint movement and leg swing of a paralyzed leg, focusing on toe clearance. Our findings revealed that the stroke patients' stride length, step length, knee flexion angle, and SHTL were significantly improved after the walking-assist robot intervention compared to the values obtained before the intervention. We also observed a significant negative correlation between the changes in the SHTL and the knee flexion angle from before to after the intervention.

Welwalk, the robot used in this study, has been reported to improve gait performance features such as the stride length and step length when the training is performed within a certain period of time after stroke

Table 2. Change in gait parameters before and after intervention.

Parameter	Before	After	*p*-Value
Time and distance factors:			
Stance time, s	1.3±0.5	1.5±0.7	0.29
Swing time, s	0.7±0.2	0.7±0.3	0.13
Double-stance phase time, s	0.5±0.4	0.5±0.3	0.77
Stride length, cm	42.9±20.6	45.4±19.6	<0.05
Step length, cm	23.1±12.6	25.5±10.8	<0.05
Kinematic factors:			
Hip flexion angle,°	20.1±6.7	20.9±7.1	0.69
Knee flexion angle,°	26.1±13.1	34.1±12.9	<0.05
Ankle dorsiflexion angle,°	–1.1±6.5	1.9±6.0	0.45
Index of toe clearance:			
Foot-to-floor distance, cm	2.7±1.1	3.0±1.1	0.32
SHTL, cm	–1.1±1.9	–2.4±1.6	<0.01

Data are mean ± SD. SHTL, Shortening of hip-toe length.

Table 3. Correlation analysis of change in SHTL and lower limb joint angles before and after intervention

	Amount of change in hip angle	Amount of change in knee angle	Amount of change in ankle angle
Amount of change in SHTL	0.16	–0.70*	0.38

Data are the correlation coefficient (*r*). SHTL, Shortening of hip-toe length. *$p<0.05$.

onset in subacute stroke patients [8]. Although the intervention in the present study consisted of only one 40-minute session, significant improvements in the stroke patients' step length and stride length were observed, similar to the results of a previous study [8]. The present findings indicate that the effects of gait training using Welwalk are immediate and can quickly improve the gait performance of hemiplegic stroke patients.

Our results also demonstrated no significant change in the foot-to-floor distance but a significant difference in the SHTL. In other words, the improvement in toe clearance in the present results is due not to the promotion of compensatory movements, but rather to the acquisition of a more normal gait pattern. The main advantages of the Welwalk robot are the precise adjustability of the assistance amount of the knee-ankle-foot robot and the front monitor that enables real-time viewing and self-correction of walking posture [5]. With these features, gait training might be repeatedly provided to the extent that compensatory movements do not appear, enabling patients to acquire a normal gait pattern. Our findings indicate that (i) the knee-ankle-foot robot assisted the patient's knee flexion movement at the appropriate timing during the swing phase, and (ii) the self-correction of trunk movement (lateral shift of the trunk) and lower-limb movement (hip-hiking and circumduction gait) based on the front monitor's display contributed to the patients' motor learning of a normal gait pattern and improved their SHTL.

The change in the patients' SHTL from before to after the intervention was significantly negatively correlated with the change in the knee flexion angle, meaning that an increase in the knee flexion angle was involved in the shortening of the SHTL caused by the intervention. The SHTL is composed of hip flexion, knee flexion, and ankle dorsiflexion movements, among which the greatest contribution is from knee flexion movement [14]. Notably, Kawasaki et al. revealed that gait training using an orthosis-attached robot that assists knee joint flexion and extension movements can directly improve the knee joint movement pattern during gait in hemiplegic stroke patients [15]; as in the present study, a significant increase in knee flexion angle occurred after that intervention. This suggests that the improvement in the SHTL caused by gait training with the Welwalk is due to the increased range of motion of the knee joint flexion angle provided by the knee-ankle-foot robot.

In summary, the results of this preliminary study suggest that adapting gait training with the Welwalk to patients who have suffered a hemiplegic stroke improves toe clearance based on increased knee joint flexion movement and contributes to the acquisition of a more normal lower-limb swing strategy. It might thus be more effective to provide Welwalk training to patients with insufficient knee flexion during the swing phase and other factors that impede toe clearance.

This study has several limitations. We did not compare level-ground walk training or other gait training devices, and it is unclear whether the Welwalk is more useful than other gait training systems for this purpose. In addition, the use of the harness and handrail by some of the patients might have caused measurement errors in the gait assessment (e.g., the harness may have affected the limitation of trunk and pelvic movement, and the use of handrails may have influenced the compensatory gait). The gait analysis in this study focused only on kinematic variables and did not examine kinetic or electrophysiological gait changes due to the Welwalk. Moreover, due to the small sample size (n = 10), the characteristics of patients who respond well to the Welwalk is unclear (degree of motor paralysis, sensory disturbance and spasticity, etc.). Continued research is needed to identify the characteristics of patients for whom the Welwalk is effective by using larger sample sizes and subgrouping based on intervention outcomes.

Further studies that also provide comparisons with other gait training (e.g., level-ground walk training) and the duration of intervention (e.g., long-term effects of continued intervention) are also necessary.

Conclusion

Gait exercise using the Welwalk walking-assist robot could increase the knee joint flexion angle during the swing phase and contribute to the acquisition of more normal leg-swing strategies.

Acknowledgements

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