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Case Study

Gait training using a stationary, one-leg gait exercise assist robot for chronic stroke hemiplegia: a case report

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Abstract. [Purpose] The Gait Exercise Assist Robot (GEAR) is a stationary, one-leg robot for gait training. The purpose of this case study was to evaluate the efficacy of rehabilitation using GEAR training for chronic stroke hemiplegia. [Participant and Methods] The participant was a 66-year-old male stroke survivor with left hemiparesis due to a right putaminal hemorrhage. He could walk slowly under supervision, although his gait had a constant forward trunk lean, with flexed knee, and a lack of hip extension movement on the affected side. Gait training using GEAR and physical therapy were performed for 14 days. Under both training conditions, the physical therapist made the participant conscious of extension movement of the hip joint in the affected-side stance phase. The robotic assistance was adjusted to maximize voluntary movement while observing gait. Physical function and gait ability parameters were evaluated before and after training. [Results] After training, extension motion of the hip joint increased in the affected-side stance phase, and body weight was transferred smoothly onto the affected-side limb, leading to an improvement in gait speed. [Conclusion] Gait training using GEAR and physical therapy may improve gait pattern and speed in patients with chronic stroke hemiplegia.
Key words: Gait training, Robot, Chronic stroke hemiplegia

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INTRODUCTION

In recent years, robotic rehabilitation has come to play a major role in improving gait ability[1]. Robotic gait rehabilitation systems can be classified into stationary and overground gait systems. Stationary systems comprise a fixed structure combined with a moving ground platform and have been developed to automate traditional therapy, usually focusing on treadmill training to improve motor skills[1]. Two groups of stationary gait systems can be distinguished based on the type of mobile platform adopted: treadmill gait trainers[2] and programmable foot end-effector trainers[3].

People who receive robot-assisted gait training in combination with physical therapy after stroke are more likely to achieve independent gait than people who undergo gait training without these devices. Specifically, people treated within the first 3 months of a stroke and those who are not able to walk seem to benefit most from this type of intervention[4].

Several studies have indicated that robot-assisted gait training in chronic stroke survivors is not superior to therapist-assisted gait training[5–7]. The robots used in the above studies were symmetric support robots and cannot attest the effectiveness

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Fig. 1. Gait Exercise Assist Robot (GEAR) system.
The components of the GEAR system include a knee-ankle-foot robot, a low floor treadmill, a safety suspension device (can be used for bodyweight support), a robot weight-support device, a monitor for patient use, and a control panel. The knee-ankle-foot robot with a knee actuator attached to the affected leg weighs approximately 5.7 kg, and is worn only on the hemiplegic limb. The robot weight-support device cancels the weight of the knee-ankle-foot robot so that the patient does not feel its weight. The foot sole of the robot is equipped with load sensors to measure foot load. The system determines the gait cycle from the load sensor information and the knee joint angle, and executes flexion and extension of the knee joint at the appropriate timing. The knee extension assist level and the swing assist level can be adjusted from the control panel. The knee extension assist provides the knee joint extension torque during the stance phase and can be set from level 10 (maximum) to level 1 (minimum). The swing assist provides swing motion support for the affected leg by controlling the robot weight-support force and can be set from level 6 (maximum) to level 1 (minimum). Also, there is a versatile visual and auditory feedback function.

for post-stroke hemiplegic patients. It is contentious because if residual paralysis is severe, compensatory motion is required and symmetrical gait is imposed by the training method, the gait during training would differ greatly from the patient's usual gait, and task transferability may be limited.

Hirano et al.[8] developed the Gait Exercise Assist Robot (GEAR) with Toyota Motor Corporation to provide a highly efficient gait training environment for post-stroke hemiplegic patients, which assists only the hemiplegic lower limb and allows flexible adjustments of the motor learning variables (Fig. 1). Rehabilitation with gait training using GEAR in subacute stroke patients with hemiplegia significantly facilitated early improvement in gait independence[9]. However, GEAR's use in chronic hemiplegia has not been reported. The purpose of this case study was to evaluate the usefulness of rehabilitation using GEAR training in chronic stroke hemiplegia.

PARTICIPANT AND METHODS

The participant was a 66-year-old male stroke survivor (57 months' post-stroke) suffering left hemiparesis due to a right putaminal hemorrhage. After treatment in the acute phase, he underwent rehabilitation for 6 months, involving indoor walking under supervision using a cane and an ankle-foot orthosis (AFO). However, his spasticity and gait ability gradually worsened. Treatment of spasticity with intrathecal baclofen therapy was initiated 41 days before participating in this study. The participant could walk slowly under supervision, although his gait had a constant forward trunk lean, flexed-knee, and a lack of hip extension movement on the affected side. The participant provided written informed consent by signing a form that was approved by the Kyoto Prefectural University of Medicine Institutional Review Board (No.ERB-C-270).

Three periods of in-hospital GEAR training and physical therapy were designed. Each training period consisted of preparation, break and exercise, totaling 40 mins each period per day, five times a week. Both training methods aimed to increase hip extension movement on the affected side during the stance phase. Also, the participant was instructed to keep his trunk upright during both training methods. During GEAR training, the amount of robotic assistance (knee extension assist, swing assist), the treadmill gait speed and visual feedback were adjusted to maximize the function of the lower extremity on the affected side. In physical therapy, stretching and muscle strengthening training, stepping, one-leg standing training, and overground gait training using an AFO were performed.

Physical function and gait ability parameters (Table 1) were evaluated before and after the training. Maximum gait speed was calculated using the 10-meter gait test. Kinematic and kinetic data were collected with a nine-camera motion-capture system (VICON MX, Vicon Motion Systems Ltd., Oxford, UK) and four forceplates (Kistler, 9281B1) on the 8-meter walkway at 120 Hz under the maximum gait. Reflective markers were placed on 39 anatomical landmarks according to the Plug-In Gait model. During walking, the participant used a cane and an AFO. The temporal-distance factors and kinematic and kinetic factors in the hip, knee and ankle during gait were calculated using Vicon's Plug-In Gait model.

Table 1. Physical function and gait ability assessments before and after training

	Before	After
Stroke Impairment Assessment Set		
Motor function of lower extremity (Hip-flexion test/Knee-extension test/Foot-pat test)	4/3/0	4/3/0
Trunk balance (Abdominal MMT/Verticality test)	2/3	2/3
Sensory function of lower extremity (Touch/Position)	0/0	0/0
Modified Ashworth Scale		
Knee flexion	1	1
Ankle plantarflexion	1+	1+
Gait ability		
Orthosis	AFO	AFO
Cane	T-cane	T-cane
Functional Ambulation Category	3	3
Maximum gait speed (m/sec)	0.32	0.44
Temporal-distance factors		
Stride time (sec)	2.43	1.77
Cadence (steps/min)	49.3	67.9
Step length (m)		
Affected	0.26	0.30
Unaffected	0.20	0.32
Gait cycle* (%)		
Initial double-limb stance phase	50.7	25.9
Single-limb support phase	12.0	22.6
Terminal double-limb stance phase	8.6	16.5
Swing phase	28.8	34.9

AFO: Ankle-foot orthosis; MMT: Manual Muscle Test.
*The defined gait cycle was from affected-side foot contact to affected-side foot contact.

RESULTS

Table 2 shows the intensity and duration of GEAR training and physical therapy. In the first training period, the following adjustments were made to extend the hip extension movement in the stance phase of the affected side: an image of the participant's feet was displayed on the front monitor; the participant was instructed to shorten his step length; the knee extension assist level was adjusted between 10 and 5 and the swing assist level between 3 and 1; and the treadmill gait speed was set between 0.4 km/h and 1.1 km/h, which is slower than the maximum overground gait speed. In the second period, the participant was instructed to use a short step length similar to the first period in order to enhance the hip extension movement in the stance phase on the affected side. The knee extension assist level was adjusted between 5 and 2, the swing assist level between 5 and 2, and the treadmill gait speed was set between 0.7 km/h and 0.9 km/h. For the third training period, in order to match the gait pattern during GEAR training to the overground gait pattern, the robot's assistance was reduced and step length was gradually increased. The treadmill gait speed was adjusted in the range of 0.9 km/h to 1.1 km/h and the front monitor was not used. During physical therapy, the participant also consciously extended the hip in the stance phase on the affected side.

Total gait time and distance per day for both training methods, and the number of steps per day with GEAR training are shown in Table 2. GEAR training involved approximately 1,000 steps per day. In the second period, during gait, the participant complained of pain in the right abdomen during the swing phase on the affected side. Therefore, in both training methods, the gait time and distance were reduced in the second and third periods. On the other hand, stretch time was increased to improve the pain. On the first day of the third period, the participant experienced weakness in the upper and lower extremities of the affected side, and medical examinations, such as physical and imaging studies, were conducted. Although no new lesions were observed, the dose of baclofen was changed from 150 µg/day to 130 µg/day, and training on that day was canceled.

Table 1 shows the results for physical function and gait ability assessments before and after training. There was no change in physical function, including muscle tone, after training. The maximum overground gait speed increased from 0.32 m/sec

Table 2. Durations and intensities of GEAR training and physical therapy

	First period	Second period	Third period
GEAR training			
Knee extension assist (level)	5 (10–5)	5 (5–2)	2 (6–1)
Swing assist (level)	2 (3–1)	2 (5–2)	2 (5–1)
Treadmill gait speed (km/h)	0.8 (0.4–1.1)	0.7 (0.7–0.9)	0.9 (0.9–1.1)
Total gait exercise time per day (sec)	972 (776–1146)	735 (679–909)	704 (675–724)
Total gait distance per day (m)	214 (200–249)	140 (136–200)	184 (174–196)
Number of steps per day	1,108 (912–1,354)	1,030 (906–1,180)	914 (826–946)
Physical therapy			
Total exercise time per day (min)			
Stretching	5 (5–5)	15 (5–30)	10 (10–15)
Muscle strengthening	10 (10–10)	0 (0–10)	5 (5–5)
Stepping and one-leg standing	5 (5–5)	5 (0–5)	5 (0–5)
Overground gait	20 (20–20)	20 (10–20)	20 (20–20)
Total gait distance per day (m)	60 (40–60)	40 (20–60)	40 (40–40)

Data are expressed as the median values (range; minimum value–maximum value) for each period.

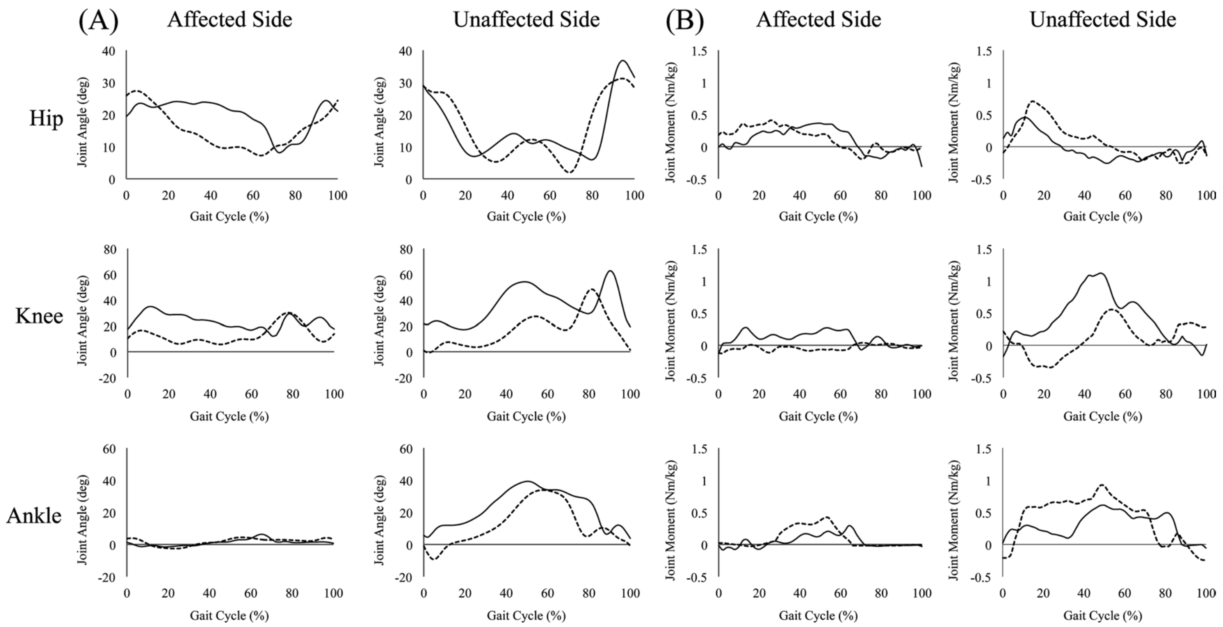

Fig. 2. Hip, knee, and ankle joint angles (A) and moments (B) in the sagittal plane before and after training.
Solid lines indicate the joint angles and moments before training and dashed lines indicate those after training. Positive joint angle values represent flexion and dorsiflexion. Negative joint angle values represent extension and plantarflexion. Positive joint moment values represent the extension and plantarflexion of force. Negative joint moment values represent the flexion and dorsiflexion of force.

to 0.44 m/sec. The stride time shortened by 0.66 sec and step length increased by 4 cm on the affected side and 12 cm on the unaffected side. The gait cycle decreased in the initial double-limb stance phase and increased in the single-limb support phase, terminal double-limb stance phase, and swing phase. Joint movement and moment for the affected and unaffected limbs during the gait cycle are shown in Fig. 2A and B, respectively. In the affected limb, the extensional movement appeared in the hip joint from the initial stance to the terminal stance, the flexion angle decreased in the knee joint during the stance phase, the hip extension moment increased during the initial stance to the mid stance phase, and the knee extension moment decreased during the stance phase. In the unaffected limb, after training, the flexion position of the hip joint was unchanged, the plantar flexion movement from dorsiflexion of the ankle was observed during the initial stance, and the flexion angle in the knee joint was decreased in the stance phase. Also on the unaffected side, hip extension moment increased and the knee joint extension moment decreased during the stance phase. The unaffected-side ankle joint plantar flexion moment was observed in the initial stance.

DISCUSSION

A participant with chronic stroke left hemiplegia performed GEAR training and physical therapy at indoor walking level[9] for 14 days, resulting in a change in gait pattern and improved gait speed. When the affected-side hip joint extension during the stance phase is insufficient, it limits forward propulsion of the hip[10], and decreases step length on the unaffected side[11]. Increased hip joint extension motion in the affected-side stance phase and the smooth transfer of bodyweight onto a paretic limb lead to an improvement in step length (including symmetry), cadence and gait speed. Also, along with the change in the motion pattern of the paretic lower limb, the pattern of joint motion and moment of the opposite lower limb changed.

Robot-assisted gait training could be more effective than conventional gait training at improving gait ability since participants can practice a high number of steps in the device and it promotes symmetric movements[12]. However, robot-assisted gait training may have several drawbacks. Robotic guidance may reduce voluntary muscle activity and subsequent learning. Patient effort may not always be maximal because the robot provides the necessary assistance to complete the movement trajectory[13]. Furthermore, the lack of variability in kinematic trajectories of the lower limbs during gait in the robot-assist device may limit the amount of error experienced during training, which is thought to be critical for successful motor adaptation[14].

GEAR can focus assistance on paralyzed lower limb function and the patient controls the rest of the body themself. To maximize the voluntary movement of the paralyzed lower limb, the physical therapist conducts a sophisticated training program that gradually reduces knee extension assistance and swing assistance and increases step length. Krishnan et al.[15] reported that the robot can provide minimal assistance, commensurate with the patient's capability, creating opportunities for the patient to actively control all four limbs. They suggested that this training strategy contributed to increasing functional improvement compared with passive, repetitive training of gait pattern. In training using GEAR in this case, minimizing the assistance level may also have increased the opportunities for active motions by the participant, which may have led to the improvements in gait capability. In particular, the degree of freedom constraint from adjusting the knee extension assistance may make it easier for weakened hip and knee joint muscles to activate in the paralyzed-side stance phase. This mechanism would be similar to that from a report showing that rectus femoris muscle activity increased as a result of restricting the degree of freedom of the ankle with an AFO for hemiplegics[16]. Participants with severe sensory disturbance tend to look at their feet while walking to confirm the foot contact position. This often causes the hip joint to flex, leading to pelvis retraction. In the present case, displaying the foot image, together with the target position of contact, on the front monitor gave the participant feedback on the ground contact position while maintaining good posture.

Rodrigues et al.[17] suggested that because slow (i.e., discrete) robot-assisted locomotor training on a bodyweight-supported treadmill (LT-BWST) may actively engage participants more than fast (i.e., rhythmic) robot-assisted LT-BWST, the former may drive functional gait recovery more effectively, particularly in cases of severely impaired gait after stroke. Schaal et al.[18] showed that rhythmic movements were associated with minimal activation of primary motor areas, while discrete movements activated broader cortical areas (e.g., primary motor areas, contralateral nonprimary motor areas, bilateral cerebellar activation). The treadmill speed during GEAR training in this case was slower than the participant's maximum overground gait speed. We think the discrete movement would have contributed to the improvement in gait capability. Also, step length asymmetry improved. Patients who walk with longer paretic than nonparetic steps typically rely on the nonparetic leg; thus, improving paretic leg output in these individuals may improve their gait symmetry[19]. The changes in the movement pattern of paretic lower limbs may be responsible for improved gait speed.

While the participant had severe paresis, his ambulatory ability was preserved. These findings are limited to individuals with similar functional ability and cannot be generalized to all chronic stroke survivors. Therefore, a larger multicenter, randomized trial is required to investigate the effectiveness of GEAR training and physical therapy in chronic stroke hemiplegia. We attempted to match the gait pattern during GEAR training with that during physical therapy, but have not confirmed the therapy was appropriate. In conclusion, the GEAR appears to be a useful instrument for training aimed at improving gait pattern and speed in patients with chronic stroke hemiplegia. To make GEAR training more effective, it is necessary to clarify the optimized assistance in gait training consisting of paretic lower limb function and compensatory movement.

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Conflict of interest

No benefits in any form have been or will be received from a commercial party related directly or indirectly to the participant of this manuscript.

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