Japanese Journal of Comprehensive Rehabilitation Science (2024)

Case Report

A Case with Left Hemiplegia after Cerebral Infarction with Improved Walking Ability Through Robot-assisted Gait Training Combined with Neuromuscular Electrical Stimulation for Foot Drop

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ABSTRACT

Yamaguchi A, Kanazawa Y, Hirano S, Aoyagi Y. A Case with Left Hemiplegia after Cerebral Infarction with Improved Walking Ability Through Robot-assisted Gait Training Combined with Neuromuscular Electrical Stimulation for Foot Drop. Jpn J Compr Rehabil Sci 2024; 15: 88−93.

Background: Gait training-assist robots and neuromuscular electrical stimulation devices have been shown to be useful in gait training for patients with hemiplegia. However, no case reports have documented the combined use of a gait training-assist robot and a neuromuscular electrical stimulator for gait rehabilitation. In this study, we present the case of a patient with left hemiplegia who demonstrated remarkable improvement in walking ability after using a combination of a gait training-assist robot and a neuromuscular electrical stimulator for foot drop.

Case Presentation: A 60-year-old man developed severe left hemiplegia following a stroke in the right middle cerebral artery region. His lower limb motor function, as assessed by the Stroke Impairment Assessment Set (SIAS), was completely impaired (score of 0), and he was unable to walk by the 57th day post-onset. By the 66th day, his lower limb motor function remained unchanged (SIAS score of 0), and he frequently stumbled on his left foot at the start of the swing phase during gait training. As a result, robot-assisted gait training combined with neuromuscular electrical stimulation for foot drop was initiated. By the 88th day, his lower limb motor function improved to a score of 1 on the SIAS, and his Functional Independence Measure (FIM) walk item improved to a score of 4 with the use of an ankle-foot orthosis and a cane. On the 89th day, he transitioned to conventional therapy without the devices. By the 114th day, he was able to walk with a T-cane without the need for an orthosis.

Conclusion: The combination of a gait training-assist robot and a neuromuscular electrical stimulator for foot drop facilitated dorsiflexion of the ankle during the swing phase, allowed the patient to practice walking with minimal assistance. This promoted active patient-led walking and more efficient motor learning, ultimately leading to independent walking.

Key words: gait training-assist robot, functional electrical stimulation, motor learning

Introduction

Wandel et al. reported that 21% of patients with complete paralysis of a paralyzed lower extremity immediately after a stroke were able to achieve independent walking with the use of assistive devices [1]. One reason for the inability to achieve walking independence is dysfunction of ankle dorsiflexion. Orthotic therapy is a common compensatory measure in the rehabilitation treatment of hemiplegic patients. However, in recent years, robotic rehabilitation, such as gait-assist devices and functional electrical stimulation, has become an option [2], and robot-

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Accepted: October 10, 2024
Conflict of Interests: The authors have no conflict of interest directly relevant to the content of this article.

doi.org/10.11336/jjcrs.15.88

assisted gait training has been reported to be effective [3]. There have been very few reports regarding the combined use of gait training-assist robots and neuromuscular electrical stimulation devices for healthy subjects [4] and hemiplegic patients [5, 6]. Both reports [5, 6] focused on chronic-phase hemiplegic patients, and there are no reports regarding convalescent patients; therefore, this is an issue that warrants consideration. In the present report, a patient with severe left hemiplegia after a cerebral infarction, who was admitted to a recovery phase rehabilitation ward, required assistance for foot clearance when using a gait training-assist robot. We report this case in which a neuromuscular electrical stimulator was used in combination with a gait training-assist robot, allowing the patient to repeat gait practice with less assistance, resulting in a marked improvement in gait ability and the acquisition of independent walking.

Case Presentation

A 60-year-old male was diagnosed with a cerebral infarction in the right middle cerebral artery region and was treated conservatively. On the 9th day after onset, a head MRI (T2-weighted image) revealed a high-intensity area in the right middle cerebral artery region (Figure 1). He had a history of pre-existing hypertension.

He was transferred to our hospital for convalescent rehabilitation 47 days after onset. At the time of transfer, the Glasgow Coma Scale (GCS) score was E4V4M6, and the Revised Hasegawa's Dementia Scale (HDS-R) score was 12/30. The Functional Independence Measure (FIM) score was 39 (26 for motor items and 13 for cognitive items), and the gait item of the FIM was 1. Robot-assisted gait training was initiated 57 days after the onset of stroke.

1. Robots Used in This Study

The Welwalk WW-1000® (Toyota Motor Corporation, Aichi, Japan; hereafter "gait training-assist robot") is designed to assist with gait rehabilitation for hemiplegic patients who have lower limb paralysis due to stroke or other causes. The robot leg is attached to the paralyzed lower limb, allowing the patient to practice walking on a treadmill while adjusting the assist level to a difficulty appropriate for their ability. Assistance includes knee extension during the stance phase on the paralyzed side and lower limb swing during the swing phase on the paralyzed side. Additionally, gait practice can be conducted while monitoring real-time gait images on a video monitor and audibly confirming the load on the paralyzed lower limb. This setup promotes motor learning with a more appropriate gait [7] (Figure 2a). The WalkAid® (Teijin Pharma Limited, Tokyo, Japan; hereafter "neuromuscular electrical stimulator") assists with ankle dorsiflexion during walking by electrically stimulating the peroneal nerve in the late stance phase on the paralyzed side in accordance with the gait cycle [8, 9] (Figure 2b).

2. Evaluation and Progress

On the 57th day after the onset, the lower extremity motor scores of the Stroke Impairment Assessment Set (SIAS) were all 0, the lower limb sensation score was 3, the lower limb positional perception score was 3, and trunk function for verticality and abdominal muscle strength scored 2 and 1, respectively. The patient used a knee-ankle foot orthosis and a side cane, as he required maximum assistance from a physical therapist due to trunk forward-leaning and pelvic retraction during the left stance phase, as well as difficulty in swinging the left lower limb during the left swing phase (Figure 3).

Robot-assisted gait training was initiated on the same day to improve stability during the stance phase of the left lower limb and the ability to swing the left lower limb during the swing phase. This training was conducted daily for approximately 40 minutes. The dorsiflexion angle of the ankle joint of the robot leg was set to move between 4 to 8 degrees. While walking on the gait training robot, the patient frequently stumbled on the left foot at the beginning of the swing phase, necessitating the physical therapist to raise the robot leg to ensure foot clearance (Figure 4a).

In general, the dorsiflexion angle of the robot leg can be adjusted, or supplemental elevation on the non-paralyzed side may be used to enhance left foot clearance. However,

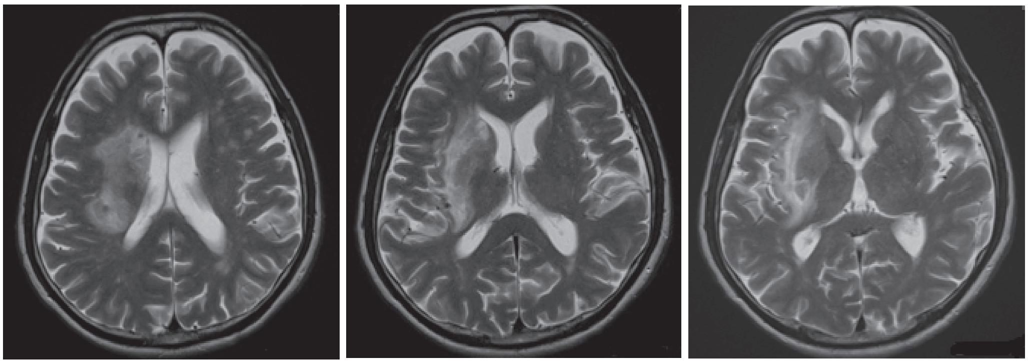

Figure 1. Head MRI performed 9 days after onset. T2-weighted images revealed a high-intensity area in the right middle cerebral artery region.

changing the plantar flexion restriction to the dorsiflexion direction tilts the lower leg forward during the stance phase, potentially compromising stability. Additionally, excessive elevation on the non-paralyzed side may cause a crash upon initial contact on the paralyzed side, further destabilizing the stance phase.

To reduce the assistance required for swinging without inhibiting motor learning during the stance phase, treatment with a neuromuscular electrical stimulator was introduced during robot-assisted gait training 66 days after the onset of stroke. Electrical stimulation was applied using a hand switch during the swinging of the left lower limb (Figure 4b). The neuromuscular electrical stimulator induced dorsiflexion of the ankle joint during the left lower limb swing, which improved clearance in the swing phase, ultimately resulting in a reduction of left foot stumbles. Consequently, the need for assistance in swinging the left lower limb by raising the robot leg was eliminated, allowing the patient to walk during the swing phase with only assistance in shifting the center of gravity at the pelvis.

At 74 days post-onset, the lower extremity motor items of the SIAS remained unchanged from 57 days post-onset; lower extremity sensation was rated at 3, lower extremity positional perception was also 3, and trunk function for verticality and abdominal muscle strength were rated at 2 and 1, respectively. While walking on level ground, the use of an ankle foot orthosis and a side cane improved trunk and pelvis stability during stance, improved knee folding, and reduced the amount of assistance required. The amount of assistance needed for swinging out was also decreased. While mainly using the gait training-assist robot and neuromuscular electrical stimulator, the patient also practiced walking on level ground without the robots. The frequency of robot-assisted gait training was reduced to once every two days. At the evaluation 88 days after onset, all SIAS lower limb

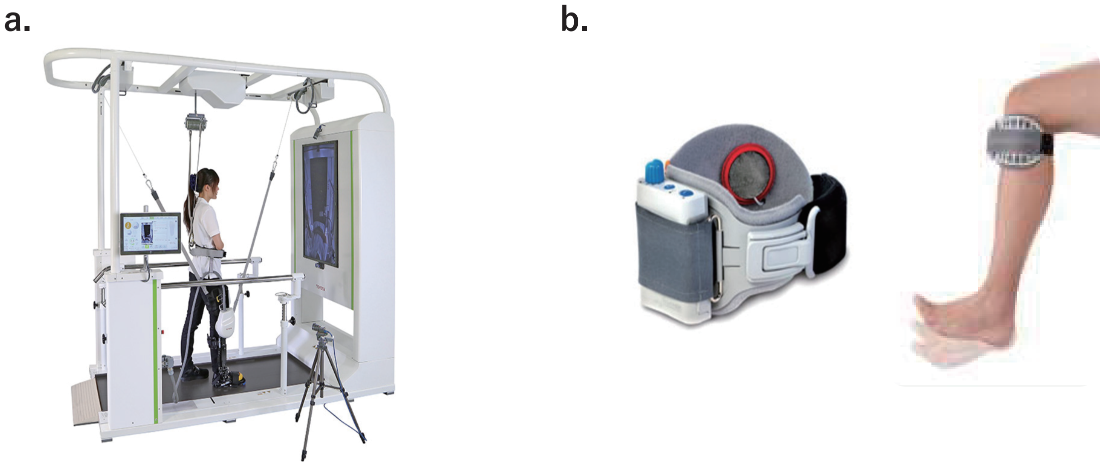

Figure 2. Gait training-assist robot and neuromuscular electrical stimulator for foot drop used in this study. **a.** Gait training-assist robot (Welwalk WW-1000®, Toyota Motor Corporation). **b.** Neuromuscular electrical stimulator for foot drop (WalkAid®, Teijin Healthcare).

	57th day post-onset	74th day	88th day	114th day
SIAS motor function				
Hip-Flexion Test	0	0	1	2
Knee-Extension Test	0	0	1	2
Foot Pat Test	0	0	1	2
Walking speed	0.12km/h	0.48km/h	1.0km/h	3.0km/h
Cadence (Amount of assistance)	16.8 steps/min (severe care)	48.6 steps/min (moderate aide)	54.6 steps/min (minimum aide)	120 steps/min (monitoring)
FIM Locomotion: Walk	1	3	4	5

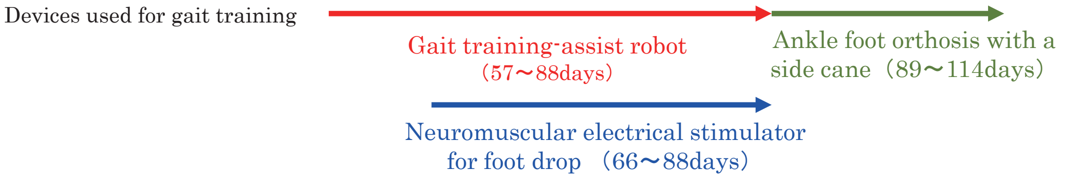

Figure 3. Summary of gait training and the changes in Stroke Impairment Assessment Set (SIAS) lower limb motor function and gait-related parameters.
Abbreviation: FIM, Functional Independence Measure.

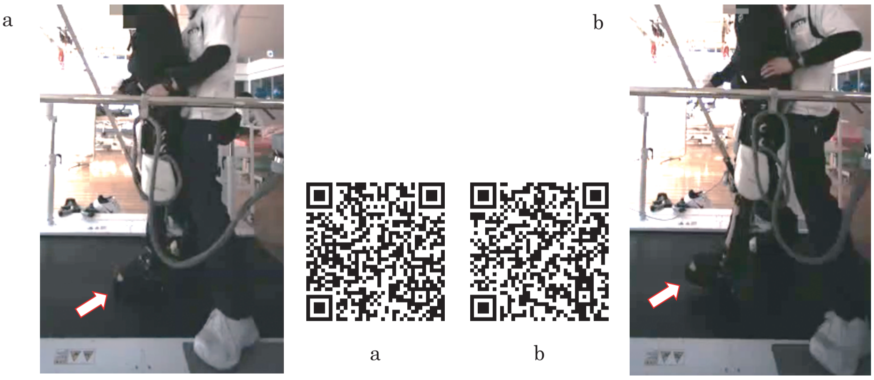

Figure 4. Gait training on the 66th day after the onset under the same conditions (walking speed of 0.60 km/h, knee extension assistance set to 8, and swing assistance set to 5). Please refer to the QR code below for the video. **a.** Training using only the gait training-assist robot. The arrow indicates the patient's paralyzed left foot. The patient required assistance to swing his left lower limb. **b.** Training using the gait training-assist robot in combination with a neuromuscular electrical stimulator. When the neuromuscular electrical stimulator was applied, ankle dorsiflexion occurred during the swing phase on the paralyzed side, eliminating the need for swing phase assistance.

motor items improved to 1, and trunk function improved to 3 for verticality and 2 for abdominal muscle strength. In level walking, the ankle foot orthosis and side cane further improved trunk and pelvic stability, decreased knee folding, and enabled the patient to swing his left lower limb, allowing him to walk with minimal assistance. Walking on the gait training robot improved trunk and pelvic fixation during the left stance phase, reduced stumbling during the left swing phase, and enabled the patient to walk with minimal assistance with pelvic support. The amount of assistance provided by the gait training robot was reduced to 6 for extension assist and 3 for swing assist, compared to the beginning of treatment with the robot. As a guideline for the end of treatment with the gait training robot at our clinic, we set the "acquisition of a supervised gait with the assistance function under the minimum extension and swing assist" as the end criterion. The patient's strong desire to "walk on level ground," as well as the improvement in his ability to walk on level ground, led us to terminate use of the gait training robot at this stage.

3. Final Evaluation

Four weeks after ceasing use of the Welwalk (day 114 of onset), the evaluation revealed that all SIAS lower extremity motor items scored 2, lower extremity sensation scored 3, lower extremity positional perception scored 3, and trunk function for verticality and abdominal muscle strength both scored 3. The patient was able to walk barefoot with a T-cane at a speed of 3.0 km/h under supervision. The FIM improved to a total score of 73 (50 for motor items and 23 for cognitive items), with a score of 5 for gait items.

Discussion

This case showed a significant loss of trunk and pelvic stability and left lower extremity support when walking on level ground. A knee-ankle foot orthosis is usually used when performing gait training for such a patient. However, knee joint flexion during the swing phase is difficult when gait training is performed with the patient wearing a knee-ankle foot orthosis. With a gait training-assist robot, knee joint flexion can be supported through the swing-out assistance of the hip. Therefore, gait practice can be repeated early without excessive compensatory movements [10]. This case was treated using robot-assisted gait training to take advantage of these benefits. However, the patient stumbled during the swing-out phase, requiring a physical therapist's assistance. The gait training robot has functions to assist with knee joint flexion and the swing of the paralyzed leg, but it does not promote dorsiflexion of the ankle joint.

A randomized controlled trial [11] was conducted using a gait training device (Lokomat) combined with a neuromuscular electrical stimulator for patients with chronic hemiplegia, which showed improvements in gait parameters in the combined group. There is also a case report on the chronic phase of the clinical application of robot-assisted gait training combined with electrical myogram-triggered ankle robotic training, specifically the medical single joint HAL® (HAL-SJ, HAL-MS01) [6]. However, there are no reported cases of the clinical application of a gait training-assist robot combined with a neuromuscular electrical stimulator for patients in the recovery phase. In the present case, the neuromuscular electrical stimulator was used alongside the gait training robot to induce dorsiflexion of the ankle joint during the swing-out phase, allowing gait training to be performed with less assistance. As a result, the patient was able to practice walking with fewer excessive compensatory movements and required less assistance from the gait training-assist robot. Previous studies have reported that electrical stimulation of the common peroneal nerve promotes sustained cortical motor-evoked potentials [12]. In this case, the lower limb motor items of the SIAS showed improvement after combining neuromuscular electrical stimulation, increasing to 1 at the 88th-day post-onset assessment.

The gait training-assist robot alone cannot directly induce ankle joint dorsiflexion during the swing phase. To secure clearance during the swing phase on the paralyzed side using the function of the gait training-assist robot, strategies such as fixing the ankle joint in dorsiflexion or lengthening the non-paralyzed side with supplemental height could be considered. However, these strategies may cause instability during the stance phase. In the present study, ankle dorsiflexion was promoted by using electrical stimulation without changing the settings, which could have led to disadvantages during the stance phase. This trial may have resulted in improved ankle dorsiflexion function [9]. Furthermore, it is possible that the patient was able to practice with a better gait by achieving clearance through electrical stimulation. This may have reduced the amount of assistance needed from the gait training-assist robot, and generalization to level walking was observed, resulting in the acquisition of independent gait under supervision within four months of onset.

This patient improved by 3 points in the FIM walk item and 3 points in the SIAS lower limb total after 33 days of robot-assisted gait training (11 days with the gait training-assist robot only and 22 days with the gait neuromuscular electrical stimulation device). In our data, 13 stroke patients (mean duration of use 63.9 days) who were admitted to the recovery rehabilitation ward in our hospital from January 2023 to December 2023 and used only the gait training-assist robot without the gait neuromuscular electrical stimulation device had a mean improvement of 0.7 points in the FIM walk item and a mean improvement of 0.7 points in the SIAS lower limb total score (unpublished data). This suggests that the combination of the gait training-assist robot with the gait neuromuscular electrical stimulator significantly impacted the improvement of lower limb motor function and gait function.

If a robot were to attempt to provide the same type of walking practice with ankle-joint motion, a possible method would be to add a motor to the ankle joint for control. However, this would increase the mass and weight of the robot leg, complicating the control of the swing and grounding position of the paralyzed side. To reliably prevent giving way of the knee joint during the stance phase, using motors to control the knee joint in combination with electrical stimulation for ankle dorsiflexion is considered more reasonable than relying solely on motor control, and this case demonstrated the potential of such an approach.

Conclusion

The use of the neuromuscular electrical stimulator in combination with robot-assisted gait training enabled a reduction in the amount of assistance and promoted patient-centered motor learning. Therefore, we believe that the neuromuscular electrical stimulator for foot drop may be a useful auxiliary device to effectively enhance gait training-assist robot therapy. However, in this case report, there was no comparative subject, making it impossible to determine whether the treatment's effect was influenced by spontaneous recovery. Further case studies are needed to verify the effectiveness of robotic devices in the future.

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