Clinical Notes

Intensive Gait Treatment Using a Robot Suit Hybrid Assistive Limb in Acute Spinal Cord Infarction: Report of Two Cases

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Context: Spinal cord infarction (SCI) causes gait disturbance because of paresis, spasticity, and sensory disturbance of the lower limbs. There is no effective medical treatment for SCI, and conventional rehabilitation alone is the main approach to helping individuals work toward independent walking. The aim of this study was to evaluate the effect of gait treatment using the Hybrid Assistive Limb (HAL) on acute SCI.

Findings: A 61-year-old female and a 62-year-old male with incomplete paraplegia participated in this study. Our study participants received gait treatment with HAL 3–4 times per week, with a total of 7–8 sessions (20 min), in addition to conventional physical therapy. The American Spinal Injury Association Impairment Scale, Lower Extremity Motor Score (LEMS), Modified Ashworth Scale (MAS), the Walking Index for Spinal Cord Injury (WISCI II), comfortable gait speed (CGS), stride, cadence, Barthel Index (BI), Functional Independence Measure (FIM), modified Rankin Scale (mRS), joint angles, and adverse effects were assessed prior to HAL treatment and post-HAL treatment. HAL facilitated intensive gait treatment in people during the acute phase after SCI. Improvements in LEMS, WISCI II, CGS, stride, cadence, BI, FIM, mRS, and joint angles were observed in both study participants. Furthermore, decreased spasticity in the gastrocnemius muscle was found in one participant as assessed by MAS.

Conclusion: Gait treatment using HAL may be beneficial for paraplegic, non-ambulatory individuals with acute SCI. HAL may be useful for intensive gait treatment without increasing spasticity.

Keywords: Spinal Cord Infarction, Hybrid Assistive Limb, Gait Treatment, Independent Walking, Spasticity

Introduction

The incidence of spinal cord infarction (SCI) is extremely low compared with that of stroke.¹ Ischemia of the spinal cord causes sensorimotor and urinary disturbances below the affected spinal level; however, no effective treatments have been developed for SCI, whereas ischemic stroke can

be treated with anti-platelet therapy and thrombolysis.^{2,3} Conventional rehabilitation alone is the main approach for treating paraplegia, spasticity, and sensory disturbance.^{4,5} A previous study found the following functional outcomes for SCI at hospital discharge: 57% of individuals were wheelchair users, 25% were ambulatory with a walking aid, and 18% were fully ambulatory.⁶ Many individuals with SCI remain wheelchair users for the rest of their lives; they cannot walk without using an assistive

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device.^{7,8} No reports are available on the effect of rehabilitation on acute SCI. In a previous report, the outcome of rehabilitation for individuals with SCI was assessed with the activities of daily living (ADL), the Functional Independence Measure (FIM), and the Barthel Index (BI).⁹ However, little has been reported on motor function, independent walking, spatiotemporal gait parameters, and joint angles during the gait cycle in SCI.

The Hybrid Assistive Limb® (HAL; Cyberdyne, Inc., Tsukuba, Japan) was developed to assist voluntary control of hip and knee joint motion, and is able to detect weak bioelectrical signals on the surface of the skin.^{10,11} Several studies have reported that gait treatment using HAL may have beneficial effects on post-stroke gait function and independent walking.^{12–14} However, there have been no reports using HAL on individuals with acute SCI. Gait treatment using HAL on individuals with SCI may enhance recovery of motor function and contribute to independent walking in the early stages of treatment. The aim of the present study was to evaluate the effect of using HAL, a new tool in robotic-assisted gait treatment, in the early stages after SCI.

Case report

The subjects in this study were two individuals who were diagnosed with paraplegia caused by acute-phase SCI.

The ethics committee of the University of Tsukuba approved this study in June 2014, and informed consent was provided by both subjects. This study is registered in the University Hospital Medical Information Network (UMIN) clinical trials registry in Japan with the registration number UMIN000014336.

Case 1

A 61-year-old female (Case 1) presented sudden onset paraparesis, and was transferred to University of Tsukuba Hospital by the emergency medical services. She exhibited symptoms of paraplegia and sensory disturbance below the Th11 level. Magnetic resonance imaging (MRI) of the spine showed high signal intensity in the T2-weighted image of the spinal cord at the Th8–10 level (Fig. 1). Physical therapy was started on day 10 from SCI onset, and HAL intervention was started on day 14.

She was classified by the American Spinal Injury Association (ASIA) Impairment Scale (AIS) as an ASIA C, her Lower Extremity Motor Score (LEMS) was 30, and no increase in the muscle tone of the gastrocnemius muscle was observed. Her Walking Index for Spinal Cord Injury (WISCI II) score was 4. The characteristics and demographics of both individuals are shown in Table 1.

Figure 1 The sagittal MRI (A) and axial MRI (B) findings after spinal cord infarction in Case 1. MRI of the spine showed high signal intensity in the T2-weighted image of the spinal cord at the Th8–10 level.

Table 1 Demographics and Clinical characteristics

	Case 1	Case 2
Age	61	62
Sex	female	male
Diagnosis	Spinal Cord Infarction	Spinal Cord Infarction
Height (cm)	155	173
Weight (kg)	48.2	75.1
Injury level	Th8-Th10	Th12-L1
Period since onset (days)	14	7
Hospitalization period (day)	21	31
ASIA	C	D
WISCI II	4	5

ASIA, American Spinal Injury Association; WISCI II, Walking Index for Spinal Cord Injury.

The participant received gait treatment with HAL 3–4 times per week, for a total of 8 sessions, in addition to conventional physical therapy. Conventional therapy focused on improving lower extremity strength, standing balance, and gait. The intensity of training was approximately 60 minutes, 5 times per week for both participants. Both individuals were fitted with the bilateral-leg version of the HAL (Fig. 2).

One 20–30-min session was completed once a day. The participants were harnessed in a mobile suspension system (All-In-One Walking Trainer; Ropox A/S, Næstved, Denmark) in which the degree of suspension was adjusted for each participant. The HAL trainers were licensed to use the HAL. The cybernics voluntary control mode was selected during HAL treatment. The level of assistance was set to a minimal level of

Figure 2 Gait treatment using a bilateral-leg version of the HAL. Abbreviation: HAL, Hybrid Assistive Limb; SCI, Spinal Cord Infarction.

support for each participant's gait, and it was gradually decreased with ambulatory improvement.

The AIS, LEMS, Modified Ashworth Scale (MAS), WISCI II, comfortable gait speed (CGS), stride, cadence, right and left leg swing time during the gait cycle, hip and knee joint angle during the gait cycle, BI, FIM, modified Rankin Scale (mRS), and adverse effects were assessed prior to HAL treatment and post-HAL treatment. Gait analysis was performed using a three-dimensional gait analysis system (Vicon Motion Systems Ltd., Oxford, UK) for spatiotemporal gait parameters. Markers were put on the heel, toe, and lateral malleolus. These data were collected with 16 T20 cameras at 100 fps. The study participants walked 16 m on the ground at their CGS. Walking posture was recorded by a digital video camera in the sagittal plane. Hip and knee joint angles were calculated using the Dartfish 8 TeamPro Data software (Dartfish Japan Co., Ltd., Tokyo, Japan) in the sagittal plane of three gait cycles. The mean joint angles in each participant were compared without HAL and with HAL for the first, middle (4 session), and last sessions using wilcoxon signed-rank test. We used SPSS (version 23.0; IBM Corp., Armonk, NY, USA) for all statistical analyses. Statistical significance was set at $P < 0.05$.

No serious adverse effects were found. The mean walking distance during each session was 319 ± 36 m ($\pm$ SD) in Case 1. The following improvements were found in Case 1: the AIS improved from classification C to D, LEMS from 30 to 39, WISCI II from 4 to 13, CGS from 21.6 m/min to 60.6 m/min, stride from 0.4 m to 0.6 m, and cadence from 52.0 steps/min to 97.3 steps/min (Tables 2 and 3). The participant's BI score improved from 60 to 80, and she was able to transfer herself from her wheelchair to bed, ambulate, and step up stairs. Her motor score using the FIM improved from 65 to 78 in particular, self-care, mobility, and ambulation. Further, her score on the mRS improved from 4 to 3 (Table 2).

After HAL treatment, Case 1 showed improvement in the right knee flexion angle at the initial swing phase. Additionally, the right hip and knee extension also showed improvement at the terminal stance phase. In particular, we noted improvements in the right back knee during the terminal stance phase after HAL treatment (Table 3). When comparing the joint angles, between treatments with and without HAL, we found increased hip flexion angles during the mid-swing phase and increased right knee flexion angles during the initial swing phase in Case 1 ($P < 0.05$). The participant could repeat gait treatment assisted by HAL without back knee at the terminal stance phase (Table 4).

Table 2 Comparison of clinical outcome measures between pre and post-HAL treatment

Measurement	Case 1		Case 2	
	Pre	Post	Pre	Post
ASIA	C	D	D	D
LEMS	30	39	39	43
Ashworth	0	0	1	0
BI	60	80	35	60
FIM-M	65	78	49	67
FIM-C	35	35	35	35
FIM-T	100	113	84	102
mRS	4	3	4	3

ASIA, American Spinal Injury Association; LEMS, Lower Extremity Motor Score; BI, Barthel Index; FIM-M, Functional Independence Measure-Motor; FIM-C, FIM-Cognitive; FIM-T, FIM-Total; mRS, Modified Rankin Scale.

The cybernic voluntary control mode was used at the first session of HAL treatment. The second session, we changed the mode of HAL to the cybernic impedance control mode (in which the output depends on the movement of the joint, instead of active assistance) for the left hip and left knee joints.^{10,11}

Case 2

A 62-year-old male (Case 2) presented with progressive paraparesis and suspected spinal infarction at the level of the third lumbar vertebra as assessed by MRI. He was transferred to University of Tsukuba Hospital for further examination and HAL treatment. MRI of the spine showed high signal intensity in the T2-weighted image in the medullary cone at the Th12–L1 level

(Fig. 3). Physical therapy was started on day 3 from onset, and HAL intervention was started on day 7. Spinal angiography performed at 10 days from onset did not show any abnormalities that may have caused spinal cord damage.

He showed symptoms of paraplegia, with weakness and numbness of the lower extremities. The participant demonstrated sensory disturbances in the territory below L3 on both sides.

The individuals with SCI received gait treatment with HAL 3–4 times per week, with a total of 7 sessions, in addition to conventional physical therapy and occupational therapy. The other methods of HAL treatment, outcome measures, and methods of gait analysis were the same as for Case 1.

No serious adverse effects were observed. The mean walking distance during each session was 399 ± 88 m ($\pm$ SD) in Case 2. The following improvements were found in Case 2: the LEMS improved from 39 to 43, the MAS score for the gastrocnemius muscle from 1 to 0, WISCI II from 5 to 18, CGS from 21.5 m/min to 39.6 m/min, stride from 0.3 m to 0.4 m, and cadence from 61.9 steps/min to 99.5 steps/min (Tables 2 and 3). The participant's BI score improved from 35 to 60, and he was able to ambulate and step up stairs. His motor score, using the FIM improved from 49 to 67, in particular in self-care, mobility, and ambulation. Moreover, his mRS score improved from 4 to 3 (Table 2).

In terms of joint angle, both the hip extension angle at the terminal stance phase and right knee flexion angle at

Table 3 Comparison of spatiotemporal gait parameters and joint angles between pre and post-HAL treatment

Measurement	Case 1		Case 2	
	Pre	Post	Pre	Post
WISCI II	4	13	5	18
CWS (m/min)	21.63	60.67	21.56	39.60
Stride (m)	0.42	0.63	0.35	0.40
Cadence (steps/min)	52.04	97.30	61.96	99.50
Right leg step length (m)	0.41	0.58	0.30	0.38
Left leg step length (m)	0.38	0.56	0.35	0.38
Right leg swing time (s)	1.65	0.80	1.31	0.78
Left leg swing time (s)	1.72	0.78	1.29	0.77
Joint angles (°)				
Right hip flexion	26.2 ± 1.2	33.2 ± 7.6	25.5 ± 1.4	28.3 ± 1.9
Right hip extension	5.6 ± 3.6	23.8 ± 4.3	$-60.5 \pm 5.0^{\dagger}$	$-29.4 \pm 3.5^{\dagger}$
Right knee flexion	51.1 ± 4.0	67.0 ± 2.5	41.8 ± 1.5	59.4 ± 3.8
Right knee extension	$5.1 \pm 0.7^{\#}$	-2.0 ± 2.3	-17.3 ± 3.5	-14.6 ± 2.3
Left hip flexion	26.9 ± 4.1	26.9 ± 4.9	19.1 ± 0.8	20.5 ± 2.0
Left hip extension	1.7 ± 6.4	8.3 ± 3.2	$-40.4 \pm 2.1^{\dagger}$	$-31.5 \pm 2.1^{\dagger}$
Left knee flexion	57.0 ± 4.7	53.5 ± 9.1	34.9 ± 5.8	32.6 ± 7.8
Left knee extension	-7.4 ± 2.5	-5.3 ± 1.8	$2.8 \pm 0.6^{\#}$	-4.2 ± 0.8

WISCI II, Walking Index for Spinal Cord Injury; CWS, Comfortable Gait Speed.

[†] Participant cannot hip extension at the terminal stance phase.

[#] Participant become back knee at the terminal stance phase.

Table 4 Comparison of joint angles between treatment without HAL and with HAL for the gait cycles

Joint angles (°)	Case 1		Case 2	
	Without HAL	With HAL	Without HAL	With HAL
Right hip flexion	28.5 ± 5.7	41.2 ± 3.3 *	27.0 ± 1.7	26.0 ± 6.7
Right hip extension	15.4 ± 9.2	11.1 ± 8.5	-37.1 ± 18.1 †	-24.7 ± 6.9 † *
Right knee flexion	58.2 ± 8.0	69.0 ± 4.4 *	50.6 ± 7.9	49.4 ± 12.4
Right knee extension	1.0 ± 3.7 #	-7.7 ± 8.9 *	-16.8 ± 3.1	-13.9 ± 11.0
Left hip flexion	26.8 ± 3.5	34.0 ± 6.3 *	19.5 ± 1.9	21.8 ± 3.3
Left hip extension	5.1 ± 5.6	2.7 ± 7.3	-28.6 ± 11.8 †	-20.3 ± 11.1 †
Left knee flexion	53.2 ± 7.0	57.9 ± 13.1	36.7 ± 6.8	43.4 ± 11.2
Left knee extension	-6.4 ± 2.0	-17.0 ± 8.3 *	-0.7 ± 3.1	-2.2 ± 2.1

† Participant cannot hip extension at the terminal stance phase.

Participant become back knee at the terminal stance phase.

* $p < .05$, wilcoxon signed-rank test.

the initial swing phase improved in Case 2 after HAL treatment. In particular, left back knee at the terminal stance phase improved after HAL treatment (Table 3). Conversely, an increase in the right hip extension angle was found in this participant at the terminal stance phase when comparing the joint angles between treatment with and without HAL for the gait cycles ($P < 0.05$; Table 4).

The cybernic voluntary control mode was used at the first session of HAL treatment. In the sixth session, we changed the mode of HAL to the cybernic impedance control mode for both knee joints.^{10,11}

Discussion

The results of this study showed that gait treatment using HAL is feasible and safe in the early stage after SCI. Our results indicate that gait treatment using HAL may be beneficial for paraplegic and non-ambulatory individuals with acute SCI. Previous reports showed a promising effect of robot-assisted gait therapy on the restoration of functional walking in individuals with stroke, spinal cord injury, and limb-girdle muscular dystrophy type 2I in both chronic disease and during recovery.^{13–19} However, there have been no reports on gait treatment using HAL for individuals in

Figure 3 The sagittal MRI (A) and axial MRI (B) findings after spinal cord infarction in Case 2. MRI of the spine showed high signal intensity of the T2-weighted image in the medullary cone at the Th12–L1 level.

the acute phase of SCI. To our knowledge, the present study is the first to show the improvement of gait ability using HAL treatment for individuals with acute SCI.

A previous paper demonstrated the safety and feasibility of HAL for intensive gait treatment in individuals with hemiparetic stroke.²⁰ The results showed that intensive gait treatment using HAL in the early stage after experiencing a stroke improved walking speed and independent walking. In a previous study, an individual with a subacute incomplete spinal cord injury (day 77 from onset) was treated with HAL intervention during 12 weeks.²¹ The AIS improved from classification C to D and the WISCI II score improved from 8 to 18 in this participant.²¹ Our results show that it is possible to administer gait treatment using HAL to individuals with acute SCI earlier after its onset than previously reported. Consequently, the AIS improved from classification C to D and the WISCI II score improved from 4 to 13 in Case 1. Similarly, the WISCI II score improved from 5 to 18 in Case 2 after HAL treatment. Furthermore, we found improvements in our two cases in terms of the spatiotemporal gait parameters and the joint angles during the gait cycle.

Our data showed improved independent walking, gait speed, LEMS, ADL, and joint angles during the gait cycle in our participants. Furthermore, our report revealed decreased spasticity of the gastrocnemius muscle after HAL treatment in one of our participants as assessed by MAS. A recent research article reported decreased spasticity after treadmill walking with HAL in a participant with complete C4 quadriplegia and chronic spinal cord injury.²² Our data showed that HAL supported repetitive gait treatment by providing motion assistance in response to the participant's voluntary drive using exclusive cybernetic voluntary control and cybernetic impedance technology.^{10,11} Therefore, robotic-assisted gait treatment with HAL enables enlargement of the hip and knee joint angles. The exoskeleton support and assist provided by HAL in flexion and extension exercise of hip and knee joint make it possible for individuals to repeat a walk by appropriate walk posture. This new type of robotic-assisted gait treatment using HAL may facilitate recovery of motor function and gait ability in the early stage after SCI.

A limitation of this study is that this is a report on only two cases in the acute phase of SCI. The effect of HAL should be evaluated in more individuals with SCI, and a randomized control trial is needed to eliminate the effects of conventional physical therapy and spontaneous recovery.

Conclusion

Gait treatment using HAL may be beneficial for paraplegic and non-ambulatory individuals after acute SCI. Our results demonstrate that gait treatment using HAL may be useful for improving gait ability without increasing spasticity in the acute phase of SCI. Further studies are needed in order to compare the efficacy of gait treatment using HAL with conventional physical therapy alone.

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