

Functional Neurorehabilitation using the Hybrid Assistive Limb (HAL): A First Experience in the United States

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Abstract

Introduction: The Hybrid Assistive Limb (HAL, Cyberdyne, Japan) facilitates voluntary, user-driven ambulation through a neurologically-controlled system based on bioelectrical signals derived from the user. This allows for the repeated execution of physiologically faithful gait patterns, crucial to recovery in cases of neurologic motor deficit. In this series, we present the first three patients in the United States to undergo HAL neurorehabilitation training.

Patient and methods: A case series of three patients participating in a single-center prospective, interventional pilot study, suffering neurologic motor deficits secondary to spinal cord infarct following a pulmonary embolism (patient 1), multiple sclerosis (patient 2) and the surgical resection of a petroclival meningioma (patient 3). The patients underwent 60 sessions of body weight-supported treadmill training in the HAL over the course of 12 weeks. Measures of functional ambulation (10 Minute Walk Test, 10MWT) were performed out of the HAL before and after each session and at the 12 week and 6 month follow-up. Timed Up & Go (TUG) test was performed each week. Treadmill data (time, distance) while in HAL was recorded at each session. Measures of endurance (6 Minute Walk Test, 6MWT), risk of fall (TUG), balance impairment (Berg Balance Scale) and improvements in walking performance (Walking Index for Spinal Cord Injury II, WISCI II) were measured at baseline, after 12 weeks and at 6 months follow-up.

Results: Patients 2 and 3 completed 60 visits, patient 1 completed 56 visits. All patients achieved markedly increased treadmill paces, improved functional scores, increased distance in the 6MWT and decreased TUG times at 6-month follow-up. In the 10MWT, all patients achieved a clinically significant decrease in time and steps and showed improvements in the required assistance level to perform the test. Patients 1 and 3 showed improvement on the Berg Balance Scale. Patient 2 had no change between baseline and 6-month follow-up. Only minor adverse effects were reported, including skin abrasions and irritation secondary to chaffing of the HAL unit and EMG electrodes.

Conclusion: These data show that HAL training is both feasible and effective in the neurorehabilitation of patients suffering neurologic motor deficits secondary to trauma and/or pathological/neurodegenerative processes after they have undergone normal rehab. A greater number of patients are required to meaningfully assess the differences in improvement from baseline, based upon underlying pathologies.

Keywords: Hybrid assistive limb; HAL; Exoskeleton; Neurorehabilitation; Gait training; Treadmill training

Introduction

The treatment of neurologic motor deficits following spinal cord injury (SCI), stroke (CVA), multiple sclerosis (MS) and other neuromuscular disorders continues to pose a major challenge for the affected patients, their families and health care systems as a whole due to the absence of meaningful restorative therapies. To date, there has been no major breakthrough therapeutic success beyond trying to gain the best possible functional independence given the respective impairments of these patients.

Several neurorehabilitation therapies exist for patients suffering from neurologic motor dysfunction ranging from conventional gait training, balance and strength training, neuromuscular electrical stimulation, treadmill training and drug therapy. The generally accepted timeframe for plateauing after functional interventions is three months [1-4].

More recently, exoskeletons such as Re-Walk (Argo Medical Technologies Ltd, Yokneam Ilit, Israel), Rex-Bionics (Auckland, New Zealand) or Wearable Power-Assist Locomotor exoskeleton (WPAL; Fujita Health University, Japan) have been introduced to improve mobility. The principle of an exoskeletal support as well as functional myoelectric stimulation for neurorehabilitation has been used for many years [5-9]. In comparison to these passive exoskeletons, the concept of the interactive neurologically-controlled exoskeleton Hybrid Assistive Limb (HAL, Cyberdyne Inc. and Japan) combines both principles. HAL uses a neurologically-controlled system to detect minute surface action potentials on the patient's skin surface and assists user-driven

locomotive action based on these signals, allowing patient's a voluntarily driven range of motion [10].

Several international studies have demonstrated the safety and feasibility of the HAL in the context of several conditions, including CVA, SCI, both chronic incomplete SCI and chronic complete SCI with zones of partial preservation (ZPP) and in other cases of neurologic motor dysfunction secondary to traumatic events and/or neurodegenerative pathologies. Furthermore, these studies have shown that training with HAL improves quality of life, decreases neuropathic pain and increases patient's functional mobility, over-ground walking, muscle strength and motor function in and out of HAL [11-14].

Purpose of the Study

In this series, we present the first three patients in the United States to undergo HAL neurorehabilitation training.

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Patients and Methods

We present the first three patients participating in a single-center prospective, interventional pilot study, who were suffering from chronic neurologic motor deficits secondary to spinal cord infarct following a pulmonary embolism (patient 1), MS (patient 2) and the surgical resection of a petroclival meningioma (patient 3). Patients were included who had achieved a stable non-progressive state in their motor neurologic deficit following (a) SCI with American Spinal Injury Association (ASIA) A through D functional status with thoracic and lumbar levels of paralysis (b) cervical spinal cord injury with incomplete injuries below C6, or (c) stroke, MS, or other neurodegenerative disorders that cause significant gait impairment. Patients on active medications for spasticity were required to be on a stable dose for at least three months prior to study entry.

Patient 1

31 year old female with a 6 week old spinal cord infarction after cardiac arrest during surgery resulting in a T12 ASIA C paraplegia.

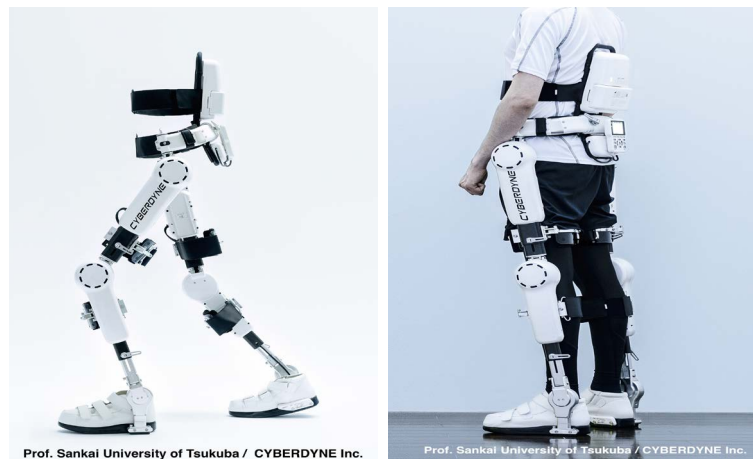
Patient 2

60 year old male with a 20 year history of relapsing-remitting MS. He has always been on disease modifying therapy for MS and is currently on Fingolimod. His MS expanded disability status scale (EDS) score prior to the study was 6.5, which remained constant throughout the study.

Patient 3

54 year old female with initially left greater than right hemiparesia and significant ongoing bilateral ataxia status following resection of a large right petroclival meningioma resection 6 months ago.

All patients underwent 60 sessions of Body Weight-Supported Treadmill Training (BWSTT) in the HAL[®] over the course of 12 weeks (Figures 1 and 2). All training was performed under the supervision of a trained neuro physiotherapist in the Swedish Multiple Sclerosis Center rehabilitation facility. Required level of assistance, number of steps and time were assessed using the 10 Minute Walk Test (10MWT) out of the HAL[®] before and after each session [15]. The 10MWT was also evaluated at baseline, 6 weeks and at the 12 week and 6 month



Note: Pictures of a HAL[®] exoskeleton (left/right). With written consent obtained from CYBERDYNE Inc. Copyright and courtesy of CYBERDYNE Inc.

Figure 1: The HAL[®] exoskeleton.



Figure 2: Training on a treadmill with HAL[®]

All patients underwent 60 sessions of Body Weight Supported Treadmill Training (BWSTT) in the HAL[®]. All training was performed under the supervision of a trained neuro physiotherapist. With written consent obtained from CYBERDYNE Inc. Copyright and courtesy of CYBERDYNE Inc.

follow-up. The Timed Up & Go (TUG) test was performed each week, measuring the time and assistance needed for standing up from a chair, walking 3 m, turning around, walking back and sitting down. Treadmill data (time, distance, blood pressure, heart rate) while in HAL¹ was recorded at each session. Measures of endurance (6 Minute Walk Test, 6MWT), risk of fall (TUG), balance impairment (Berg Balance Scale) and improvements in walking performance (WISCI II) were measured at baseline, 12 weeks training and 6 month follow-up. The WISCI II score is a 20 item scale measuring the walking capabilities of a patient based on the requirements of assistance from walking aids, personal assistance or braces. Grade 0 means that the patient has neither standing nor walking abilities. Grade 20 means that no assistance is needed to walk a distance of 10 m [16-19].

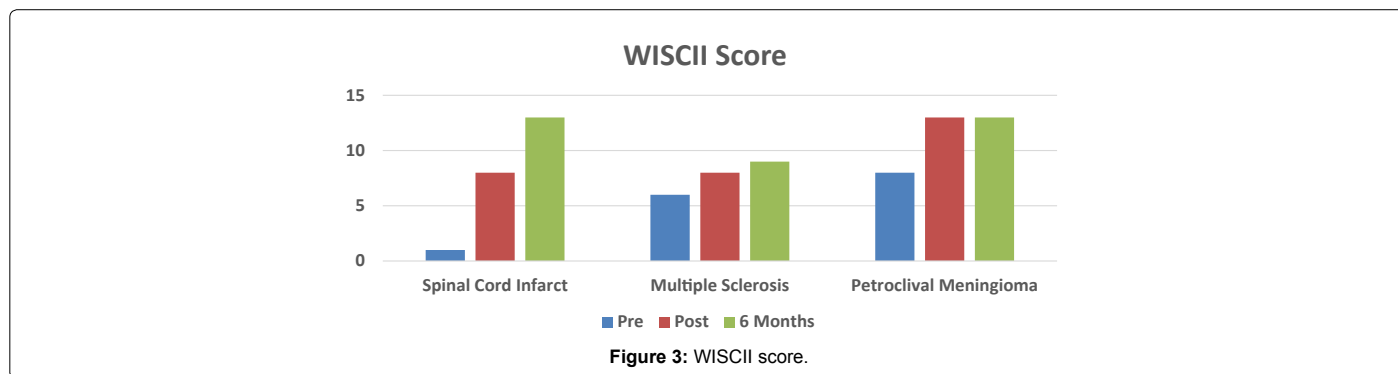
Results

All three patients with an age of 31, 60 and 54 underwent protocolled

treadmill training with HAL¹ in 2016. Patient 1 completed 56 out of 60 visits. Patients 2 and 3 completed 60 visits. The mean WISCI II score increased from 5.0 at baseline, to 11.3 at the 6-month follow-up (Figure 3). Improvements in speed and endurance were achieved in all patients (Tables 1 and 2). The required time for the 10MWT decreased on average by 21.1% and the mean number of steps decreased by 17.0% (Table 1). The mean time to complete the TUG test decreased by 11.3% and the mean walk distance covering during the 6MWT improved by 21.1% (Figures 4 and 5). The results are summarized in Tables 1 and 2.

Patient 1

The WISCI II score improved from 1 at baseline to 13 at the 6 month follow-up (Figure 3). The time to complete the 10MWT at 6 months follow-up was reduced by 11.7 s relative to baseline (64.7 s vs. 53.0 s). The number of steps needed to complete the 10MWT at 6 months follow-up decreased by 8 steps compared to baseline (42 steps



Spinal Cord Infarct	Baseline	Tx start	6 week	Last day	12 weeks	6 months	Change*	Change %
VISIT	0	1	30	60		62		
WISCIII	1	-	-	-	8	13	12	
10 Meter Walk Test (s)	64.7	37.0	36.8	-	60	53	-11.7	-18.1%*
Assistance Level	-	min A	cga	-	mod a	sup	-	
10 Meter Test (steps)	42	24	32	-	38	34	-8	-19.1%*
Tug Time Before	-	-	-	-	92	81		-12.0%**
6 Minute Walk Distance	-	-	-	-	43	60		+39.5%**
BERG	7	-	-	-	9	9	2	
Multiple Sclerosis	Baseline	Tx start	6 week	Last day	12 weeks	6 months	Change*	Change %
VISIT	0	1	30	60	61	62		
WISCIII	6	-	-	-	8	-	-	
10 Meter Walk Test (s)	25.6	22.4	24.9	17.6	20.6	19.1	-7.5	-25.4%*
Assistance Level	sbg	cga	cga	cga	sup	sup	-	
10 Meter Test (steps)	24	22	24	19	22	19		-20.8%*
Tug Time Before	29.8	-	31.2	-	30.9	27.9	-1.9	-6.4%*
6 Minute Walk Distance	104.1	-	-	-	104.5	-		+0.4%***
BERG	29	-	-	-	28	-	-	
Petroclival Meningioma	Baseline	Tx start	6 week	Last day	12 weeks	6 months	Change*	Change %
VISIT	0	1	30	60	61	62		
WISCIII	8	-	-	-	13	13	5	
10 Meter Walk Test (s)	42.7	40.0	47.1	34.6	33.8	34.1	-8.6	-20.1%*
Assistance Level	cga	cga	sbg	sbg	sbg	sbg	-	
10 Meter Test (steps)	27	26	28	25	26	24	-3	-11.1%*
Tug Time Before	80.8	-	-	-	53.6	65.9	-14.9	-18.4%*
6 Minute Walk Distance	66.2	-	-	-	87.3	81.6	15.5	+23.3%*
BERG	13	-	-	-	21	25	12	

Change*: Difference from baseline; **: Change 12 weeks to 6 months; ***: Change 12 weeks to baseline; - Blank cells represent missing data, Tx: Training Start_{min}; a: Minimum Assistance; cga: Contact Guard; ma: Moderate Assistance; sup: Supplement; sbg: Standby-By Guard

Table 1: Shows the changes of walking abilities during the time of treadmill training and the 6 months follow-up for all three patients.

vs. 34 steps). The assistance level improved from, minimum assistance “to „supplemental “at the 6 month follow-up. Relative to the 12 week reevaluation (92 s) the time to complete the TUG Test (Figure 4) decreased by 11 s at 6 months follow-up (81 s). Relative to the 12-weeks

	Start (miles)	Min-max (miles)	End (miles)
SCI	0.02	0.02-0.41	0.17
MS	0.18	0.16-0.46	0.36
PM	0.08	0.08-0.6	0.57

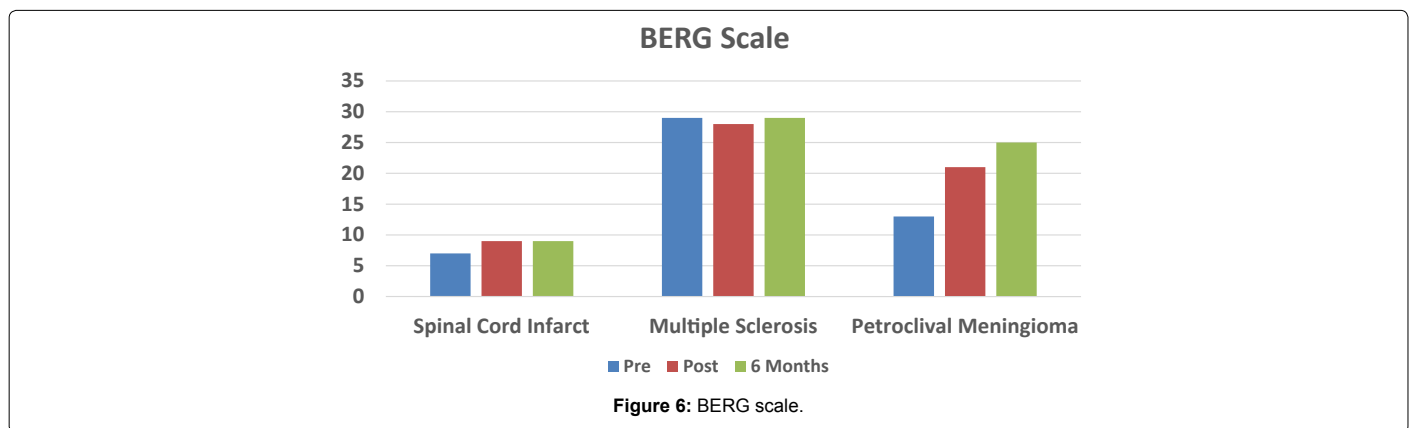
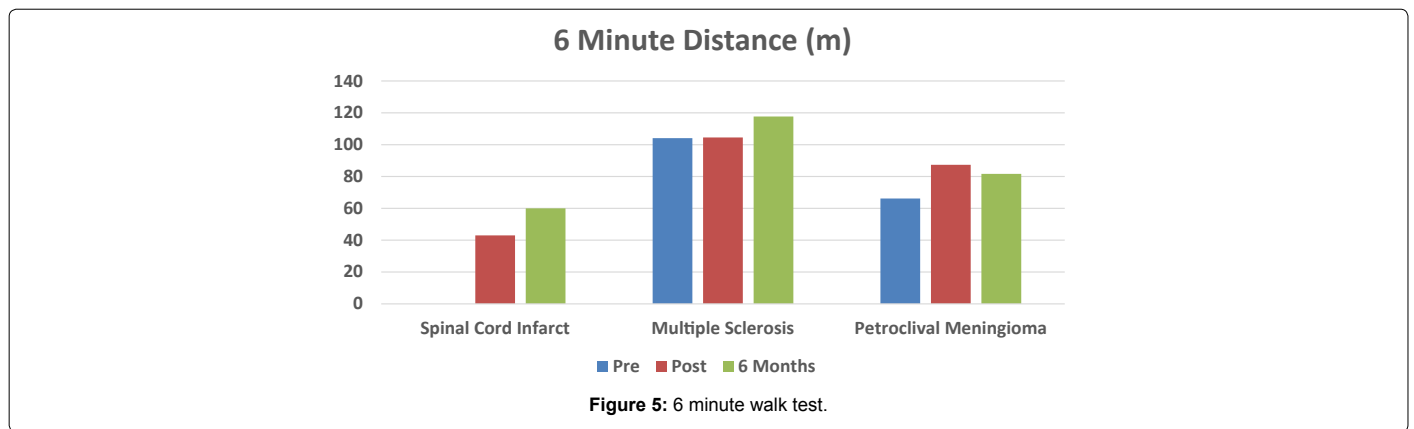
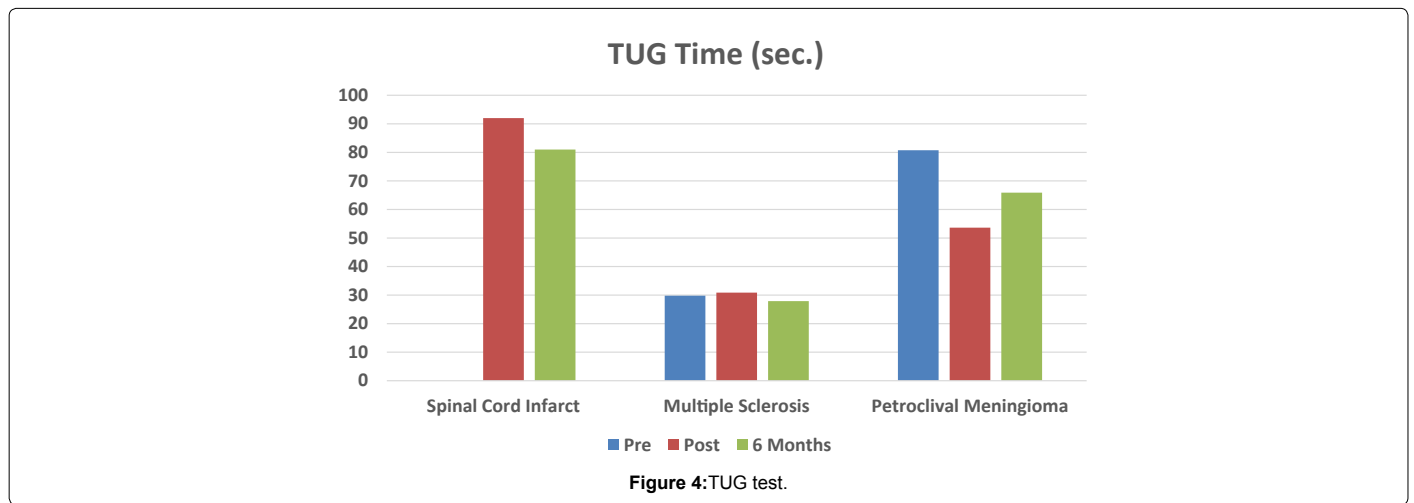
SCI: Spinal Cord Infarct; MS: Multiple Sclerosis; PM: Petroclival Meningioma

Table 2: Distance covered on a treadmill.

follow-up (43 m), distance covered during 6MWT (Figure 5) increased by 17 m at 6 months follow-up (60 m). At the 6-month follow-up (9 points) the patient’s BERG balance (Figure 6) score had increased two points relative to baseline (7 points). Between the first and the last HAL training session the patient increased the distance covering on the treadmill from 0.02 miles to 0.17 miles (Figure 7). The results are summarized in Tables 1 and 2.

Patient 2

The WISCI II score improved from 6 at baseline to 8 at the 3-month follow-up (Figure 3). The time to complete the 10MWT at 6 months



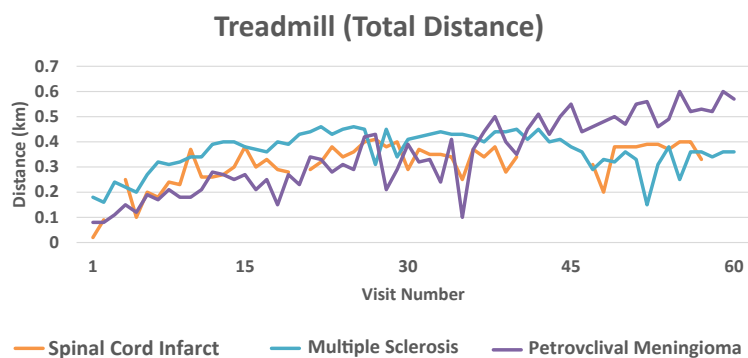


Figure 7: Treadmill distance.

follow-up was reduced by 7.5 s relative to baseline (25.6 s vs. 19.1 s). The number of steps needed to complete the 10MWT at 6-months follow-up decreased by 5 steps compared to baseline (24 steps vs. 19 steps). The assistance level improved from “stand-by guard” to “supplemental” at the 6 month follow-up. Relative to baseline (29.8 s) the time to complete the TUG Test (Figure 4) decreased by 1.9 s at 6 months follow-up (27.9 s). Relative to baseline (104.1 m), the distance covered during the 6MWT (Figure 5) increased to 140.5 m at 3 months follow-up. At the 3 months follow-up (28 points) the patients BERG balance score (Figure 6) had decreased one point relative to baseline (29 points). The results are summarized in Tables 1 and 2. The ambulated distance on the treadmill at the first session was 0.18 miles and increased to 0.36 miles at the end of the HAL[®] training (Figure 7). Prior to HAL[®] training, the patient was unable to stand and was taking fewer steps with his walker in a lurching gait pattern. After the study, the patient was able to stand unsupported for short periods and walks more smoothly with a walker.

Patient 3

The WISCI II score improved from 8 at baseline to 13 at the 6 month follow-up (Figure 3). The time to complete the 10 MWT at 6 months follow-up was reduced by 8.6 s relative to baseline (42.7 s vs. 34.1 s). The number of steps needed to complete the 10MWT at 6-months follow-up decreased by 3 steps compared to baseline (27 steps vs. 24 steps). The assistance level improved from “contact guard” to “stand-by guard” at the 6 month follow-up. Relative to the 12 week reevaluation (80.8 s) time to complete the TUG Test (Figure 4) decreased by 14.9 s at 6 months follow-up (65.9 s). Relative to baseline (66.2 m), the distance covered during 6MWT (Figure 5) had increased by 15.5 m at 6 months follow-up (81.6 m). At the 6-month follow-up (25 points) the patients BERG balance score (Figure 6) had increased 12 points relative to baseline (13 points). The distance covered on the treadmill improved from 0.08 miles to 0.57 miles at the end of treadmill training with HAL[®] (Figure 7). The results are summarized in Tables 1 and 2).

Only minor adverse effects were reported, including skin abrasions and irritation secondary to chaffing of the HAL[®] unit and EMG electrodes.

Discussion

This study describes the first cohort in the United States undergoing treadmill training with HAL[®]. The purpose of this study was to determine whether training with HAL[®] improves functional mobility in patients with neurologic disorders or spinal cord injuries.

Treadmill training with HAL[®] is postulated to aid cortical plasticity and the restoration of spinal reflex circuits through the recruitment

and repeated use of remaining somatosensory afferent pathways and corticospinal tracts [12,20]. Patient 3 experienced a decline in performance in the 6MWT and TUG test between the 12 week and 6 month follow-up. This may evidence regression without HAL[®] training. Furthermore, electrophysiological data has demonstrated a normalization of primary somatosensory cortex activation, the disinhibiting and reorganization of which is a staple of spinal cord injury [12].

Although evidence is only beginning to emerge in the literature, the effectiveness of bodyweight supported treadmill training with HAL[®] in patients with spinal cord injuries and neurologic disorders has been analyzed and suggests promising results [13,21-23].

All patients achieved markedly increased treadmill performance, increased WISCI II scores, increased distance in the 6MWT and decreased TUG Test times at 6-months follow-up. In the 10MWT, all patients achieved a decrease in time and steps and showed improvements in the required assistance level to perform the test. Patients 1 and 3 showed improvement on the Berg Balance Scale. Patient 2 had no change between baseline and the 6-month follow-up. These results imply HAL[®] supported treadmill training can improve walking abilities and motor function in patients with neurologic disorders or spinal cord injuries. Our results in this limited pilot study suggest that treadmill training with HAL[®]-support can improve walking abilities in terms of speed, gait and distance in spinal cord injury and brainstem lesion patients and may have some more limited benefit in stroke patients.

This study has several limitations, including the small number of patients (n=3) and the heterogenous group of patients. However, all patients were treated by the same multidisciplinary team, according to a standardized protocol in the same facility. During this first trial only minor adverse effects were reported, including skin abrasions and irritation secondary to chaffing of the HAL[®] unit and EMG electrodes.

Conclusion

These data show that HAL[®] training is both feasible and effective in the neurorehabilitation of patients suffering neurologic motor deficits secondary to trauma and/or pathological/neurodegenerative processes after they have undergone normal rehab. A greater number of patients are required to meaningfully assess the functional improvement based upon underlying pathologies. Further studies in the form of randomized trials are needed to assess the comparative effectiveness of the changes in functional mobility and to determine which patients benefit from training with neurologically-controlled exoskeletons.

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