

Effects of Walkbot gait training on kinematics, kinetics, and clinical gait function in paraplegia and quadriplegia

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Abstract.

BACKGROUND: The robotic-assisted gait training (RAGT) system has gained recognition as an innovative, effective paradigm to improve functional ambulation and activities of daily living in spinal cord injury and stroke. However, the effects of the Walkbot robotic-assisted gait training system with a specialized hip-knee-ankle actuator have never been examined in the paraplegia and quadriplegia population.

OBJECTIVE: The aim of this study was to determine the long-term effects of Walkbot training on clinical for hips and knee stiffness in individuals with paraplegia or quadriplegia.

METHODS: Nine adults with subacute or chronic paraplegia resulting from spinal cord injury or quadriplegia resulting from cerebral vascular accident (CVA) and/or hypoxia underwent progressive conventional gait retraining combined with the Walkbot RAGT for 5 days/week over an average of 43 sessions for 8 weeks. Clinical outcomes were measured with the Functional Ambulation Category (FAC), Modified Rankin Scale (MRS), Korean version of the Modified Barthel Index (K-MBI), Modified Ashworth Scale (MAS). Kinetic and kinematic data were collected via a built-in Walkbot program.

RESULTS: Wilcoxon signed-rank tests showed significant positive intervention effects on K-MBI, maximal hip flexion and extension, maximal knee flexion, active torque in the knee joint, resistive torque, and stiffness in the hip joint ($P < 0.05$). These findings suggest that the Walkbot RAGT was effective for improving knee and hip kinematics and the active knee joint moment while decreasing hip resistive force. These improvements were associated with functional recovery in gait, balance, mobility and daily activities.

CONCLUSIONS: These findings suggest that the Walkbot RAGT was effective for improving knee and hip kinematics and the active knee joint moment while decreasing hip resistive force. This is the first clinical evidence for intensive, long-term effects of the Walkbot RAGT on active or resistive moments and stiffness associated with spasticity and functional mobility in individuals with subacute or chronic paraplegia or quadriplegia who had reached a plateau in motor recovery after conventional therapy.

Keywords: Paraplegia, quadriplegia, robotic-assisted gait training, Walkbot, stiffness, gait, neurorehabilitation

1. Introduction

Paraplegia and quadriplegia are common neurological impairments in spinal cord injury or brain

injury, and they are often implicated in locomotor dysfunction. In the United States alone, as many as 17,000 people are newly diagnosed with SCI (National Spinal Cord Injury Statistical Center, 2016) or 795,000 people in brain injury every year (Writing Group et al., 2016). Most patients with paraplegia or quadriplegia suffer from locomotor impairment, as well as muscle weakness, proprioceptive deafferentation, and spasticity (Balaban & Tok, 2014; Thibaut

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et al., 2013), resulting from spinal cord injury or CVA. As a result, quality of life and activities of daily living (ADL) are also compromised.

To improve locomotor function, clinicians have used conventional gait rehabilitation approaches, including neurodevelopmental treatments, task-oriented gait training, and partial weight-bearing treadmill gait training (Liepert, Storch, Fritsch, & Weiller, 2000; Manganotti, Acler, Zanette, Smania, & Fiaschi, 2008). Outcome studies have shown positive results in gait function; however, conventional gait rehabilitation presents practical issues associated with its labor intensiveness, increased physical stress on the therapists, risk of falls, and lack of repetition to generate sufficient neuroplasticity (De Santis et al., 2014; J.H. Jung, Lee, You, & Lee, 2009; S.Y. Kim et al., 2015; Schwartz & Meiner, 2015).

To mitigate the inherent problems of conventional physical therapy, we have recently developed an advanced robotic gait training system (WALKBOT™, P&S Mechanics, Seoul, Republic of Korea) for individuals with paraplegia or quadriplegia. The Walkbot system is designed to provide intensive training with minimal labor or physical stress to the therapist, decrease the risk of falling, and resolve problems with repetition (S.Y. Kim et al., 2015). However, no previous studies have examined the effects of Walkbot robotic gait training on locomotor recovery and clinical functional improvement in patients with paraplegia or quadriplegia. Therefore, the purpose of the present study was to determine the long-term effects of Walkbot training on clinical outcomes as measured by the Functional Ambulation Category (FAC), Modified Rankin Scale (MRS), Korean version of the Modified Barthel Index (K-MBI), and Modified Ashworth Scale (MAS) for hips and knee stiffness in individuals with paraplegia or quadriplegia. Our hypothesis was that Walkbot training would improve clinical measures, reduce resistive stiffness, and improve active torque in individuals with subacute or chronic paraplegia/quadriplegia.

2. Materials and methods

2.1. Materials

The Walkbot System is designed to provide accurate kinematic and kinetic locomotor feedback during gait training in individuals with gait impairments (J.H. Jung et al., 2009). Walkbot robotic

gait training leads to earlier mobilization in acute or subacute patients with gait dysfunction. Hence, it accelerates faster locomotor recovery in gait rehabilitation. Unparalleled compared to other conventional robotic-assisted gait training systems, the Walkbot is equipped with a 6-degree of freedom actuator-controlled exoskeleton for the hip, knee, and ankle joint, augmented by virtual reality, as well as adjustable partial body weight suspension support (Jung et al., 2009). Therefore, the Walkbot gait training system offers real-time visual and haptic biofeedback for torque, kinematics, and active and resistive stiffness of the hip, knee, and ankle joint movements during gait rehabilitation.

2.2. Subjects

A convenience sample of nine individuals (5 males; mean age = 50.11 ± 18.04 years) who were diagnosed with paraplegia resulting from spinal cord injury or quadriplegia resulting from brain injury at a major university medical center participated in this study. Inclusion criteria were as follows: (1) non-progressive injury; (2) between 20 and 80 years old; (3) had reached a potential locomotor motor recovery plateau after conventional rehabilitation; (4) classified by the ASIA scale as C or D for patient with spinal cord injury. (5) A total Mini-mental state examination (MMSE) score of more than 24 for patients with brain injury. Exclusion criteria were as follows: (1) classified by the ASIA scale as A or B; (2) severe spasticity (MAS > 2) or tremor; (3) impaired cognitive function or severe visual and cognitive impairments; (4) musculoskeletal or cardiopulmonary system impairments; (5) overweight (>135 kg) or short height (<150 cm). The institutional review board (IRB) of Pusan National University Hospital approved the study. Informed consent obtained from all participants.

2.3. Procedure

The present experiment employed a pretest-posttest design without a blind control. All participants were recruited from inpatients who were admitted to a major university rehabilitation hospital and who underwent the pretest, consisting of robotic-assisted gait training utilizing WALKBOT, and posttest. The test included Functional Ambulation Category (FAC), Modified Rankin Scale (MRS), the Korean version of the Modified Barthel Index (K-MBI), Modified Ashworth Scale (MAS), and

joint stiffness measurements, and was administered by a certified therapist. Intervention was provided by another physical therapist who was trained in Walkbot robotic-assisted gait training.

2.4. Clinical function tests

Gait function assessed by standardized clinical measurements, including the FAC, MRS, Korean version of the Modified Barthel Index (K-MBI), and Modified Ashworth Scale (MAS) before and after the intervention. FAC was used to determine the level of assistance during ambulation with a scale ranging from 0 (non-ambulatory) to 5 (normal) (Mehrholz, Wagner, Rutte, Meissner, & Pohl, 2007). The MRS was used to assess the severity of disability associated with ambulation, with a scale ranging from 0 (no symptoms at all) to 6 (death) (Banks & Marotta, 2007). The MAS was used to measure the severity of muscle tone at the hamstring and ankle plantar flexors, with a grading scale of 0 (no increase in muscle tone) to 4 (rigidity) (Bohannon & Smith, 1987). The K-MBI was used to determine functional levels of assistance in activities of daily living on a scale of 1 (totally dependent) to 5 (independent) (H.Y. Jung et al., 2007). The reliability or validity of the FAC (Holden, Gill, & Maglioni, 1986; Mehrholz et al., 2007), MRS (Cup, Scholte op Reimer, Thijsen, & Van Kuyk-Minis, 2003), K-MBI (Derick T Wade, 1987; Hsueh, Lin, Jeng, & Hsieh, 2002; H.Y. Jung et al., 2007), and MAS (Allison, Abraham, & Petersen, 1996; Fosang, Galea, McCoy, Reddihough, & Story, 2003; Skold, Harms-Ringdahl, Hultling, Levi, & Seiger, 1998) are reported.

2.5. Intervention

All patients received conventional physical therapy (40 minutes) combined with the Walkbot RAGT (40 minutes), 5 days/week over an average of 43 sessions for 8 weeks. Physical therapy included: the bed mobility exercise; sit to stand exercise (5 minutes); functional strengthening exercise for the iliopsoas, gluteus maximus, gluteus medius, quadriceps, hamstring, tibialis anterior, flexor and extensor hallucis longus and brevis, and gastrocnemius muscles (10 minutes); dynamic standing balance exercise (10 minutes); symmetrical, partial weight-support treadmill gait training, which progressed to over-ground gait training with or without assistive devices; and application of functional electrical stimulation (FES) (10 minutes) whenever initial tibialis anterior

muscle activation in the paretic limb(s) was weak (Veerbeek et al., 2014).

After conventional physical therapy, the Walkbot RAGT was added for another 40 minutes. Anthropometric and clinical data were encoded in the Walkbot system to create optimal gait kinematics and kinetics parameters for each patient. Then, the patient entered the Walkbot system, donned a suspension harness, and aligned the hip, knee, and ankle joints with the corresponding exoskeletal system's hip, knee, and ankle joint actuators. Initial body weight bearing (BWB) started at approximately 40% to 50% (adjustable range 0% to 100%) and was then progressed to 5% to 10% BWB per session. Stride length was initially set at 1.0 m/cycle to 1.6 m/cycle. Walking velocity started at 1.00 km/h to 1.20 km/h and was increased by 0.1 km/h every 5 minutes up to a tolerable speed (2.40 km/h to 2.60 km/h; maximum speed, 3.0 km/h). The target speed was maintained in successive sessions.

Important vital signs, including abnormal respiration, blood pressure, and heart rate, were closely examined during training, and we attempted to maintain them below 80% of the age-appropriate performance level. A resting interval was provided if required.

2.6. Joint stiffness measurements

The Walkbot-STIFF program is a built-in program in the Walkbot system to quantify real-time changes in muscle stiffness associated with spasticity during gait training (J.H. Jung et al., 2009). Both knee and hip joint stiffness data were acquired from the Walkbot system via the Walkbot-STIFF program. Acquired kinematic hip and knee angular displacement and moment data provided real-time kinematics and kinetics biofeedback information on the computer screen and were also used to compute the active and resistive stiffness. The stiffness, k , of a joint segment is a measure of the resistance offered by an elastic body segment to deformation. For a joint segment with a single degree of freedom (DOF) (e.g., stretching or compression of a hip segment), resistive stiffness is defined as

$$k_{\text{net}} = \frac{F}{\theta}$$

where F is the resistive force on the joint and θ is the angular displacement induced by the active force on the joint. The joint moment data were acquired by the servomotors that controlled the accurate

trajectories of the hip, knee, and ankle joint kinematics and kinetics using the specialized encoders. Each encoder recorded the joint angle, angular velocity, and acceleration signals, which were then auto-filtered and transformed to calculate moment data associated with active and resistance forces of the body segment acting on the hip and knee joints as the patient walked on the Walkbot treadmill. Active torque (AT) was defined as the moment that pivots around a certain joint in the same direction, whereas the resistive torque (RT) was defined as the moment that rotates in the opposite direction (I. Rodríguez-Santiago, 2007). Hence, a greater AT value indicates greater recovery in movement strength during gait, while a greater RT value indicates greater resistance to active limb movement (Birmingham et al., 1997).

2.7. Statistical analysis

Data were summarized as means and standard deviations. Wilcoxon signed-ranks tests were used to determine the intervention-related changes in clinical FAC, MRS, K-MBI, kinematics, and kinetics before and after the Walkbot RAGT. Nonparametric Wilcoxon tests were used because the baseline data were not normally distributed. The Chi square (χ^2) test was used for MAS data because it is considered a nominal measure of spasticity (Johnson, 2002). The Wilcoxon test was used to analyze kinematics, kinetic, and stiffness data. SPSS for Windows (version 12.0, Chicago, IL, USA) was used for analysis with statistical significance set at $\alpha = 0.05$.

3. Results

3.1. Mean clinical function data (N = 9)

Table 1 summarizes the demographic and clinical characteristics of participating patients. The Wilcoxon test revealed a significant difference in K-MBI between the pretest and posttest ($P = 0.008$), but other clinical measures such as FAC ($P = 0.317$) and MRS ($P = 0.317$) were not significantly different. Chi square analysis indicated that MAS_U/E was not significant, χ^2 (4, N = 9) = 7.11, $P = 0.130$, while MAS_L/E was statistically nonsignificant, χ^2 (4, N = 9) = 3.78, $P = 0.437$. Overall, the Chi square analysis demonstrated that the observed proportions did not differ from the hypothesized proportions for upper and lower extremity MAS variables,

Table 1
Demographic and clinical characteristics of the participants (N = 9)

Characteristic	Patients
Age (years $\pm$ SD)	24–75 (50.11 $\pm$ 18.04)
Gender (male/female)	5/4
Onset (months)	1–43 (9.83 $\pm$ 11.60)
Paraplegia/Quadriplegia	4/5
Paraplegia (n = 4)	T10 ASIA D (n = 1) T11 ASIA C (n = 2) T9/10, T10/11 Spinal Stenosis (n = 1)
Quadriplegia (n = 5)	Subarachnoid hemorrhage (n = 3) Both medullary infarction (n = 1) Hypoxic brain damage (n = 1)

*ASIA = American Spinal Injury Association, T = Thoracic spine.

Table 2
Comparison of clinical outcome between the pretest and posttest

Tests	Pretest	Posttest	P-values
FAC	1.56 $\pm$ 1.13	1.67 $\pm$ 1.00	0.317
MRS	4.11 $\pm$ 0.93	4.33 $\pm$ 0.87	0.317
K-MBI	24.33 $\pm$ 17.80	38.44 $\pm$ 25.62	0.008*
Post test data for MAS			
Tests	Median	IQR	P-values
MAS_U/E	0.00	0.50	0.130
MAS_L/E	1.00	1.75	0.437

*The data was statistically significant at $P < 0.05$. Wilcoxon test was used for FAC, MRS and K-MBI, Chi Square test was applied to MAS. FAC = Functional Ambulation Category; MRS = Modified Rankin Scale; K-MBI = Korean version of the Modified Barthel Index; MAS_U/E = MAS in the upper extremity muscle (biceps); MAS_L/E = MAS in the lower extremity muscle (planter flexor). Data are mean $\pm$ standard deviation. χ^2 statistical analysis and interquartile range (IQR) were used for the posttest MAS data. The interquartile range formula is the first quartile subtracted from the third quartile: $IQR = Q3 - Q1$.

suggesting that spasticity was unaffected by the intervention (Table 2).

3.2. Kinematic data for hip and knee angular displacement

Kinematic analysis revealed a significant increase in the maximal hip flexion angle after Walkbot training ($P = 0.011$). Maximum hip extension ($P = 0.008$) and knee flexion ($P = 0.008$) angles increased ($P < 0.01$), whereas the maximum knee extension angle did not change significantly (Table 3). Figures 1 and 2 illustrates a representative hip joint kinematic trajectory at the terminal swing phase.

3.3. Kinetic and stiffness data

Paired *t*-tests demonstrated that resistive hip joint torque was significantly decreased ($P = 0.038$), while

Table 3

Comparison of kinematic data for the hip and knee joint between the pretest and posttest

Tests	Pretest	Posttest	P-values
Hip Flexion	27.58 ± 0.75	29.33 ± 0.95	0.011*
Hip Extension	13.25 ± 0.31	16.49 ± 2.44	0.008*
Knee Flexion	50.45 ± 1.80	54.67 ± 1.78	0.008*
Knee Extension	2.32 ± 0.64	2.25 ± 0.89	0.515

*Wilcoxon test was significant at $P < 0.05$. Data are mean ± standard deviation.

active knee joint torque was increased ($P = 0.012$) after the intervention. However, there were no significance differences in stiffness data (Table 4).

4. Discussion

This study demonstrated the long-term effects of the Walkbot RAGT on hip and knee joint kinetics, kinematics, stiffness, and clinical outcome measures in individuals with paraplegia or quadriplegia. As anticipated, the Walkbot RAGT enhanced the active knee joint moment and diminished resistive hip joint stiffness while increasing hip flexion kinematics. Most importantly, these biomechanical improvements were associated with a functional level of gait

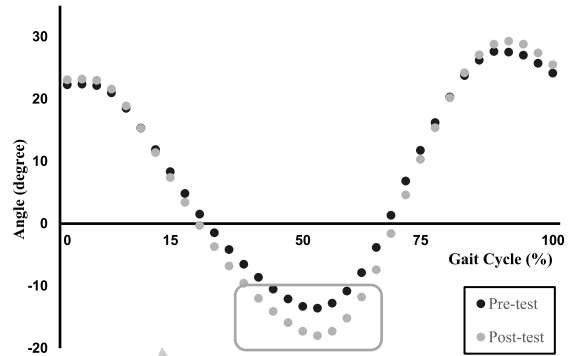


Fig. 2. Hip joint kinematics.

and independent motor performance in activities of daily life as evident in the KMBI.

Kinematic data analysis revealed a significant improvement in hip flexion, knee flexion, and hip extension as a result of the intervention. These results support earlier research (S.Y. Kim et al., 2015; Schwartz & Meiner, 2015) that examined the therapeutic effects of the RAGT on kinematics in stroke patients. Clinically, the majority of the patients in the present study initially presented with increased knee extension gait pattern (i.e., genu recurvatum), secondary to extensor synergy or spasticity, which was evident in increased knee extension kinematics at the pretest. However, after the robotic training, as the active knee moment control improved, increased knee extension was slightly reduced. However, such change was not statistically significant.

Kinetic data analysis demonstrated substantial improvement in the resistive hip stiffness, whereas the active hip joint torque tended to increase after the intervention. Similarly, a significant improvement in the active knee joint moment was observed, while resistive knee joint stiffness tended to decrease after the intervention. These findings are in agreement with earlier work (S.Y. Kim et al., 2015; Schwartz & Meiner, 2015) that examined the therapeutic effects of the Walkbot or Lokomat RAGT on muscle strength, muscle tone gait velocity, balance, and gait distance in stroke patients. Kim and colleagues reported that improved knee joint stiffness was associated with increased knee joint extension kinematics in the terminal swing phase (Zehr & Duyens, 2004). A recent clinical trial has assessed the effects of Walkbot robotic assisted training on gait, balance, and ADL in individuals with hemiparetic stroke (Kim et al., 2015). However, to date, this is the first clinical evidence on the effects of the Walkbot



Fig. 1. Robotic-assisted gait training using Walkbot.

Table 4
Comparison of kinetic and stiffness data for hip and knee joints on pretest and posttest

Tests	Pretest	Posttest	P-values
Kinetics (N·m)			
Active torque on hip	1.12 ± 1.15	1.64 ± 1.54	0.086
Resistive torque on hip	0.52 ± 0.31	0.31 ± 0.21	0.038*
Active torque on knee	0.15 ± 0.11	0.42 ± 0.42	0.012*
Resistive torque on knee	0.40 ± 0.46	0.18 ± 0.18	0.066
Stiffness (N/°)			
Hip	-0.01213 ± 0.01275	-0.02631 ± 0.02911	0.484
Knee	0.00726 ± 0.00734	0.00554 ± 0.00647	0.401

*Wilcoxon test was significant at $P < 0.05$. Data are mean ± standard deviation.

training on active torque and resistive torque, kinematics, and activities of daily living in individuals with paraplegia or quadriplegia.

Perhaps the enhanced active moment in the knee joint was associated with reciprocal inhibition of the hamstring muscle and autogenic facilitation of the quadriceps muscle (Aagaard et al., 2000). In the hip joint, decreased resistive stiffness may have resulted from inhibition of the spastic hip flexors because the Walkbot probably provided accurate and augmented kinesthetic and proprioceptive signals via the ascending dorsal lemniscus and columns to the contralateral sensorimotor cortex (H.Y. Kim, Yang, Park, Kim, & You, 2016). This enriched kinematic (joint angle) and kinetic (ground reaction force) sensorimotor feedback, which occurred during the repetitive, intensive, and active-assisted long-term Walkbot RAGT, may have produced neural plasticity (Arya, Pandian, Verma, & Garg, 2011; Diserens et al., 2007; Shimodozono et al., 2013). It is also plausible that such enhanced proprioceptive sensory input may influence inhibitory interneurons in the spinal cord that modulate abnormal corticospinal excitability, thereby reducing spasticity and associated stiffness (Katusic & Mejaski-Bosnjak, 2011; Struppler, Havel, & Muller-Barna, 2003). In fact, our recent functional near-infrared spectroscopy neuroimaging evidence demonstrated increased sensorimotor cortex activation during robotic-assisted gait, supporting the important role of sensorimotor feedback (e.g., real-time kinetic and kinematic information from the robotic-assisted gait system) (H.Y. Kim et al., 2016). Further research is warranted to validate the importance role of sensory feedback.

Interestingly, decreased hip resistive torque and increased active knee active torque resulted from the Walkbot gait intervention, but hip and knee joint stiffness were unaffected. One possible explanation of these results could be that initial hip and knee joint stiffness had relatively small and large variance,

respectively, to begin with (-0.01213 ± 0.01275 and 0.00726 ± 0.00734 , respectively). In particular, the present knee joint stiffness results were compatible with previous evidence (0.0083 Nm/degree) (D.H. Kim et al., 2013). Such large variance accounted for the individual variability associated with different neuromechanical and clinical characteristics in the present study.

Clinical outcome measures showed that activities of daily living, such as mobility and ascending stair ascent climbing, were particularly improved after the Walkbot intervention, even in patients with subacute or chronic paraplegia or quadriplegia who had already reached a functional motor recovery plateau after conventional neurorehabilitation. Interestingly, other clinical scores from the MRS and FAC remained unchanged. It is possible that the differences between the clinical outcome measures occurred because of different measurement sensitivity in response to the intervention-related changes. The present findings corroborate previous results that examined the effects of robotic-assisted gait training on functional ambulation measures for individuals with paraplegia or quadriplegia (Sale, Franceschini, Waldner, & Hesse, 2012; Shin, Kim, Park, & Kim, 2014). Similarly, the functional level of independence, endurance, coordination, and balance on ambulation and daily motor performance increased after Walkbot-RAGT intervention in individuals with hemiparetic stroke (S.Y. Kim et al., 2015). As such, the underlying treatment rationale may be related to an increased hip extension moment, which reciprocally inhibits an unwanted resistive hip flexion moment, thereby allowing appropriate hip and knee joint movement. These kinetic and kinematic changes are consistently reflected in increased gait symmetry, stride length, cadence, velocity and quality of movement (S.Y. Kim et al., 2015). Cumulatively, these clinical studies indicate that RAGT is an efficient and safe instrument for early gait rehabilitation and is beneficial for restoring

functional and reciprocal ambulation and functional movement independence in daily activities (Schwartz & Meiner, 2015).

Clinically, spasticity is an important biomarker for neurological locomotor movement disorders such as stroke and spinal cord injury and is often assessed via the semi-qualitative Ashworth, Modified Ashworth, and Tardieu and Barthly scales (Charalambous, 2014; V.A. Scholtes, Becher, Beelen, & Lankhorst, 2006; V.A.B. Scholtes, Becher, Beelen, & Lankhorst, 2005). However, these semi-qualitative measures are not sufficiently discriminative and sensitive to provide reliable and valid quantitative information about spasticity because they tend to reflect the degree or magnitude of spasticity during a certain passive movement. To mitigate the limitations of the current clinical spasticity tests, we developed the Walkbot system, which is equipped to measure active and resistive stiffness during robotic-assisted gait. This neuromechanical device provides real-time feedback about active and resistive stiffness during gait training and is a velocity-dependent device for assessing stiffness associated with spasticity of the lower extremities. In the present study, after Walkbot robotic gait training, the magnitude of stiffness and MAS score were unaffected by robotic gait training ($p > 0.05$). The results suggest that MAS might not be sensitive enough to detect spasticity and support of the idea that the Walkbot stiffness measurement system can be used for accurate clinical evaluation of stiffness and spasticity in stroke patients.

This study had several limitations. The first limitation is that although the stiffness measurement is reliable and valid for quantifying the overall joint stiffness associated with spasticity, active and passive stiffness, viscoelastic properties, reflex-mediated activation, and antagonistic co-activation factors (D.H. Kim et al., 2013), the present stiffness measurements taken by the Walkbot system are not capable of deciphering such confounding factors mentioned above. Alternatively, electromyography (EMG) could be useful for assessing the impact of reflex-mediated activation factors on stiffness (Granata & Rogers, 2007).

The second limitation is that MAS was used to measure the severity of spasticity (Fleuren et al., 2010; Naghdi et al., 2008). The reliability and validity of MAS have recently been challenged because the test does not accurately measure spasticity, the measurement of which is confounded by associated factors including active (muscle activation, muscle tone, tightness) and passive (joint ligament-capsule

shortness or contracture) stiffness elements, viscoelastic properties, reflex-mediated activation, and antagonistic co-activation factors (Granata & Rogers, 2007).

Other valid and reliable spasticity measurements such as the Pendulum test and Tardieu scale should be considered in addition to quantitative Walkbot stiffness measurement. Lastly, this preliminary study invites a future study with a more robust design and larger sample size to improve the generalizability of our novel findings. Nonetheless, the Walkbot effectively facilitated neuromechanical changes in stiffness and associated clinical outcomes in paraplegic and quadriplegic patients. Moreover, the Walkbot stiffness measurement was sensitive enough to discriminate very small changes in active and resistive stiffness after the intervention.

5. Conclusion

The present study demonstrated the long-term therapeutic effects of the Walkbot RAGT on active torque and resistive torque, kinematics, stiffness, and activities of daily living in paraplegia and quadriplegia. Intensive gait training with the Walkbot system was beneficial for stiffness control, range of motion, and restoration of functional mobility associated with activities of daily living in individuals with sub-acute or chronic paraplegia and quadriplegia who had reached a plateau in locomotor recovery after conventional physical therapy.

Conflict of interest

None to report.

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