

Efficacy of rehabilitation robotics for walking training in neurological disorders: A review

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Abstract—Robotic technologies are becoming more prevalent for treating neurological conditions in clinical settings. We conducted a literature search of original articles to identify all studies that examined the use of robotic devices for restoring walking function in adults with neurological disorders. We evaluated and rated each study using either the Physiotherapy Evidence Database scale for randomized controlled trials (RCTs) or the Downs and Black scale for non-RCTs. We reviewed 30 articles (14 RCTs, 16 non-RCTs) that examined the effects of locomotor training with robotic assistance in patients following stroke, spinal cord injury (SCI), multiple sclerosis (MS), traumatic brain injury (TBI), and Parkinson disease (PD). This review supports that locomotor training with robotic assistance is beneficial for improving walking function in individuals following a stroke and SCI. Gait speed and endurance were not found to be significantly different among patients with motor incomplete SCI after a variety of locomotor training approaches. Limited evidence demonstrates that locomotor training with robotic assistance is beneficial in populations of patients with MS, TBI, or PD. We discuss clinical implications and decision making in the area of gait rehabilitation for neurological dysfunction.

Key words: gait, locomotor training, multiple sclerosis, neurological disorders, rehabilitation, robotics, spinal cord injury, stroke, traumatic brain injury, walking.

INTRODUCTION

More than 5 million people in the United States are paralyzed (<http://www.christopherreeve.org>). Common neurological causes of immobility in the adult population

include stroke, spinal cord injury (SCI), traumatic brain injury (TBI), and progressive neurological diseases such as multiple sclerosis (MS) or Parkinson disease (PD). Neurological injuries and diseases often result in physical impairments that interfere with a person's ability to walk. Loss of walking function often creates dependency on a wheelchair or other restrictive assistive mobility device. Many people with these types of injuries and illnesses

Abbreviations: 2MWT = 2-minute walk test, 5MWT = 5-meter walk test, 6MWT = 6-minute walk test, 10MWT = 10-meter walk test, 25FWT = 25-foot walk test, ADL = activities of daily living, ASIA = American Spinal Injury Association impairment scale, BBS = Berg Balance Scale, BI = Barthel Index, BWS = body-weight support, D&B = Downs and Black (scale), EDSS = Expanded Disability Status Scale, EMG = electromyography, FAC = Functional Ambulatory Capacity, FAI = Frenchay Activities Index, FES = functional electrical stimulation, FIM = Functional Independence Measure, fMRI = functional magnetic resonance imaging, MAS = Modified Ashworth Scale, MI = Motricity Index, MS = multiple sclerosis, PD = Parkinson disease, PEDro = Physiotherapy Evidence Database (scale), RCT = randomized controlled trial, RMI = Rivermead Mobility Index, SCI = spinal cord injury, TBI = traumatic brain injury, TUG = Timed "Up and Go" Test, WISCI = Walking Index for Spinal Cord Injury.

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have reported improving their walking ability as an important goal of their rehabilitation program.

Improving walking function is often a key component of the rehabilitation program for a person diagnosed with a neurological impairment. Traditionally, physical therapists retrain walking function in people with mobility deficits by providing support for standing and walking (for example, through use of orthoses). Although compensation-based strategies using orthoses may facilitate walking, such strategies may limit the recovery of walking ability as experienced prior to the injury or neurological disease. A person who walks with a knee-ankle-foot orthosis or a reciprocating gait orthosis may not be able to walk or at the very least may exhibit poor kinematics if the orthosis is removed. To facilitate and enhance the recovery of locomotor function, researchers have developed new therapeutic strategies and treatment options in the past two decades.

Research on locomotor training through the use of partial body-weight support (BWS) and manual assistance first began with spinalized cats in the 1980s [1–5] and then progressed to human subjects [6–9]. This rehabilitative intervention involves supporting part of the patient's weight over a motorized treadmill while clinicians use manual facilitation techniques to produce stepping motions with the patient's legs. This technique is based on a normal physiological gait pattern, with attention to the ideal kinematic and temporal aspects of gait [7]. The therapeutic goals of this approach are built on entirely different principles than conventional gait training and seek to achieve restoration and recovery of walking through the inherent capacities of the spinal and supraspinal locomotor centers [10]. Through the remediation of gait impairments over time, the locomotor skills being practiced are anticipated to persist once the individual stops the training.

To replicate a normal gait pattern during manually facilitated locomotor training, two or three therapists are needed to control or assist with trunk and limb kinematics. Locomotor training with manual assistance can be physically taxing on therapists when faster training speeds, which have demonstrated improved gait kinematics and muscle activation patterns [11], are used. The success of treadmill training with BWS in restoring or improving overground locomotion has been documented in individuals following SCI [12–16], stroke [17–21], MS [22], PD [23–25], and TBI [26–27]. Despite these promising reports, the use of this specific therapeutic

intervention in most rehabilitation settings is limited because of the strenuous and exhausting nature of manual training for the therapist. As the therapist fatigues, maintaining the temporal and spatial symmetry between the steps becomes increasingly difficult. In addition, treadmill systems with BWS are not common to all rehabilitative settings because many clinics do not have the resources to commit three therapists to one patient's training [28].

Due to the significant resources required for clinical deployment of manual-assistance treadmill training with BWS and to improve the delivery of BWS in the clinical setting, sophisticated automated electromechanical devices have been developed [29]. These consist of either a robot-driven exoskeleton orthosis or a robotic device with two driven foot plates that produce stepping motions [30–31]. At the time of this review, no previous systematic evaluation had been performed on the effectiveness of robotic approaches on the rehabilitation of walking function after a variety of neurological insults or diseases. Therefore, a systematic review of the evidence to assess the effectiveness of robotic locomotor training was warranted. The objective of this systematic review was to assess the efficacy of robotic locomotor training on improvement in overground walking for adults with neurological injury or disease. We targeted literature pertaining to the following adult patient populations: stroke, SCI, MS, TBI, and PD.

METHODS

We completed a systematic review using multiple databases (MEDLINE/PubMed, CINAHL, and EBSCOhost) to identify and include all appropriate literature published from 1990 to 2009 that evaluated the effectiveness of robotic technology in improving walking ability in people with neurological injuries or diseases. One author (CT) independently examined the titles and abstracts of citations identified by the electronic searches to identify potentially relevant studies. The full text of all relevant studies was then obtained, and two authors (CT and PW) independently assessed the studies for inclusion against predefined criteria. Disagreement was resolved through discussion with all authors.

Studies that examined locomotor training with a robotic device with the goal of improving walking ability were included. Additionally, several articles examining the kinesiological and metabolic aspects of locomotor

training with robotics were included to further understand the potential of this method of locomotor training. Studies with adult participants (mean age of 18 years and older) with a neurological diagnosis were included, regardless of the duration of illness (acute or chronic) or level of initial walking ability. Studies using hybrid strategies such as overground gait training or functional electrical stimulation (FES) were also included. Studies included reported measurable outcomes for walking ability such as the following: (1) walking speed—either free cadence or fast walking (10-meter walk test [10MWT], 5-meter walk test [5MWT], 25-foot walk test [25FWT]); (2) walking endurance, defined as the capacity to cover a distance in a defined time (6-minute walk test [6MWT], 2-minute walk test [2MWT]); (3) timed measures of functional mobility, such as the Timed “Up and Go” Test (TUG); and (4) level of independence in walking, measured by the Functional Independence Measure (FIM), Walking Index for Spinal Cord Injury (WISCI or WISCI II), Functional Ambulatory Capacity (FAC), EU-Walking Scale, or Expanded Disability Status Scale (EDSS). Studies were also included if they measured specific aspects of the gait cycle, including muscle activation patterns via electromyography (EMG) or metabolic expenditure via oxygen consumption. Any studies not published in English were excluded, and no animal studies were included in this review.

Once articles were deemed appropriate for inclusion in the review, we used the Physiotherapy Evidence Database (PEDro) scale [32] or the Downs and Black (D&B) scale [33] to assess the rigor and quality of each study. All randomized controlled trials (RCTs) that met the defined inclusion criteria were assessed using the PEDro scale, which is an 11-item scale designed to evaluate the methodological quality of a published study. The maximum score achievable on this scale is 10. Higher scores on this scale identify those studies with better methodological quality. Scores have been divided into the following qualitative categories: excellent 9 to 10, good 6 to 8, fair 4 to 5, and poor <4 [32].

All non-RCTs that met the defined inclusion criteria for this review were evaluated using the D&B scale, which is a 27-item scale. These 27 items are divided into the following assessment areas: reporting, internal validity, and external validity. We used a modified version of the D&B scale that was first reported by Eng et al. and that limited the maximum score on the scale to 28 [34].

Studies attaining higher scores on this scale are also considered to be of better methodological quality.

Studies were blocked by diagnostic groups and divided among the authors. Each study was examined independently using the appropriate scale by two authors, who first reported their findings independently and then came to a consensus verbally about any discrepancies. After each article was rated with the appropriate tool, all four authors independently extracted data and provided a detailed description of each study. A standardized form was used to independently record the following details: age, sex, and diagnosis of subjects; daily duration, weekly frequency, and total number of treatment sessions; type of intervention; outcomes measured; and pre- and posttest results of primary outcomes; in addition, any significant findings deemed appropriate by each author were recorded. All the extracted data were checked for agreement between authors, with discussion arbitrating any items for which consensus was not reached. If any review author was involved in any of the selected studies, another author handled the information from that study.

RESULTS

A total of 30 articles—14 RCTs and 16 non-RCTs—on the effects of locomotor training with robotic assistance and partial BWS in patients with a variety of neurological diagnoses including stroke, SCI, MS, and TBI were reviewed. No literature was found regarding the effects of locomotor training with robotic assistance on patients with PD. All studies included in this review examined the effect of locomotor training on walking function with one of the following robotic-assisted devices: Lokomat (Hocoma; Zurich, Switzerland) [35], Electromechanical Gait Trainer (referred to here as “Gait Trainer” (Reha-Stim; Berlin, Germany) [30], or LokoHelp (Lokohelp Group; Weil am Rhein, Germany) [36]. Four of the studies contained a total of four subjects who were younger than 18, but the group mean for all subjects in the selected studies was well above 18.

Studies Using Locomotor Training with Robotic Assistance and BWS in Stroke

Twenty-four potentially eligible trials were identified that examined persons with stroke; eight of which were excluded. Trials were excluded if their primary outcomes were not related to gait or, as in two of the studies, the

data were previously presented or were a subset of a larger study [31,37]. Thirteen trials were analyzed and met our inclusion criteria [28,31,36,38–47]. An additional three studies were included because they addressed aspects of walking in hemiparetic patients during a single session of robotic-assisted walking. These studies addressed joint torques [48], muscle activation [49], and energy expenditure [50] during robotic-assisted walking in patients with hemiparesis. Ten of the studies were RCTs, and scores on the PEDro scale ranged from 5 [38] to 8 [47], with a mean of 6.5 indicating good methodological quality in the studies as a whole [32]. The remaining six studies were assessed using the D&B scale, with a range of 10 [31] to 19 [36] and a mean of 13.8. As stated previously, a score of 28 is the maximum available on this scale and higher numbers indicate better methodological quality [33]. **Table 1** summarizes the characteristics of the RCTs on stroke that were included in this review. **Table 2** summarizes the characteristics of the non-RCTs on stroke that were included in this review.

These 16 studies included a total of 558 subjects. All studies used either the Gait Trainer [30], the Lokomat [35], or the LokoHelp [36]. For the intervention studies, treatment intensity included 20 to 30 minutes daily, 3 to 5 times a week. Most studies chose a duration of 4 to 6 weeks, for a total number of sessions ranging from 12 [28,39] to 48 [44]. Two of the studies used a crossover design so that the intervention periods were only 2 [47] and 3 [41] weeks. However, the investigators repeated the intervention two additional times for a total duration of 6 [47] and 9 weeks [41]. Gait training time did not differ between the control and experimental groups in any of the included RCTs.

The mean age in all but one of the included studies ranged from 52 [39,42] to 71 years [45]. In the exception, Freivogel et al. reported an average age of 26 years in two individuals following a stroke [36]; the setting of this study was a neurological rehabilitation center for children, adolescents, and young adults. Males outnumbered females (63% males). Subjects with right ($n = 282$) versus left ($n = 268$) hemiparesis were almost equally distributed. Large variability was noted among the studies in the time since onset of stroke. Time in weeks poststroke ranged from 3 [44–45] to nearly 300 [39]. Accordingly, large variability was found in the subjects' walking ability at study entrance. In 10 of the included studies, subjects were not ambulating independently at study entrance. In many of the studies, subjects were excluded

based on a minimum FAC score. A score of <4 indicates dependency in walking (supervision, assistance, or both must be given during walking). Three of the studies required that the subjects be able to ambulate a certain distance independently overground in order to be included [28,38–39]. **Tables 3** and **4** provide a detailed description of patient characteristics in the stroke RCTs and non-RCTs, respectively. Most studies investigated improvement in walking function as the primary outcome and used the FAC or comparable scales (EU-Walking Scale) to assess independent walking [36,41–45,47]. Furthermore, most studies also included outcomes of walking function, such as gait speed (meters/second), gait endurance (2MWT or 6MWT), or functional mobility. Secondary measures included ability to perform activities of daily living (ADLs) and measures of motor function, balance, and spasticity. A detailed description of the primary outcomes for each stroke trial can be found in **Table 5**.

Gait Outcomes in Stroke Studies

Ten studies with a total of 406 subjects [31,36,38,40–41,43–47] measured recovery of independence by use of the FAC or EU-Walking Scale. A significantly greater number of subjects who trained with the Lokomat, Gait Trainer, or LokoHelp than control patients who received conventional gait training reached a FAC score of >3 as reported in five of the seven RCTs [41,43–45,47]. Of these five studies, three used the Gait Trainer [43,45,47] and two used the Lokomat [41,44]. No studies demonstrated a significantly improved FAC with conventional physical therapy or treadmill training with BWS and manual assistance versus treadmill training with BWS and robotic assistance [38,40].

Thirteen studies with a total of 515 subjects [28,31,36,38–47] measured changes in walking speed at study end using the 10MWT, the 5MWT, or an instrumented walkway. The use of electromechanical devices in gait rehabilitation resulted in increased walking speeds in all the studies. Three studies demonstrated a significant improvement in overground gait speed in the group that used the Gait Trainer [43,45] or Lokomat [41] compared with control participants who received conventional therapy. In contrast, two of the studies [38–39] reported significantly greater gains in the group that received locomotor training with BWS and manual assistance or conventional gait training compared with Lokomat training. Careful examination reveals that distinct differences exist in the five studies. Patients recruited for the

Table 1.

Stroke studies: Characteristics of randomized controlled trials (RCTs).

Article	Study Type	PEDro Rating	Sample Size	Device Type	Daily Intensity & Weekly Frequency	Treatment Duration	Total No. of Sessions
Werner et al., 2002 [1]	RCT Crossover	8	30	Gait Trainer	15–20 min, 5×/wk	2 wk × 3	30*
Peurala et al., 2005 [2]	RCT	6	45	Gait Trainer	20 min, 5×/wk	3 wk	15
Tong et al., 2006 [3]	RCT	7	50	Gait Trainer	20 min, 5×/wk	4 wk	20
Husemann et al., 2007 [4]	RCT	7 [†]	30	Lokomat	30 min, 5×/wk	4 wk	20
Mayr et al., 2007 [5]	RCT Crossover	6	16	Lokomat	30 min, 5×/wk	3 wk × 3	45*
Pohl et al., 2007 [6]	RCT	8	155	Gait Trainer	20 min, 5×/wk	4 wk	20
Hornby et al., 2008 [7]	RCT	6	48	Lokomat	30 min, 3×/wk	4 wk	12
Hidler et al., 2009 [8]	RCT	5	63	Lokomat	45 min, 3×/wk	8–10 wk	24
Schwartz et al., 2009 [9]	RCT	6	56	Lokomat	30 min, 3×/wk	6 wk	42–48
Westlake & Patten, 2009 [10]	RCT	6	16	Lokomat	30 min, 3×/wk	4 wk	12

*Werner et al. included 10 sessions in every 2 wk treatment repeated three times, and Mayr et al. included 15 sessions in every 3 wk treatment repeated three times.

[†]Husemann et al. was rated 6 in PEDro database; however, intention to treat analysis was performed resulting in score of 7.

- Werner C, Von Frankenberg S, Treig T, Konrad M, Hesse S. Treadmill training with partial body weight support and an electromechanical gait trainer for restoration of gait in subacute stroke patients: A randomized crossover study. *Stroke*. 2002;33(12):2895–2901. [PMID: 12468788]
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DOI:10.1016/j.apmr.2006.06.016
- Husemann B, Müller F, Krewer C, Heller S, Koenig E. Effects of locomotion training with assistance of a robot-driven gait orthosis in hemiparetic patients after stroke: A randomized controlled pilot study. *Stroke*. 2007;38(2):349–54. [PMID: 17204680]
DOI:10.1161/01.STR.0000254607.48765.cb
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DOI:10.1177/1545968307300697
- Pohl M, Werner C, Holzgraefe M, Kroczeck G, Mehrholz J, Wingendorf I, Hoölig G, Koch R, Hesse S. Repetitive locomotor training and physiotherapy improve walking and basic activities of daily living after stroke: A single-blind, randomized multicentre trial (DEutsche GAngrainerStudie, DEGAS). *Clin Rehabil*. 2007;21(1):17–27. [PMID: 17213237]
DOI:10.1177/0269215506071281
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DOI:10.1161/STROKEAHA.107.504779
- Hidler J, Nichols D, Pelliccio M, Brady K, Campbell DD, Kahn JH, Hornby TG. Multicenter randomized clinical trial evaluating the effectiveness of the Lokomat in subacute stroke. *Neurorehabil Neural Repair*. 2009;23(1):5–13. [PMID: 19109447]
DOI:10.1177/1545968308326632
- Schwartz I, Sajin A, Fisher I, Neeb M, Shochina M, Katz-Leurer M, Meiner Z. The effectiveness of locomotor therapy using robotic-assisted gait training in subacute stroke patients: A randomized controlled trial. *PM R*. 2009;1(6):516–23. [PMID: 19627940]
- Westlake KP, Patten C. Pilot study of Lokomat versus manual-assisted treadmill training for locomotor recovery post-stroke. *J Neuroeng Rehabil*. 2009;6:18. [PMID: 19523207]
DOI:10.1186/1743-0003-6-18

PEDro = Physiotherapy Evidence Database (scale).

studies that demonstrated an improvement in gait speed with robotic training were in the acute to subacute phase, ranging from 2.5 to 14 weeks poststroke [25,41,45], while the patients in the two studies who improved their gait speed with BWS treadmill training with manual

assistance (200 to 292 weeks poststroke) [39] or conventional gait training (15.7 to 19.8 weeks poststroke) [38] were in the chronic phase. Furthermore, Hornby et al. [39] and Hidler et al. [38] recruited patients who were able to walk overground independently for at least 5 meters

Table 2.

Stroke studies: Characteristics of non-randomized controlled trials.

Article	Study Type	D&B Rating	Sample Size	Device Type	Daily Intensity & Weekly Frequency	Treatment Duration	Total No. of Sessions
Hesse et al., 1999 [1]	Case Series	13	14	Gait Trainer	NA	Single Session	1
Hesse et al., 2000 [2]	Case Report	10	2	Gait Trainer	20 min, 4×/wk	4 wk	20
Tong et al., 2006 [3]	Case Report	12	2	Gait Trainer	20 min, 5×/wk	5 wk	18–19
Krewer et al., 2007 [4]	Case Control	15	10	Lokomat	NA	Single Session	1
Freivogel et al., 2008 [5]	Case Series	19	2	LokoHelp	30 min, 3–5×/wk	6 wk	20
Neckel et al., 2008 [6]	Case Control	14	10	Lokomat	NA	Single Session	1

1. Hesse S, Uhlenbrock D, Sarkodie-Gyan T. Gait pattern of severely disabled hemiparetic subjects on a new controlled gait trainer as compared to assisted treadmill walking with partial body weight support. *Clin Rehabil.* 1999;13(5):401–10. [PMID: 10498347]
DOI:10.1191/026921599673896297

2. Hesse S, Uhlenbrock D, Werner C, Bardeleben A. A mechanized gait trainer for restoring gait in nonambulatory subjects. *Arch Phys Med Rehabil.* 2000; 81(9):1158–61. [PMID: 10987154]
DOI:10.1053/apmr.2000.6280

3. Tong RK, Ng MF, Li LS, So EF. Gait training of patients after stroke using an electromechanical gait trainer combined with simultaneous functional electrical stimulation. *Phys Ther.* 2006;86(9):1282–94. [PMID: 16959676]
DOI:10.2522/ptj.20050183

4. Krewer C, Müller F, Husemann B, Heller S, Quinter J, Koenig E. The influence of different Lokomat walking conditions on the energy expenditure of hemiparetic patients and healthy subjects. *Gait Posture.* 2007;26(3):372–77. [PMID: 17113774]
DOI:10.1016/j.gaitpost.2006.10.003

5. Freivogel S, Mehrholz J, Husak-Sotomayor T, Schmalohr D. Gait training with the newly developed 'LokoHelp'-system is feasible for non-ambulatory patients after stroke, spinal cord and brain injury. A feasibility study. *Brain Inj.* 2008;22(7–8):625–32. [PMID: 18568717]
DOI:10.1080/02699050801941771

6. Neckel ND, Blonien N, Nichols D, Hidler J. Abnormal joint torque patterns exhibited by chronic stroke subjects while walking with a prescribed physiological gait pattern. *J Neuroeng Rehabil.* 2008;5:19. [PMID: 18761735]
DOI:10.1186/1743-0003-5-19

D&B = Downs and Black (scale), NA = not applicable.

in contrast to the other three studies [41,43,45] that recruited subjects who were unable to walk without assistance.

Seven trials with a total of 399 patients [28,38–39,41–44] measured walking endurance (6MWT or 2MWT) at study end. Peurala et al. reported an improvement in 6MWT when the data were pooled across the three groups of patients trained with the Gait Trainer, the Gait Trainer plus FES, or the control groups [42]. However, no significant difference was found between groups. Pohl et al. reported that the use of the Gait Trainer for 20 minutes, 5 times a week significantly increased the 6MWT for individuals who presented with hemiparesis [43]. Similarly, Mayr et al. reported that training with the Lokomat for 30 minutes, 5 times a week significantly increased the walking endurance of subjects after stroke [41]. However, in contrast, Hornby et al. [39] and Hidler et al. [38] both reported that participants who received BWS treadmill training with manual assistance or conventional gait training 30 to 45 minutes, 3 times a week experienced significantly greater gains in walking distance than those trained on the Lokomat. Two other studies compared the Lokomat with BWS treadmill train-

ing and manual assistance [28] or conventional gait training [44] but were unable to demonstrate any differences between groups for 6MWT or 2MWT. As noted previously, a more impaired participant population at an earlier time poststroke [41,43] versus a participant population that is already ambulating and at an extended duration poststroke [38–39] may possibly explain the differences observed in these studies. Another confounding factor is the differences observed in training schedule. Pohl et al. [43] and Mayr et al. [41] both used a more intense training schedule, 5 days a week compared with 3 days a week in Hornby et al.'s [39] and Hidler et al.'s [38] studies.

Secondary Outcomes in Stroke Studies

Secondary outcomes that were collected in many of the studies included the following: (1) balance as measured by the Berg Balance Scale (BBS) or postural sway tests; (2) spasticity as measured by the Modified Ashworth Scale (MAS); (3) measures of disability/ADL as measured by the Barthel Index (BI), FIM, or Frenchay Activities Index (FAI); (4) assessment of motor function as measured

Table 3.

Stroke studies: Patient characteristics in randomized controlled trials.

Article	Age, yr (mean \pm SD)		Time Poststroke, wk (mean \pm SD)		Sex (M/F)		Hemiparetic Side (R/L)		Able to Walk at Study Entrance
	Exp	Con	Exp	Con	Exp	Con	Exp	Con	
Werner et al., 2002 [1]	59.7 \pm 10.2	60.3 \pm 8.6	7.4 \pm 2.0	6.9 \pm 2.0	5/10	8/7	8/7	8/7	FAC = 2
Peurala et al., 2005 [2]	52 \pm 8	52 \pm 7	130 \pm 130	208 \pm 302	26/4	11/4	13/17	10/5	10/45 subjects had FAC = 3
Tong et al., 2006 [3]	71 \pm 14	64 \pm 10	2.5 \pm 1.2	2.7 \pm 1.2	19/11	12/8	13/17	7/13	FAC = 3
Husemann et al., 2007 [4]	60 \pm 13	57 \pm 11	11.3 \pm 8.0	12.7 \pm 8.7	11/5	10/4	12/4	11/3	FAC = 1
Mayr et al., 2007 [5]	65.6 \pm 11.7	61.3 \pm 18.7	14 \pm 14	8 \pm 6	4/4	2/6	2/6	6/2	Unable to walk unaided
Pohl et al., 2007 [6]	62 \pm 12	64 \pm 11	4.2 \pm 1.8	4.5 \pm 1.9	50/27	54/22	36/41	33/45	Unable to walk or required help of 1–2 therapists
Hornby et al., 2008 [7]	52 \pm 12	53 \pm 6	200 \pm 204	292 \pm 348	15/9	15/9	16/8	16/8	Able to walk overground independently >10 m (speed 0.8 m/s)
Hidler et al., 2009 [8]	59.9 \pm 11.5	54.6 \pm 9.4	15.7 \pm 8.9	19.8 \pm 8.7	21/12	18/12	17/13	11/22	Able to walk overground independently 5 m (speed 0.1–0.6 m/s)
Schwartz et al., 2009 [9]	62.0 \pm 8.5	65.0 \pm 7.5	3.1 \pm 2.1	3.4 \pm 1.4	21/16	20/10	20/17	22/8	FAC = 3
Westlake & Patten, 2009 [10]	58.6 \pm 16.9	55.1 \pm 13.6	175.2 \pm 107.2	147.2 \pm 81.2	6/2	7/2	4/4	3/5	Unlimited household ambulation (speed >0.3 m/s)

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- Westlake KP, Patten C. Pilot study of Lokomat versus manual-assisted treadmill training for locomotor recovery post-stroke. *J Neuroeng Rehabil*. 2009;6:18. [PMID: 19523207]
DOI:10.1186/1743-0003-6-18

Con = control group, Exp = experimental group, F = female, FAC = Functional Ambulatory Capacity (score), L = left, M = male, R = right, SD = standard deviation.

Table 4.

Stroke studies: Patient characteristics in non-randomized controlled trials.

Article	Age, yr (mean ± SD)	Time Poststroke, wk (mean ± SD)	Sex (M/F)	Hemiparetic Side (R/L)	Able to Walk at Study Entrance
Hesse et al., 1999 [1]	58.8; range 36–79	9; range 5–10	11/3	7/7	Unable to walk unaided
Hesse et al., 2000 [2]	58.0 ± 4.9	10.0 ± 1.4	1/1	1/1	FAC = 1
Tong et al., 2006 [3]	67.0 ± 11.3	4 ± 0	2/0	1/1	FAC = 1
Krewer et al., 2007 [4]	54.0 ± 14.0	79.6 ± 134.1	2/8	4/6	>10 subjects had FAC >3
Freivogel et al., 2008 [5]	25.5 ± 7.8	4 ± 0	1/1	1/1	FAC = 0 and FAC = 4
Neckel et al., 2008 [6]	56.5 ± 4.9	>1 yr	NP	NP	NP

- Hesse S, Uhlenbrock D, Sarkodie-Gyan T. Gait pattern of severely disabled hemiparetic subjects on a new controlled gait trainer as compared to assisted treadmill walking with partial body weight support. *Clin Rehabil.* 1999;13(5):401–10. [\[PMID: 10498347\]](#)
[DOI:10.1191/026921599673896297](#)
- Hesse S, Uhlenbrock D, Werner C, Bardeleben A. A mechanized gait trainer for restoring gait in nonambulatory subjects. *Arch Phys Med Rehabil.* 2000;81(9):1158–61. [\[PMID: 10987154\]](#)
[DOI:10.1053/apmr.2000.6280](#)
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[DOI:10.2522/ptj.20050183](#)
- Krewer C, Müller F, Husemann B, Heller S, Quintern J, Koenig E. The influence of different Lokomat walking conditions on the energy expenditure of hemiparetic patients and healthy subjects. *Gait Posture.* 2007;26(3):372–77. [\[PMID: 17113774\]](#)
[DOI:10.1016/j.gaitpost.2006.10.003](#)
- Freivogel S, Mehrholz J, Husak-Sotomayor T, Schmalohr D. Gait training with the newly developed ‘LokoHelp’-system is feasible for non-ambulatory patients after stroke, spinal cord and brain injury. A feasibility study. *Brain Inj.* 2008;22(7–8):625–32. [\[PMID: 18568717\]](#)
[DOI:10.1080/02699050801941771](#)
- Neckel ND, Blonien N, Nichols D, Hidler J. Abnormal joint torque patterns exhibited by chronic stroke subjects while walking with a prescribed physiological gait pattern. *J Neuroeng Rehabil.* 2008;5:19. [\[PMID: 18761735\]](#)
[DOI:10.1186/1743-0003-5-19](#)

F = female, FAC = Functional Ambulatory Capacity (score), L = left, M = male, NP = not provided, R = right, SD = standard deviation.

by the Motricity Index (MI), Fugl Meyer, or Motor Assessment Scale; and (5) bodily mobility as measured by the Rivermead Mobility Index (RMI). Although not direct measures of gait, these are components that may affect an individual’s ability to walk.

Six studies included the BBS [28,36,38–39,45–46], and Peurala et al. measured dynamic balance using postural sway tests [42]. No statistically significant change was noted in balance by any researchers, except Hidler et al., who reported that both groups (Lokomat and conventional gait training) improved on the BBS [38]. Westlake and Patten reported that they observed an improvement on the BBS in the Lokomat training group [28].

Spasticity was assessed with the MAS in five studies [36,40–42,47]. Peurala et al. reported a decrease in ankle spasticity in the group that walked overground but not in either Gait Trainer group [42]. Mayr et al. reported a significant improvement in the MAS score during the Lokomat training phase compared with the conventional gait training phase [41]. No other studies reported any difference in spasticity as measured by the MAS.

Nine studies examined measures of disability/ADL with the BI, [40,43,45–46], FIM [42,44–45], or FAI [38–39]. Although two studies reported a significant increase in the BI following training [40,45], no significant differences were found between the groups that received robotic gait training and conventional gait training. Only one study reported that subjects who received locomotor training on the Gait Trainer improved significantly on the BI [40].

Motor function was assessed with the MI [36,40–41,43,45–46], Fugl Meyer [28], or Motor Assessment Scale [38,42] in nine studies. Although five studies reported a significant improvement in motor function from baseline to posttraining [36,38,40,45–46], no differences were noted between the experimental or control groups. Pohl et al. was the only group to report that subjects who received locomotor training with the Gait Trainer had significantly improved MI scores [43].

Six studies specifically measured the RMI as an index of bodily mobility [31,36,38,41,43,47]. The RMI was developed from the Rivermead Motor Assessment

Table 5.
Stroke studies: Outcomes.

Article	Study Type	Intervention	Gait Outcomes	Other Outcomes	Results
Werner et al., 2002 [1]	Crossover RCT (2 arms)	2 wk each of Gait Trainer, manual BWSTT, Gait Trainer; 2 wk each manual BWSTT, Gait Trainer, manual BWSTT	FAC, fast walking speed (10MWT)	RMI, ankle MAS	FAC, gait velocity, and RMI improved in both groups; ankle MAS did not change. Median FAC ↑ in group that received Gait Trainer intervention.
Peurala et al., 2005 [2]	RCT (3 arms)	Gait Trainer, Gait Trainer + FES, walking overground	10MWT, 6MWT	Dynamic balance (postural sway tests), LL MAS, MMAS, FIM	Gait speed, 6MWT, dynamic balance, and MMAS improved irrespective of group. No change in FIM scores. Ankle spasticity ↓ only in overground walk group. Ankle dorsiflexion force ↑ in Gait Trainer + FES group and hip flexion force ↑ in Gait Trainer group.
Tong et al., 2006 [3]	RCT (3 arms)	Gait Trainer, Gait Trainer + FES, conventional PT	FAC, 5MWT	EMS, BBS, MI, BI, FIM	All groups showed statistically significant improvements from baseline to posttraining in FAC, walking speed, EMS, and MI. No difference in FIM, BBS, or BI. Gait Trainer and Gait Trainer + FES groups improved significantly in EMS, walking speed, MI, and FAC vs control group.
Husemann et al., 2007 [4]	RCT (2 arms)	Lokomat, conventional PT	FAC, 10MWT, temporal stride parameters	BI, body tissue composition, MAS, MI	Both groups demonstrated significant improvement in FAC, 10MWT, BI, and MI over 4 wk trial. No difference was noted in MAS. Between-group differences were noted in single stance phase and body composition. Lokomat group demonstrated longer stance time on paretic leg and lost fat mass and ↑ muscle mass compared with control group.
Mayr et al., 2007 [5]	Crossover RCT (2 arms)	3 wk each Lokomat, conventional PT, Lokomat; 3 wk each conventional PT, Lokomat, conventional PT	EU-Walking Scale, 10MWT, 6MWT	RMI, MRCS, MI, MAS	EU-Walking Scale, RMI, 6MWT, MRCS, and MAS demonstrated significantly more improvement during Lokomat training phase than during conventional PT phase. Significant ↑ noted in 10MWT in group that received two 3 wk periods Lokomat training compared with group that received only one 3 wk period Lokomat training.
Pohl et al., 2007 [6]	RCT (2 arms)	20 min Gait Trainer + 25 min conventional PT; 45 min conventional PT	FAC, 10MWT, 6MWT	BI, RMI, MI	More subjects who received Gait Trainer could walk independently: 41 of 77 vs 17 of 78 in group who only received conventional PT. Significantly more subjects receiving Gait Trainer had reached BI >75: 44 of 77 vs 21 of 78. Subjects receiving Gait Trainer had significantly improved gait speed, 6MWT, BI, RMI, and MI.

Table 5. (cont)

Stroke studies: Outcomes.

Article	Study Type	Intervention	Gait Outcomes	Other Outcomes	Results
Hornby et al., 2008 [7]	RCT (2 arms)	Lokomat; manual BWSTT	Self-selected and fast gait speed, % single limb stance; self-selected and fast velocity, step asymmetry; self-selected and fast velocity, 6MWT	mEFAP, BBS, FAI, Physical SF-36	Greater improvements in speed observed in subjects who received manual BWSTT, with larger speed improvements in those with less severe gait deficits. Significant ↓ in single limb stance time on impaired leg during fast velocity observed in subjects receiving manual BWSTT. Perceived rating of effects of physical limitations on quality of life improved only in subjects with severe gait deficits who received manual BWSTT.
Hidler et al., 2009 [8]	RCT (2 arms)	Lokomat; conventional gait training	5MWT, 6MWT, FAC, cadence	BBS, NIH Stroke Scale, Motor Assessment Scale, RMI, FAI, SF-36	Both groups improved on FAC, RMI, BBS, and Motor Assessment Scale. Participants who received conventional gait training experienced significantly greater gains in walking speed and distance than those trained on Lokomat. Nonsignificant twofold greater improvement in cadence was observed in conventional vs Lokomat group.
Schwartz et al., 2009 [9]	RCT (2 arms)	Lokomat; conventional PT	FAC, 10MWT, TUG, 2MWT	NIH Stroke Scale, SAS, FIM, No. of climbed stairs	Significantly greater number subjects trained with Lokomat reached FAC >3 compared with control patients. No significant findings between groups noted in 10MWT, TUG, or 2MWT. Significant difference noted in number of stairs climbed in subjects trained on Lokomat. Both groups showed significant improvement in SAS at end of 6 wk treatment without significant difference between groups.
Westlake & Patten, 2009 [10]	RCT (2 arms)	Lokomat; manual BWSTT	Self-selected walking speed, fast walking speed, 6MWT, absolute step length ratio	FM, BBS, Short Physical Performance Battery, LLFDI	No significant differences in primary outcomes revealed between Lokomat and manual groups as result of training. However, within Lokomat group, self-selected walk speed, paretic step length ratio, FM, BBS, and short physical performance battery improved. Within manual group, only BBS improved.
Hesse et al., 1999 [11]	Case Control	Gait Trainer; manual BWSTT	NA	Comparison of velocity, cadence, stride length; Mean EMG activity of LL and trunk muscles	Velocity, cadence, and stride length were within 5% of those on treadmill. Mean EMG activity was not significantly different except for following: tibialis anterior muscle was more active during swing phase (+66%) on treadmill, while biceps femoris muscle was more active on Gait Trainer (+122%) during early stance phase.

Table 5. (cont)

Stroke studies: Outcomes.

Article	Study Type	Intervention	Gait Outcomes	Other Outcomes	Results
Hesse et al., 2000 [12]	Case Report	Gait Trainer	FAC, 10MWT	RMI	FAC improved in both subjects (0–4 and 1–5). Gait speed ↑ in both subjects to average of 0.61 ± 0.03 m/s. RMI ↑ to 10 for both subjects.
Tong et al., 2006 [13]	Case Report	Gait Trainer + FES	FAC, 5MWT	BI, BBS, MI	FAC improved in both subjects from 1–3. Gait speed ↑ in both subjects to average of 0.32 ± 0.01 m/s. Secondary measures demonstrated improvements as follows: BI 45%, BBS 29%, MI 70%.
Krewer et al., 2007 [14]	Case Control	Lokomat: 5 walking conditions: 100% BWS 1 km/h; 100% BWS 2 km/h; 30% BWS 1 km/h; 30% BWS 2 km/h, 60% guidance force bilateral; 30% BWS, 2 km/h, 0% guidance force unilateral	NA	Rate of O ₂ consumption and HR during 5 walking conditions	Walking in Lokomat not passive. O ₂ uptake is significantly ↑ because of effect of loading during active stance phase. Speed is not factor leading to ↑ O ₂ consumption. Patients do not significantly ↑ O ₂ uptake because of advanced force control scheme.
Freivogel et al., 2008 [15]	Case Series	LokoHelp	FAC, 10MWT	MI, BBS, MAS, RMI	FAC improved in both subjects (0–4 and 4–5). Gait speed ↑ in both subjects. Secondary measures demonstrated improvements as follows: MI 92%, BBS 88%, RMI 73%. MAS ↓ by average of 1.
Neckel et al., 2008 [16]	Case Control	Lokomat	NA	Kinematic measures: ankle and hip ROM, maximum vertical pelvic displacement at heel strike, time in gait cycle at which minimum pelvic displacement occurred. Kinetic measures: maximum vertical GRF, maximum ankle dorsiflexion torque, knee extension torque at initial swing, time maximum hip extension torque occurred, hip adduction torque at mid swing	Kinematic patterns of stroke subjects in Lokomat are similar to those of control subjects, except for ankle ROM between impaired hemiparetic LL and control LL. Kinetic patterns were very different between control and hemiparetic subjects while walking in Lokomat. During stance phase, unimpaired limb of stroke subjects produced greater hip extension and knee flexion torques than control group. At preswing, stroke subjects inappropriately extended their impaired knee, while during swing they tended to abduct their impaired leg.

Table 5. (cont)

Stroke studies: Outcomes.

1. Werner C, Von Frankenberg S, Treig T, Konrad M, Hesse S. Treadmill training with partial body weight support and an electromechanical gait trainer for restoration of gait in subacute stroke patients: A randomized crossover study. *Stroke*. 2002;33(12):2895–2901. [PMID: 12468788]
DOI:10.1161/01.STR.0000035734.61539.F6
2. Peurala SH, Tarkka IM, Pitkänen K, Sivenius J. The effectiveness of body weight-supported gait training and floor walking in patients with chronic stroke. *Arch Phys Med Rehabil*. 2005;86(8):1557–64. [PMID: 16084808]
DOI:10.1016/j.apmr.2005.02.005
3. Tong RK, Ng MF, Li LS. Effectiveness of gait training using an electromechanical gait trainer, with and without functional electric stimulation, in subacute stroke: A randomized controlled trial. *Arch Phys Med Rehabil*. 2006;87(10):1298–1304. [PMID: 17023237]
DOI:10.1016/j.apmr.2006.06.016
4. Husemann B, Müller F, Krewer C, Heller S, Koenig E. Effects of locomotion training with assistance of a robot-driven gait orthosis in hemiparetic patients after stroke: A randomized controlled pilot study. *Stroke*. 2007;38(2):349–54. [PMID: 17204680]
DOI:10.1161/01.STR.0000254607.48765.cb
5. Mayr A, Kofler M, Quirbach E, Matzak H, Fröhlich K, Saltuari L. Prospective, blinded, randomized crossover study of gait rehabilitation in stroke patients using the Lokomat gait orthosis. *Neurorehabil Neural Repair*. 2007;21(4):307–14. [PMID: 17476001]
DOI:10.1177/1545968307300697
6. Pohl M, Werner C, Holzgraefe M, Kroczeck G, Mehrholz J, Wingendorf I, Hoölig G, Koch R, Hesse S. Repetitive locomotor training and physiotherapy improve walking and basic activities of daily living after stroke: A single-blind, randomized multicentre trial (DEutsche GAngrainerStudie, DEGAS). *Clin Rehabil*. 2007;21(1):17–27. [PMID: 17213237]
DOI:10.1177/0269215506071281
7. Hornby TG, Campbell DD, Kahn JH, Demott T, Moore JL, Roth HR. Enhanced gait-related improvements after therapist- versus robotic-assisted locomotor training in subjects with chronic stroke: A randomized controlled study. *Stroke*. 2008;39(6):1786–92. [PMID: 18467648]
DOI:10.1161/STROKEAHA.107.504779
8. Hidler J, Nichols D, Pelliccio M, Brady K, Campbell DD, Kahn JH, Hornby TG. Multicenter randomized clinical trial evaluating the effectiveness of the Lokomat in subacute stroke. *Neurorehabil Neural Repair*. 2009;23(1):5–13. [PMID: 19109447]
DOI:10.1177/1545968308326632
9. Schwartz I, Sajin A, Fisher I, Neeb M, Shochina M, Katz-Leurer M, Meiner Z. The effectiveness of locomotor therapy using robotic-assisted gait training in subacute stroke patients: A randomized controlled trial. *PM R*. 2009;1(6):516–23. [PMID: 19627940]
10. Westlake KP, Patten C. Pilot study of Lokomat versus manual-assisted treadmill training for locomotor recovery post-stroke. *J Neuroeng Rehabil*. 2009;6:18. [PMID: 19523207]
DOI:10.1186/1743-0003-6-18
11. Hesse S, Uhlenbrock D, Sarkodie-Gyan T. Gait pattern of severely disabled hemiparetic subjects on a new controlled gait trainer as compared to assisted treadmill walking with partial body weight support. *Clin Rehabil*. 1999;13(5):401–10. [PMID: 10498347]
DOI:10.1191/026921599673896297
12. Hesse S, Uhlenbrock D, Werner C, Bardeleben A. A mechanized gait trainer for restoring gait in nonambulatory subjects. *Arch Phys Med Rehabil*. 2000; 81(9):1158–61. [PMID: 10987154]
DOI:10.1053/apmr.2000.6280
13. Tong RK, Ng MF, Li LS, So EF. Gait training of patients after stroke using an electromechanical gait trainer combined with simultaneous functional electrical stimulation. *Phys Ther*. 2006;86(9):1282–94. [PMID: 16959676]
DOI:10.2522/ptj.20050183
14. Krewer C, Müller F, Husemann B, Heller S, Quintern J, Koenig E. The influence of different Lokomat walking conditions on the energy expenditure of hemiparetic patients and healthy subjects. *Gait Posture*. 2007;26(3):372–77. [PMID: 17113774]
DOI:10.1016/j.gaitpost.2006.10.003
15. Freivogel S, Mehrholz J, Husak-Sotomayor T, Schmalohr D. Gait training with the newly developed ‘LokoHelp’-system is feasible for non-ambulatory patients after stroke, spinal cord and brain injury. A feasibility study. *Brain Inj*. 2008;22(7–8):625–32. [PMID: 18568717]
DOI:10.1080/02699050801941771
16. Neckel ND, Blonien N, Nichols D, Hidler J. Abnormal joint torque patterns exhibited by chronic stroke subjects while walking with a prescribed physiological gait pattern. *J Neuroeng Rehabil*. 2008;5:19. [PMID: 18761735]
DOI:10.1186/1743-0003-5-19

2MWT = 2-minute walk test, 5MWT = 5-meter walk test, 6MWT = 6-minute walk test, 10MWT = 10-meter walk test, BBS = Berg Balance Scale, BI = Barthel Index, BWS = body-weight support, BWSST = body-weight supported treadmill training, EMG = electromyographic, EMS = Elderly Mobility Scale, FAC = Functional Ambulatory Capacity, FAI = Frenchay Activities Index, FES = functional electrical stimulation, FIM = Functional Independence Measure, FM = Fugl-Meyer, GRF = ground reaction force, HR = heart rate, LL = lower limb, LLLFDI = Late Life Function Disability Instrument, MAS = Modified Ashworth Scale, mEFAP = modified Emory Functional Ambulatory Profile, MI = Motricity Index, MMAS = Modified Motor Assessment Scale, MRCS = Medical Research Council Scale, NA = not applicable, NIH = National Institutes of Health, PT = physical therapy, RCT = randomized controlled trial, RMI = Rivermead Mobility Index, ROM = range of motion, SAS = Stroke Activity Scale, SF-36 = 36-Item Short Form Health Survey, TUG = Timed “Up and Go” Test.

Gross Function subscale as a means to quantify mobility disability in clients with stroke. The RMI is clinically relevant in testing functional abilities such as gait, balance,

and transfers [51]. Four of the RCTs reported a significant improvement in the RMI following locomotor training [38,41,43,47]; however, only two of the studies reported

a significant difference between the groups that received robotic training [41,43]. Additionally, two case series reported substantial improvement in the RMI following 4 to 6 weeks of training with the Gait Trainer and Loko-Help [31,36].

Two case studies examined qualitative aspects of walking in the robotic device. Hesse et al. reported differences in mean EMG activity during a bout on the Gait Trainer and compared them with walking on a treadmill with BWS [49]. Mean EMG activity of lower-limb muscles between the two conditions was not significantly different except for the anterior tibialis muscle during swing and the biceps femoris muscle during early stance. Specifically, the anterior tibialis muscle was more active during the swing phase on the treadmill, while the biceps femoris muscle was more active on the Gait Trainer during early stance phase. Similarly, Neckel et al. examined differences in kinematic and kinetic data during Lokomat training in hemiparetic subjects and nondisabled control subjects [48]. Neckel et al. reported that the kinematic patterns of the stroke subjects in the Lokomat were similar to those of control subjects, except for ankle range of motion between the impaired hemiparetic lower limb and the control leg. The kinetic patterns while walking in the Lokomat were very different between the control and hemiparetic subjects. During stance phase, the unimpaired limb of stroke subjects produced greater hip extension and knee flexion torques than the control group. At preswing, stroke subjects inappropriately extended their impaired knee, while during swing they tended to abduct their impaired leg. Neckel et al. concluded that despite the fact that the Lokomat provides symmetric, normal kinematics, the kinetic patterns of stroke subjects are consistent with the pathological patterns often exhibited during overground walking [48].

One study reported metabolic demand via the rate of oxygen consumption during five walking conditions on the Lokomat to examine whether walking in the Lokomat was passive and, secondly, to determine whether energy expenditure increased with increased loading or speed [50]. The five walking conditions in the Lokomat varied BWS, treadmill speed, and the amount of passive guidance force. The five walking paradigms were (1) 100 percent BWS at 1 km/h; (2) 100 percent BWS at 2 km/h; (3) 30 percent BWS at 1 km/h; (4) 30 percent BWS at 2 km/h, 60 percent guidance force bilateral; and (5) 30 percent BWS at 2 km/h, 0 percent guidance force unilateral. The results demonstrated that controlling treatment param-

eters in the Lokomat was associated with changes in metabolic cost. Furthermore, oxygen uptake was significantly increased with increased loading, but surprisingly, increased treadmill speeds did not result in increased oxygen consumption. Decreasing passive guidance force either bilaterally or unilaterally did not result in any significant increase in oxygen uptake.

Studies using Locomotor Training with Robotic Assistance and BWS in SCI

Nineteen SCI studies were recognized for possible inclusion in this review, of which six were excluded because primary outcomes were not related to gait or were strictly related to reflex activity [52]. **Tables 6 and 7** summarize the characteristics of the SCI RCTs and non-RCTs, respectively, that were included in this review. Nine trials were analyzed and deemed appropriate as they met all aspects of our inclusion criteria [14,29,36,51,53–58]. An additional four studies were included because they addressed specific aspects of walking in SCI patients during a single session of robotic-assisted walking. These studies addressed EMG activity [59–61] and metabolic costs [62] during robotic-assisted walking in patients with SCI. Only two of the included studies were RCTs and were scored using the PEDro scale. Both studies scored a 4 on the PEDro scale, revealing fair methodological quality [32]. The remaining 11 studies were assessed using the D&B scale, and scores ranged from 10 [53] to 19 [36], with a mean of 13.6. Again, a score of 28 is the maximum available on this scale, and higher numbers indicate those studies with better methodological quality [33].

The 13 studies included a total of 182 subjects. We should note that the sample of 27 subjects reported on in Field-Fote et al. [14] were also included in the sample of 51 subjects reported on in the follow-up by Nooijen et al. [56]. Therefore, the total sample size represented in these two studies is probably more indicative of the sample size presented in Nooijen et al. ($n = 51$) [56]. All studies used either the Gait Trainer [49], the Lokomat [35], or the LokoHelp [36]. For the intervention studies, treatment intensity ranged from 20 to 45 minutes a day and frequency varied from 2 to 5 times a week. Most studies had a duration of 8 to 12 weeks, for a total number of sessions that ranged from 18 to 25 [53,55] to 50 to 60 sessions [54,56]. Two of the studies reported on outcomes in which subjects initially participated in locomotor training with robotic assistance but were transitioned to treadmill

Table 6.

Spinal cord injury studies: Characteristics of randomized controlled trials (RCTs).

Article	Study Type	PEDro Rating	Sample Size	Device Type	Daily Intensity & Weekly Frequency	Treatment Duration	Total No. of Sessions
Field-Fote et al., 2005 [1]	RCT	4	27	Lokomat	45 min, 5×/wk	12 wk	44.5 (mean)
Nooijen et al., 2009 [2]	RCT	4	51	Lokomat	45 min, 5×/wk	12 wk	50.0 ± 6.6

1. Field-Fote EC, Lindley SD, Sherman AL. Locomotor training approaches for individuals with spinal cord injury: A preliminary report of walking-related outcomes. *J Neurol Phys Ther.* 2005;29(3):127–37. [PMID: 16398945]

2. Nooijen CF, Ter Hoeve N, Field-Fote EC. Gait quality is improved by locomotor training in individuals with SCI regardless of training approach. *J Neuroeng Rehabil.* 2009;6:36. [PMID: 19799783]
DOI:10.1186/1743-0003-6-36

PEDro = Physiotherapy Evidence Database (scale).

Table 7.

Spinal cord injury studies: Characteristics of non-randomized controlled trials.

Article	Study Type	D&B Rating	Sample Size	Device Type	Daily Intensity & Weekly Frequency	Treatment Duration	Total No. of Sessions
Hornby et al., 2005 [1]	Case Series	12	3	Lokomat	45 min, 3×/wk	8–9 wk	27–60
Hesse et al., 2004 [2]	Case Series	10	4	Gait Trainer	25 min, 5×/wk	5 wk	25
Winchester et al., 2005 [3]	Case Series	14	4	Lokomat	60 min, 3×/wk	12 wk	36
Winchester et al., 2009 [4]	Case Series	14	38	Lokomat	40–45 min, 3×/wk	12 wk	36
Wirz et al., 2005 [5]	Pre–Post	17	20	Lokomat	45 min, 3–5×/wk	8 wk	26.0 ± 4.3
Moreh et al., 2009 [6]	Case Report	12	1	Lokomat	NR	9 wk	18
Lam et al., 2008 [7]	Pre–Post	14	9	Lokomat	Single Session	Single Session	1 min recording
Dietz et al., 2002 [8]	Case Control	12	9	Lokomat	Single Session	Single Session	30 min recording
Israel et al., 2006 [9]	Cohort	15	12	Lokomat	Single Session	Single Session	NR
Colombo et al., 2001 [10]	Case Report	11	2	Lokomat	Single Session	Single Session	NR
Freivogel et al., 2008 [11]	Case Report	19	1	LokoHelp	30 min, 3–5×/wk	6 wk	20

1. Hornby TG, Zemon DH, Campbell D. Robotic-assisted, body-weight-supported treadmill training in individuals following motor incomplete spinal cord injury. *Phys Ther.* 2005;85(1):52–66. [PMID: 15623362]

2. Hesse S, Werner C, Bardeleben A. Electromechanical gait training with functional electrical stimulation: Case studies in spinal cord injury. *Spinal Cord.* 2004;42(6):346–52. [PMID: 14993895]
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3. Winchester P, McColl R, Query R, Foreman N, Mosby J, Tansey K, Williamson J. Changes in supraspinal activation patterns following robotic locomotor therapy in motor-incomplete spinal cord injury. *Neurorehabil Neural Repair.* 2005;19(4):313–24. [PMID: 16263963]
DOI:10.1177/1545968305281515

4. Winchester P, Smith P, Foreman N, Mosby JM, Pacheco F, Query R, Tansey K. A prediction model for determining over ground walking speed after locomotor training in persons with motor incomplete spinal cord injury. *J Spinal Cord Med.* 2009;32(1):63–71. [PMID: 19264051]

5. Wirz M, Zemon DH, Rupp R, Scheel A, Colombo G, Dietz V, Hornby TG. Effectiveness of automated locomotor training in patients with chronic incomplete spinal cord injury: A multicenter trial. *Arch Phys Med Rehabil.* 2005;86(4):672–80. [PMID: 15827916]
DOI:10.1016/j.apmr.2004.08.004

Table 7. (cont)

Spinal cord injury studies: Characteristics of non-randomized controlled trials.

6. Moreh E, Meiner Z, Neeb M, Hiller N, Schwartz I. Spinal decompression sickness presenting as partial Brown-Sequard syndrome and treated with robotic-assisted body-weight support treadmill training. *J Rehabil Med.* 2009;41(1):88–89. [PMID: 19197576]
DOI:10.2340/16501977-0279
7. Lam T, Wirz M, Lünenburger L, Dietz V. Swing phase resistance enhances flexor muscle activity during treadmill locomotion in incomplete spinal cord injury. *Neurorehabil Neural Repair.* 2008;22(5):438–46. [PMID: 18780879]
DOI:10.1177/1545968308315595
8. Dietz V, Müller R, Colombo G. Locomotor activity in spinal man: Significance of afferent input from joint and load receptors. *Brain.* 2002;125(Pt 12):2626–34. [PMID: 12429590]
DOI:10.1093/brain/awf273
9. Israel JF, Campbell DD, Kahn JH, Hornby TG. Metabolic costs and muscle activity patterns during robotic- and therapist-assisted treadmill walking in individuals with incomplete spinal cord injury. *Phys Ther.* 2006;86(11):1466–78. [PMID: 17079746]
DOI:10.2522/ptj.20050266
10. Colombo G, Wirz M, Dietz V. Driven gait orthosis for improvement of locomotor training in paraplegic patients. *Spinal Cord.* 2001;39(5):252–55. [PMID: 11438840]
DOI:10.1038/sj.sc.3101154
11. Freivogel S, Mehrholz J, Husak-Sotomayor T, Schmalohr D. Gait training with the newly developed ‘LokoHelp’-system is feasible for non-ambulatory patients after stroke, spinal cord and brain injury. A feasibility study. *Brain Inj.* 2008;22(7–8):625–32. [PMID: 18568717]
DOI:10.1080/02699050801941771

D&B = Downs and Black (scale), NR = not reported.

training with BWS and manual assistance once a level of independence with overground walking had been reached [16,63]. One study combined overground training and locomotor training with robotic assistance using BWS once subjects were able to ambulate with less than 20 percent BWS with the robotic system [57]. Only one article reported outcomes for patients who had received a combination of locomotor training with robotic assistance and BWS and FES [53]. Two RCTs compared outcomes between four types of locomotor training with BWS in persons with chronic injuries (>1 year) [14,56]. The four BWS conditions were treadmill training with manual assistance, treadmill training with electrical stimulation, overground training with electrical stimulation, and treadmill training with robotic assistance. Gait training time did not differ between the four conditions in either of the included RCT studies.

These studies included a mean age range of 24 [36] to 63 years [61]. In accordance with the reported prevalence of SCI in males, significantly more males were reported on in these studies than females. Large variability was also found in time post-SCI, which ranged from 3 weeks [55] to 226 months [62]. The majority of studies included subjects who were motor incomplete, American Spinal Injury Association impairment scale (ASIA) classification C or D [14,53–58,62–64]. However, two studies also included information regarding EMG activity in subjects with motor complete SCI, ASIA classification A or B [59–60]. Large variability was found in the subjects’ baseline walking ability. Out of the 94 subjects included in the non-RCT studies, 58 subjects were able to partici-

pate in overground walking with or without assistance, orthoses, and assistive devices, while 36 subjects were unable to complete any form of overground walking at study entrance. However, due to overlap of subjects studied in the two RCTs, it can only be determined that those participants at least had the ability to stand and initiate a step at baseline. Three studies involved subjects with lumbar level injuries [55–56,58], while all the other studies included subjects with thoracic and cervical injuries only. **Table 8** provides a detailed description of patient characteristics for all SCI RCTs, and **Table 9** provides the same information for all SCI non-RCTs.

The majority of studies investigating improvement in overground walking function included outcomes of timed walking tests using gait speed (meters/second or centimeters/second) and/or gait endurance (6MWT). Some studies were stratified by lower-limb motor score [56], while others were stratified by initial walking speed [14,63]. Changes in stride length, step length, and step length ratio were reported to evaluate the effects of robotic treadmill training on gait quality [14,56]. Changes in physical assistance, assistive devices, and lower-limb orthotics were captured using the WISCI or WISCI II [54–55,57–58]. Only two studies reported the effects of treadmill training with robotic assistance on ASIA classifications [55,57]. One study reported functional magnetic resonance imaging (fMRI) changes associated with this intervention [57], and another study demonstrated the use of a prediction model in determining which types of patients may benefit most from treadmill training using robotic technology [63]. EMG data were reported that

Table 8.

Spinal cord injury (SCI) studies: Patient characteristics* (randomized controlled trials).

Article	Age, yr				Sex (M/F)				Time Post-SCI, yr				Neurological Level	Stratification for Walking (speed or LEMS)
	TM	TS	OG	LR	TM	TS	OG	LR	TM	TS	OG	LR		
Field-Fote et al., 2005 [1]	41	41	48	43	7/1	5/2	6/1	5/1	3.1	9.0	4.2	8.7	C3–T10	<0.1 m/s, n = 15; >0.1 m/s, n = 12
Nooijen et al., 2009 [2]	38	39	42	44	11/2	11/4	8/3	10/2	4.4	6.8	3.7	9.2	C3–L2	LEMS: 1–10; 11–21; 22–32; >32

*All patients in both studies were American Spinal Injury Association impairment scale level C or D.

1. Field-Fote EC, Lindley SD, Sherman AL. Locomotor training approaches for individuals with spinal cord injury: A preliminary report of walking-related outcomes. *J Neurol Phys Ther.* 2005;29(3):127–37. [PMID: 16398945]
2. Nooijen CF, Ter Hoeve N, Field-Fote EC. Gait quality is improved by locomotor training in individuals with SCI regardless of training approach. *J Neuroeng Rehabil.* 2009;6:36. [PMID: 19799783]
DOI:10.1186/1743-0003-6-36

C = cervical, F = female, L = lumbar, LEMS = lower-extremity motor score, LR = treadmill training with robotic assistance, M = male, OG = overground training with electrical stimulation, T = thoracic, TM = treadmill training with manual assistance, TS = treadmill training with electrical stimulation.

Table 9.

Spinal cord injury (SCI) studies: Patient characteristics (non-randomized controlled trials).

Article	Age Range (yr)	Time Post-SCI Range (wk)	Sex % (M/F)	ASIA	Neurological Level	Able/Unable to Complete Walking
Hornby et al., 2005 [1]	13–43	6–72; 2 acute; 1 chronic	33/67	C	C6–T2	1/2
Hesse et al., 2004 [2]	50	12–72; 4 subacute; 1 chronic	75/25	C & D	C5–T8	3/1
Winchester et al., 2005 [3]	20–49	14–192; 2 subacute; 2 chronic	100/0	C & D	C5–C6	0/4
Winchester et al., 2009 [4]	14–65	<240; 30 chronic; 8 subacute	74/26	C & D	NP	14/16*
Wirz et al., 2005 [5]	16–64	416–3,536; 20 chronic	90/10	C & D	C3–L1	16/4
Moreh et al., 2009 [6]	42	3; 1 acute	100/0	C	T11	NP
Lam et al., 2008 [7]	63	6–279; 5 subacute; 4 chronic	55/45	D	C4–L1	9/0
Dietz et al., 2002 [8]	19–62	192–480; 6 chronic	NP	A & B	C6–T7	3/6
Israel et al., 2006 [9]	15–59	20–1,024; 2 subacute; 10 chronic	NP	C & D	C4–T10	12/0
Colombo et al., 2001 [10]	NP	NP	NP	B & C	C3–C5	0/2
Freivogel et al., 2008 [11]	37	144; 1 chronic	50/50	C	T12	0/1

*Reported on initial 30 subjects only.

1. Hornby TG, Zemon DH, Campbell D. Robotic-assisted, body-weight-supported treadmill training in individuals following motor incomplete spinal cord injury. *Phys Ther.* 2005;85(1):52–66. [PMID: 15623362]
2. Hesse S, Werner C, Bardeleben A. Electromechanical gait training with functional electrical stimulation: Case studies in spinal cord injury. *Spinal Cord.* 2004;42(6):346–52. [PMID: 14993895]
DOI:10.1038/sj.sc.3101595
3. Winchester P, McColl R, Querry R, Foreman N, Mosby J, Tansey K, Williamson J. Changes in supraspinal activation patterns following robotic locomotor therapy in motor-incomplete spinal cord injury. *Neurorehabil Neural Repair.* 2005;19(4):313–24. [PMID: 16263963]
DOI:10.1177/1545968305281515
4. Winchester P, Smith P, Foreman N, Mosby JM, Pacheco F, Querry R, Tansey K. A prediction model for determining over ground walking speed after locomotor training in persons with motor incomplete spinal cord injury. *J Spinal Cord Med.* 2009;32(1):63–71. [PMID: 19264051]
5. Wirz M, Zemon DH, Rupp R, Scheel A, Colombo G, Dietz V, Hornby TG. Effectiveness of automated locomotor training in patients with chronic incomplete spinal cord injury: A multicenter trial. *Arch Phys Med Rehabil.* 2005;86(4):672–80. [PMID: 15827916]
DOI:10.1016/j.apmr.2004.08.004

Table 9. (cont)

Spinal cord injury (SCI) studies: Patient characteristics (non-randomized controlled trials).

6. Moreh E, Meiner Z, Neeb M, Hiller N, Schwartz I. Spinal decompression sickness presenting as partial Brown-Sequard syndrome and treated with robotic-assisted body-weight support treadmill training. *J Rehabil Med.* 2009;41(1):88–89. [PMID: 19197576]
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7. Lam T, Wirz M, Lünenburger L, Dietz V. Swing phase resistance enhances flexor muscle activity during treadmill locomotion in incomplete spinal cord injury. *Neurorehabil Neural Repair.* 2008;22(5):438–46. [PMID: 18780879]
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8. Dietz V, Müller R, Colombo G. Locomotor activity in spinal man: Significance of afferent input from joint and load receptors. *Brain.* 2002;125(Pt 12):2626–34. [PMID: 12429590]
DOI:10.1093/brain/awf273
9. Israel JF, Campbell DD, Kahn JH, Hornby TG. Metabolic costs and muscle activity patterns during robotic- and therapist-assisted treadmill walking in individuals with incomplete spinal cord injury. *Phys Ther.* 2006;86(11):1466–78. [PMID: 17079746]
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10. Colombo G, Wirz M, Dietz V. Driven gait orthosis for improvement of locomotor training in paraplegic patients. *Spinal Cord.* 2001;39(5):252–55. [PMID: 11438840]
DOI:10.1038/sj.sc.3101154
11. Freivogel S, Mehrholz J, Husak-Sotomayor T, Schmalohr D. Gait training with the newly developed ‘LokoHelp’-system is feasible for non-ambulatory patients after stroke, spinal cord and brain injury. A feasibility study. *Brain Inj.* 2008;22(7–8):625–32. [PMID: 18568717]
DOI:10.1080/02699050801941771

ASIA = American Spinal Injury Association impairment scale, C = cervical, F = female, L = lumbar, M = male, NP = not provided, T = thoracic.

compared nondisabled subjects with SCI subjects [60] or the robotic-assisted versus the manual-assisted conditions [59,61–62]. Metabolic cost comparisons between treadmill training with manual and robotic assistance were reported by Israel et al. [62]. Lam et al. also reported on kinematic data between robotic- and therapist-assisted interventions [61].

Gait Outcomes in SCI Studies

A detailed description of the primary outcomes for each SCI trial can be found in **Table 10**. The two RCTs included in this review [14,56] provided a direct comparison of the four BWS intervention groups previously mentioned: treadmill training with manual assistance, treadmill training with electrical stimulation, overground training with electrical stimulation, and treadmill training with robotic assistance. Overall, these results yielded no significant differences in gait speed or distance covered in a timed test between the four intervention groups. Additionally, no significant differences in gait quality were reported. Field-Fote et al. did report a trend toward greater improvement in gait speed in the two groups that received combination therapy that included FES [14], but these differences did not reach statistical significance. Post hoc speed stratification produced more robust differences than original group allocation; those patients who entered the study ambulating <0.1 m/s demonstrated an 85 percent improvement in overground walking speed, while subjects walking >0.1 m/s at baseline demonstrated only a 9 percent improvement in overground walking

speed after training. Qualitative analysis showed an increase in step length in all groups except the robotic group, but the robotic group demonstrated the greatest improvement in step symmetry. Nooinjen et al. focused on temporal distance measures of gait using the GAITRite system (CIR Systems Inc; Peekskill, New York), but no significant between-group differences could be detected between the outcomes based on group allocation [56]. The GAITRite system is a portable walkway used in clinical settings to obtain objective data regarding gait parameters. The GAITRite system measures the temporal and spatial parameters of gait. As the patient or subject walks across the walkway, the system captures data with respect to each footstep and calculates these aspects of gait using 18,432 sensors. The authors did report, however, an interaction effect showing less improvement in step and stride length in the robotic group compared with the other three intervention groups; the treadmill training with electrical stimulation group showed a significantly larger gain compared with subjects in the treadmill training with robotic assistance group in step length of the weaker leg. The overground training with electrical stimulation group had a significantly larger gain compared with subjects in the treadmill training with robotic assistance group in step length of the stronger leg and in stride length of the weaker limb. These authors hypothesized that these results could be due to the use of the robot in a state of high impedance control rather than varied to low impedance control because subjects were able to support and control more

Table 10.

Spinal cord injury (SCI) studies: Outcomes.

Article	Intervention	Gait Outcomes	Other Outcomes	Results
Field-Fote et al., 2005 [1]	TM, TM + FES, OG + FES, LR	6MWT, 2MWT	Step length, step ratio	Significant ↑ in walking speed across all subjects; differences between groups not statistically significant; 85% ↑ in speed with slower initial walking speed (<0.1 m/s); Only 9% ↑ in faster walking speed group (>0.1 m/s); Step length increased in all groups except LR; LR had greatest ↑ in symmetry.
Nooijen et al., 2009 [2]	TM, TM + FES, OG + FES, LR	Gait Rite: Cadence, step length, stride length, SI	Intralimb coordination, knee extension onset with hip cycle	↑ gait quality in all groups after training; no significant between-group differences found for any parameters; interaction effect showing least amount of step and stride length changes in LR group.
Hornby et al., 2005 [3]	Lokomat with transition to TM when overground = 4, FIM.	WISCI II, 10MWT, 6MWT, TUG	ASIA, LEMS, FIM, functional reach: sitting/standing	↑ gait speed and distance all subjects; ↑ FIM and WISCI II scores with acute subjects; no ↑ FIM or WISCI II score with chronic subject; overall, more positive ↑ in acute vs chronic subjects; ↑ gait speed and distance in all subjects; variable EMG changes.
Hesse et al., 2004 [4]	Gait Trainer + FES to quadriceps and hamstrings	Gait speed, gait distance	EMG	↑ gait speed and distance in all subjects; variable EMG changes.
Winchester et al., 2005 [5]	Lokomat	WISCI II, gait speed (Gait Rite)	fMRI	↑ WISCI II scores and gait speed in 3 of 4 subjects; ↑ cerebellum activation on fMRI in subjects who ↑ overground walking ability; > time since onset demonstrated least amount of improvement.
Winchester et al., 2009 [6]	Lokomat + TM + OG walking	10MWT	Prediction model based on voluntary bowel/bladder, functional spasticity score, initial walking speed, time postinjury	Prediction model developed using 30 subjects; validated on 8 subacute SCI subjects and able to predict final walking speed within 4.15 cm/s of actual change in walking speed after training.
Wirz et al., 2005 [7]	Lokomat	10MWT, 6MWT, TUG, WISCI II	LEMS, MAS (1 center only)	Significant ↑ in gait speed and gait distance and ↓ time to complete TUG ($p < 0.001$); no significant changes in WISCI II.
Moreh et al., 2009 [8]	Lokomat	WISCI	ASIA, SCIM, BBS ASIA Motor Composite	ASIA C to D; ↑ WISCI 1–15; ↑ SCIM 50 to 90; ↑ BBS 35 to 43.
Lam et al., 2008 [9]	Lokomat with resistance, TM with weights	NA	EMG, peak knee flexion	Addition of weights to TM ↑ hamstring activity in all subjects; no significant differences in EMG with robotic resistance; significantly ↑ peak knee flexion in TM group after weight removed; no significant changes in EMG of Lokomat group when resistance removed.

Table 10. (cont)

Spinal cord injury (SCI) studies: Outcomes.

Article	Intervention	Gait Outcomes	Other Outcomes	Results
Dietz et al., 2002 [10]	Lokomat: Air walking (100% BWS), 70%, BWS; Bilateral normal walking, bilateral "hip walking," unilateral walking	NA	EMG	70% BWS LL activation patterns similar in subjects vs nondisabled, but amplitudes of lower leg muscles ↓ significantly in SCI vs nondisabled; ↑ EMG amplitude of upper leg muscles in SCI vs nondisabled; ↓ EMG activity in proximal and distal muscles of both groups during air walking; no EMG activity present in nonmoving leg of subjects with SCI in unilateral walking; LL activation almost unchanged in "hip walking," demonstrating importance of hip joint afferents.
Israel et al., 2006 [11]	Lokomat: RA Match, RA Max, TM	NA	O ₂ consumption, EMG	Significantly ↑ metabolic expenditure in RA Max vs RA Match; metabolic costs for RA Match significantly ↓ than TM; no significant differences between RA Max and TM; abnormal EMG activity in RA Max protocol; ↑ MH, MG during swing phase.
Colombo et al., 2001 [12]	Lokomat training, TM	NA	EMG: RF, BF, GM, TA	Maximum EMG amplitude slightly ↑ in TM vs LR; VR of TA and GM ↓ in LR vs TM.
Freivogel et al., 2008 [13]	LokoHelp	Gait velocity, FAC	MRC, MAS, BBS, RMI	Significant ↑ FAC and ↑ RMI; no significant ↑ in MRC, BBS, or MAS after training; both subjects unable to complete gait testing at baseline but able to complete 10MWT at final assessment.

- Field-Fote EC, Lindley SD, Sherman AL. Locomotor training approaches for individuals with spinal cord injury: A preliminary report of walking-related outcomes. *J Neurol Phys Ther.* 2005;29(3):127–37. [PMID: 16398945]
- Nooijen CF, Ter Hoeve N, Field-Fote EC. Gait quality is improved by locomotor training in individuals with SCI regardless of training approach. *J Neuroeng Rehabil.* 2009;6:36. [PMID: 19799783]
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DOI:10.2340/16501977-0279
- Lam T, Wirz M, Lünenburger L, Dietz V. Swing phase resistance enhances flexor muscle activity during treadmill locomotion in incomplete spinal cord injury. *Neurorehabil Neural Repair.* 2008;22(5):438–46. [PMID: 18780879]
DOI:10.1177/1545968308315595
- Dietz V, Müller R, Colombo G. Locomotor activity in spinal man: Significance of afferent input from joint and load receptors. *Brain.* 2002;125(Pt 12):2626–34. [PMID: 12429590]
DOI:10.1093/brain/awf273

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Spinal cord injury (SCI) studies: Outcomes.

11. Israel JF, Campbell DD, Kahn JH, Hornby TG. Metabolic costs and muscle activity patterns during robotic- and therapist-assisted treadmill walking in individuals with incomplete spinal cord injury. *Phys Ther.* 2006;86(11):1466–78. [PMID: 17079746]
DOI:10.2522/ptj.20050266
12. Colombo G, Wirz M, Dietz V. Driven gait orthosis for improvement of locomotor training in paraplegic patients. *Spinal Cord.* 2001;39(5):252–55.
[PMID: 11438840]
DOI:10.1038/sj.sc.3101154
13. Freivogel S, Mehrholz J, Husak-Sotomayor T, Schmalohr D. Gait training with the newly developed ‘LokoHelp’-system is feasible for non-ambulatory patients after stroke, spinal cord and brain injury. A feasibility study. *Brain Inj.* 2008;22(7–8):625–32. [PMID: 18568717]
DOI:10.1080/02699050801941771

2MWT = 2-minute walk test, 6MWT = 6-minute walk test, 10MWT = 10-meter walk test, ASIA = American Spinal Injury Association impairment scale, BBS = Berg Balance Scale, BF = biceps femoris, BWS = body-weight support, EMG = electromyography, FAC = Functional Ambulatory Capacity, FES = functional electrical stimulation, FIM = Functional Independence Measure, fMRI = functional magnetic resonance imaging, GM = gluteus maximus, LEMS = lower-extremity motor score, LL = lower limb, LR = treadmill training with robotic assistance, MAS = Modified Ashworth Scale, MH = medial hamstring, MG = medial gastrocnemius, MRC = Medical Research Council, NA = not applicable, OG = overground training with electrical stimulation, RA Match = match trajectory protocol, RA Max = exert maximum effort protocol, RF = rectus femoris, RMI = Rivermead Mobility Index, SCIM = Spinal Cord Independence Measure, SI = Symmetry Index, TA = tibialis anterior, TM = treadmill training with manual assistance, TUG = Timed “Up and Go” Test, VR of TA = Variation ratio of TA, WISCI = Walking Index for Spinal Cord Injury.

of their own movements. Low impedance forces allow the subject to have more flexibility to influence the pre-defined walking pattern and activate his or her muscles in order to assist with an appropriate walking pattern. High impedance forces provide more guidance to the pattern and require less muscular input from the participant, possibly creating a more passive activity [65]. Nooijen et al. suggest that using high impedance control could have contributed to less activity in the robotic group compared with the other three interventions groups [56]. Both RCTs included information on chronic subjects only, so caution should be taken in extrapolating these results to those with acute injuries.

Gait speed was a primary outcome in 6 of the 11 non-RCTs [36,53–54,57–58,63], and gait distance was a primary outcome in 3 of the 11 non-RCTs [53–54,58]. Physical assistance, orthosis use, and the need for assistive devices was captured with the WISCI or WISCI II in several studies [54–55,57–58]. Hornby et al. initially treated all subjects with robotic-assisted locomotor training and then transitioned them to locomotor training with manual assistance once a level of independence with overground walking had been achieved [54]. These investigators reported improvements in gait speed and distance in all three subjects but reported improvements in FIM and WISCI II scores only in those subjects who had acute rather than chronic injuries. Hesse et al. [53] and Winchester et al. [57] included only subacute and chronic subjects in their studies. Hesse et al. [53] reported improvements in gait speed and distance in all four subjects, with variable changes in EMG activity [53]. However, the subject with the greatest time since onset of injury also demon-

strated the least amount of improvement in overground walking ability, requiring the addition of extensive bracing for overground walking. Winchester et al. demonstrated improved WISCI II scores and gait speed in three out of four subjects after Lokomat training [57]. Two of these subjects were subacute at baseline and were able to reach community ambulation status, while the other two chronic subjects continued to require physical assistance to ambulate or were not ambulatory at all. A novel finding in this study was the increased cerebellum activation present on fMRI in those subjects (three out of four) who demonstrated improvements in overground walking function. Freivogel et al. also demonstrated improvement in overground gait speed after training with the LokoHelp in a single subject with chronic SCI [36]. Overall, more positive changes in gait speed were noted in those subjects who had acute or subacute injuries than those with chronic injuries after locomotor training with robotic assistance and/or locomotor training that transitioned from robotic to therapist assisted. Wirz et al. included only subjects with chronic SCI in their study ($n = 20$) and reported significant improvements in gait speed and distance as well as decreased time required to complete the TUG after 8 weeks of locomotor training with robotic assistance [58]. However, they found no significant changes in WISCI II scores, resulting in questions regarding the ability of this specific intervention alone to facilitate changes in physical assistance need, assistive device need, and orthosis use in the chronic SCI population. Moreh et al. reported a case study in which a single subject with acute spinal decompression sickness was able to make clinically meaningful improvements in overground

walking ability in response to locomotor training with robotic assistance as demonstrated by the following outcome changes: ASIA classification C to D, WISCI 1 to 15, Spinal Cord Independence Measure 50 to 90, and BBS 35 to 43 [55].

A prediction model for determining overground walking speed after locomotor training was presented by Winchester et al. [63]. They completed a retrospective review and statistical modeling of 30 subjects with incomplete SCI who had previously undergone 36 sessions of progressive locomotor training beginning with robotic-assisted and transitioning to manual-assisted training. In a stepwise regression analysis, these authors identified four clinical variables that were statistically significant in predicting overground gait speed following locomotor training in this population: voluntary bowel/bladder control, functional spasticity score, overground walking speed before locomotor training, and time post-onset. The investigators subsequently validated this model in eight subacute SCI subjects and were able to predict final walking speed within 4.15 cm/s of the actual change in walking speed after 36 sessions of locomotor training that included robotic, therapist-assisted, FES, and overground walking.

Secondary Outcomes in SCI Studies

Dietz et al. [60], Israel et al. [62], and Colombo et al. [59] evaluated EMG activity changes in response to locomotor training with robotic assistance. Dietz et al. demonstrated similar lower-limb activation patterns during Lokomat training at 70 percent BWS between nondisabled subjects and subjects with motor complete SCI [60]. They also found the mean EMG amplitude of lower leg muscles to be much smaller and the amplitude of upper leg muscles to be larger in SCI subjects versus nondisabled subjects. Decreased EMG amplitudes were found in both nondisabled and SCI subjects who were receiving full BWS, suggesting the importance of maximizing loading during locomotor training to optimize muscular response. Colombo et al. investigated the differences in EMG activity using the Lokomat and treadmill training with BWS and manual assistance in both a motor complete and a motor incomplete SCI subject [59]. They found that maximum EMG amplitudes were slightly larger in therapist-assisted versus robotic conditions in the rectus femoris, biceps femoris, gastrocnemius, and tibialis anterior muscles during training with the motor incomplete subject, but reported these differ-

ences were negligible between the two therapeutic approaches.

Israel et al. examined the differences in metabolic costs for subjects with incomplete SCI between treadmill training with robotic assistance and treadmill training with manual assistance [62]. Subjects were asked to either exert maximum effort while walking in the Lokomat or simply match the trajectory of the Lokomat while walking. A comparison of oxygen consumption demonstrated a significant increase in metabolic expenditure in the maximum effort group versus the trajectory match group and a significant decrease in the trajectory match group versus the treadmill with manual assistance group. However, they found no significant differences in oxygen consumption between the maximum effort group and the treadmill with manual assistance group, demonstrating the importance of voluntary effort and appropriate therapist cueing for subjects during robotic locomotor training. Lastly, these authors reported abnormally high EMG activity in the hamstrings and gastrocnemius muscles during swing phase of the maximum exertion group that was not present in the other two groups, raising questions regarding appropriate phase activation when subjects are exerting maximal effort.

Studies Using Locomotor Training with Robotic Assistance and BWS in MS

Only two studies, both of which were RCTs, have reported on the effects of using locomotor training with robotic assistance in treating gait dysfunction in persons with MS [66–67]. Both studies met the previously discussed inclusion criteria and included a total sample size of 48. The PEDro scale was used to evaluate them on methodological quality. One scored a 6 and the other a 7 on the PEDro scale, indicating good methodological quality [32]. **Table 11** summarizes the characteristics of the two MS studies included in this review. The Lokomat was the intervention used in both of these studies [35]. Lo and Triche completed a randomized crossover design, testing two protocols of treadmill training using BWS [67]. Thirteen subjects were initially stratified by their baseline EDSS score of <5 or ≥5 and then randomly assigned to one of the following two groups: (1) 3 weeks of treadmill training with manual assistance followed by a 6-week washout period and another 3 weeks of treadmill training with robotic assistance or (2) 3 weeks of treadmill training with robotic assistance followed by a 6-week washout period and another 3 weeks of treadmill

training with manual assistance. Beer et al. completed an RCT with 35 subjects, comparing 3 weeks of Lokomat training with conventional walking training in a group of stable MS patients [66]. Daily intensity was similar (30 to 40 minutes) in the two studies; however, training intensity varied. Lo and Triche [67] used a less intense training schedule of 2 times a week for a total of only 6 sessions compared with Beer et al. [66], who used daily training 5 times a week for a total of 15 sessions.

The mean age of participants in both groups was reported to be 49.7 years old. As expected, for this diagnosis, more females than males were present (60% female and 40% male). The reported disease distribution was 23 percent relapsing/remitting, 38 percent secondary progressive, and 40 percent primary progressive. Beer et al. reported an average time since disease onset of 15 years in both control and experimental groups [66], while Lo and Triche did not report this variable [67]. Beer et al. required their subjects to have the ability to stand or walk within the last 3 months [66], while Lo and Triche required their subjects to be able to walk 25 ft without assistance at baseline [67]. Lastly, Beer et al. [66] included subjects with severe walking disabilities who required a level of assistance indicated by an EDSS score of <6 (intermittent or unilateral constant assistance [cane, crutch, brace] required to walk about 100 m with or without resting) [68]. Lo and Triche stratified subjects using their EDSS before randomization to ensure equal distribution of disability between groups [67]. The mean EDSS score for this study was 5 (ambulatory without aid or rest for about 200 meters; disability severe enough to impair full daily activities) [68]. See **Table 12** for patient characteristics.

Outcomes in MS Studies

A detailed description of the primary outcomes for both MS trials can be found in **Table 13**. Significant improvements in overground gait velocity were reported by Beer et al. in both control and experimental groups in response to both forms of locomotor training (robotic and conventional) [66]. After pooling all data, Lo and Triche also reported significant improvements in the 25FWT (31% improvement), 6MWT (38.5% improvement), double-limb support time, and EDSS after completing either training protocol [67]. No significant between-group differences were detected in either study between locomotor training with robotic assistance and conventional walking training or between treadmill training with manual assistance versus robotic assistance. Also, Lo and Triche

found no significant differences due to treatment order effect between locomotor training with robotic- and manual-assisted approaches [67]. Beer et al. reported that at 6-month follow up, all patients had returned to their baseline walking function [66]. On the contrary, Lo and Triche reported that subjects had maintained gains from the initial 3-week treatment intervention after the 6-week washout period [67], raising questions regarding long-term effects of these treatment interventions. Overall, both studies suggest efficacy for improving gait function in patients diagnosed with MS who remain ambulatory or who have been ambulatory within the preceding 12 weeks. However, the results do not support the selection of a specific locomotor intervention or an ordering effect of these interventions if completed in combination.

Studies Using Locomotor Training with Robotic Assistance and BWS in TBI

An extensive search of the literature revealed only one refereed publication concerning the use of robotic devices for locomotor training in the TBI or polytrauma patient population [36]. This case study examined the effects of 20 sessions (30 minutes, 3 to 5 times a week) of locomotor training with the LokoHelp on gait function and impairment in two subjects with TBI. The two subjects (age 22 and 26 years) were 1 and 3 years post-TBI, respectively. No clinically significant changes were observed in FAC, RMI, BBS, or spasticity (MAS) following the 6-week intervention period. Both subjects remained nonambulatory according to the FAC assessment.

Studies Using Locomotor Training with Robotic Assistance and BWS in PD

Despite an extensive search of the literature, no studies have been reported regarding the use of robotic devices to improve locomotor function in individuals with PD. Currently, an ongoing study is examining the effect of Lokomat training on freezing of gait in PD that is funded by the Department of Veterans Affairs (grant NCT00819949).

DISCUSSION

The objective of this systematic review was to assess the efficacy of robotic locomotor training on improvement in overground walking for adults with neurological injury or disease. Overall, this review supports that locomotor training with robotic assistance is beneficial in improving

Table 11.

Multiple sclerosis studies: Characteristics of randomized controlled trials (RCTs).

Article	Study Type	PEDro Rating	Sample Size	Device Type	Daily Intensity & Weekly Frequency	Treatment Duration	Total No. of Sessions
Lo & Triche, 2008 [1]	RCT (cross-over design)	6	13	Lokomat vs TT	40 min, 2×/wk	3 wk training; 6 wk washout; 3 wk training	6
Beer et al., 2008 [2]	RCT	7	35	Lokomat vs CWT	30 min, 5×/wk	3 wk	15

1. Lo AC, Triche EW. Improving gait in multiple sclerosis using robot-assisted, body weight supported treadmill training. *Neurorehabil Neural Repair*. 2008;22(6):661–71. [PMID: 18971381] DOI:10.1177/1545968308318473

2. Beer S, Aschbacher B, Manoglou D, Gamper E, Kool J, Kesselring J. Robot-assisted gait training in multiple sclerosis: A pilot randomized trial. *Mult Scler*. 2008;14(2):231–36. [PMID: 17942510] DOI:10.1177/1352458507082358

CWT = conventional walking training, PEDro = Physiotherapy Evidence Database (scale), TT = therapist-assisted treadmill training.

Table 12.

Multiple sclerosis (MS) studies: Patient characteristics (randomized controlled trials).

Article	Age, yr (mean ± SD)	MS Disease Pattern			Sex (M/F)	Baseline Ambulatory Status	EDSS Mean (range or ± SD)
		Relapsing Remitting	Secondary Progressive	Primary Progressive			
Beer et al., 2008 [1]						Able to stand or walk within 3 mo	
RAGT	49.7 ± 11.0	2	8	9	7/12		6.5 (6.0–7.5)
CWT	51.0 ± 15.5	1	10	5	5/11		6.5 (6.0–7.5)
Lo & Triche, 2008 [2]						25 ft without assistance	
R:T	50.2 ± 11.4	3	0	3	3/3		5.0 ± 1.6
T:R	49.6 ± 11.8	5	0	2	4/3		4.9 ± 0.9

1. Beer S, Aschbacher B, Manoglou D, Gamper E, Kool J, Kesselring J. Robot-assisted gait training in multiple sclerosis: A pilot randomized trial. *Mult Scler*. 2008;14(2):231–36. [PMID: 17942510] DOI:10.1177/1352458507082358

2. Lo AC, Triche EW. Improving gait in multiple sclerosis using robot-assisted, body weight supported treadmill training. *Neurorehabil Neural Repair*. 2008;22(6):661–71. [PMID: 18971381] DOI:10.1177/1545968308318473

CWT = conventional walking training, EDSS = Expanded Disability Status Scale, F = female, M = male, RAGT = robotic-assisted gait training, R:T = robot-assisted treadmill training: manual-assisted treadmill training, SD = standard deviation, T:R = manual-assisted treadmill training: robotic-assisted treadmill training.

locomotor function in individuals following a stroke and SCI. Evidence surrounding the use of locomotor training with robotic assistance in MS is limited; however, it appears that the potential effect on gait dysfunction from robotics is at least equal to that of other techniques in persons with MS that require assistance to walk. The evidence in TBI and PD is insufficient to suggest the use of locomotor training with robotic assistance is of benefit in these populations. No conclusive evidence exists to sug-

gest that manual or conventional locomotor training preferentially results in improved locomotor function. However, examining some of the confounds of pooling these studies along with applying motor learning theory in persons with neurological gait dysfunction may provide initial insights into positioning robotics in the continuum of care. The cost of each form of locomotor training may also play a role in the clinical implementation of these interventions.

Table 13.

Multiple sclerosis studies: Outcomes.

Article	Intervention	Gait Outcomes	Other Outcomes	Results
Beer et al., 2008 [1]	Lokomat vs CWT	20MWT 6MWT	Stride length Knee extensor strength	Significant improvement in gait velocity in both robotic and CWT groups; no significant between-group differences found; significant improvement in robotic 6MWT; no significant difference in CWT 6MWT; no other significant changes reported except right knee extensor strength in robotic group > CWT.
Lo & Triche, 2008 [2]	Lokomat vs TT	25FWT 6MWT	DST% SLR EDSS	Pooled data demonstrating significant changes in EDSS, 25FWT, 6MWT, and DST. No significant differences in any outcomes between treatment groups; no significant differences found due to treatment order.

1. Beer S, Aschbacher B, Manoglou D, Gamper E, Kool J, Kesselring J. Robot-assisted gait training in multiple sclerosis: A pilot randomized trial. *Mult Scler*. 2008;14(2):231–36. [\[PMID: 17942510\]](#)
[DOI:10.1177/1352458507082358](#)

2. Lo AC, Triche EW. Improving gait in multiple sclerosis using robot-assisted, body weight supported treadmill training. *Neurorehabil Neural Repair*. 2008;22(6):661–71. [\[PMID: 18971381\]](#)
[DOI:10.1177/1545968308318473](#)

6MWT = 6-minute walk test, 20MWT = 20-meter walk test, 25FWT = 25-foot walk test, CWT = conventional walking training, DST = double support time, EDSS = Expanded Disability Status Scale, SLR = step length ratio, TT = therapist-assisted treadmill training.

The use of robotic devices in gait rehabilitation for patients after stroke was found to significantly improve the independence of walking. Our conclusions are in agreement with the Cochrane review by Mehrholz et al. [69], which provided evidence that the use of robotic-assisted gait training devices in combination with physical therapy improved recovery of independent walking ability for patients following stroke. Our review expands upon this review by including additional RCT and non-RCTs. The average score for the 10 RCTs included in this review was indicative of good methodological quality. Disagreement exists among the reported studies regarding walking speed. All studies agreed that gait speed increased following locomotor training; however, three of the RCTs reported a preferential improvement in gait speed following robotic locomotor training [41,43,45]. In opposition, two RCTs reported that conventional or therapist-assisted BWS training resulted in more improvements in gait speed [38–39]. Furthermore, no statistically significant difference was found between robotic-assisted and manual-assisted locomotor training at similar levels of training intensity with regards to 6MWT or 2MWT in

subacute stroke. Variables that should be considered when attempting to interpret these results include the differences in length of time postonset, dosage of training, and clinical presentation of the subjects in the studies. The difference of these variables across the studies may account for some of the disagreement in the findings. For example, data suggest that locomotor training with robotic assistance appears to be more robust in the acute and subacute rehabilitation periods following a stroke when the patient is unable to walk independently [41,43]. Additionally, the data appear stronger with higher training doses and in persons with more severe gait dysfunction [41,43,45].

No conclusive evidence exists that locomotor training with robotics is any different than conventional or therapist-assisted gait training in improving balance, lower-limb spasticity, ADL, or motor function. Preliminary evidence shows that locomotor training with robotic technology may improve mobility disability following a stroke as measured by the RMI. Qualitative differences in gait as measured by EMG and kinematic and kinetic data do exist between walking training with robotic assistance

in subjects after a stroke. EMG and kinematic differences are minimal, but significant kinetic differences are observed between hemiparetic subjects and nondisabled control subjects. It is unclear whether the observed asymmetries would persist following a longer training schedule in the robotic device. Robotic locomotor training was not found to be a passive exercise; although percent weight bearing appears to be the major determinant of metabolic demand as opposed to speed or percent robotic assistance.

In summarizing the studies that examined locomotor training with robotic assistance in SCI, this intervention appears to be beneficial in improving overground gait speed and endurance in patients with acute, subacute, and chronic conditions of incomplete SCI. However, no statistically significant differences were seen in gait speed and endurance when patients with incomplete SCI were treated with either robotic-assisted, therapist-assisted, or overground training approaches. Only two RCTs were available for this review, and both were rated by the PEDro scale as having fair methodological quality. The results from these two studies may also represent a possible confounder in that one study appears to pool at least partial data from subjects reported on in the previous RCT. These results denote the need for further research in this area with improved study design. Some preliminary data suggest that a combination therapy of FES and locomotor training may be more beneficial than locomotor training alone, especially in the chronic SCI population. Evidence also suggests that those patients who walk at slower speeds (<0.1 m/s) before locomotor training may demonstrate more improvement from all forms of locomotor training in terms of walking speed than those patients who ambulate at faster speeds (>0.1 m/s) prior to training.

Several studies also reported on the positive effects of walking function after using progression principles and/or combined locomotor training approaches that incorporated treadmill training with robotic assistance, treadmill training with manual assistance, and overground training [39,57,63]. This transition facilitated training progression from a more restrictive environment to a less restrictive environment for walking practice as the subject's level of remediation improved and may be useful in the clinical setting. Responses to the various forms of locomotor training with robotic technology appear to be more robust in the acute and subacute populations, but also raise questions as to whether this may be

the result of natural recovery processes and not directly the result of locomotor training interventions.

Metabolic expenditure increases were reported in both robotic- and therapist-assisted locomotor training, but subjects need to be cued to provide maximum effort to reach similar levels of energy expenditure between the two conditions, indicating the continued need for skilled therapist involvement in either training approach. Maximum EMG may be larger in therapist-assisted versus robotic locomotor training, but no available data have been published demonstrating the effect of these differences on long-term walking outcomes in this population.

The two studies evaluating locomotor training with robotic assistance in persons with MS were rated good in terms of methodological rigor. However, the small number of subjects and the lack of conclusive results when comparing the various forms of locomotor training limit generalizability and translation of these results into suggestions for shaping clinical decision making. The specific stage of the disease process and clinical presentation may be more indicative of when a program of locomotor training may be successful in individuals with MS.

Robotic devices are designed to provide a physiological gait pattern to complete repetitive walking training. This provides a very safe environment for patients with significant weakness to complete repetitive walking patterns without fear of falling. The consistency between steps is superior to that which can be provided during manual BWS, but this ability to control the kinematics may also limit the degrees of freedom in the various joint segments involved in overground locomotion. This controlled patterning may limit an individual's ability to make error corrections and experience normal sensory feedback, potentially limiting the process of long-term motor learning and skill acquisition. On the other hand, it can be quite difficult for therapists to provide a safe and controlled environment for walking practice when manual assistance is required for individuals to initiate steps or support their body weight. Therefore, defining which locomotor training intervention is most effective may depend on evaluating each patient to determine which method is most appropriate given the patient's functional status. Clinical decision making for locomotor training may be most efficacious if based on a variety of factors, including functional dependency, reflexive activity, and voluntary motor control during each phase of the recovery process. Backus and Tefertiller have developed a clinical decision-making algorithm for transitioning patients with

postacute SCI through a robotic and manual locomotor training program [70]. Locomotor training progression along a continuum is based on the clinical presentation of spasticity, trunk stability, and overground walking independence. Such algorithms may be helpful in guiding clinical decisions when multiple technologies and intervention options are available.

All treadmill systems, with or without robotics and BWS, provide unique sensory feedback for patients who are being trained (moving treadmill belt vs stable floor) and result in questions regarding the specificity of this repetitive practice for walking. Treadmill systems provide a repetitive pattern that may be important for neurological recovery of walking, but task-specific practice of overground walking may also be essential for appropriate skill acquisition, especially given the mounting literature supporting the importance of sensory feedback in modulating motor output. Additionally, the resource requirements for the chosen locomotor training approach may influence clinical decision making. Resource utilization needs to be compared between the various forms of locomotor training to determine the most appropriate fit for each clinical setting given the lack of clear discernment for superior outcomes. Morrison and Backus reported that locomotor training with manual assistance using one physical therapist, two trained technicians, and one well-trained volunteer is financially feasible [71]. However, cost-effectiveness of this approach was not compared with locomotor training using robotics, which requires less resource allocation and lowers injury risk to staff but may be a higher capital equipment expense [28].

FUTURE DIRECTIONS

Although still in its infancy, the current evidence base for locomotor training with robotic assistance provides a foundation for the focus of future studies and emergent technologies. In order to gain the full potential of this new technology, careful clinical research is necessary to establish safe, effective protocols and optimal doses, as well as to eventually understand how these robotic devices should be combined with conventional rehabilitative methods. Studies specifically designed to assist clinicians in determining selection, progression, and transition over time of the various locomotor training interventions may assist in optimal positioning of these technologies in the continuum of care. While robotics is a new resource for clinicians to deliver therapy, it will

likely never replace the therapist-patient relationship but may enhance our interactions with patients.

This current review was limited to robotic technologies with published evidence reporting on outcomes associated with gait dysfunction. Other robotic systems are in various stages of development geared at improving overground walking abilities in patients with impairment. Selected examples would include exoskeletal robotic devices such as the ReWalk (Argo Medical Technologies Ltd; Haifa, Israel), the Tibion Bionic Leg (Tibion Corporation; Sunnyvale, California), and the Walking Assist Device (Honda Motor Co Ltd; Tokyo, Japan). The most obvious difference in these technologies is their portability; they are designed for overground mobility in the community.

CONCLUSIONS

Interventions aimed at restoring walking function in individuals with neurological pathology are challenged by the complexity and variability inherent to these disorders. Initial evidence supports the efficacy of locomotor training with robotic assistance on improving walking function in a variety of neurological diagnoses. However, it remains unclear where these technologies fit in the continuum of care and their comparative effect to other forms of locomotor training. Further research involving larger trials is needed to address the above limitations and guide clinical decision making.

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