Invited review

Training to achieve over ground walking after spinal cord injury: A review of who, what, when, and how

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Objectives: (1) To provide clinicians with the best evidence for effective retraining of walking after spinal cord injury (SCI) to achieve over ground walking. (2) To identify gaps in our knowledge to guide future research.

Methods: Articles that addressed the retraining of walking in adults with SCI and reported outcome measures of over ground walking ability were identified through a non-systematic search of the PubMed, Scopus, and CINAHL databases. No restriction was applied to the method of training. Selected articles were appraised using the Physiotherapy Evidence Database scale. Information was synthesized to answer who best responds to what type of treatment, how that treatment should be delivered, and at what stage after injury.

Results: Individuals with motor incomplete SCI (American Spinal Injury Association (ASIA) Impairment scale (AIS) C and D) are most likely to regain walking over ground. The effective methods of training all involved a substantial component of walking in the training, and if assistance was provided, partial assistance was more effective than total assistance. Walking training resulted in a change in over ground walking speed of 0.06–0.77 m/s, and 6 minute walk distance of 24–357 m. The effective training schedules ranged from 10 to 130 sessions, with a density of sessions ranging from 2 per week to 5 per week. Earlier training led to superior results both in the subacute (<6 months) and chronic phases (>6 months) after injury, but even individuals with chronic injuries of long duration can improve.

Conclusions: Frequent, early treatment for individuals with motor incomplete SCI using walking as the active ingredient whether on the treadmill or over ground, generally leads to improved walking over ground. Much work remains for the future, including better quantification of treatment intensity, better outcome measures to quantify a broader range of walking skills, and better ways to retrain individuals with more severe lesions (AIS A and B).

Keywords: Rehabilitation, Spinal cord injuries, Locomotion, Physical therapy, Ambulation, Body-weight supported therapy, Robotic-assisted therapy, Exoskeleton, Lokomat, Paraplegia

Introduction

Spinal cord injury (SCI) results in devastating changes for the individual and costly consequences for the individual, their families, and society. Considerable effort has been invested in finding ways to ameliorate these consequences in the acute¹ and chronic² stages after the injury. Restoration of walking has consistently ranked high in priority for the individual with SCI, their families, and their health care providers.^{3–5}

Retraining walking after SCI has been a vibrant area of research since the early 1990s, brought about by the

exciting discovery that adult mammals with complete spinal cord transections can be retrained to produce walking movements with weight bearing if they are trained intensively on a treadmill.^{6,7} In the last 20 years, clinical studies have been conducted to test the idea in human patients by adapting this method originally developed on a cat model of SCI. This method of training has been referred to by many names, including “locomotor training,”⁸ “body-weight supported treadmill training,”⁹ “Laufband therapy”¹⁰ among others. The individual trains on a treadmill with a harness to support part of his/her body weight, and therapists/trainers assist with leg movements, weight shifting from leg to leg, and trunk stability, as

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needed.⁸ There is considerable diversity in the training methods between centers, despite the use of similar equipment. For example, the walking speeds in training vary widely between centers (see Table 1) as does the way assistance is delivered, such as manually^{8,11–13,19,20,22,23,25} or with a robot.^{30–32} Furthermore, some groups incorporate over ground training as part of the method,^{8,13,19,20,22,23,33} while others confine the training to the treadmill.^{11,12,14,15,17,18,21,28} Some retrain walking entirely over ground, often combining the use of equipment to provide assistance through support of body weight via a harness and overhead track,^{8,20} or through functional electrical stimulation (FES).^{17,18} More recent studies have also used a robot to assist^{9,31} or resist walking movement^{16,34,35} on a treadmill. The diversity of physical therapy methods for retraining walking is considerable, leaving clinicians with a host of information to ponder, as they balance the evidence with their client's situation and goals.

Here, we take a broad view of the main retraining methods for walking after SCI. Instead of a systematic review focused on a specific method of retraining,^{36–39} we did not restrict our search to a particular method. Rather, we sought any retraining method that brought about quantified improvement in over ground walking ability (see Methods). Our primary goal was to determine the client characteristics and training methods that brought about independent over ground walking (i.e. not requiring manual assistance, electrical stimulation, or extensive bracing such as reciprocating gait orthoses). We also did not attempt to address the question of “recovery” vs. “compensation”,³³ as we believe that these two ways to regain walking are very difficult to separate, and likely to occur in concert in most cases. For example, individuals can regain a kinematic pattern of walking similar to the uninjured, by using a pattern of muscle activation, some similar to and others different from the uninjured.^{40,41}

In the following, we address the questions we believe practicing clinicians most want answers for: who, what, when, and how. We argue that *intensive* training using *walking* as the main activity in the training, with partial or no assistance, is the most important ingredient for success. Whether the method is carried out over ground, on the treadmill, or both, is of less importance as all produce favorable results. Although it is very likely that individual characteristics of the client, such as severity of the injury,^{8,20,22,42–44} specific motor tracts spared,¹³ time since injury,⁴⁵ ... etc. influence their response to treatment, tailoring the treatment to the person is only possible in a very general way right

now. Ideal dosage and timing of treatment remain largely unknown. Nevertheless, clinicians at the front-line of practice must do the best with the information available. It is with this in mind that we summarize what we know today, and suggest where we should go in the future.

Methods

This review considers full length, refereed papers on the retraining of walking in human adults with SCI only. We do not consider this a systematic review because our purpose is to explore what is known and unknown about the topic, rather than address a specific question. PubMed, Scopus, and CINAHL databases were searched from the earliest record until June 2012. The following controlled vocabulary and/or keywords were used: spinal cord injury/spinal cord injuries, and human, and walking/gait/ambulation/mobility/mobility limitation, and rehabilitation/physical therapy/exercise/strengthening/exercise therapy/resistance training/therapy.

Inclusion criteria:

- The training was supervised (i.e. home programs were excluded).
- Functional outcomes related to over ground walking were reported both before and after training (either categorical classification of walking or quantitative changes in over ground walking speed or distance).
- The number of participants with SCI was greater than three.
- If the training included electrical stimulation or other orthotic devices such as reciprocating gait orthoses, we only included those that reported a *therapeutic effect* (i.e. improved walking without the use of the device).
- Original articles in English.

Exclusion criteria:

- Proceedings from conferences.
- Animal studies.
- Studies where the training involved only one session.
- Studies that reported the preliminary findings from an ongoing trial, if the final results were published.
- Studies involving multiple pathologies were excluded if the results from those with SCI could not be separated from participants with other disorders.
- Pharmacological interventions for walking were not considered, as there is an excellent, recent review on this topic.⁴⁶

Searches of the PubMed, Scopus, and CINAHL databases returned 924, 1243, and 136 articles, respectively. The titles and/or abstracts were reviewed by one author (K.M.). Ninety-two articles were selected for further consideration. Both authors reviewed the full-length papers and 20 original articles were found to meet the

Table 1 Articles included in the review

Study design	Subjects	Training parameters	Outcomes	PEDro score
Manually-assisted walking training on a treadmill				
<i>Stewart et al.</i> ¹¹				
Pre- post-treatment, no blinding	<i>n</i> = 9, age 31 ± 3 yr 8.1 ± 2.5 yr (±SE) post-injury AIS: C(9) C4–T12 lesions	With BWS, 2.8 ± 0.2x/wk for 6.0 ± 0.3 months, (totaling 68 sessions) Speed: initial: <0.17 m/s, end: ~0.22 m/s BWS: initial: 65 ± 3%, end: 23 ± 5%	Modified Wernig scale: ↑1.6 ± 2.5 (0–7)	4
<i>Hicks et al.</i> ^{12**}				
Pre- post-treatment, no blinding	<i>n</i> = 13, age 29 ± 8 yr (20–53 yr) 7.4 ± 6.9 yr (1.2–24 yr) post-injury AIS: B(2), C(12) C4–T12 lesions	With BWS, 3x/week for 12 weeks Speed: initial: 0.14 ± 0.08 m/s, end: 0.39 ± 0.22 m/s BWS: initial: 73 ± 10%, end: 20 ± 12%	Modified Wernig scale: ↑1.2 ± 2.1 (0–7)	3
<i>Thomas and Gorassini</i> ¹³				
Pre- post-treatment, no blinding	<i>n</i> = 10, age 54 ± 15 yr (29–78 yr) 7.8 ± 9.8 yr (0.6–28 yr) post-injury AIS: C(7), D(3) C3–L1 lesions	With BWS, 4.1 ± 0.8x/week, for 16.6 ± 4.4 weeks (10–23 weeks) Speed: ~0.4 m/s BWS: initial: 44 ± 25%, end: 13 ± 18%	10MWT: ↓43.8 ± 102.5 s (mean) ↑speed = 0.37 m/s) 6MWT: ↑133.4 ± 54.8 m WISCI II: ↑3.4 ± 3.3	3
Robot-assisted walking training on a treadmill				
<i>Wirz et al.</i> ¹⁴				
Pre- post-treatment, multi-center (5), no blinding	<i>n</i> = 20, age 40 ± 14 yr (16–64 yr) 5.9 ± 4.9 yr (2–17 yr) post-injury AIS: C(9), D(11) C3–L1 lesions	Lokomat with BWS, ≤45 minutes of walking per day, 3–5x/week for 8 weeks (totaling 26 ± 4 sessions) Speed: 0.55 ± 0.03 m/s (0.42–0.67 m/s) BWS: 37 ± 17% (0–50%)	Speed: ↑0.11 ± 0.1 m/s 6MWT: ↑32.3 ± 37.5 m WISCI II: ↑0.2 ± 0.7	4
<i>Winchester et al.</i> ¹⁵				
Pre- post-treatment, no blinding	<i>n</i> = 4, age 40 ± 13 yr (20–49 yr) 1.5 ± 1.7 yr (0.3–4 yr) post-injury AIS: C(3), D(1) C5–C6 lesions	Lokomat with BWS and feedback 3x/week for 12 weeks Speed: initial: 0.56 m/s, end: 0.74 ± 0.11 m/s BWS: initial: 51 ± 11%, end: 24 ± 22%	WISCI II: ↑8.5 ± 7.9 Speed in GAITRite: ↑0.54 ± 0.6 m/s	4
<i>Wu et al.</i> ¹⁶				
Randomized crossover design (assistance vs. resistance), no blinding	<i>n</i> = 10, age 47 ± 7 yr (34–58 yr) 5.8 ± 3.8 yr (1.3–13.5 yr) post-injury AIS: D(10) C2–T10 lesions	Cable-driven robot with BWS ~41–45 minutes, 3x/week for 8 weeks (4 weeks/phase) Speed: initial: 0.71 ± 0.24 m/s, end: 0.92 ± 0.25 m/s BWS: initial: 24 ± 4%, end BWS: 14 ± 10%	ss speed: ↑0.09 ± 0.3 m/s Fast speed: ↑0.10 ± 0.4 m/s 6MWT: ↑24 ± 120 m	4
Combination of methods for walking training				
<i>Behrman and Harkema</i> ⁸				
Case series, no blinding	<i>n</i> = 4, age 32 ± 14 yr (20–45 yr) 0.5 ± 0.4 yr (0.08–1 yr) post-injury AIS: A(1), C(1), D(2) C6–T9 lesions	TM with BWS and manual assistance, progressing to OG walking when patient supported 80% BW and stepped with one leg 5x/week for 5–20 weeks	ss speed: ↑0.59 ± 0.4 m/s Fast speed: ↑0.6 ± 0.2 m/s 2MWT: ↑61.5 ± 7.8 m (<i>n</i> = 2)	3

Continued

Table 1 Continued

Study design	Subjects	Training parameters	Outcomes	PEDro score
<i>Field-Fote</i> ¹⁷ Pre- post-treatment, no blinding	$n = 19$, age 31.7 ± 9.4 yr 4.7 yr (median) (1–14.3 yr) post-injury AIS: C(19)	TM with BWS and FES (CPN) on weaker leg 90 minutes, 3x/week for 12 weeks	Speed: $\uparrow 0.09 \pm 0.8$ m/s	4
<i>Hesse et al.</i> ¹⁸ Case series, no blinding	$n = 4$, age 50 ± 8 yr (44–62 yr) 0.8 $\pm$ 0.5 yr (0.3–1.5 yr) post-injury AIS: C(1), D(3) C5–L1 lesions	Gait trainer with FES to quads and hams bilat 20–25 minutes of walking, 5x/week for 5 weeks	Speed: $\uparrow 0.32 \pm 0.2$ m/s Distance: $\uparrow 116 \pm 104$ m	3
<i>Fritz et al.</i> ¹⁹ Pre- post-treatment, no blinding, "lower" group initial gait speed <0.6 m/s and Berg balance score <45	$n = 15$ (10 "lower") Age 38.5 ± 13.6 yr ("lower") Age 50.4 ± 12.9 yr ("higher") 6.6 $\pm$ 6.3 yr post-injury ("lower") 5.7 $\pm$ 10.8 yr post-injury ("higher") AIS C and D	Intensive mobility training (TM with BWS and OG walking) ≥ 50 minutes of walking, 50 minutes balance, 50 minutes strength and range of motion 3–5x/week for 10 sessions total	6MWT: $\uparrow 20.6 \pm 91.9$ m ("lower"), $\uparrow 44.9 \pm 169.7$ m ("higher")	4
<i>Harkema et al.</i> ²⁰ Pre- post-treatment, multi-center (7), no blinding	$n = 196$, age 41 ± 15 yr 0.8 yr (median) (0.1–25.8 yr) post-injury AIS: C(66), D(130) Lesions: cervical (138), thoracic (58)	TM with BWS progressing to OG 60 minutes TM with BWS and ≤ 30 minutes OG practice, for a minimum of 20 sessions (median 47 (20–251 sessions))	10MWT: $\uparrow 0.20 \pm 0.6$ m/s 6MWT: $\uparrow 63 \pm 188$ m	4
Comparison between training methods				
<i>Postans et al.</i> ²¹ Randomized crossover design, no blinding	$n = 12$, age 40.3 ± 12.7 yr (19–57 yr) 0.2 $\pm$ 0.1 yr (0.1–0.4 yr) post-injury AIS: C(7), D(5) C4–T8 lesions	TM with BWS, manual assistance and FES (≤ 4 FES channels customized) vs. standard PT TM: ≤ 25 minutes, 5x/week for 4 weeks, initial BWS = ~40%, Standard PT: 5x/week	Speed: mean $\uparrow 0.2$ m/s (TM and standard PT) Distance: mean $\uparrow 68$ m (TM) and $\uparrow 49$ m (standard PT)	4
<i>Dobkin et al.</i> ²² RCT, multi-center (6), single- blinded	$n = 45$, age 16–69 yr ≤ 0.15 yr post-injury AIS: B, C, and D C5–L3 lesions	TM with BWS and manual assistance vs. OG training ≤ 5 x/week for ≤ 12 weeks TM: 20–30 minutes at 0.72–1.07 m/s OG: 30–45 minutes stand and walk	No difference between groups Speed: median $\uparrow 1.0$ –1.2 m/s 6MWT: median $\uparrow 312$ –401 m WISCI II: median $\uparrow 18$	7
<i>Musselman et al.</i> ²³ Randomized crossover design, single-blinded	$n = 4$, age 43.5 ± 15.3 yr (24–61yr) 7.3 $\pm$ 10.6 yr (0.9–23.0 yr) post-injury AIS: C(4) C5–L1 lesions	TM with BWS and manual assistance vs. OG skill walking TM: 28 ± 6 minutes, 3.5 ± 0.5 x/week for 12 weeks, mean speed 0.5–1.3 m/s, mean BWS 0–41% OG walking: 36 ± 5 minutes, 3.5 ± 0.5 x/week for 12 weeks	ss speed: $\uparrow 0.02 \pm 0.03$ m/s (TM), $\uparrow 0.11 \pm 0.09$ m/s (OG) 6MWT: $\uparrow 10.3 \pm 14.3$ m (TM) $\uparrow 27.5 \pm 14.7$ m (OG)*	6

Continued

Table 1 Continued

Study design	Subjects	Training parameters	Outcomes	PEDro score
<i>Field-Fote and Roach</i> ²⁴ RCT, single-blinded	<i>n</i> = 64, mean age/group 38–45 yr ≥1-yr post-injury AIS: C and D Lesion at T10 or above	Four methods (TM with BWS and manual assistance, TM with FES, OG with FES, and Lokomat) FES (CPN) bilat 5x/week for 12 weeks (mean #sessions = 49) BWS ≤30% provided for all methods	Speed: ↑ of 0.04 m/s (TM with BWS), ↑0.05 m/s (TM with FES), ↑0.09 m/s (OG with FES), and ↑0.01 m/s (Lokomat) 2MWT: significant ↑ in TM with FES (3.8 m) and OG with FES (14.2 m)	7
<i>Alexeeva et al.</i> ²⁵ RCT, single-blinded	<i>n</i> = 35, age 38.5 ± 13.6 yr (19–63 yr) 7.0 ± 7.7 yr (1–37 yr) post-injury AIS: C(8), D(27) C2–T10 lesions	TM with BWS vs. OG with BWS vs. PT ≤60 minutes, 3x/week for 13 week BWS ≤30%	Max speed: no difference between groups, ↑0.12 ± 0.45 m/s	8
<i>Schwartz et al.</i> ²⁶ Pre- post-treatment, single-blinded historical controls	<i>n</i> = 56, Lokomat: age 42 ± 21 yr, 0.06 ± 0.04 yr post-injury Control: age 43 ± 14 yr, 0.07 ± 0.06 yr post-injury AIS: A(6), B(7), C(13), D(2) (Lokomat) Lesions: 26 cervical, 16 thoracic, 14 lumbar	Lokomat with BWS plus PT vs. PT Lokomat: 30–45 minutes, 2–3x/week plus PT 5x/week for 12 weeks, initial BWS ~50% Control: 30–45 minutes, 5x/week for 12 weeks	WISCI II: No difference between groups ↑1(0–2) to 7.5(1.2–13.7) (Lokomat) ↑0(0–6) to 6(0–11.2) (control)	6
<i>Lucareli et al.</i> ²⁷ RCT, single-blinded	<i>n</i> = 24, age 31.5 ± 10.8 yr (23–40 yr) 0.8 ± 0.08 yr (0–0.9 yr) post-injury AIS: C(11), D(13) C4–L2 lesions	TM with BWS vs. OG training 30 minutes, 2x/week for 15 weeks (30 sessions total)	Speed: ↑0.4 ± 0.5 m/s (TM), ↑0.02 ± 0.8 m/s (OG) Distance: ↑10.8 ± 12.7 m (TM), ↑1.8 ± 9.9 m (OG)	6
<i>Benito-Penalva et al.</i> ²⁸ Pre- post-treatment, no blinding, historical controls, randomized to one of two robotic devices	<i>n</i> = 105, mean age 45 yr (19–75 yr) Time post-injury: <0.5 yr (81), ≥0.5 yr (24) AIS: A or B (11), C(44), D(50) 45 tetraplegia, 60 paraplegia	Lokomat or Gait trainer with BWS ≤45 minutes, 5x/week for 8 weeks Initial speed: 0.42 m/s Initial BWS: 40%	Speed: ↑0.18 ± 0.03 m/s WISCI II: ↑5.2 ± 0.8	5
Other training methods <i>Ness and Field-Fote</i> ²⁹ Pre- post-treatment, no blinding	<i>n</i> = 17, age 48 ± 10 yr (28–65 yr) ≥1-yr post-injury C6–T8 lesions	WBV, a session involved 4 45-s bouts of vibration (50 Hz), 1 minute rest between bouts, 3x/week for 4 weeks	Speed: ↑0.06 ± 0.01 m/s (±SE)	4

Means reported with ±1 standard deviation and (range), unless otherwise noted.

SE, standard error; TM, treadmill training; BWS, body weight support; OG, over ground; AIS, American Spinal Cord Injury Association Impairment Scale, with number of subjects/level reported in parentheses; 2MWT, 2-minute walk test; ss speed, self-selected speed; 10MWT, 10-meter walk test; 6MWT, 6-minute walk test; WISCI II, Walking Index for Spinal Cord Injury II; FES (CPN), functional electrical stimulation of the common peroneal nerve; PT, physical therapy; RCT, randomized controlled trial; bilat, intervention applied bilaterally; WBV, whole body vibration.

*Data for phases 1–3 included for calculations of speed and distance, i.e. Participant 4 results from phases 4 and 5 removed.

**The 9 subjects in Stewart *et al.* were also in Hicks *et al.*

inclusion criteria. Table 1 provides a summary of all the papers, organized according to broad categories of the intervention method. From each article, the following information was extracted, if available: training method, training parameters (e.g. number of minutes/session, number of sessions/week, total number of weeks, training speed, and amount of body weight support), subject characteristics (e.g. age, time since injury, AIS (American Spinal Injury Association Impairment scale) classification, level of neurological injury), and outcomes (e.g. change in over ground walking speed and/or distance, change in categorical classification of walking). Data pertaining to training parameters and outcomes were pooled across studies and the range was reported.

The quality of the paper was judged using the Physiotherapy Evidence Database (PEDro) scale⁴⁷ (www.pedro.org.au/english/downloads/pedro-scale). The scale ranks clinical trials on 11 items, with a best possible score of 11. The two authors independently scored the 20 papers. Disagreements were discussed and a consensus was reached.

Results and discussion

In spite of the fact that we did not restrict our search to a specific method of retraining, the 20 articles that fit our inclusion/exclusion criteria generally used training methods that focused on walking, either on the treadmill or over ground, with one exception.²⁹ Papers were most commonly excluded because (1) they were not original articles, (2) there was no outcome measure of over ground walking, (3) they did not report a therapeutic effect (i.e. the outcome was measured with the training device, such as braces or FES), (4) the number of participants was less than four, or (5) the study involved a single training session.

Limitations

We did not exhaustively search all pertinent databases, so some relevant papers could have been missed. We excluded studies that involved three or less participants. We recognize that these papers, typically reports of case series, could have included important details about the training method.

Who should I train?

Individuals who best respond to treatment by showing improvements in over ground walking during both the subacute (<6 months) and chronic phases (>6 months) after injury are those with motor incomplete SCI. For example, even in the subacute phase, individuals classified as AIS A or B have generally not

recovered the ability to walk over ground after different types of walking training.^{8,22,42,43} Moreover, these same individuals are unable to walk over ground once they return to the community after training⁴⁸ (see caveat regarding children, below). Thus, if the aim of the treatment is *over ground walking*, then the promising candidates are clearly those with motor incomplete lesions, although there are case reports of individuals with minimal motor ability regaining limited walking through extensive training.^{49,50} (See below for benefits besides over ground walking.)

Two studies have specifically addressed the predictive value of various patient characteristics for responsiveness to training on the treadmill, one using robot-assisted walking with feedback⁴⁵ and one using manually assisted walking.⁴⁴ An important difference between the studies is the outcome chosen for prediction: one was final walking speed,⁴⁵ while the other was change in walking speed.⁴⁴ We believe that measures of improvement in walking are better, because they reflect how much an individual benefited from the training, not how good a walker they were in general. In our study,⁴⁴ we showed that individuals with minimal motor recovery (i.e. AIS C with lower motor function, see definition below) may also show limited response to training when the training occurs in the chronic phase after injury.⁴⁴ Specifically, participants who were at least 0.8-year post-injury with combined manual muscle test⁵¹ scores of <30/80 (pooling scores by summing hip flexors, extensors, abductors, adductors, knee flexors, extensors, ankle plantarflexors, and dorsiflexors) did not improve in over ground walking speed. Those who could not walk prior to training still could not walk after training. These findings remain to be confirmed in a larger pool of participants. Nevertheless, there may be a small proportion of individuals in the AIS C category that do not respond to treatment.^{20,44} One caveat to the above is children, who may have much greater potential for recovery,^{52,53} and must be considered separately from adults. Prognostic studies in the future may provide a more detailed guide for predicting who best responds to what type of treatment.

No prognostic studies have emerged from other types of walking training besides the above. Logically, one would expect that certain types of treatment might be more effective for certain individuals. For example, those with very good walking ability may benefit more from training that challenges the more difficult aspects of walking (i.e. balance and skill) compared to methods that focus on rhythmic stepping. Those with very low function may benefit more from methods that

provide greater assistance during training, with greater focus on the rhythmicity of stepping. These ideas remain to be tested.

Individuals with injuries categorized as AIS A or B generally have not regained over ground walking, although information remains very limited for training with FES³⁹ and exoskeletons.⁵⁴ Whether these methods will lead to therapeutic effects of better walking over ground without the device is unknown. Nevertheless, aside from the therapeutic effect of unassisted over ground walking, there are many other potential benefits of weight bearing and assisted walking.⁵⁵ These important improvements in blood lipid profile, regulation of heart rate and blood pressure, muscle mass, muscle composition, and life satisfaction have been well described in the above review and will not be considered here. Thus, depending on the aim of the intervention, individuals with AIS A or B may also be appropriate candidates for training of walking. Finding ways to improve walking for individuals with AIS A and B classifications will be an important direction for future work.

What should I train?

Focus on walking

All studies that have included walking as the main treatment method with partial or no assistance reported improvements in over ground walking, particularly for individuals with motor incomplete injuries (Table 2). The walking training often included assistance with weight support via a body harness, and therapists or robots to assist the leg motion as needed. How much assistance is provided, and how well it matches the participants' abilities is likely very important. We considered manual assistance to be "partial assistance", because walking with or without manual assistance did not change the electromyography (EMG) amplitudes of individuals with SCI.⁵⁶ In contrast, robot-assisted walking in which the motion can be produced with no participant effort and with no feedback or modification to impedance was considered to be *complete assistance*. This is justified, because both EMG and VO_2 were reduced during robot-assisted compared to manual-assisted walking in individuals with SCI⁵⁷ (cf Ref.⁵⁸). Robot-assisted walking was considered partial assistance in the following situations: (a) participants were provided with feedback of their own force generated against the robot to encourage participation¹⁵ or (b) the robot could not entirely reproduce the kinematics of walking without effort from the participant.¹⁶

Improvements in over ground walking after training took the form of advances in the walking category as

measured by classification scales such as the Wernig Walking scale¹⁰ and its modifications,^{11,12} as well as the Walking Index for Spinal Cord Injury version II (WISCI-II).^{13–15,22,26,28,59,60} The amount of change on the walking scales that we considered important was one on the Wernig scale and two on the WISCI II.⁶¹ Improvements have more commonly been reported as changes in over ground walking speed and/or distance, detailed in Table 2. The range of change in over ground walking speed, reported either as self-selected or maximum walking speeds pre- to post-training, was 0.06–0.77 m/second. To factor out natural recovery, the training-induced change in over ground walking speed with chronically injured participants only ranged from 0.06 to 0.37 m/second. Thus, whether the studies with subacutely injured participants are included or not, the changes were greater than the minimally important difference (MID) for walking speed, estimated to be ~ 0.1 m/second for SCI.^{61,62} Improvements in walking distance were considered meaningful if the change was >20 m in the 6-minute walk test (6 MWT), estimated from older adults with and without stroke,⁶³ since no values are available from those with SCI. The range of changes in walking distance for the 6 MWT was 24–357 m (all studies included), and 24–133 m (studies of chronically injured only), both well above 20 m. In summary, when walking is the major part of the intervention with partial or no assistance, regardless of the method or the outcome measure, the improvements made in over ground walking have generally been clinically important with one exception.²⁴

Direct comparison between training methods

A small number of studies have directly contrasted different training methods for walking in individuals with incomplete SCI, including randomized controlled trials^{22,24,25,27} and two small studies using crossover designs.^{21,23} In all cases where direct statistical comparisons were made between the methods, no major differences have emerged with one exception. In one randomized controlled trial (RCT) comparing four different training methods, the group using complete robot assistance improved less in chronically injured individuals compared to others who trained over ground, or used therapist, or FES assistance.²⁴ Curiously, however, all groups improved only a small amount (mean change in over ground walking speed ranged 0.01–0.09 m/second). One caveat to keep in mind is the statistical power of all the studies. Because of the unavoidable heterogeneity of the participants with SCI, comparison between groups requires very large numbers for sufficient statistical power, which

Table 2 Changes in over ground walking measures in studies that train walking with partial or no assistance

Study	Δ walking speed (m/second)		Δ walking distance (6MWT) (m)		Comments
	Mean	SD	Mean	SD	
Subacute injury					
Behrman and Harkema ⁸	0.77	0.33			Calculated from individual scores of two participants with subacute injury
Postans <i>et al.</i> ²¹	0.19		59		Weighted mean of two methods of training
Dobkin <i>et al.</i> ²²	0.11		357		Median values
Harkema <i>et al.</i> ^{20*}	0.29	0.31	91	89	Participants were <1 year post-injury
Range	0.11–0.77		59–357		
Chronic injury					
Behrman and Harkema ⁸	0.12	0.17			Calculated from individual scores of two participants with chronic injury
Field-Fote ¹⁷	0.09	0.8			
Thomas and Gorassini ¹³	0.37		133	55	
Musselman <i>et al.</i> ²³	0.15	0.13	53	35	Calculated from individual scores
					Mean of two methods of training
Field-Fote and Roach ²⁴	0.06				Weighted mean of three methods of training
Fritz <i>et al.</i> ¹⁹			29		Weighted mean of lower- and higher-functioning groups
Lucareli <i>et al.</i> (2011) ²⁷	0.21	0.7			Weighted mean of two methods of training
Alexeeva <i>et al.</i> ²⁵	0.12	0.45			Mean calculated from all participants, independent of training method
Wu <i>et al.</i> ¹⁶	0.09	0.3	24	120	
Harkema <i>et al.</i> ²⁰	0.10		33		Weighted mean of two chronic groups (1–3 years and ≥ 3 years post-injury)
Range	0.06–0.37		24–133		

Includes studies where (1) the major component of the training was walking, with partial or no assistance and (2) the mean change in over ground self-selected walking speed and/or 6-minute walk test (6MWT) distance was reported or could be calculated. "Subacute injury" includes studies where participants were <6 month-post-injury. *Could not extract data for participants <6 months post-injury, included data from group <1 year post-SCI.

are usually not met. Comparison within individuals in the crossover designs provides more statistical power, but the generalizability of the findings are then more limited. Thus, with this caveat in mind, no major differences have been detected between most treatment methods.

Training with complete robotic assistance

In many individuals with SCI, walking movements are difficult to perform unaided, particularly during the subacute phase of recovery, or in more severely injured individuals. In these cases, active attempts to walk are usually assisted manually by therapists/trainers or automatically by robots.³¹ In the subacute phase after injury, therapist-²² or robot-assisted walking²⁸ has produced encouraging findings. For example, robot-assisted walking of individuals with AIS D (mostly subacutely injured) from Spain showed steeper recovery curves in walking measures (WISCI-II and 10 MWT) than matched, historical controls from the European Multi-centre Study, in which participants received conventional treatment²⁸ that included some walking training. Thus, in the subacute phase, there is support for robot-assisted training.

In the chronic phase after injury, results are more complex. Complete robotic assistance resulted in a smaller training effect when compared with other

methods in chronically injured participants in one study,²⁴ while a multi-center trial with the Lokomat providing full assistance reported strong results in participants with chronic SCI: the change in over ground walking speed and change in 6 m walking test distance was 0.11 ± 0.1 m/second, and 32.3 ± 37.5 m, respectively.¹⁴ Evidence also remains limited regarding the effort required of the participant in robot- vs. therapist-assisted walking in individuals with SCI (see above). A head-to-head comparison of the VO_2 consumption and EMG during robot- vs. therapist-assisted walking indicates that full robot-assisted walking without any other instructions to the participant resulted in lower heart rate and VO_2 consumption compared to therapist-assisted walking.⁵⁷ In contrast, adding feedback of the forces generated by the participant against the robot plus additional verbal encouragement removed these differences. In summary, robot-assisted training of walking in the chronic phase after SCI may require added features to enhance participant effort to achieve a better outcome.

Recent advances in robotic design

There are many recent attempts to enhance the active participation of individuals training with robots, such as allowing more error in the movement,^{64,65} providing feedback to the individual,^{65,66} and providing resistance

to the movement.^{16,34} The effectiveness of these new modifications has not been tested in a training regime with a large cohort of SCI participants, but these modifications are all very promising and in a direction that enhances the participation and effort from the individual. Recent studies with a small number of participants suggest that using either a robot that provides feedback during training,⁴⁵ or one that provides some assistance or resistance during training¹⁶ resulted in improvements in over ground walking. These are all promising directions for the future.

How long and intensely should I train?

The intensity or dosage of training to produce a clinically important difference in functional walking has not been tested specifically and should be tested.⁶⁷ Indeed, there is no consensus among researchers on how best to measure intensity.⁶⁸ Most studies report the walking time (Table 3) and the approximate walking speed during the intervention. Some have reported the distance covered and/or the number of steps taken. Unfortunately, the “difficulty” of the training is not represented by any of these measures, because it depends on the individual. We used “near falling” as a

measure of difficulty in our over ground training,²³ but of course, this would not be applicable for training on a treadmill with support. Change in heart rate might be another way to include the characteristics of the participant, as has been done in participants with stroke,⁶⁹ but there are obvious problems with this method in individuals who have SCI lesions above T6. Future work should explore ways to quantify intensity of training, in order to determine the ideal dosage to promote improvements in walking.

In the absence of specific studies that manipulate the intensity of training, we have summarized the treatment intensity in all studies that have reported improvements greater than the MID in walking speed, distance (see above) or categorical changes in walking ability (Table 3). The total session numbers ranged from 10 to 130. Note that the session duration in some studies referred to “walking” time, while in others simply reflected the total time an individual was attending treatment, so better quantification of “walking time” is certainly needed. In some instances, the distance walked was reported, with distances generally approaching or exceeding 1000 m/session.^{12,16,21} Interestingly, a recent study using a very intensive (3 hours per day,

Table 3 Type and intensity of training from studies reporting MID in walking outcomes*

Study	Training type	Session duration: walking (minutes)	Times/week	#Weeks	#Sessions (actual or estimated)
Behrman and Harkema ³	TM with BWS + OG	NA	5	5–20	15–85
Stewart <i>et al.</i> ¹¹	TM with BWS	NA	2.8 ± 0.2	24	68
Hesse <i>et al.</i> ¹⁸	Gait trainer + FES	20–25	5	5	~25
Postans <i>et al.</i> ²¹	TM with BWS + FES	≤25	5	4	~20
Hicks <i>et al.</i> ¹²	TM with BWS	NA	3	12	~36
Thomas and Gorassini ¹³	TM with BWS	NA	4.1 ± 0.8	16.6 ± 4.4	~68
Wirz <i>et al.</i> ¹⁴	TM with BWS + Lokomat	≤45	3–5	8	26 ± 4
Winchester <i>et al.</i> ¹⁵	TM with BWS + Lokomat with feedback	NA	3	12	~36
Dobkin <i>et al.</i> ²²	TM with BWS or OG	30–50	≤5	≤12	52 ± 9 (TM with BWS) 40 ± 16 (OG)
Musselman <i>et al.</i> ²³	TM with BWS + OG	31 ± 7	3.6 ± 0.6	36	~130
Schwartz <i>et al.</i> ²⁶	TM with BWS + Lokomat + PT	30–45	2–3	12	~24–36
Fritz <i>et al.</i> ¹⁹	TM with BWS + OG	≥50	3–5	2–3	10
Lucareli <i>et al.</i> ²⁷	TM with BWS	30	2	15	30
Alexeeva <i>et al.</i> ²⁵	TM with BWS or BWS OG or PT	≤60	3	13	~39
Wu <i>et al.</i> ¹⁶	TM with BWS + cable-driven robot	41–45	3	8	~24
Benito-Penalva <i>et al.</i> ²⁸	TM with BWS + Lokomat or Gait trainer	≤45	5	8	~40
Harkema <i>et al.</i> ²⁰	TM with BWS + OG	≤90	NA	NA	47(20–251)
Range		20–90	2–5	2–24	10–130

*The following MIDs were used: self-selected walking speed >0.1 m/second, 6MWT distance >20 m, WISCI II score ≥2, and Wernig scale score ≥1.

Average values reported as mean ± 1 standard deviation or median (range). Estimated values denoted as ~.

TM, treadmill training; OG, over ground training; BWS, body-weight support; PT, physical therapy treatment as determined by the therapist; FES, functional electrical stimulation; NA, not available.

5 × /week for 2 weeks; walking ~50 minutes per day) training schedule for individuals >6 month-post-injury, did not result in changes in walking speed over ground, but reasonable improvements in walking distance (6 MWT)¹⁹. This suggests that 10 sessions may be insufficient, even when the training schedule was long (3 hours per day). The specificity of the training in this study may also have been no more than previous studies, since 50 minutes out of the 3 hours per day was devoted to walking. In summary, much remains to be done to determine the optimal training schedule and intensity.

We also urgently need to know how much walking training is provided in current practice. Careful quantification across jurisdictions must be done. Only by understanding the intensity of training in current practice can we provide a comparison with known optima (best practice), in order to advocate for changes in health care policy, should this be indicated.

When should I train?

At what point in the recovery process should training start? Since many SCIs in humans are the result of trauma, stabilizing individuals medically in the acute phase is the first priority. Once this is achieved, the earliest reported start time for locomotor training is ≤1-month post-injury.^{8,22,40,42,43,48} No adverse effects have been reported in these individuals. In the subacute phase after injury, participants who started earlier after injury (<4 weeks) showed significantly faster walking speeds and walking distance than those who started later (>4 weeks) when outcomes were measured at 6-month post-injury.²² Comparisons between slightly longer windows of post-injury times also support the importance of earlier training. For example, those who started training <6-month post-injury ended up with higher final walking scores (WISCI-II and 10 MWT) than those who started >6-month post-injury.²⁸ In the chronic phase after injury, there was also evidence that those more recently injured may be at an advantage.^{20,45} Overall, there is increasing evidence that earlier intervention may be advantageous. Nevertheless, individuals with long-term chronic injuries can still improve, although it may take a longer treatment time and the degree of improvement may be less.²⁰

Summary

To achieve meaningful gains in functional walking ability after a SCI, we have the following recommendations for therapists, based on our summary of the literature.

Who: Individuals with motor incomplete lesions and some preservation of strength in the legs. Individuals with AIS C and D lesions are more likely to achieve improved over ground walking than individuals with AIS A and B injuries.

What: Walking must be a major part of the therapy. Walking on the treadmill, or over ground, or both all produce favorable results.

How: Walking training can be unassisted or with partial assistance from either a robot or therapists. Methods that encourage participation from the individual are likely superior to those that do not.

When: As soon as possible – better walking outcomes are achieved with early training, but individuals with chronic injuries can still improve.

Future directions

The evidence with current training methods favors motor incomplete SCIs, with a clear shortage of studies focusing on individuals with motor *complete* lesions. Future studies targeting these individuals so that they may benefit from being upright and walking remains an important goal.

SCIs are heterogeneous, so the best treatment will depend on the severity of the lesion and perhaps the specific neural pathways affected. Tailoring the treatment for the individual remains a goal for the future. The optimal intensity, how best to quantify intensity, and the ideal schedule for training remain to be determined. For example, is it better to train intensively for a shorter time, or less intensively for a longer time? The outcome measures that have been used so far have been objective, but still lack in scope with respect to what is needed in home and community walking.⁷⁰ A number of outcomes are likely needed to capture the many ways in which walking training affects the individual.

Finally, as Table 1 indicates, the levels of evidence generally remain moderate to low. Besides the specific criteria set out by PEDro, we would further recommend that details regarding the training methods and intensity be documented more clearly. For example, where possible, the speed of walking, the distance traveled in a session, the number of steps, and the change in heart rate could all help better define the training delivered. Details regarding the severity of the lesion beyond AIS, such as manual muscle test scores, would also be very helpful. We hope that with increasingly stronger evidence, policy makers will see the benefit of intensive training of walking, such that all individuals with SCI will benefit from improved interventions for walking.

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