

Locomotor Training Progression and Outcomes After Incomplete Spinal Cord Injury

Background and Purpose. The use of locomotor training with a body-weight–support system and treadmill (BWST) and manual assistance has increased in rehabilitation. The purpose of this case report is to describe the process for retraining walking in a person with an incomplete spinal cord injury (SCI) using the BWST and transferring skills from the BWST to overground assessment and community ambulation. **Case Description.** Following discharge from rehabilitation, a man with an incomplete SCI at C5–6 and an American Spinal Injury Association (ASIA) Impairment Scale classification of D participated in 45 sessions of locomotor training. **Outcomes.** Walking speed and independence improved from 0.19 m/s as a home ambulator using a rolling walker and a right ankle-foot orthosis to 1.01 m/s as a full-time ambulator using a cane only for community mobility. Walking activity ($\bar{X} \pm SD$) per 24 hours increased from $1,054 \pm 543$ steps to $3,924 \pm 1,629$ steps. **Discussion.** In a person with an incomplete SCI, walking ability improved after locomotor training that used a decision-making algorithm and progression across training environments. [Behrman AL, Lawless-Dixon AR, Davis SB, et al. Locomotor training progression and outcomes after incomplete spinal cord injury. *Phys Ther.* 2005;85:1356–1371.]

Key Words: *Gait, Locomotor training, Recovery, Spinal cord injury.*

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This case report presents the progression and clinical decision-making algorithms for a patient with incomplete SCI undergoing locomotor training to improve walking ability.

Since Barbeau and colleagues^{1,2} first reported suspending a human over a treadmill to assess feasibility for walking retraining, clinicians have increasingly adopted the use of a body-weight-support (BWS) system in clinical practice. This approach came from observations by neuroscientists that complete midthoracic spinalized cats could be trained to step with their hindlimbs on a treadmill when trained intensely and repetitively using a suspended sling for trunk support and manual assistance for stepping.³⁻⁵ Scientists attributed the stepping response to peripheral sensory input processed by the central nervous system. It was demonstrated that specific sensory input associated with locomotion was integrated and interpreted by the spinal cord neural circuitry to generate a coordinated stepping pattern called “central pattern generation.”⁵

Since that time, subsequent research has linked basic science with rehabilitation science to advance the development of effective and science-based rehabilitation for the recovery of walking after neurologic injury.⁴⁻⁷ Manufacturers of rehabilitation equipment have developed and continue to redesign products that provide suspension and support capabilities for use in research laboratories and in clinical practice. Clinical administrators are

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purchasing BWS devices, and clinicians are implementing their use in rehabilitation practice.

Although the body-weight–support system and treadmill (BWST) appear essential to the locomotor training,⁸ little has been published describing the progression on the treadmill and the progression across the continuum from the clinic to community ambulation. Seven studies that conducted training with people with incomplete spinal cord injury (SCI)^{9–15} and one methodology article for a locomotor training trial¹⁶ thoroughly described the initial training parameters for the BWST and the training intensity, frequency, and total duration. Limited information, however, is provided describing the training progression, clinical decision making, and evaluation of progression steps.

In the 8 studies, BWS was initially set at 32%,¹⁵ at 40%,^{9,10,14,16} or at up to 80%,^{12,13} or it was adjusted to maximize bilateral lower-limb loading without the knee flexing or buckling during stance.¹¹ Initial training speeds were set at the speed most comfortable for the patient,^{9,10} at 0.42 m/s,^{12,13} at 0.67 m/s,¹⁵ at 0.04 m/s,¹⁴ or at a speed approximating the patient's normal walking speed (0.88–1.32 m/s).^{11,16} Manual assistance was provided at the lower extremities^{9,10,12,14} or at the lower extremities and trunk,^{11,16} or it was not provided.^{11,15} In the 8 studies, arm support provided balance during training only,^{9,10,14,15} it was not provided,^{11,16} or it was not specified.^{12,13} Training intensity was reported to be 15 minutes,^{12,13} 20 minutes,¹⁵ or 30 minutes at a frequency of 3 days a week¹⁵ or 5 days a week.^{9–14,16} The total study durations were from 3 to 28 weeks.

Beyond the initial training parameters, the most frequent instructions for progression with the BWST were to simply decrease BWS and to increase speed in order to optimize the quality of each step.^{11–13} Some researchers provided rules for predesignated decreases in BWS based on goals to increase endurance,^{9,10} for increases in speed based on patient performance (ie, no scuffing of the foot),¹⁵ or for increases in speed as a daily probe of patient abilities and progress.¹⁴ Five studies^{9–11,14,16} introduced overground walking training in conjunction with use of the BWST modality, although these studies introduced overground walking at varying time points during the course of training. Two of the 5 reports^{11,16} described overground and community ambulation training that was modified to maintain consistency between the process of skill progression for the patient on the treadmill and the training for the patient overground. For example, because patients did not bear weight through their arms during treadmill training, weight bearing through the arms was limited during overground training.

None of the 8 studies described the decision-making process for progression by altering BWS, speed, or other variables (eg, manual assistance, duration of training bouts) and the assessment of its effect. Because physical therapists were trained to conduct locomotor training at the clinical sites participating in the locomotor training trial¹⁶ and in research laboratories,^{11,17,18} questions emerged concerning the decision-making process for progression while training using BWST: how to set training goals, how to decide which training parameters to change and when to change them, how to determine the interactive effect of altering the parameters, and how to maintain consistency between training and progression in the treadmill environment to walking overground or community ambulation training.

The purpose of this case report is to describe the progression for a person with an incomplete SCI and an American Spinal Injury Association (ASIA) Impairment Scale¹⁹ classification of D who was undergoing locomotor training in a clinical trial. We depict the decision-making process and treatment progression for altering training parameters that aimed to improve walking using: (1) the BWST for step training, (2) overground assessment and training, and (3) transfer of skills from the treadmill to community ambulation. In addition, we report the outcomes following locomotor training for measures of impairment, activity, and participation.²⁰

Case Description

Patient Description

Information concerning this patient's acute hospitalization, inpatient rehabilitation, and outpatient therapy was obtained from a medical chart review and abstraction that complied with the Health Information Portability and Accountability Act. After outpatient therapy was completed, locomotor training was initiated and is the primary focus of this case report.

The patient was a 55-year-old man who fell about 6 m (20 ft) down a flight of stairs and sustained a herniated disk and fractures to the fifth and sixth cervical vertebrae and who subsequently had central cord and Brown-Séquard syndromes. Past medical and surgical history included hypertension, depression, a recent urinary tract infection, allergic rhinitis, and a tonsillectomy. He lived with his wife and daughter. He had a prior military career, had an education level of 16 years, and led an active life employed as a school principal while also working on his farm.

On the day of his accident, he was taken to the emergency department where steroids were administered and a cervical discectomy was performed. Physical therapy was initiated on day 3 of his acute hospital stay (Tab. 1).

Table 1.
Acute Hospitalization Course

	Initial Physical Therapist Evaluation (Day 3)	Treatment and Discharge (Day 4)
Functional mobility	Long-term goals × 4 wk: stand-pivot transfer with maximal assistance, wheelchair mobility >30.5 m (100 ft) independently	Maximal assistance to sit on the edge of the bed × 20 min
Manual muscle test	Right—hip: 1+/5, knee: 2-/5, ankle: 1/5 Left—hip flexor: 2-/5, abductor: 1/5, knee: 2/5, ankle: 1+/5	Right—hip flexor: 3/5, knee extensor: 3/5
Tone (state of muscle activity at rest)	Increased resistance to passive range of motion of right lower extremity	
Sensation	Pinprick decreased on left side to T4, decreased light touch on soles of feet and perirectal areas	
Proprioception	Absent at great toes, decreased at ankles	
Gait training	No goals set or initiated	

Table 2 outlines the patient's inpatient rehabilitation course and Functional Independence Measure (FIM) scores. At the completion of rehabilitation, he had a FIM score of 75/91. He required minimal assistance, a rolling walker, and a right ankle-foot orthosis (AFO) to ambulate on level surfaces and maximal assistance to manage stairs.

Physical therapy and occupational therapy continued for a total of 9 outpatient visits each across 3 weeks. Goals focused on activities of daily living with gait training using a rolling walker and a right AFO. Home care was not recommended. The occupational therapist informed the patient of the locomotor study, and he contacted the principal investigator (ALB).

The patient reviewed and signed a consent form approved by the Institutional Review Board of the University of Florida Health Science Center to participate in a study examining the effect of long-term locomotor training and treadmill speed on reflex modulation and gait speed in people with incomplete SCI. The patient presented in this case report was accepted into the study because he met the research protocol criteria of having an incomplete SCI, having an ASIA impairment classification of C or D, having upper motor neuron involvement, ambulating at a speed less than 0.8 m/s, and having an SCI within the past 3 years. The decision to develop a case report demonstrating progression was made prospectively in the midst of the trial. This patient had recently begun training and thus afforded us the opportunity to thoroughly document the training parameters and decision-making process over the entire

course of his training. The patient had resumed his position as a school principal using a power wheelchair for mobility at school and outside the home. His medications included Sudafed* (as needed), Zolof* (50 mg every day), baclofen (5 mg twice daily), Coumadin† (6 mg every day), and hydrocodone (as needed). Lisinopril (20 mg twice daily) was added 2 weeks into the training.

Examination, Evaluation, and Prognosis

The patient had an ASIA impairment classification of D, with an Upper-Extremity Motor Score of 38/50 and a Lower-Extremity Motor Score of 35/50.¹⁹ Hip flexor strength (force-generating capacity of muscle) improved from 1+/5 and 2-/5 on the right and left, respectively, on day 3 after his injury to 2/5 and 4/5 on the right and left, respectively, on day 94

after his injury (the day of the initial examination described in this case report). Knee extensor strength improved on the right from 2-/5 to 4/5 and on the left from 2/5 to 5/5. Observational gait analysis (Fig. 1) showed a flexed posture and an uneven step-to gait pattern overground. He used a rolling walker and a right AFO, and exhibited hip hiking (elevation of the pelvis on the right) with full knee extension throughout the swing phase of gait on the right and vaulting on the left.

His walking potential was assessed during an initial trial of step training with the BWST and the manual assistance of trainers (Fig. 2A). The trainers used observational gait analysis to evaluate his capacity to maintain an upright posture and to generate coordinated steps. *Coordinated stepping* was defined as a reciprocal pattern of stepping consistent with walking and characterized by its spatial and temporal pattern; trunk and lower-limb and upper-limb kinematics; and speed. The challenge of standing and walking upright without arm support was a new demand because the patient had consistently walked overground while bearing weight on a walker since his injury. The BWS and overhead safety device (to prevent a fall) provided a safe opportunity for him to attempt an upright posture while walking.

Although a fully erect posture was not achieved, nor expected, on the first day using the BWST, his posture was observed to be more upright. With the trainers' assistance to move the lower extremities, the patient was

* Pfizer Inc, 235 E 42nd St, New York, NY 10017-5755.

† Bristol-Myers Squibb Co, PO Box 4500, Princeton, NJ 08543-4500.

Table 2.
Inpatient Rehabilitation Course^a

Week	FIM Score	Gait Training	Other Physical Therapy Documentation
1	24/91	No gait goal due to weakness	Goal: sit-pivot transfer with supervision; propelling wheelchair with 1–3 grade 152.4 m (500 ft) modified independent
2	32/91	No gait goal due to weakness	Goal: sit-pivot transfer modified independent, propelling on wheelchair ramps with contact guard assistance
3	37/91	Goal: gait train × 4.6 m (15 ft) with rolling walker and maximal assist to propel right lower extremity and contact guard assist for balance (assist of 2 people); goal achieved	Pattern of gait: right lower-extremity hip hiking with poor active hip and knee flexion
4	45/91	Goal: gait train 45.7 m (150 ft) with rolling walker and minimal assist to propel right lower extremity and contact guard assist for balance (assist of 2 people); goal achieved	Manual muscle testing: Right: hip 2–/5, knee extensor 3–/5, flexor 2–/5, ankle dorsiflexor 1/5, plantar flexor 2/5 Left: hip 3+/5, knee extensor 4/5, flexor 3/5, dorsiflexor 4/5, plantar flexor 3/5 Tone: Increased in right lower extremity
5	54/91	Goal: gait train 45.7 m with rolling walker minimal assist (assist of 1 person), 5 stairs minimal assist with right AFO Goal not achieved due to stair climbing	
6	63/91	Goal: 10 stairs minimal assist with right AFO	Midweek: seen in emergency department with deep vein thrombosis in right lower extremity, returned to inpatient hospital same day
7	66/91	Acute care physical therapy evaluation: 5 steps with minimal assist and rolling walker	Beginning of week: admitted to acute care for a pulmonary embolism for 5 d
8	75/91	Discharged: gait train 92.4 m (300 ft) rolling walker and right AFO modified independent Pattern of gait: right hip hiking, left lower-extremity vaulting, right lower extremity exhibits increased tone (eg, state of muscle activity at rest assessed by amount of resistance to passive range of motion)	Readmitted inpatient rehabilitation hospital Discharge equipment: power wheelchair, commode, shower chair, rolling walker

^aFIM=Functional Independence Measure, AFO=ankle-foot orthosis.

able to take even step lengths and achieve right knee flexion of approximately 35 degrees, neither of which was observed during overground walking with the walker at his initial examination. We viewed his improved posture, improved lower-limb kinematics, and step symmetry with verbal cueing and manual assistance during this initial session in the BWST as positive indicators for long-term training benefit.

Outcome Measures

The outcome measures addressed: (1) impairments (ASIA Impairment Scale and motor scores¹⁹), (2) activity (gait speed and spatial gait characteristics; level of walking independence measured with the Walking Index for Spinal Cord Injury II [WISCI II]²¹), and (3) participation (amount of home and community walking activity,²² patient interviews, and observations).

A description of each measure, its reported validity and reliability, and the testing procedure follows. All tests were conducted before and after 45 sessions of locomotor training and 1 month after training completion. Interim measurements for gait speed, spatial characteristics of gait, and level of independence also were recorded weekly during the 45 sessions.

ASIA Assessment of Neurological Impairment. Sensory and motor testing was conducted according to ASIA guidelines before and after locomotor training.¹⁹ Kappa values for interrater reliability of the ASIA evaluation have been estimated to range from .47 to .87 for the motor portion and from .06 to .93 for the sensory portion.²³ It is, however, the recommended instrument for assessing sensory and motor function after SCI²⁴ and is used in clinical trials of locomotor training.¹⁶ The same examiner conducted the ASIA evaluation before



Figure 1.
Pretraining observational gait analysis.

	Week 1	Week 3	Week 6	Week 9
Step Training with BWST	<p>Speed: 0.62-1.07 m/s BWS: 32% to 23%</p>	<p>Speed: 0.98-1.25 m/s BWS: 20% to 16%</p>	<p>Speed: 1.07-1.25 m/s BWS: 16% to 9%</p>	<p>Speed: 0.98-1.48 m/s BWS: 9%</p>
Overground Walking Training				
Community Ambulation Training	<p>Gait Speed = 0.19 m/s WISCI II = 9</p>	<p>Gait Speed = 0.20 m/s WISCI II = 13</p>	<p>Gait Speed = 0.43 m/s WISCI II = 16</p>	<p>Gait Speed = 1.01 m/s WISCI II = 19</p>

Figure 2.
Locomotor training progression for weeks 1, 3, 6, and 9 for step training with the body-weight support and treadmill (BWST), overground weight training, and community ambulation training. WISCI II=Walking Index for Spinal Cord Injury II, BWS=body-weight support.

and after training to enhance reliability. The ASIA impairment level was determined from these findings.

Gait speed and spatial pattern of walking. The patient walked 3 times over a 3.8-m × 0.6-m computerized pressure-sensitive mat (GaitMat II [software version 2.016][‡]) at his self-selected walking speed, then at a fast walking speed in comfortable walking shoes. The GaitMat II recorded the footfalls from the spatial-temporal distribution of switch closures and subsequent openings. Then, the analysis software calculated the gait parameters. The patient used his customary rolling walker and right AFO for the initial testing. A second set of data was collected without the AFO. The first trial was considered a warm-up trial.

Data from the second trial were averaged to acquire gait speed and step length. In our laboratory, the intraclass correlation coefficients (ICCs) for intrarater reliability

for measuring gait speed with the GaitMat II were estimated to be .99 for both self-selected and fast speeds. The ICC for test-retest reliability was .94 for self-selected speed and .99 for fast speed. Concurrent validity for the GaitMat II for gait speed was estimated by comparing GaitMat II derived speeds to those calculated from handheld stopwatch measurements.²⁵ The ICCs were .94 for self-selected speed and .90 for fast speeds. The ICCs for intrarater reliability for step-length measurement with the GaitMat II were .88 for self-selected speed and .92 for fast speeds. Test-retest reliability for step length was .99 for both self-selected and fast speeds (Behrman, unpublished data).

Observational gait analysis. Each trial was videotaped from the lateral view and reviewed for gait deviations and use of compensatory strategies for upright posture, limb advancement, weight support, and balance (eg, forward trunk posture, lack of right knee flexion, right hip hiking).²⁶

Level of walking independence. The WISCI II was selected as an instrument to categorize the level of physical assistance and use of assistive devices or braces required for walking.²¹ The WISCI II is a 20-item scale with a score of 0 (meaning the patient is unable to walk) and 20 (meaning the patient can walk with no assistive device, no braces, and no assistance for at least 10 m). Criterion validity of the WISCI for examining people with SCI has been estimated by comparing it to the Barthel Index of Activities of Daily Living ($r=.67$), the Rivermead Mobility Index ($r=.67$), the Spinal Cord Independence Measure ($r=.97$), the FIM ($r=.70$), and the Lower-Extremity Motor Score of the ASIA assessment ($r=.58$).²⁷ In one study,²¹ the researchers found a correlation coefficient (Spearman r) of .77 for concurrent validity of the WISCI with the FIM, and interrater reliability had 100% accuracy.

Walking activity in the home and community. The patient's amount of walking in the home and community was measured using a Step Activity Monitor (SAM).[§] The SAM is a small, lightweight device, about the size of a pager that is worn on the ankle and does not interfere with walking. The device is a microprocessor-driven

[‡] EQ Inc, PO Box 16, Chalfont, PA 18914-0016.

[§] Cyma, 8515 35th Ave NE, Ste C, Seattle, WA 98115-3675.

accelerometer, which is more reliable for step counting than other measurement devices such as pedometers.²⁸ The programming capabilities of the microprocessor permit the clinician or researcher to both count strides and observe activity during predetermined time spans, providing more information than basic accelerometers.²² The SAM is safe²² for use. The SAM had 99.46% accuracy in people who were healthy,²⁹ 96% accuracy in people who were elderly and a Pearson r of .84 for interrater reliability in elderly people,³⁰ and 98% to 99% accuracy and a Pearson r of .98 for test-retest reliability in people who have had a stroke.³¹ In our laboratory, 98% accuracy was achieved between manual counts of steps and the SAM measurements, and an ICC of .99 was achieved for test-retest reliability when monitoring step activity with the SAM in people with incomplete SCI (Behrman, unpublished data).

Programming parameters of cadence and sensitivity to motion were adjusted at each testing session until agreement between the device recordings and manual counts was greater than 90%. The SAM was programmed to capture steps taken every 60 seconds so that a community-based cadence could be established.

The patient was instructed to wear the device on his left, or less involved, lower extremity just proximal to the medial malleolus. He wore it for 4 consecutive days, covering 2 weekdays and 2 weekend days, on 2 different occasions: before training and after 45 sessions of training had been completed. Weekend and weekdays were included to capture the differences in the amount of ambulation during vocational and avocational activities. The device was returned to the laboratory after 4 days, and the data were downloaded to the software package[§] for analysis.

Patient report. The patient's experiences and perceptions related to the effect of the training on his life were assessed through interviews. The interviews were conducted prior to the start of training, during weeks 4 and 8 of training, and at 1 month after completion of training.

Intervention

The locomotor training intervention consisted of 45 sessions, 5 times a week for 9 weeks. This included 30 minutes per day of step training with BWST,¹¹ immediately followed by 20 minutes of level overground walking and community ambulation training. Additional time spent on the treadmill included standing training and standing rest breaks. The total session duration was approximately 75 to 90 minutes per day including stretching and donning/doffing the harness before and after training. To monitor the patient's response to locomotor training, heart rate and blood pressure were

measured before and after sessions and during training if any symptoms of stress or overfatigue (eg, shortness of breath, profuse sweating above the level of the lesion, complaint of headache) were observed or reported. The AFO was not used during the training.

The intervention has been described previously^{11,16} and will be summarized briefly. The overall aim of the locomotor training was for the patient to achieve independent community walking at normal speeds without the use of an assistive device, orthoses, or compensatory movements and to improve his quality of life. "Train like you walk" emphasized training that maximized lower-limb loading (as opposed to upper-limb loading), approximated normal walking speeds with posture and limb kinematics consistent with walking, and minimized the use of compensatory strategies.¹¹ The immediate aim of step training using the BWST was to promote and intensely practice coordinated stepping. Trainers provided tactile cues to promote extension and flexion movements in the gait cycle. The long-term goal for locomotor training using the BWST was for the patient to walk independently for 20 continuous minutes at 10% BWS (the amount required to suspend the overhead hanger over the patient's head) and at a minimum of 1.0 m/s without using compensatory strategies. For some sessions, a trainer used 1 or 2 walking poles,^{||} held horizontally by the patient and the trainer, to coordinate arm swing with stepping. This trainer was eventually replaced by an overhead suspension for the pole. Trainers also explained the relevance of the task being practiced (eg, upright posture) to the goal of walking.

Immediately following the daily training on the treadmill, the patient's ability to stand and walk on level surfaces was evaluated. Thus, skills acquired on the treadmill were assessed and transferred to overground walking. The question guiding the evaluation process was "What is limiting this patient from walking independently in the community at normal walking speeds without an assistive device, orthosis, or compensatory movements?" Community ambulation training followed to give the patient the knowledge and tools to apply the training principles beyond the treatment session to his everyday life and prepare him for independent home and community ambulation.

Progression of Locomotor Training

In each daily training session, locomotor training was progressed on the treadmill and when transferring walking skills from the BWST to overground and community ambulation. Training goals were set for 6 parameters: (1) load (the amount of BWS), (2) speed (treadmill speed), (3) postural control and kinematics for walking,

^{||} Exerstrider Products Inc, PO Box 3087, Madison, WI 53714-3087.

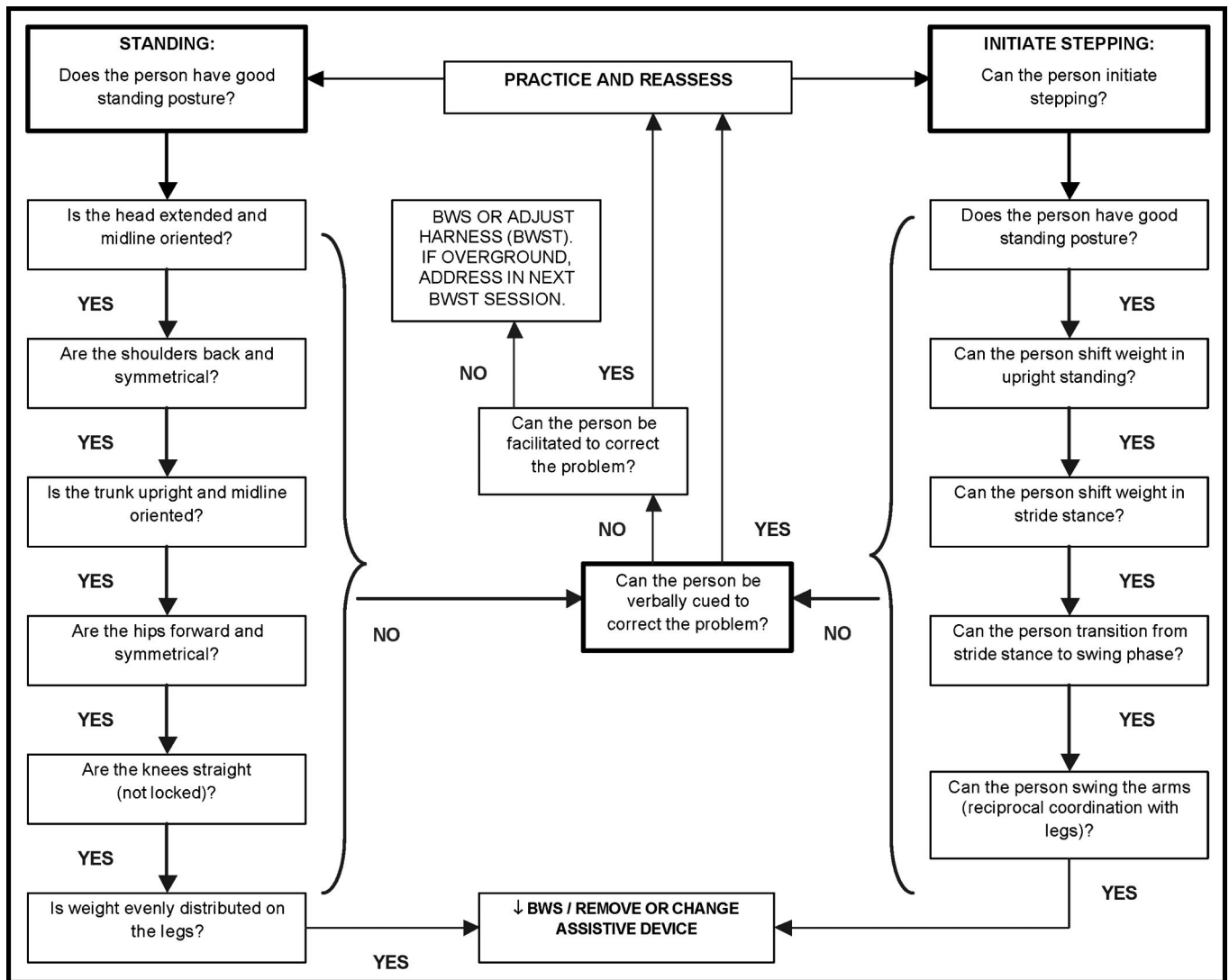


Figure 3. Decision-making algorithm for standing and step initiation progression. BWST=body-weight support and treadmill, BWS=body-weight support.

(4) endurance (total amount of time stepped during a session and length of individual stepping bouts during a session), (5) independence (ability to control posture and limbs in a coordinated stepping pattern without manual assistance), and (6) adaptability (ability to adapt to environmental demands or behavioral goals such as stopping and starting, uneven terrain, speed up or slow down walking, and so on).

During training, clinicians assessed the patient's stepping capacity using a decision-making algorithm (Fig. 3). In addition to guiding the decision-making process for the evaluation of the patient's stepping kinematics, this algorithm also facilitated decisions concerning modifications to BWS, treadmill speed, verbal cueing, or manual assistance. The adjustments to these parameters were directed by the kinematic evaluation to challenge and advance the patient beyond his current capabilities; therefore, the process was dynamic as illustrated in

Figure 3. The following sections describe in detail how the decision-making algorithms (Figs. 3 and 4) were applied to progress the locomotor training in all 3 environments—BWST, overground, and community.

Week 1 to week 3 progression. Following the algorithm (Fig. 3), the initial BWS was established as the amount of support that afforded an overall coordinated stepping pattern, an upright trunk, and lower-limb support for knee extension. The initial BWS was set at 23% to 32% and treadmill speed ranged from 0.62 to 1.07 m/s with 3 trainers providing manual assistance (Fig. 2A). The trunk/pelvis trainer encouraged and guided upright posture of head and trunk, assisted pelvic rotation, cued the patient to eliminate hip hiking, and facilitated weight shift. The leg trainers used verbal cues and manual assistance to strive for interlimb coordination. During week 1, the left-leg trainer assisted only with foot placement for step-length symmetry, whereas the right-

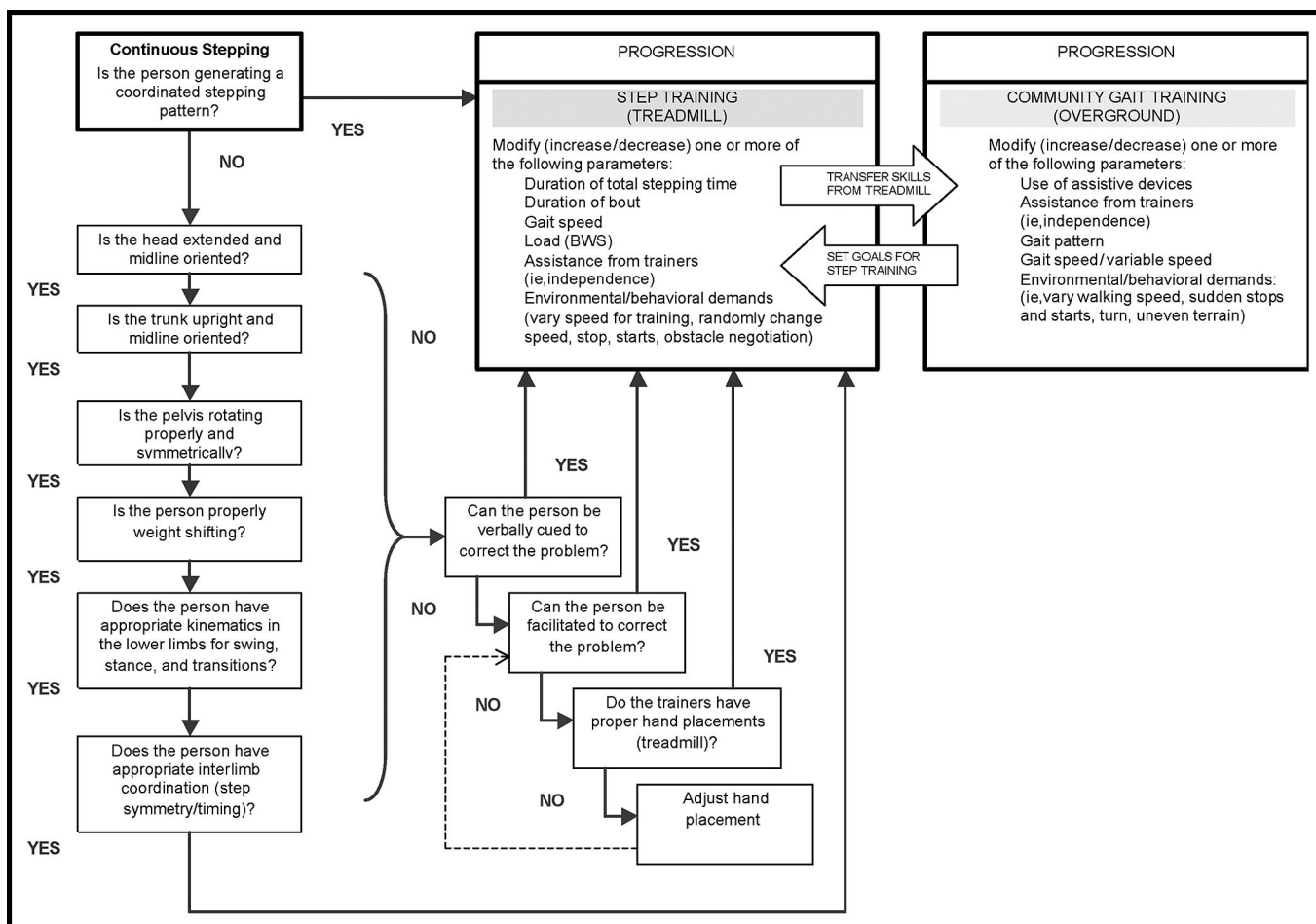


Figure 4. Decision-making algorithm for continuous stepping progression. BWS=body-weight support.

leg trainer facilitated right knee flexion and extension kinematics and spatial-temporal symmetry. Between stepping bouts, the patient stood on his left leg, with the right-leg trainer flexing the right knee to 90 degrees and maintaining neutral hip alignment. These training strategies were based on the analysis of the patient's specific problems, particularly his inability to flex the right hip and knee during stepping. Step training proceeded with the aim of generating coordinated stepping with spatial-temporal symmetry and limb kinematics consistent with normal walking. Stepping continued only as coordinated steps were achieved. Thus, early training bouts were brief and increased in length only as the number of coordinated steps increased.

As the initial goals of coordinated stepping with manual assistance and a capacity to train for a total stepping time of 20 minutes were achieved in the BWST setting, the algorithm (Fig. 4) was used to direct further progression. Overall, progression from week 1 to week 3 was accomplished by increasing the body-weight load, increasing the speed range for training, decreasing manual assistance by eliminating the trainer for the left lower

extremity and attempting 2-minute bouts without the trunk/pelvis trainer, and increasing the duration of a continuous training bout to ≥ 3 minutes while still meeting the 20-minute training intensity. By the end of week 3, the goal to complete a total of 30 minutes of step training with manual assistance (2 trainers) at 16% to 20% of BWS and a normal walking speed of 1.25 m/s had been met.

In the overground component of training, the patient stood while trainers held walking poles horizontally beside him, similar to parallel bars, to provide minimal balance support. Examination (Figs. 3 and 4) indicated: (1) an inability to maintain an upright posture in standing without assistance or cueing, (2) an inability to independently flex the right hip, knee, and ankle, (3) an inability to advance the right limb without use of a compensatory hip-hiking pattern, and (4) a dependency on support for balance.

On the basis of this examination, standing and weight shift within a diagonal position were practiced (Fig. 2B). Verbal cueing and manual assistance were provided as

necessary to achieve an upright posture. When an independent upright posture in standing and gait initiation from a stride position were achieved similar to that practiced on the treadmill, then overground training progressed to continuous stepping. Because the patient could initiate swing of the right leg without the hip hike and with adequate knee flexion, walking at speeds approaching normal was emphasized. Trainers and the patient held poles horizontally and reciprocally moved them consistent with arm swing to advance speed and provide minimal balance. The trainers used daily overground examination to establish the training goals for the next day's step training using the BWST and to emphasize community ambulation training.

For community ambulation training, the patient was instructed to practice the upright standing posture at home using a wall for safety and feedback and the walker for balance assistance (Fig. 2C). As a progression of community practice, he was to stand upright supporting his weight on the left leg with the right hip joint in neutral position, the right knee flexed, and lower leg supported on a chair (Fig. 2C). Walking upright while using the rolling walker, adjusted to increased height, was reinforced from week 1 to 3. By week 3, forearm crutches with a 4-point gait pattern were introduced to increase lower-limb loading and reduce upper-limb loading, encourage a more upright posture, and ultimately increase the speed of walking with good kinematics for stepping. The gait pattern was adapted to encourage primary loading of the lower limb by loading the lower limb prior to loading the forearm crutch.

Week 3 to week 6 progression. Referring to the algorithm (Fig. 4), as coordinated stepping and upright posture were achieved under the current training parameters, progression in the BWST environment was guided by goals to: (1) increase independence by decreasing manual assistance at the right leg and pelvis while further decreasing body-weight load (20% to 16% to 9%), (2) increase endurance by step training at normal speeds (up to 1.25 m/s) for fewer bouts of greater length and training for a continuous 30-minute bout (a primary goal of the patient), (3) introduce training at variable speeds, and (4) require adaptive responses to starts and stops of the treadmill (Fig. 2D).

Examination in the overground setting indicated that the patient had improved balance and independent control of upright posture. He also demonstrated independence in initiating right-leg swing without hiking and with minimal toe drag (Fig. 2E). Accordingly, the horizontal poles were eliminated from overground training as a means of providing balance and arm swing assistance (Fig. 2H). To increase independence in arm swing and balance, a handhold was used. A trainer would

simply hold the patient's right hand and promote the speed and amplitude of arm swing consistent with the alternating left upper extremity or 2 trainers would walk hand-in-hand with the patient, facilitating arm swing. Increasing the rate of assisted arm swing increased walking speed overground. Ultimately, no assistance for arm swing was provided. The patient advanced to a 2-point gait pattern, promoting a faster gait speed, a step-length symmetry, and an upright posture (Fig. 2F). He used the forearm crutches routinely in his home and the community. At the patient's request, he was examined using a single-point cane. The trainers agreed that this device was not the most appropriate choice at that time because it reinforced asymmetrical loading. Training continued to emphasize upright posture with symmetrical limb loading and speed while walking. Finally, to further progress community ambulation training, negotiation of uneven terrain such as grass, inclines, and a curb was practiced (Fig. 2I).

Week 6 to week 9 progression. During this period, the BWS was reduced to the minimal amount (9% maintained the overhead hanger safely in place), treadmill speed remained at normal walking speed (1.2 m/s), and the patient trained for 30 continuous minutes with intermittent manual assistance if stepping deteriorated or fatigue occurred (Fig. 2G). Adaptability was challenged by training at variable speeds, by randomly adjusting the treadmill speed quickly from fast to slow or vice versa, and by suddenly stopping and starting the treadmill. An independent stepping bout for 13 minutes at 1.2 m/s and 9% BWS was achieved, a personal best (Fig. 2J). Two-minute high-speed bouts (greater than normal walking speed) were conducted with manual assistance to challenge the patient beyond his current capabilities. Obstacles were placed on the treadmill for the patient to step over while continuing to step and maintain his balance. During translation to overground walking, he walked independently over level surfaces and grass, maintaining good trunk and limb kinematics, speed, and symmetry (Fig. 2K).

The patient progressed to walking in the home without an assistive device and intermittently in the community without an assistive device or with a single-point cane. The cane provided support should the environment or demands require balance beyond his capabilities. Sudden stops, turns, negotiating uneven terrain, and carrying items while walking were practiced (Fig. 2L). The patient chose not to use an AFO on the right because he felt safe with adequate toe clearance and thought the AFO and its weight compromised his walking.



Figure 5.
Posttraining observational gait analysis.

Outcomes

ASIA Impairment

Post-training examination classified the patient at ASIA D with an Upper-Extremity Motor Score that increased from 38/50 (left=22/25, right=16/25) to 42/50 (left=23/25, right=19/25) and a Lower-Extremity Motor Score that decreased from 35/50 (left=24/25, right=11/25) to 32/50 (left=22/25, right=10/25).¹⁹ Sensory scores for pinprick were 94/112 before training and 93/112 after training, and scores for light touch were 97/112 before training and 110/112 after training. The most caudal right and left sensory segments with normal function were C6 and C5 before and after training. The most caudal left and right motor segments with normal function were C8 and C7 before training and T1 and C7 after training, representing a one-point increase in left finger flexor strength.

Gait Speed and Spatial Pattern of Walking

Gait speed improved overground with the least restrictive assistive device from a self-selected speed of 0.19 m/s to 1.01 m/s, and fastest comfortable speed improved from 0.36 m/s to 1.2 m/s.^{32,33} The improvements in gait speed were sustained 1 month after completion of the 9 weeks of locomotor training, with a self-selected speed of 0.93 m/s and fast gait speed 1.21 m/s. Step length at a self-selected speed improved from 0.27 m on the left and 0.13 m on the right to 0.58 m on the left and 0.57 m on the right. Step length at the fastest comfortable speed improved from 0.45 m on the left and 0.19 m on the right to 0.70 m on the left and 0.63 m on the right. Consequently, interlimb step-length ratios (left/right) improved for self-selected speed from 2.07 to 1.01 and for fastest comfortable speed from 2.37 to 1.11, indicating improved step-length symmetry after training.

Observational Gait Analysis

Before training. The patient initially used a rolling walker and right AFO to walk on level surfaces (Fig. 1). He walked with his head forward and looking toward the ground. His trunk was flexed while leaning forward to bear weight through his arms on the rolling walker. Right hip hiking and lack of push off, vaulting on the left, and increasing shoulder and elbow extension using

the walker all contributed to the strategy for advancing his right leg. As the right leg was advanced, the knee maintained full extension and the ankle was in a neutral position due to the AFO. The left leg was advanced with usual hip, knee, and ankle kinematics. Neither the left or right leg achieved hip extension beyond neutral, thus abbreviating terminal stance to the mid-stance position. Step-length asymmetry

was apparent with the left step length appearing nearly twice the length of the right step length. He had no arm swing due to use of the assistive device. Walking without the AFO resulted in an exaggeration of the gait deviations of vaulting, hip hiking, and shoulder and elbow extension to clear the right foot during swing.

After training. The patient walked with his head upright, aligned over his shoulders and trunk, and looking forward (Fig. 5). His trunk also was upright and aligned with his pelvis over his base of support. Both legs moved through a pattern of hip, knee, and ankle flexion and extension consistent with reciprocal and symmetrical walking. The right knee flexion and dorsiflexion were adequate to clear the right foot during swing, although foot contact occurred upon loading in lieu of full heel contact. Hip extension beyond neutral position was achieved during terminal stance. Arm swing was present and coordinated with the legs.

Walking Index for SCI

The patient's level of independence for walking improved from a WISCI II score of 6 (using a rolling walker and right AFO) to 20 (no assistive device or AFO). Use of a cane was limited to community mobility or at home on the farm.

Walking Activity in the Home and Community

The subject improved from an average (\pm SD) of $1,054 \pm 543$ steps per 24 hours to $3,924 \pm 1,629$ steps per 24 hours recorded Thursday through Sunday (Fig. 6). Consistent walking activity throughout the day after training substantiated the patient's report that he no longer used the power wheelchair for mobility.

Patient Interviews

The interviews with the patient suggested psychosocial benefits from the locomotor training. He reported increased confidence that, in turn, led to increased "risk taking" when walking at home and in the community. This risk-taking behavior enabled him to engage in many of the same activities and roles that he had prior to his injury. During the patient's initial interview, he talked about how his SCI had affected his life. He described the difficulties he had in relearning how to do activities of



Figure 6. Pretraining and posttraining number of steps and step activity for single 24-hour period.

daily living and expressed frustration about his inability to participate in household and family responsibilities as he had prior to his injury. When asked what he hoped to accomplish through locomotor training, the patient replied, “I hope at the end of 9 weeks I’m walking much better than I’m walking now.” During his final interview, he said he had fulfilled his expectations. For example, he enthusiastically described his renewed abilities in helping his wife set the dinner table, emptying the dishwasher, walking in the cafeteria at school (workplace) and across his uneven yard to get to his barn, and climbing the stairs to his second-story bedroom.

Discussion

This case report presents the progression for locomotor training to improve walking ability in a person with an incomplete SCI and an ASIA D classification, which was initiated 114 days after injury and after discharge from rehabilitation. Progression was achieved by: (1) using a decision-making algorithm; (2) resetting identified training parameters of body-weight load, speed, posture and kinematics, endurance, independence, and adaptability; (3) daily examination of the patient’s stepping ability on the treadmill and overground; (4) establishing new goals based on the examination results; and (5) daily transfer of skills from the treadmill to community ambulation.

This model for training and progression is based on achieving the fundamental requirements for the control of walking: a reciprocal stepping synergy, upright posture and equilibrium during propulsion, and the ability to adapt to the environment and a person’s behavioral goals.³⁴ Overground and community ambulation training were modified for consistency with the process and principles of skill acquisition on the treadmill^{11,16} and thus differ from some researchers who also incorporate overground practice^{9,10,14} and differs from conventional gait training. In retrospect, the patient demonstrated the full spectrum of progression from the initial use of a power wheelchair as his primary means of mobility to full-time ambulation, and thus presents an excellent example to illustrate the elements of progression.

The progression process is probably applicable to other people with incomplete SCI, ASIA C or D upper motor neuron lesions, and who are undergoing locomotor training using the BWST and community ambulation training. The progression algorithm may be applied to people who already ambulate full time or for people who use a wheelchair as the primary means of mobility, with the goal of improving the control of walking and community ambulation. The algorithm provides a stepwise process for daily decision making, progression of training, and prioritizing goals by applying a hierarchy of

multiple and interactive training variables. Because the algorithm's framework is built on the essential control elements for the task of walking, it may be applied to people with motor incomplete SCI who exhibit a variety of motor control deficits.

The rate of progression and outcomes may vary according to the person's initial motor abilities, severity of injury, time since injury, premorbid health status, and support system. In addition, the positive outcome for this patient may be due in part to his past life experience and family support. This patient was initially able to stand independently, although with a flexed posture and a walker; he had relatively coordinated movement of one lower limb during the stance, swing, and phase transitions of walking; he had adequate upper-limb strength and grip to allow him to use an assistive device (although the left hand was stronger than the right); and his only range-of-motion limitation was in the right ankle. To achieve limited walking at 0.19 m/s, he had used several compensatory movement strategies. His first trial walking with BWST and manual assistance indicated that a less compensated movement pattern could be practiced.

Although the training occurred within a period of potential natural recovery from SCI, this patient did not demonstrate lower-limb motor recovery during the course of training. A comparison of ASIA Lower-Extremity Motor Scores before and after training did not indicate any strength gains or recovery associated with voluntary muscle activation that would account for improvements in gait speed. More sensitive, quantitative measures of strength testing, muscle hypertrophy, or voluntary activation may provide better insight into muscle changes associated with training or recovery. Intense skill practice for walking was followed by the achievement of his goal of an upright posture, balance without an assistive device, hip and knee flexion while walking, and a normal walking speed of 1.0 m/s.

Beneficial results might be attributed to improved muscle coordination or activation, balance, or task-specific training of walking, but are not likely to be due to gains in voluntary strength or an interactive effect of natural recovery. Long-term use of a compensatory strategy to achieve ambulation in people with incomplete SCI may increase the degree of learning that must occur during locomotor training to replace a habitual strategy with a new strategy for walking. Thus, the time since SCI and the time spent walking with a compensated gait pattern may alter the rate of progress or even limit a person's potential. This patient's prior life experiences, family responsibilities, and employment as a school principal also may have contributed to his problem-solving skills, initiative outside of the training session, and self-motivation.

The interactions between the training team and the patient also may have influenced the progression. First, the patient was educated throughout the training about the tasks being practiced and their relevance to accomplishing walking. For instance, education began on day 1 of training concerning why an upright posture that promoted hip extension would aid hip flexion. Working toward independent control of upright posture then became a goal not only for step training on the treadmill, overground walking, and community ambulation training, but also a responsibility for the patient at home and in his community. Providing knowledge, accompanied by skill development for walking, was intended to afford the patient the means to make behavioral choices at home and in the community. Such choices may, for instance, have led to increased time spent attending to upright posture alignment, increased walking activity with less use of a power wheelchair, and to testing new abilities in the home and community (eg, walking up a flight of stairs). In the interview process, the patient repeatedly described circumstances outside the clinical environment demonstrating his exploration and testing of new skills. Trainers also routinely asked the patient, "What is limiting you from walking full time in your home and community?" The response to this question was used to set training goals and to directly address the needs the patient identified. Patient education, combined with routine reexamination of the factors viewed as limiting achievement of his walking goals, likely contributed to the successful outcome.

A finding of improved walking ability after 45 sessions of locomotor training that applied an integrated continuum of training progression is consistent with previous case reports and work examining the effect of locomotor training in people with chronic SCI.^{8-10,35,36} Although the FIM score for walking improved from a 4 (walk 45.7 m [150 ft] with assistance using a rolling walker and AFO) at discharge from inpatient rehabilitation to a score of 7 after locomotor training (walk 45.7 m within a reasonable amount of time without physical assistance, brace, or device), greater demands are required to walk within the community.^{37,38} An outcome of 1.01 m/s for self-selected walking speed exceeded the threshold for community ambulation (0.8 m/s)³³ and approached normal walking speed (1.2 m/s). The patient also achieved full-time ambulation. The overall goals of achieving independent community walking at normal speeds without the use of an assistive device, orthoses, or compensatory movements and to improve his quality of life were attained.

The increase in walking activity measured by the number of steps per day provided an interesting perspective into the actual translation of the training benefit to the real world. This patient's gain in self-selected walking activity

approached the average $7,370 \pm 3,080$ steps per day for people who are healthy and 44.9 ± 15.8 years of age.³⁹ This outcome reflects a major shift from pretraining use of a power wheelchair as the primary means of mobility to after training, when the patient walked as his sole means of mobility.

Using interviews and observations, we were able to identify potential psychosocial benefits of locomotor trainings. Although the reports of this patient support the work of Nymark et al,⁴⁰ he provided insight into how the physical and psychosocial benefits of locomotor training may culminate in a renewed sense of identity and increased confidence and participation. The incremental changes in activity and ability reflected the patient's increased independence and signaled his return to preinjury roles within his family and community. These changes were consistent with enhanced quality of life as defined by the patient. Quantitative assessments of the effect of locomotor training on quality of life could be implemented in the clinical setting.

Because this training occurred in a research laboratory, addressing the feasibility of providing locomotor training in the clinic is important. Current perceptions about staffing needs and equipment costs to provide locomotor training may be a challenge in translating this intervention from the research laboratory to the clinic. The perception that staffing requirements for locomotor training exceed those for current physical therapy services and thus exceed possible reimbursement is often cited as a limitation to translation. This perception also has led to the fabrication of the first generation of robotic devices to replace the staff providing manual assistance.⁴¹ The feasibility of providing locomotor training, whether manually assisted or robotic-assisted, could be appropriately assessed by conducting a cost-benefit analysis relative to patient outcomes, staffing patterns required (eg, for licensed and nonlicensed personnel), capital expenditures, and other costs. Implementing locomotor training in a clinic will require managers to examine staffing patterns, costs to train personnel, initial capital outlay for equipment, maintenance cost, space utilization, reimbursement policies, and cost-benefit.

Based on the experience in the research laboratory, the personnel required for providing locomotor training is comparable to the staffing patterns in the clinic. Depending on the severity of the patient's impairments, physical therapists in the clinic often are assisted by 1 or 2 aides or a physical therapist assistant for specific intervals to aid in transfers, guarding, or gait training. To provide locomotor training using the BWST for this patient in the research laboratory, a licensed physical therapist and 2 additional trainers or aides were necessary for weeks 1 to 2, a physical therapist and one trainer

or aide for the next 5 weeks, and a physical therapist alone for weeks 8 to 9. The number of personnel required for locomotor training decreased as the patient became more independent.

Certainly, many dimensions require feasibility assessment and planning, as well as a cost-benefit analysis before acceptance by clinical management, health care systems, and payers. These analyses are beyond the scope of this case report but will be valuable should the evidence for the clinical effectiveness of locomotor training for specific patient populations cause it to exceed current practice. In order to prioritize resources, future research in this area will need to focus on determining the characteristics of potential study participants who have a high likelihood of recovery. Identification of responders will be necessary to effectively translate this intervention into clinical practice.

Whether 45 additional sessions of usual care or an alternative treatment using modalities such as functional electrical stimulation or aquatic therapy matching the dose and attention provided during locomotor training would have resulted in the same outcome is not known. The patient in this case report was discharged from outpatient therapy walking at 0.19 m/s with a rolling walker, using a right AFO, and using a recommended power wheelchair for community mobility. If an outcome of full-time ambulation at 1.0 m/s were expected and achievable with 45 more sessions of usual care, it seems likely that the therapy and payment could be justified. The outcomes achieved following usual care, the decision for discharge, and recommendation and subsequent use of a power wheelchair do not seem to support this expectation. Whether usual care or an alternative therapy of matched intensity compared with locomotor therapy and provided during inpatient rehabilitation, during outpatient therapy following discharge, or after chronic SCI would result in the same outcomes are testable alternative hypotheses. We suggest that the increase in health and quality of life reported by this patient was associated with improvements in ambulatory abilities and return to preinjury roles. A viable, alternative hypothesis is that the changed perceptions were a result of the time and professional attention received during 45 training sessions. Future research targeting these important questions will resolve this uncertainty.

Summary

This case report provides an extension of previous reports¹¹ by presenting the progression and clinical decision-making algorithms for a patient with incomplete SCI undergoing locomotor training to improve walking ability. The training principles, parameters, and clinical decision making will continue to be refined

along with the translation of research findings into practice. Establishing clinical guidelines to direct appropriate selection of candidates for locomotor training is a goal of future research and may be achieved with further investigation into the mechanisms of recovery and an understanding of an individual's initial presentation. Further investigation may refine guidelines and decision-making algorithms to include adjunctive therapies⁴²⁻⁴⁴ or a hierarchy of therapies to achieve optimal outcomes in the most efficient manner. Together, these findings may improve the clinical feasibility of the locomotor training intervention.

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