Volitional Muscle Strength in the Legs Predicts Changes in Walking Speed Following Locomotor Training in People With Chronic Spinal Cord Injury

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Background. It is unclear which individuals with incomplete spinal cord injury best respond to body-weight–supported treadmill training.

Objective. The purpose of this study was to determine the factors that predict whether a person with motor incomplete spinal cord injury will respond to body-weight–supported treadmill training.

Design. This was a prognostic study with a one-group pretest-posttest design.

Methods. Demographic, clinical, and electrophysiological measurements taken prior to training were examined to determine which measures best predicted improvements in walking speed in 19 individuals with chronic (>7 months postinjury), motor-incomplete spinal cord injuries (ASIA Impairment Scale categories C and D, levels C1–L1).

Results. Two initial measures correlated significantly with improvements in walking speed: (1) the ability to volitionally contract a muscle, as measured by the lower-extremity manual muscle test (LE MMT) ($r = .72$), and (2) the peak locomotor electromyographic (EMG) amplitude in the legs ($r = .56$). None of the demographics (time since injury, age, body mass index) were significantly related to improvements in walking speed, nor was the clinical measure of balance (Berg Balance Scale). Further analysis of LE MMT scores showed 4 key muscle groups were significantly related to improvements in walking speed: knee extensors, knee flexors, ankle plantar flexors, and hip abductors ($r = .82$). Prediction using the summed MMT scores from those muscles and peak EMG amplitude in a multivariable regression indicated that peak locomotor EMG amplitude did not add significantly to the prediction provided by the LE MMT alone. Change in total LE MMT scores from the beginning to the end of training was not correlated with a change in walking speed over the same period.

Limitations. The sample size was limited, so the results should be considered exploratory.

Conclusions. The results suggest that preserved muscle strength in the legs after incomplete spinal cord injury, as measured by MMT, allows for improvements in walking speed induced by locomotor training.
Intensive, body-weight–supported treadmill training (BWSTT) is an effective way to improve over-ground walking in individuals with spinal cord injury (SCI). Individuals in ASIA Impairment Scale (AIS) categories C and D with motor incomplete lesions are more likely to improve with BWSTT than are those in AIS categories A and B with motor complete lesions. However, the AIS categories are very broad, making it difficult to predict, based on AIS scores alone, whether a given individual will benefit from BWSTT. Recently, Winchester et al showed that a combination of 4 initial measures (time since injury, voluntary bowel and bladder voiding, functional spasticity [hypertonicity] score, and walking speed) predicted the final walking speed in a group of individuals with chronic injuries who participated in BWSTT. Although walking speed is one of the best measures of overall walking ability, final walking speed is not necessarily indicative of improvement. For example, an individual could start with a fast walking speed, show no improvement, and still have a fast final walking speed. Thus, change in walking speed would be a better indicator of response to locomotor training.

The neural mechanisms underlying improvements with BWSTT remain unclear. Improvements in walking have occurred without measurable change in volitional ability to activate leg muscles, leading to suggestions that the training helps to reactivate pattern generators for walking in the spinal cord, without the need for engaging volition. In contrast, Barthelemy et al suggested that impairment in the descending input from the primary motor cortex (ie, corticospinal tract) is directly related to problems in walking, such as drop-foot. Moreover, Thomas and Gorassini found that individuals who improved with BWSTT showed strengthened corticospinal input to the leg muscles, suggesting that residual volitional ability may provide important advantages for good training outcomes. Our recent findings further indicate that individuals who respond to BWSTT show higher leg electromyographic (EMG) amplitudes while walking prior to training than do individuals who show no improvement, suggesting that the ability to generate strong muscle contractions during walking may be a good predictor of success with BWSTT. Thus, initial EMG amplitude during walking may be a good predictor of success.

Relatively high manual muscle test (MMT) scores soon after injury are predictive of spontaneous recovery of function by the time of discharge, but improvement in MMT scores does not always parallel improvement in walking soon after injury. In the chronic stage, MMT scores are positively correlated with walking ability measured at the same time point, but what remains unknown is whether they predict the responsiveness to retraining of walking. The purpose of this study, therefore, was to determine which initial measures, including clinical, demographic, and electrophysiologic measures, will lead to the best improvement in walking function after BWSTT.

**The Bottom Line**

**What do we already know about this topic?**

People with spinal cord injury who have some ability to contract their leg muscles can improve walking function with treadmill training, but it is not clear which muscles are most important for predicting who will be helped by the training.

**What new information does this study offer?**

This study found that people with incomplete spinal cord injury who have greater preservation of muscle strength after injury will respond better to retraining walking, and that strength in 4 key muscles (knee extensors, knee flexors, ankle plantar flexors, and hip abductors) are most important.

**If you’re a patient, what might these findings mean for you?**

If you have relatively good muscle strength soon after injury, your walking speed is more likely to improve when you are being retrained for walking. This study, however, had a small number of patients, so the results are still preliminary and will need to be verified by other studies with larger numbers of patients.
Method

Participants

We initially recruited 22 participants for the study. The participants were recruited from the community, physical therapy clinics, and local hospitals. Means of recruitment included postings in newsletters and Web sites for individuals with SCI, identification of potential participants by physical therapists and physicians in the community, and by word of mouth. All participants provided informed written consent before the start of the study. Inclusion criteria were a motor-incomplete SCI (ie, AIS C or D) at levels between C1 and L1, occurring at least 7 months previously, to exclude spontaneous recovery. Exclusion criteria included impaired mental capacity, orthopedic problems that could affect walking ability, bone density of 30% or less of the mean in age-matched controls who were healthy, and any other medical contraindications to treadmill training. Clearance for training was confirmed with the individual’s family physician.

Of 22 participants who started the study, 2 dropped out for personal reasons after 1 month of training, and another did not attend regularly (ie, <3×/wk). Of the 19 participants who completed the study (Tab. 1), 14 (74%) were men and 5 (26%) were women, which is close to the typical distribution reported for Alberta, Canada, and similar to the distribution reported for North America. There were more participants in AIS category C (n=14) than in AIS category D (n=5).

Clinical Measures

Clinical measurements were taken by a physical therapist prior to training. For the majority of participants (15/19), measurements were taken within 1 month of the beginning of training. For the remaining participants, measurements were taken within 2 months prior to the start of training.

Table 1. Demographics, Injury Characteristics, Body Dimensions, and Clinical Scores for the Participants in the Study

<table>
<thead>
<tr>
<th>Participant Code</th>
<th>Mechanism of Injury</th>
<th>Level of Injury</th>
<th>AIS Category</th>
<th>Years Since Injury</th>
<th>Age (y)</th>
<th>BMI (kg/m²)</th>
<th>LE MMT (Total)</th>
<th>LE Asymmetry Index</th>
<th>Initial Speed (m/s)</th>
<th>Final Speed (m/s)</th>
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<tr>
<td>1F</td>
<td>MVA</td>
<td>T10</td>
<td>C</td>
<td>1.0</td>
<td>24</td>
<td>24</td>
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<tr>
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<td>Fall</td>
<td>C3</td>
<td>C</td>
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<td>28</td>
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<td>2.4</td>
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<tr>
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<td>D</td>
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<td>20</td>
<td>59.0</td>
<td>1.2</td>
<td>0.33</td>
<td>0.77</td>
</tr>
<tr>
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<td>Sport</td>
<td>C5</td>
<td>C</td>
<td>23.0</td>
<td>47</td>
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<td>25.0</td>
<td>1.5</td>
<td>0.11</td>
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<td>C</td>
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<td>VE</td>
<td>T4</td>
<td>C</td>
<td>5.0</td>
<td>59</td>
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<td>13.0</td>
<td>1.0</td>
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<td>0</td>
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<tr>
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<td>Tumor</td>
<td>T4</td>
<td>D</td>
<td>2.2</td>
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<td>56.0</td>
<td>1.1</td>
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<td>T2</td>
<td>C</td>
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<td>0.08</td>
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<td>C</td>
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<td>C</td>
<td>1.1</td>
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<tr>
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<td>C</td>
<td>3.8</td>
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</tr>
<tr>
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<td>C</td>
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<td>L1</td>
<td>C</td>
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<td>37</td>
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<td>1.1</td>
<td>0.89</td>
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<tr>
<td>17F*</td>
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<td>47</td>
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<td>43.0</td>
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<td>1.3</td>
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<td>L1</td>
<td>C</td>
<td>0.8</td>
<td>20</td>
<td>20</td>
<td>30.5</td>
<td>1.1</td>
<td>0.28</td>
<td>0.44</td>
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<td></td>
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<td>5.8 (8.9)</td>
<td>44 (13)</td>
<td>26 (5)</td>
<td>36 (12.5)</td>
<td>1.4 (0.7)</td>
<td>0.25 (0.29)</td>
<td>0.39 (0.40)</td>
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<td>Range</td>
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<td>0.6–28.2</td>
<td>20–77</td>
<td>17–36</td>
<td>9–58.7</td>
<td>1–3.5</td>
<td>0–0.89</td>
<td>0–1.23</td>
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</table>

*Participants were coded by number, with the participant’s sex indicated after the number (F=female, M=male). **Indicates participant who did some overground training. Indicates nonresponder (change in walking speed less than 0.1 m/s and no change in Walking Index for Spinal Cord Injury [WISC-II] score). Level of injury is listed as the lowest intact neurological level. Shading indicates individuals with low-level lesions (T11 or lower). MVA=motor vehicle accident; sport=injury during sporting activity; VE=viral encephalitis; AIS=International Standards for Neurological and Functional Classification of Spinal Cord Injury; BMI=body mass index; LE MMT=lower-extremity manual muscle test score summed across 16 muscle groups (8 per side), with a maximum possible score of 80; LE asymmetry index=asymmetry index estimated as strong side LE MMT/weak side LE MMT; NA=not available; initial and final speed refer to walking speed estimated from the Ten-Meter Walk Test.
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date. In each of the latter cases, the injury occurred more than 1.3 years previously, so function had remained stable for some time.

The Ten-Meter Walk Test (10MWT) was our primary outcome measure because it is responsive, reliable, and valid for the SCI population. Participants walked at their comfortable speed from a stance position. Although some researchers allow 2 m of walking prior to the timing of the 10-m walk for acceleration, we feel the transition from a stationary stance to walking is an important subtask of walking that may better characterize a person’s functional walking ability. When walking aids and braces were used, the same assistive devices also were used after training to ensure that their use did not confound the scores. Changes to the use of walking aids were accounted for in the Walking Index for Spinal Cord Injury (WISCI-II). Individuals who could not walk 10 m with maximal assistance were given a score of zero.

The WISCI-II is a 21-point categorical scale of walking ability. It has good psychometric properties and is moderately correlated with other timed measures of walking. The WISCI-II and the 10MWT were recommended as the most valid and clinically useful tests of ambulation after SCI. The WISCI-II was especially useful for measuring change in individuals who could not perform the 10MWT.

Manual muscle strength (force-generating capacity) was estimated for 16 muscle groups bilaterally: shoulder flexors, extensors, abductors, and adductors; elbow flexors and extensors; wrist flexors and extensors; hip flexors, extensors, abductors, and adductors; knee flexors and extensors; and ankle dorsiflexors and planar flexors. The standard testing positions that are widely used in clinical practice were used for all muscles. Modification to the testing was made for the plantar flexors, which could not be tested against gravity in the standing position in all participants. Thus, plantar flexion was tested with the participant in a sitting position, with knees flexed at approximately 90 degrees and with the feet resting on the floor. Antigravity (grade 3) was defined as the ability to perform plantar flexion through full range against the ground (ie, against the weight of the leg). Manual resistance was applied downward on the knee for grades 4 and 5. The traditional 6-point scale (0–5) was used; half-point scores were allowed between all grades except 4 and 5,17,28 which require manual resistance that cannot be graded reliably between testers.

Although dynamometers are more sensitive than MMT to small differences in muscle strength, they are not routinely used in the clinic. The agreement between MMT and dynamometry is moderate to strong, suggesting that MMT provides valid, but less-detailed, information about volitional muscle strength. Moreover, for the purposes of predicting success with training, finely graded muscle strength scores may not be necessary. The MMT has good intrarater and interrater reliability in a range of disabilities, including SCI.

The Berg Balance Scale was used to estimate static and dynamic balance, with a best possible score of 56. Reliability of Berg Balance Scale scores is excellent for individuals with SCI, as are the concurrent validity and predictive validity.

Demographics

Demographic measures were age (in years), body weight (in kilograms), height (in meters), and time since injury (in years). Body mass index (BMI) was computed as body weight/height.

Electromyographic Measures

Surface EMG measurements were obtained in a single session for each participant prior to the beginning of training. The EMG measurements were obtained from the tibialis anterior, soleus, quadriceps, and hamstring muscles, either bilaterally or unilaterally, while participants walked on a treadmill with body-weight support. These muscles were chosen to represent the major flexor and extensor muscle groups crossing the hip, knee, and ankle joints. In cases where more than one muscle from a muscle group were accessible from the surface, we chose the one with more-consistent activity based on the literature on people with injuries. Disposable silver/silver chloride electrodes (Kendall SOFT-E H59P) were placed approximately 1.5 cm apart center-to-center over the muscle belly after standard skin preparation. The signals were band-pass filtered (10–1,000 Hz), amplified (AMT-8†), analog-to-digital converted at 5,000 Hz, and recorded online (Axoscope‡). Recordings were made within 2 weeks of starting BWSTT. Approximately 3 minutes of walking was recorded.

Movement at the knee and sometimes also at the ankle (ie, when no ankle-foot orthoses were used) was recorded with electrogoniometers.§ Participants walked at a comfortable speed with enough body-weight support to prevent knee collapse. Manual assistance for foot clearance was provided only if needed. Participants held on to side bars (at shoulder...
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Training
Training sessions were approximately 1 hour per day, 5×/week. The initial amount of body-weight support (X=44%, SD=15%, range=9%–65%) was determined by the minimum support needed to prevent knee collapse during the stance phase. Initial walking speed (range=0.2–0.6 m/s) on the treadmill was selected by trial and error so that walking could be sustained for approximately 3 minutes, with participants actively participating in walking (ie, not passively allowing their legs to be moved). During training, the therapist aimed to achieve an upright trunk position, hip extension during the latter part of the stance phase, and good weight transfer between the legs. Arm swing was encouraged, if possible. Trunk support was provided manually by a trainer or with elastic straps anchored to supports as needed.41

Progression of training included a gradual increase in bout duration, decrease in manual assistance, decrease in body-weight support, and increase in treadmill speed. When participants could support more than 80% of their own weight, overground sessions (≤2×/wk) were incorporated. Training continued until a point when training parameters of treadmill speed, body-weight support, assistance, and bout duration did not progress for 2 weeks. In cases where no improvement (ie, no change in the training parameters outlined above) was seen, a minimum of 10 weeks of training was provided.

Data Analysis
Manual muscle test scores were summed separately for the upper and lower extremities (UEs and LEs; left and right sides) to provide composite scores, as reported by other authors.17 The asymmetry in strength of the LEs was estimated by the ratio of the total MMT score from the strong side to the weak side.17 To determine the predictive ability of individual muscle groups, the MMT score from each group was calculated by summing the scores for that group from the left and right sides (ie, knee extensor muscle score = left knee extensor score + right knee extensor score).

Because the LE MMT turned out to be an excellent predictor, we further identified the best threshold above which participants responded to BWSTT using the receiver operating characteristic (ROC) curve.42 Participants were classified into 2 groups: responders and nonresponders. Responders improved in walking speed by ≥0.1 m/s (ie, average smallest real difference reported for people with SCI; range=0.06 m/s13 to 0.13 m/s22); nonresponders improved in walking speed by <0.1 m/s.

The ROC curve was generated as follows. Manual muscle test scores from 0 to 80 (80=maximum LE MMT) were iteratively used as the threshold to determine the number of: (1) true positives (correctly identified responders), (2) false positives (incorrectly identified nonresponders), (3) true negatives (correctly identified nonresponders), and (4) false negatives (incorrectly identified responders). These 4 numbers were used to estimate the true positive rate (ie, correctly identified responders/all responders, also called sensitivity) and the false positive rate (ie, incorrectly identified nonresponders/all nonresponders, equal to 1 − specificity) for each MMT score. The ROC curve consists of the true positive rate (y-axis) versus the false positive rate (x-axis) for each iterated score. The ideal threshold is a true positive rate of 1.0 and a false positive rate of 0 (ie, top left corner of the ROC curve, Fig. 1B). In reality, an ideal threshold rarely happens, so the best threshold is normally the MMT value that is associated with the point closest to the top left corner. In this study, the best threshold was established as a value lower than what would normally be considered best in order to minimize false negatives (ie, denying treatment to someone who could benefit). We acknowledge that ROC curves traditionally have been used with large sample sizes, and our sample size was very small in comparison, so the results must be considered exploratory. Nevertheless, given the strong predictive ability of LE MMT, this analysis was deemed valuable to provide preliminary estimates that may aid clinical practice in the future.

Electromyographic recordings during treadmill walking were used to estimate the magnitude of muscle contraction during walking, determined from the peak EMG amplitude after the signals were rectified and smoothed with a 150-millisecond sliding average, as described previously.13 The maximum and minimum amplitudes of muscle activity during each step were automatically determined for individual muscles using custom-written software (Matlab®). The peak EMG amplitude for each step was the difference between the maximum signal and the minimum signal, which then was averaged across all the steps for each muscle. Peak EMG amplitude for a muscle group was the average between the left and right sides. Summing the left and right sides allowed us to test the general importance of that muscle group, which was our primary interest. Summing
of left and right sides, however, may mask more subtle differences between the sides when there is a strong asymmetry. An overall average of the peak EMG amplitude also was calculated across all muscles by summing the average peak EMG amplitude from each muscle and dividing the sum by the total number of muscles. This overall average was entered into regression analysis. The EMG values were not normalized, as sometimes is done, because the amplitude of the EMG signal reflects the force of the muscle contraction, which would be lost by expressing all values as a percentage of, for example, the peak EMG amplitude produced during a maximum voluntary contraction. To determine the variation in EMG amplitude from day to day in walking, we repeated the experiment on another day prior to training in 3 individuals who were part of this study and in 6 additional individuals with incomplete SCI.

Prediction of outcomes was estimated with correlations between the change in walking speed (ie, from the 10MWT before and after training) and the various initial measures. The initial measures included were

Figure 1.
(A) The total lower-extremity manual muscle test (LE MMT) score is highly predictive of outcome, as measured by a change in walking speed. Linear regression (solid line) is shown for those individuals with LE MMT above the best threshold (dotted vertical line), estimated by the receiver operating characteristic (ROC) curve. (B) The ROC curve indicated that an LE MMT score of 32 to 38 (numbers inserted beside corresponding data point) best differentiated participants who showed an improvement in walking speed from those who did not. However, a score of 30 is our proposed best threshold; it ensures zero false negatives, as the true positive rate is 1.0. (C) Participants with asymmetry scores ≥1.5 and LE MMT scores >15/40 for each side (n = 6) showed a statistically significant correlation between outcome and LE MMT score of the strong side, but not with the weak side (not shown). (D) Relationship between the sum of the initial LE MMT scores from the 4 key muscles and improvement in walking speed.
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based on the theoretical reasoning that the following variables are important to training outcome: (1) severity of the injury, particularly related to motor function, quantified by the initial MMT scores of the UEs and LEs, by initial walking speed, and by balance in sitting and standing (ie, Berg Balance Scale); (2) age, because age affects functional recovery;47–49; (3) time since injury, because neural plasticity may diminish with time;8,50; and (i) BMI, because a large BMI imposes physical demands on locomotion that may be difficult to meet.

The Pearson product moment correlation coefficient (r) was used first for all measures. Correlations also were calculated after removal of 5 individuals who had spinal cord lesions at or below the T11 level, resulting in possible damage to spinal roots that could affect their voluntary ability in those muscles. Multivariable linear regression then was used to evaluate potential confounds between predictors. This confounding would occur if the predictors themselves were significantly correlated, thereby measuring the same underlying phenomenon, such that using more than one predictor is no better than using just one. A forced-entry approach was taken, with those variables that correlated significantly with outcome in the univariate analysis (ie, LE MMT and EMG amplitude only) being added simultaneously to the final linear regression model only to determine whether both predictors added significantly to the prediction of outcome. The overall adjusted \( R^2 \) value was calculated to determine fit of the final model, along with the contribution to the \( R^2 \) value from individual variables.

Role of the Funding Source

The Faculties of Medicine and Dentistry and of Rehabilitation Medicine and the Spinal Cord Injury Treatment Centre Society of Edmonton provided the initial funding for this study. Subsequent funding was provided by the Canadian Neurotrauma Fund, the Christopher and Dana Reeve Foundation, the National Institutes of Neurological Disorders and Stroke (United States), and the Canadian Institutes of Health Research.

Results

The severity of the motor impairment in the legs is best reflected by the total score from the initial MMT, which ranged considerably among the participants (Tab. 1). Six participants had highly asymmetric LE MMT scores (ie, LE MMT asymmetry score \( \geq 1.5 \)). All participants provided MMT scores for the LEs. Fifteen participants had good EMG measurements during walking, with sufficient steps for estimating peak EMG amplitude. Twelve of them also were included in a previous article on EMG amplitude changes with training.13

Progress in Training Sessions

Participants trained for a mean of 18 weeks (SD=10). Most participants improved in the parameters of training: 17/19 improved in the total duration of walking in a session (mean increase=15 minutes, SD=11, minimum \( \geq 5 \)), 16/19 improved in treadmill speed (mean=0.14 m/s, SD=0.11, minimum \( \geq 0.1 \)), and 16/19 improved in their ability to support their own body weight (mean decrease in body-weight support=18%, SD=19%, minimum decrease \( \geq 5\% \)). In 5 participants, overground sessions were incorporated toward the end of training for \( \leq 4 \) weeks; in another participant (3M), the sessions were 1×/wk for 11 weeks (Tab. 1).

Effectiveness of BWSTT

The participants showed a range of success with training. The improvement in overground walking speed ranged from 0 m/s to 0.58 m/s. Nine participants showed improvements exceeding the smallest real difference in overground walking speed of 0.1 m/s (see “Data Analysis” section). Of these 9 participants, 5 were classified as AIS C and 4 were classified as AIS D. Four participants showed improvements in overground walking speed of less than 0.1 m/s, but showed improvements in WISCI-II scores. Thus, in total, 13 participants responded to the treatment. Six participants showed either no change in walking speed or a change in walking speed of less than 0.1 m/s, and no change in WISCI-II scores. Four participants were unable to walk overground even with maximal assistance, before and after training, so their level of function was among the lowest. The other 2 participants could walk overground, but at very slow speeds (0.08 and 0.11 m/s). No other factors were common among the nonresponders (Tab. 1).

Correlation Between Initial Conditions and Change in Walking Speed

Correlations between the change in walking speed and initial conditions are shown in Table 2 in order of the absolute value of the correlation magnitude. Only 2 initial conditions were significantly correlated with change in walking speed: the total LE MMT score and the peak EMG amplitude from the LEs during walking. When participants with low lesions (at or below T11) were removed, the same 2 predictors of change in walking speed were even stronger (\( r=77 \) for LE MMT score, \( r=74 \) for EMG amplitude). In addition, initial walking speed became significantly correlated with change in walking speed (\( r=.58 \)).

When comparing the correlations across the different initial conditions, only 2 were significant. The 2 best predictors for change in walking speed (ie, LE MMT score and peak EMG amplitude) were significantly correlated with each other,
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Table 2.
Pearson Product Moment Correlation Matrix for All Variables

<table>
<thead>
<tr>
<th>Variable</th>
<th>ΔWS</th>
<th>LE MMT</th>
<th>EMG</th>
<th>iWS</th>
<th>BBS</th>
<th>BMI</th>
<th>UE MMT</th>
<th>TSI</th>
<th>Age</th>
</tr>
</thead>
<tbody>
<tr>
<td>ΔWS</td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LE MMT</td>
<td>.72</td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EMG</td>
<td>.56</td>
<td>.70</td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>iWS</td>
<td>.45</td>
<td>.37</td>
<td>.25</td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BBS</td>
<td>.23</td>
<td>.33</td>
<td>.22</td>
<td>.65</td>
<td>1.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BMI</td>
<td>-.20</td>
<td>-.17</td>
<td>-.52</td>
<td>-.06</td>
<td>.07</td>
<td>.18</td>
<td>1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>UE MMT</td>
<td>-.13</td>
<td>.10</td>
<td>-.11</td>
<td>.39</td>
<td>.46</td>
<td>.18</td>
<td></td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>TSI</td>
<td>-.12</td>
<td>-.02</td>
<td>.36</td>
<td>.32</td>
<td>.40</td>
<td>-.43</td>
<td>.19</td>
<td>.74</td>
<td>1.0</td>
</tr>
<tr>
<td>Age</td>
<td>.11</td>
<td>.02</td>
<td>.27</td>
<td>.09</td>
<td>.02</td>
<td>.11</td>
<td>-.10</td>
<td>-.25</td>
<td>1.0</td>
</tr>
</tbody>
</table>

*Variables are arranged in order of the size of the correlation with the primary outcome measure of change in walking speed. Correlations that were significant at the .05 level are shown in bold type. All correlations were based on n=19, except for EMG (n=15) and BMI (n=18). ΔWS=change in walking speed; LE MMT=lower-extremity manual muscle test score (total); EMG=peak electromyography amplitude during walking, averaged across 4 muscle groups on both legs; iWS=initial walking speed; BBS=Berg Balance Scale score; TSI=time since injury; BMI=body mass index; UE MMT=upper-extremity manual muscle test score (total).

and Berg Balance Scale scores were positively correlated with measurements of initial walking speed.

Relationship Between Total LE MMT Score and Change in Walking Speed

The relationship between total LE MMT prior to training and change in walking speed is shown in Figure 1A. The ROC curve is shown in Figure 1B. Each point on the ROC curve represents a different total LE MMT score, with the x and y values corresponding to the false positive rate and true positive rate for that score, respectively (see “Method” section for more details). The area under the ROC curve was 0.822, with a 95% confidence interval of 0.635 to 1.101. Based on the ROC statistics, the LE MMT was successful at predicting whether the participants responded to the training (P=.018). The step-like increments on the ROC curve result from the addition of a single individual with each change in the MMT threshold, which would change either the false positive rate or the true positive rate. The ideal threshold is the point closest to the top left corner: LE MMT scores=32–38 (shown in Fig. 1B beside the corresponding data point). Because it is more desirable to accept false positives than false negatives in this instance (ie, favor specificity over sensitivity), we used a threshold MMT of 30/80 (vertical dashed line in Figure 1A), below which there are no false negatives. Further justification for a threshold of 30/80 was based on 4 individuals whose change in walking speed was below 0.1 m/s, but who showed improvements in WISCHII. In these 4 individuals, the lowest LE MMT score was 31/80. Using a threshold of 30, the sensitivity was 100% and the specificity was 40%. When individuals below the threshold were excluded, the correlation between total LE MMT score and change in walking speed was strengthened slightly (Fig. 1A, solid line, r=.74 compared with r=.72 in Tab. 2).

Improvement in individuals with substantial asymmetry may depend more on the strength of the strong side. Therefore, correlations were estimated for those individuals with asymmetry scores of 1.5 or higher (n=6) and total scores greater than 15 on the strong side (ie, half of the threshold of 30). In these individuals with asymmetry who had muscle strength above the threshold, the correlation between outcome and muscle strength was higher for their strong side (Fig. 1C, r=.99, P<.1) than for their weak side (not shown, r=.74, P>.1).

Relationship Between Initial Strength in Individual Leg Muscles and Change in Walking Speed

Because volitional muscle strength of the LEs was an especially important predictor, the predictive ability of each leg muscle was estimated for participants with total scores above the threshold of 30. Significant Pearson correlations between change in walking speed and muscle group (left and right sides combined) were found for 4 out of the 8 muscle groups: knee extensors, knee flexors, ankle plantar flexors, and hip abductors (Tab. 3). Correlations improved for all muscle groups except the knee flexors when participants with low-level lesions were removed (Tab. 3, right column). The strength of the 4 key muscle groups was not highly correlated among themselves (2 out of 6 combinations significant), so each muscle group may be providing important and complementary information. The correlation between the change in walking speed and the sum of the 4 key muscle scores is shown in Figure 1D (r=.82, P<.01).
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**Relationship Between Initial EMG Amplitudes From Individual Muscle Groups and Change in Walking Speed**

Prior to training, the day-to-day repeatability of peak EMG amplitudes was confirmed in a group of 9 participants with incomplete SCI, 3 of whom also were part of this prediction analysis. Intraclass correlation coefficients\(^1\) for the 4 muscle groups were strong (>.75) to moderate to good (.4-.75)\(^2\) for the tibialis anterior (.88), soleus (.87), hamstrings (.75), and quadriceps (.48) muscles. Thus, the EMG amplitudes were compared among participants without normalization.

The average peak EMG signal during treadmill walking prior to training was a significant predictor of change in walking speed (\(r = .56\)). The correlation was stronger when individuals with low-level lesions were excluded (\(r = .74\)). Correlations for each of the 4 muscle groups (tibialis anterior, soleus, quadriceps, and hamstrings) were significant except for the soleus muscle when all 15 participants with EMG data were included and were significant for all muscle groups when those with low-level lesions were removed (Tab. 4). The correlation between change in walking speed and peak EMG amplitude averaged among the 3 muscle groups that were individually correlated significantly with change in walking speed (excluding soleus) was .69 when all participants were included (Fig. 2, solid line) and .78 when subjects with low lesions were removed (Fig. 2, dashed line).

**Relationship Between Change in Walking Speed and Change in LE MMT Score**

Because initial LE MMT scores were a strong predictor of success with BWSTT, we determined whether gain in muscle strength during training also was greater in individuals who responded well to BWSTT. The change in total LE MMT score (ie, final score minus initial score) was not significantly correlated with change in walking speed (\(r = .274, P > .1\)).

**Multivariable Regression**

Finally, as only EMG amplitude and LE MMT scores were significant predictors of outcome in univariate correlation analysis, we used multivariable linear regression to test whether adding the peak EMG amplitude from walking would provide a stronger prediction of change in walking speed than the LE MMT alone. Due to the limited sample size, only these 2 variables (summed LE MMT score from the 4 key muscle groups and peak EMG amplitude from the 3 muscle groups that were individually correlated significantly with change in walking speed) were entered into the model as independent variables. Fifteen participants contributed data to the regression because we did not have good EMG data from 4 participants. In the final model (Tab. 5), the association between LE MMT and outcome remained statistically significant (\(P = .001\)), whereas the EMG variable became nonsignificant (\(P = .21\)). The adjusted \(R^2\) value of the final model was .78, with only a small amount of unique variance explained by the EMG variable (<2%). Thus, EMG activity is likely measuring underlying phenomena.

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**Table 3.** Pearson Correlation Coefficient (\(r\)) Between Change in Walking Speed and Initial Muscle Strength in the Lower Extremities Estimated With the Manual Muscle Test\(^a\)

<table>
<thead>
<tr>
<th>Muscle Group</th>
<th>All Participants With MMT Score &gt; 30 (n = 13)</th>
<th>Low-Level Lesions Excluded (n = 9)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Knee extensors</td>
<td>.69</td>
<td>.92</td>
</tr>
<tr>
<td>Knee flexors</td>
<td>.66</td>
<td>.59</td>
</tr>
<tr>
<td>Ankle plantar flexors</td>
<td>.61</td>
<td>.87</td>
</tr>
<tr>
<td>Hip abductors</td>
<td>.56</td>
<td>.71</td>
</tr>
<tr>
<td>Ankle dorsiflexors</td>
<td>.43</td>
<td>.45</td>
</tr>
<tr>
<td>Hip extensors</td>
<td>.40</td>
<td>.45</td>
</tr>
<tr>
<td>Hip flexors</td>
<td>.05</td>
<td>.42</td>
</tr>
<tr>
<td>Hip adductors</td>
<td>-.31</td>
<td>.03</td>
</tr>
</tbody>
</table>

\(^a\) Manual muscle test (MMT) strength scores were summed bilaterally for each muscle group and arranged in order of the correlation size. Individuals with total scores less than 30 were not included. Statistically significant correlations (\(P < .05\)) are bolded. Similar trends were seen when the data from 3 individuals with low-level lesions were removed.

**Table 4.** Pearson Correlation Coefficients (\(r\)) Between Change in Walking Speed and the Peak Electromyographic Activity During Walking Prior to Training\(^a\)

<table>
<thead>
<tr>
<th>Muscle Group</th>
<th>All Participants (n = 15)</th>
<th>Low-Level Lesions Excluded (n = 13)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tibialis anterior</td>
<td>.638</td>
<td>.761</td>
</tr>
<tr>
<td>Soleus</td>
<td>.139</td>
<td>.528</td>
</tr>
<tr>
<td>Quadriceps</td>
<td>.604</td>
<td>.638</td>
</tr>
<tr>
<td>Hamstrings</td>
<td>.642</td>
<td>.712</td>
</tr>
<tr>
<td>All muscles combined</td>
<td>.558</td>
<td>.739</td>
</tr>
</tbody>
</table>

\(^a\) Significant correlations (\(P < .05\)) are bolded.
related to the LE MMT, and adding EMG activity as a predictor does not add anything useful beyond that provided by the LE MMT alone. We tested the adequacy of the relevant regression assumptions, and all assumptions were met (Tab. 5). Nevertheless, these results still should be considered exploratory because the sample size was small. The low incidence of SCI and the difficulty in performing well-controlled training studies limit available sample sizes for this type of research.

**Discussion**

Among the 10 initial measures taken prior to BWSTT, total LE MMT score and peak EMG amplitude in walking were significantly correlated with change in walking speed. These 2 measures also were significantly correlated with each other, suggesting they were measuring related underlying phenomena. Among the 8 muscle groups tested with the LE MMT, 4 were individually correlated with outcome. The LE MMT scores of these 4 key muscles together provided the best prediction ($r=.82$). Adding the peak EMG amplitude in a multivariable regression did not improve the prediction beyond that provided by LE MMT alone. Thus, predicting success with BWSTT may be possible with a standard clinical test routinely performed by physical therapists.

**Volitional Ability to Activate Muscles Is the Best Predictor of Success With BWSTT**

The 2 best predictors, LE MMT and peak EMG amplitude during walking, are both direct measures of leg muscle contraction. Volitional activation of the muscle during an MMT includes contributions from the motor cortex and afferent feedback via reflex circuits. Similarly, muscle contractions during walking have contributions from both spinal circuits and descending activity from the motor cortex. Although individuals with clinically complete SCIs exhibit sensory-responsive EMG activity in assisted treadmill walking, the activity level in these individuals is much lower than in those with motor-incomplete lesions, and this EMG activity is insufficient to generate functional overground walking. Thus, the ability to activate muscles is an important predictor of success with BWSTT, but the relative importance of descending and afferent input remains unknown. However, the good correlation between the presence of foot-drop during walking and the strength of descending input from the corticospinal tract, as well as poor recovery of walking when the corticospinal tract is damaged, together suggest that volitional input from the corticospinal tract is important for the recovery of walking.

**Other Potential Predictors**

The only other study that has attempted a similar prediction of success with BWSTT using initial mea-

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**Table 5.**

Multivariable Linear Regression Model Examining the Relationship Between Predictors and Outcome: Dependent Variable Change in Walking Speed ($n=15$)

<table>
<thead>
<tr>
<th>Independent Variable</th>
<th>Standardized Beta Coefficient (95% Confidence Interval)</th>
<th>$P$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manual muscle testing (sum of 4 key muscles)</td>
<td>.74 (.37 to 1.00)</td>
<td>.001</td>
</tr>
<tr>
<td>Electromyographic activity (average peak amplitude across 3 muscles)</td>
<td>.22 (.22 to .88)</td>
<td>.27</td>
</tr>
</tbody>
</table>

*Adjusted $R^2$ value=.78. Assumptions of linearity, normality, independence, and homoscedasticity were met.
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measures reported somewhat different predictors. One important difference between that study and ours is the measure of outcome, which was a change in walking speed in our study and final walking speed in the study by Winchester et al (see introduction section). Also, although muscle strength was one of the potential predictors they considered, they used the LE muscle score from AIS, which, as we show, does not include all of the ideal muscles for predicting walking. For example, they included some muscles (ie, hip flexors) that are poor predictors of success, and excluded others (ie, knee flexors) that are good predictors of success. Nevertheless, the factors identified in both studies should be considered in future studies, as both had relatively low numbers of participants.

Which Muscle Groups Provide the Best Prediction?

No other study has tried to predict the response to BWSTT using the strength of individual muscles. Only one study has considered the importance of strength in a large number of LE muscles to walking ability measured at the same point in time after SCI (ie, without an intervention). Kim and colleagues found the strength in 7 muscle groups (hip flexors, hip abductors, knee flexors, hip extensors, ankle plantar flexors, knee extensors, and ankle dorsiflexors), listed in order of the strength of the correlations, to be important, with the 4 key muscles from the present study italicized. Because their participants were higher functioning than ours (all able to walk for 6 minutes) and had greater asymmetry in strength, the differences may be related to the individual participants in each study. Larger, multicenter trials or meta-analysis of multiple studies will be necessary to discern differences among individuals with different clinical presentations. It is possible that the specific muscle group most important for prediction will depend on the nature of the injury.

We showed that the LE MMT scores for the quadriceps and hamstring muscles were the strongest predictors of success. In addition, the peak EMG amplitude from these same 2 muscles during walking was highly correlated with change in walking speed (Tab. 4). Because these 2 muscles also were much more active in individuals with SCI than in uninjured controls, it is likely that voluntary control of these 2 muscles allowed individuals to make the necessary compensations in their walking to become functional. The importance of the knee muscles for walking after SCI is in direct contrast to the small role that these muscles play in the walking of individuals without injuries. In individuals without injuries, knee muscles are generally much less active than ankle muscles during comfortable walking speeds, and the muscle moments about the knee are very low. We speculate that, after SCI, the muscles around the ankle that are normally very important for walking are weakened, leading to the need to compensate with the knee muscles to support the leg during stance and to lift the leg during swing.

Clinical Implications

Finally, we have focused on functional recovery of overground walking in this article. Our predictors of success do not apply to other possible gains related to BWSTT, such as preservation of muscle, bone, and cardiovascular health, which have been shown to be substantial for those with more-severe injuries. Although people with low muscle strength may not show gains in overground walking speed, they may show other physiological improvements important to their general health. Our predictions also may not apply to children, who may show greater plasticity for recovery of walking.

Our current findings suggest that the gains in walking speed obtained during BWSTT were not related to gains in muscle strength of the LE (ie, change in walking speed not correlated with change in LE MMT score). Our earlier study and the study by Grasso et al further suggested that gains in walking are related to the ability to modify muscle activation patterns during walking (ie, making EMG activity bursts more focused and making them occur at the appropriate time). Together, the results suggest that training individuals with SCI with and with residual control of the muscles in the actual task of walking is extremely important. Although strengthening of muscles may contribute to better walking, it cannot replace the need to learn new, specific muscle activation patterns during the execution of the task itself. The small number of participants in this study, however, must be interpreted with caution and will require verification in studies with larger sample sizes.

Dr Yang and Dr Gorassini provided concept/idea/research design, fund procurement, and facilities/equipment. All authors provided writing and data analysis. Dr Yang, Ms Nevett-Duchcherer, and Dr Gorassini provided data collection. Dr Yang provided project management and participants. Dr Norton provided consultation (including review of manuscript before submission).

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