ORIGINAL ARTICLE

Relationship Between ASIA Examination and Functional Outcomes in the NeuroRecovery Network Locomotor Training Program

Jeffrey J. Buehner, PT, MS, Gail F. Forrest, PhD, Mary Schmidt-Read, MS, DPT, Susan White, PhD, Keith Tansey, MD, PhD, D. Michele Basso, PT, EdD

ABSTRACT. Buehner JJ, Forrest GF, Schmidt-Read M, White S, Tansey K, Basso DM. Relationship between ASIA examination and functional outcomes in the NeuroRecovery Network Locomotor Training Program. Arch Phys Med Rehabil 2012;93:1530-40.

Objective: To determine the effects of locomotor training on: (1) the International Standards for Neurological Classification of Spinal Cord Injury examination; (2) locomotion (gait speed, distance); (3) balance; and (4) functional gait speed stratifications after chronic incomplete spinal cord injury (SCI).

Design: Prospective observational cohort.

Setting: Outpatient rehabilitation centers in the NeuroRecovery Network (NRN).

Participants: Individuals (n=225) with American Spinal Injury Association Impairment Scale (AIS) grade C or D chronic motor incomplete SCI having completed locomotor training in the NRN.

Intervention: The NRN Locomotor Training Program consists of manual-facilitated body weight–supported standing and stepping on a treadmill and overground.

Main Outcome Measures: AIS classification, lower extremity pin prick, light touch and motor scores, ten-meter walk and six-minute walk tests, and the Berg Balance Scale.

Results: Significant gains occurred in lower extremity motor scores but not in sensory scores, and these were only weakly related to gait speed and distance. Final Berg Balance Scale scores and initial lower extremity motor scores were positively related. Although 70% of subjects showed significantly improved gait speed after locomotor training, only 8% showed AIS category conversion.

Conclusions: Locomotor training improves gait speed to levels sufficient for independent in-home or community ambulation after chronic motor incomplete SCI. Changes in lower extremity motor and sensory scores do not capture the full extent of functional recovery, nor predict responsiveness to locomotor training. Functional classification based on gait speed may provide an effective measure of treatment efficacy or functional improvement after incomplete SCI.

Key Words: Locomotion; Postural balance; Recovery of function; Rehabilitation; Spinal cord injuries.

PEOPLE WITH SPINAL cord injury (SCI) describe the inability to ambulate among their most devastating disabilities.[1] Given the relatively young age of onset and an increasing longevity, improving functional independence, specifically ambulation, could substantially impact quality of life. Therefore, it is crucial that rehabilitation strives to maximize locomotor ability and functional recovery after SCI. Experimental evidence of improvement in stepping and motor control after activity-based training in animal models and human SCI has been translated into clinical neurorehabilitation.[2-12] Manual-facilitated locomotor training is an activity-based therapeutic intervention with the goal of reproducing kinematics of locomotion and providing sufficient afferent input to the nervous system to promote motor relearning after SCI. The multisite NeuroRecovery Network (NRN) applies locomotor training for chronic, motor incomplete SCI.[13] One focus of the NRN is to induce functional gains, including locomotion, during and beyond traditional treatment periods after injury. Whether functional changes reflect some resolution of neural deficits in chronic SCI remains unknown.

The International Standards for Neurological Classification of Spinal Cord Injury (ISNCSCI) developed by the American Spinal Injury Association (ASIA) and endorsed by the International Spinal Cord Society, is a well-accepted classification of neurologic deficit after SCI.[14-16] The examination uses dermatomal light touch and pin prick sensation and motor strength of selected muscle groups of the upper and lower extremities to determine the neurologic level of the injury. The ASIA Impairment Scale (AIS) classifies the extent of the SCI according to motor complete (AIS grades A and B) and motor incomplete injury (AIS grades C and D). AIS grade C differs from AIS grade D based on the proportion of key muscle groups below the level of injury that have muscle grades of 3 or higher.[15,16] Though the ISNCSCI examination was designed to classify impairment, a recent clinical trial has used motor scores and

List of Abbreviations

AIS	American Spinal Injury Association Impairment Scale
ASIA	American Spinal Injury Association
ISNCSCI	International Standards for Neurological Classification of Spinal Cord Injury
LEMS	lower extremity motor scores
NRN	NeuroRecovery Network
SCI	spinal cord injury

From the School of Health and Rehabilitation Sciences, The Ohio State University, Columbus, OH (Buehner, White, Basso); Human Performance and Movement Analysis Laboratory, Kessler Foundation Research Center, West Orange, NJ (Forrest); Department of Physical Medicine and Rehabilitation, University of Medicine and Dentistry of New Jersey, Newark, NJ (Forrest); Magee Rehabilitation Hospital, Philadelphia, PA (Schmidt-Read); and the Shepherd Center, Atlanta, GA (Tansey).

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Reprint requests to D. Michele Basso, PT, EdD, 106 Atwell Hall, The Ohio State University, 453 W 10th Ave, Columbus, OH 43210, e-mail: *basso.2@osu.edu*.

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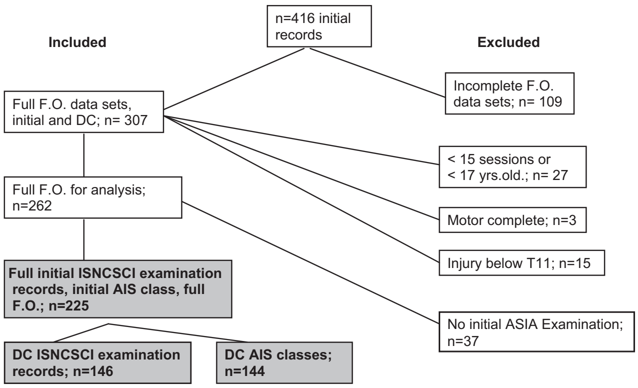

Fig 1. Data inclusion process. Shaded boxes indicate final datasets analyzed. Of the total 416 records analyzed, a 2.18% error rate in data entry or AIS classification procedures occurred. Abbreviations: DC, discharge; F.O., functional outcomes data.

AIS category conversion as a measure of therapeutic efficacy.[17] After SCI, spontaneous AIS conversion rates are 70% to 90% within the first year and 21% between 1 and 5 years.[18-21]

Certain ISNCSCI examination parameters collected acutely appear predictive of future ambulation. Early lower extremity or sacral pin prick sensation (72h or 4-wk postinjury) or early lower extremity motor scores (LEMS) correlate with walking at 1 year after SCI.[19,22-30] While the predictive ability of the ISNCSCI examination appears most accurate and reliable 72 hours after acute SCI, its ability to predict both changes in impairment at chronic time points with interventions like locomotor training or their relationship to functional improvements are unknown.[18]

Currently, gait speed is a widely used measure of walking ability after SCI, and it appears to be a good indicator of community ambulation.[8,9,31-35] van Hedel et al[34] established gait speed stratifications for independent ambulation after SCI. For 886 individuals with SCI (AIS grades A–D), attaining a minimum gait speed of .44m/s resulted in independent community ambulation with aid or assistive device. Thus, .44m/s may serve as a functionally relevant threshold to stratify individuals with SCI in order to gauge changes in other outcome measures and components of the ISNCSCI examination.

Recovery of walking and balance after SCI appear to be related.[36,37] The Berg Balance Scale demonstrates good validity and reliability for SCI.[38,39] However, a recent component analysis found limitations in sensitivity as a function of performance capacity for SCI.[40] Whether the extent of balance recovery is related to sensory and motor performance on the ISNCSCI examination is unknown.

This article evaluates the relationship between changes in ISNCSCI motor and sensory scores, locomotion, and balance induced by NRN locomotor training. This study had 3 objectives. The first was to identify the effect of locomotor training on AIS conversion, gait speed stratifications,[34] gait distance, Berg Balance Scale, sensation, and LEMS in chronic incomplete SCI. The second objective was to determine if pretraining ISNCSCI measures are related to locomotor and balance performance after locomotor training. The last objective was to examine gait speed stratifications relative to the proportion of strong or weak lower extremity muscles.

METHODS

Research Design

This prospective cohort design analyzed functional outcome and ISNCSCI examination data collected from March 2005 to July 2010 within the NRN. Briefly, subjects with incomplete SCI that no longer participated in acute inpatient rehabilitation and did not have lumbar lower motor neuron signs received locomotor training in the NRN. Patients with pacemakers, ventilators, or open wounds were ineligible to participate.[13]

Participants

The study included 225 participants with chronic incomplete SCI (fig 1). Participants were categorized based on AIS classification, tetra- and paraplegia, and initial gait speed at enrollment. All participants gave informed consent.

Outcome Measures

Trained clinicians conducted the ISNCSCI examination and AIS classification[15,16,41] at enrollment and discharge. LEMS (maximum of 50) represent the sum of individual strength scores on a 6-point scale across 5 muscle groups bilaterally: hip flexors, knee extensors, ankle dorsiflexors, great toe extensors, and ankle plantar flexors. We defined lower extremity pin prick and light touch scores as the sum of T11 to S4/5 dermatomes bilaterally (44 point maximum score). In all tests, higher scores represent better outcome.

Gait speed derived from the ten-meter walk test[42,43] and six-minute walk test,[42-44] gait distance from the six-minute walk test, which is considered a measure of functional endurance,[44] and balance (Berg Balance Scale)[45] were collected at initial evaluation, all reevaluations, and at the discharge evaluation. The Berg Balance Scale score was derived from 14 sitting and standing balance tasks (56 point maximum). When participants progressed across assistive devices, we used the

Table 1: Demographics (n=225)

Demographics	Total
Age at enrollment (y)	42.5±15.9 (17.4–85.7) n=225
Time since injury (y)	2.45±3.79 (.09–25.8) n=219
Sex M:F (n=225)	167:58
No. of sessions	60.3±53.24 (15–312) n=225
Paraplegia/tetraplegia (n=225)	59/166
AIS grade C/D at enrollment (n=224)	57/167
AIS grade C (n=57) paraplegia/tetraplegia	17/40
AIS grade C no. of sessions	81.7±76.5 (15–312) n=57
AIS grade C time from injury (y)	2.92±4.57 (0.20–25.8) n=54
AIS grade C age at enrollment (y)	35.1±12.0 (18.3–69.4) n=57
AIS grade D (n=167) paraplegia/tetraplegia	41/126
AIS grade D no. of sessions	52.1±38.6 (15–213) n=167
AIS grade D time from injury (y)	2.29±3.51 (0.09–22.0) n=164
AIS grade D age at enrollment (y)	45.1±16.3 (17.4–85.7) n=167

NOTE. Values are mean ± SD (range) or number of people in each category.
Abbreviations: F, female; M, male.

highest gait speed attained regardless of the device. No bracing or assistance was provided during gait or balance testing.

Locomotor Training

Locomotor training within the NRN consists of 3 components, which are fully described elsewhere[13,46]: (1) manual-facilitated, body weight–supported step training within the treadmill environment lasting 1 hour; (2) overground assessment; and (3) community reintegration lasting 15 to 30 minutes. Treatment frequency was approximately 5 times per week for nonambulatory participants, 4 days a week for ambulators requiring pronounced assistance and 3 days a week for independent walkers with moderate impairments. Reevaluations occurred approximately every 20 locomotor training sessions. Standardized progression of locomotor training has been described elsewhere.[13] Physical therapists, physical therapist assistants, and rehabilitation technicians provided treatment sessions and underwent yearly hands-on standardization.

Statistical Analyses

Statistical analyses used SAS Version 9.2.[a] Descriptive statistics were calculated for all variables using mean ± SD. Functional outcome variables, speed classifications, and sensory and motor scores at enrollment and discharge were compared using Wilcoxon signed-rank tests. The level of significance was adjusted for multiple comparisons via a Bonferroni adjustment.

Linear regression described the relationship between motor and sensory scores at enrollment and final gait speed (ten-meter walk test), distance (six-minute walk test), and Berg Balance Scale scores. Separate regression models were formulated for paraplegia and tetraplegia and AIS grades C and D. Pearson correlation coefficients (r) and coefficient of determination (r^2) were estimated for all comparisons.

Indicator variables were constructed for each of the lower extremity motor component scores (L2, L3, L4, L5 and S1) to specify if a subject exhibited fair to normal function (4 or 5) or paralysis/trace function (0 or 1). We did not evaluate intermediate functional levels (ratings of 2 or 3). McNemar test was used to compare the initial and discharge frequency of participants in each gait speed category (0, 0–<.44m/s, ≥.44m/s), and a chi-square test was used to determine statistical significance.

RESULTS

Rate of AIS Conversion After Locomotor Training

Some AIS conversion occurred with locomotor training regardless of level of injury. Of the 144 participants with AIS classifications recorded pre- and postlocomotor training, a significant number of participants (28.1%) classified as AIS grade C improved to AIS grade D (9/32; $P<.001$), while 92% of the overall sample remained unchanged (n=23 AIS grade C; n=109 AIS grade D). Three participants (2%) regressed from AIS grade D to AIS grade C. No regression to AIS grade B occurred. An average of 60 training sessions was delivered over a mean treatment duration ± SD of 5.0±5.0 months (table 1). Longer treatment durations occurred for AIS grade C than for AIS grade D. Participants with tetraplegia or paraplegia had

Table 2: Functional Outcome Measures Pre- and Postintervention for the Overall Sample, AIS Grades C and D

Outcome Measures	Pretraining	Posttraining	P (adjusted for multiple comparisons)
Overall sample	n=198–225	n=118–225	
Upper extremity motor score	38.36±10.83 (4–50) n=222	41.44±8.27 (13–50) n=129	<0.001
LEMS	31.85±13.98 (0–50) n=221	38.61±12.29 (2–50) n=130	<0.001
Touch	26.61±10.19 (0–44) n=198	27.75±10.17 (1–44) n=118	NS
Pin prick	19.92±12.34 (0–44) n=207	19.72±11.40 (0–44) n=124	NS
Six-minute walk test distance	94.4±115.09 (0–542.91) n=221	164.42±159.82 (0–577.29) n=217	<0.001
Six-minute walk test gait speed	0.26±0.32 (0–1.51) n=221	0.46±0.44 (0–1.60) n=217	<0.001
Ten-meter walk test gait speed	0.32±0.40 (0–2.34) n=219	0.55±0.55 (0–2.08) n=218	<0.001
Berg Balance Scale Scores	20.48±17.70 (0–56) n=225	29.24±20.60 (0–56) n=225	<0.001
AIS grade C	n=51–57	n=22–57	
Upper extremity motor score	33.33±14.26 (4–50) n=57	36.88±11.42 (13–50) n=25	0.016
LEMS	12.045±8.43 (0–34) n=56	22.5±14.77 (2–50) n=26	<0.001
Touch	22.86±11.11 (0–44) n=51	23.64±11.54 (2–44) n=22	NS
Pin prick	16.10±10.55 (0–36) n=53	15.25±13.38 (0–43) n=24	NS
Six-minute walk test distance	10.14±24.93 (0–133.5) n=53	39.50±82.95 (0–452.6) n=53	0.008
Six-minute walk test gait speed	0.03±0.07 (0–0.37) n=53	0.11±0.23 (0–1.26) n=53	0.008
Ten-meter walk test gait speed	0.03±0.07 (0–0.39) n=53	0.12±0.25 (0–1.42) n=53	0.008
Berg Balance Scale	5.17±4.44 (0–25) n=57	10.77±12.38 (0–56) n=57	<0.001
AIS grade D	n=147–167	n=96–167	
Upper extremity motor score	40.10±8.76 (14–50) n=165	42.54±6.94 (20–50) n=104	<0.001
LEMS	38.43±8.14 (10–50) n=165	42.63±7.37 (10–50) n=104	<0.001
Touch	27.91±9.55 (5–44) n=147	28.70±9.64 (4–44) n=96	NS
Pin prick	21.24±12.66 (0–44) n=154	20.79±10.67 (0–44) n=100	NS
Six-minute walk test distance	121.58±119.66 (0–542.91) n=167	206.00±157.65 (0–577.29) n=163	<0.001
Six-minute walk test gait speed	0.34±0.33 (0–1.51) n=167	0.57±0.44 (0–1.6) n=163	<0.001
Ten-meter walk test gait speed	0.41±0.42 (0–2.34) n=165	0.67±0.53 (0–2.08) n=162	<0.001
Berg Balance Scale Scores	25.78±17.50 (0–56) n=167	35.67±18.97 (0–56) n=167	<0.001

NOTE. Mean ± SD (range) and sample size per variable. Sample size is expressed as a range for each cohort because of missing cases or missing subsets of data primarily within the ASIA examination. Nonparametric Wilcoxon signed-rank test ($P<.05$).
Abbreviation: NS, not significant.

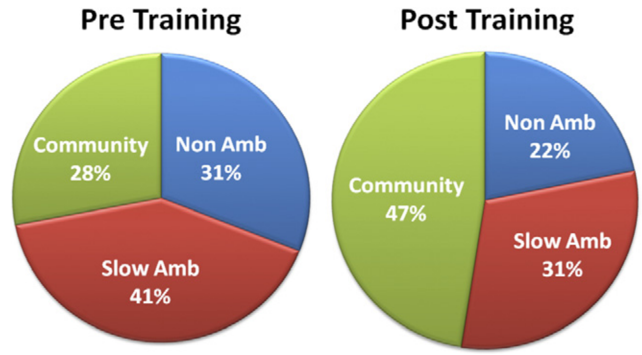

Fig 2. Functional stratifications based on van Hedel et al[34] cutoffs of nonambulatory, slow in-home ambulators (>0 to <.44m/s) and community ambulators (≥.44m/s) before and after manual locomotor training. Of the overall sample, 70% significantly improved in gait speed (P<.001) with almost half the sample walking at community speeds after locomotor training. The improved gait speed resulted in a significant shift to higher functional classifications after locomotor training (P<.001). Twenty-two percent of the sample remained nonambulatory after training. Abbreviation: Amb, ambulation.

treatment sessions and durations similar to the overall mean (57±49.5 and 70±62.1 sessions, 4.8±4.3 and 5.4±6.5mo, respectively).

Overall Changes in Functional Outcomes After Locomotor Training

Significant gains in gait speed, ambulation distance, and balance occurred after locomotor training regardless of initial AIS classification (n=225) (P<.01) (table 2). In general, functional outcomes were highly variable, reflecting the diversity of the sample (see table 2). For the overall sample, the mean gait speed (ten-meter walk test) improved by 72% after locomotor training (see table 2). Ambulation distance (six-minute walk test) improved by 74% (see table 2). Berg Balance Scale scores improved by 43% (see table 2). Also, significant improvements in balance, locomotor speed, and endurance occurred within both AIS grades C and D groups with less variability (P<.01) (see table 2). Overall values and the extent of relative change for participants classified as AIS grade D were similar to the overall sample, likely because of the high proportion of AIS grade D in the overall sample (see table 2). For AIS grade C, the overall values and extent of change were generally 10% to 30% of the overall sample. Relative gains for AIS grade C were much higher (200%–300%); although, this is, in part, influenced by lower overall functional outcome scores and a smaller sample (see table 2).

Conversion Rates Between Functionally Stratified Groups

Using van Hedel's[34] gait speed thresholds, participants were initially stratified into 3 functionally unique groups: (1) unable to ambulate; (2) slow or household ambulators (0–<.44m/s); and (3) community ambulators (≥.44m/s). Gains in gait speed resulted in significant conversion between these functionally stratified groups after locomotor training (P<.001) (fig 2).

Initial and discharge gait stratifications were available for 213 participants. At enrollment, 31% were nonambulatory, 41% were slow ambulators, and 28% walked at speeds sufficient for community ambulation (see fig 2). Of the 66 participants entering the program unable to ambulate, 44 (66.7%) remained nonambulatory, 18 (27.3%) became slow ambulators, and 4 (6.1%) attained speeds at or above .44m/s after locomotor training. Two participants that were slow ambulators at enrollment were nonambulatory at discharge (2.3%), and 2 participants that were faster ambulators became slow walkers (3.4%). Of the participants who never ambulated, 32 (73%) enrolled as AIS grade C and 12 (27%) were AIS grade D. In general, more participants classified as AIS grade D at admission converted from nonambulatory status to higher stratifications than AIS grade C. A modest number of participants of both classes converted to slow walking speeds (AIS grade C, n=7; AIS grade D, n=11), while 4 AIS grade D and none of the AIS grade C participants converted to fast ambulators (table 3). Functional stratification conversion was not different between para- and tetraplegia and resembled the overall sample.

Table 3: Maximum Gait Speed (ten-meter walk test) at Discharge for the Overall Group, AIS Grade (C and D), and Para/Tetraplegia and Conversion Between Functional Stratifications Per van Hedel's Cutoff (.44m/s)[34]

Initial Status	Discharge Status	Overall Gt Speed (m/s)	AIS Grade C (m/s)	AIS Grade D (m/s)	Paraplegia (m/s)	Tetraplegia (m/s)
Nonamb (n=66)	Nonamb	0 n=44	0 n=32	0 n=12	0 n=13	0 n=31
	<.44m/s	0.18±0.13 n=18	0.23±0.17 n=7	0.14±0.09 n=11	0.10±0.04 n=4	0.20±0.14 n=14
	≥.44m/s	0.97±0.52 n=4	NA n=0	0.97±0.52 n=4	NA n=0	0.97±0.52 n=4
<.44m/s (n=88)	Nonamb	0 n=2	0 n=1	0 n=1	0 n=1	0 n=1
	<.44m/s	0.23±0.12 n=45*	0.20±0.14 n=6	0.24±0.12 n=38	0.19±0.13 n=13	0.25±0.12 n=32
	≥.44m/s	0.84±0.35 n=41	0.78±0.45 n=4	0.85±0.35 n=37	0.79±0.33 n=12	0.86±0.36 n=29
≥.44m/s (n=59)	<.44m/s	0.32±0.03 n=2	NA n=0	0.32±0.03 n=2	0.34 n=1	0.30 n=1
	≥.44m/s	1.18±0.42 n=57	NA n=0	1.18±0.42 n=57	1.15±0.47 n=13	1.19±0.41 n=44

NOTE. Values are mean ± SD and sample size per variable.
Abbreviations: Gt, gait; NA, not applicable; NonAmb, nonambulatory.
*1 subject lacking preintervention AIS classification.

Fig 3. Lower extremity pin prick (A and C) and light touch (B and D) scores at enrollment compared with the maximum ten-meter walk gait speed (A and B) and Berg Balance Scale scores at discharge (C and D) for AIS grades C and D subsets. No relationship exists for either AIS classification. Note the prevalence of high gait speeds and high Berg Balance Scale scores despite low pin prick scores.

At enrollment, 88 participants were categorized as slow ambulators (<.44m/s) and nearly half (n=41; 47%) improved to fast ambulators (≥.44m/s) after locomotor training (*P*<.001). Participants classified as AIS grade D made up the majority of slow ambulators at enrollment (87% for AIS grade D vs 13% for AIS grade C), but there was no significant difference (*P*>.05) in rates of functional conversion between AIS grades (see table 3).

Fast ambulators at enrollment (≥.44 m/s) (n=59) were classified as AIS grade D. The majority remained in the fast ambulation category (96.6%) with a mean final gait speed ± SD of 1.2±0.4m/s. Two participants converted to slow ambulators with a mean final gait speed ± SD of .32±.03m/s (see table 3).

Sensation and Locomotor Training

Initial pin prick or light touch scores were widely distributed across final gait speeds, distances, and Berg Balance Scale scores after locomotor training (fig 3). In participants that never ambulated, marked variability occurred in both light touch scores (3–44) and pin prick scores (0–44). As expected, those classified as AIS grade C had mean pin prick and light touch scores 5 to 6 points lower than AIS grade D. A small group of participants (n=6) with pin prick scores of 0 became ambulators after locomotor training and 3 had gait speeds greater than .44m/s (fig 3A). In contrast, only 1 participant with a light touch score of 0 ambulated after locomotor training (~0.3m/s) (fig 3B). For Berg Balance Scale scores, several participants (n=13) had lower extremity pin prick scores of 0 and 2 demonstrated Berg Balance Scale scores greater than 50 (fig 3C). There are 2 fairly distinct and equal groupings (42%) of Berg Balance Scale scores for both pin prick and light touch: 1 group with scores ≥40 and another group with scores ≤20 (fig 3C and 3D, respectively). Our sample rarely had lower extremity light touch scores <10 (n=10; 4%), whereas many more

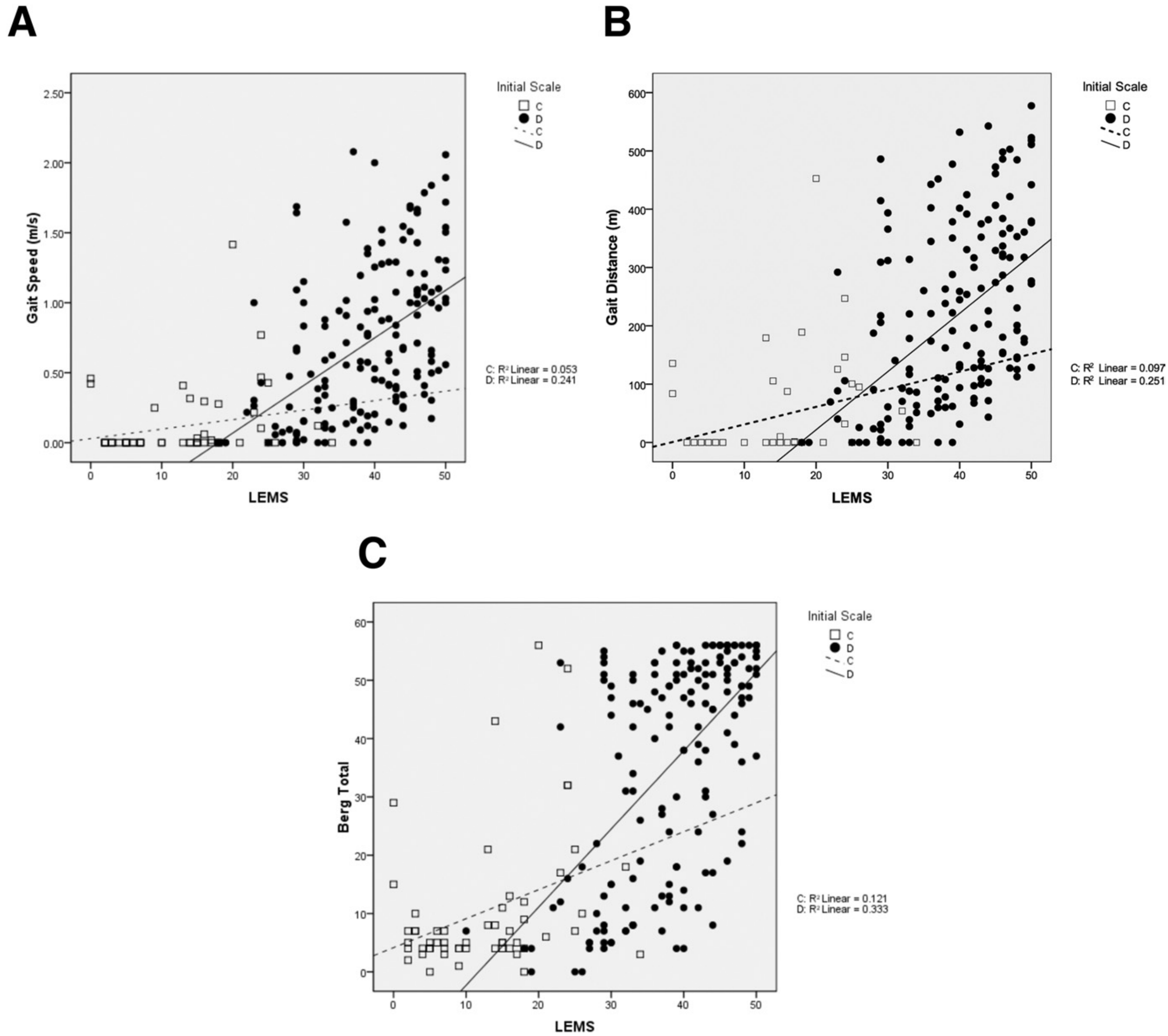

Fig 4. LEMS at enrollment compared with (A) maximum ten-meter walk test gait speed, (B) maximum six-minute walk test gait distance, and (C) Berg Balance Scale scores at discharge for AIS grades C and D subsets. Note no significant relationship occurred for LEMS and gait speed or distance in AIS grade C. Significant yet weak positive relationships occurred for AIS grade D.

participants (n=42; 19%) had lower extremity pin prick scores <10 (see fig 3). Pin prick scores of 0 to 30, which included ~75% of the sample, failed to distinguish differences in Berg Balance Scale scores (see fig 3C) and the six-minute walk test and ten-meter walk test (see fig 3A) after training.

Pin prick and light touch scores at enrollment did not correlate with gait speed, endurance, or balance after locomotor training, regardless of AIS grade or level of injury (see fig 3). Locomotor training did not induce changes in either pin prick or light touch scores (see table 2).

Overall LEMS Versus Gait Speed, Distance, and Balance

LEMS at enrollment did not correlate well with gait speed, endurance, or balance after locomotor training (fig 4). However, locomotor training induced a significant 21% improvement in LEMS ($P<.001$) (see table 2). Generally, participants with fast gait speeds, good gait distances, and high Berg Balance Scale scores at discharge had modest but not low LEMS at enrollment; however, wide variability existed. For example, several participants with high initial LEMS had very low gait speeds, gait distances, and balance scores at discharge (see fig 4). Likewise, posttraining walking speeds ≥.44m/s occurred in participants with LEMS as low as 0 (see fig 4A).

The relationships between initial LEMS and final gait speed, distance, and Berg Balance Scale scores differed between AIS grades C and D (see fig 4). In AIS grade D, weak but significant correlations existed between initial LEMS and posttraining gait speed, distance, and Berg Balance Scale scores (r^2=.24, .25, and .33, respectively; $P<.05$), whereas no correlations occurred for AIS grade C.

Moderately strong correlations occurred between the LEMS and final Berg Balance Scale scores for paraplegia (r^2=.49; $P<.05$) and tetraplegia (r^2=.47; $P<.05$) (fig 5). Weaker correlations occurred for the LEMS and distance (paraplegia: r^2=.38,

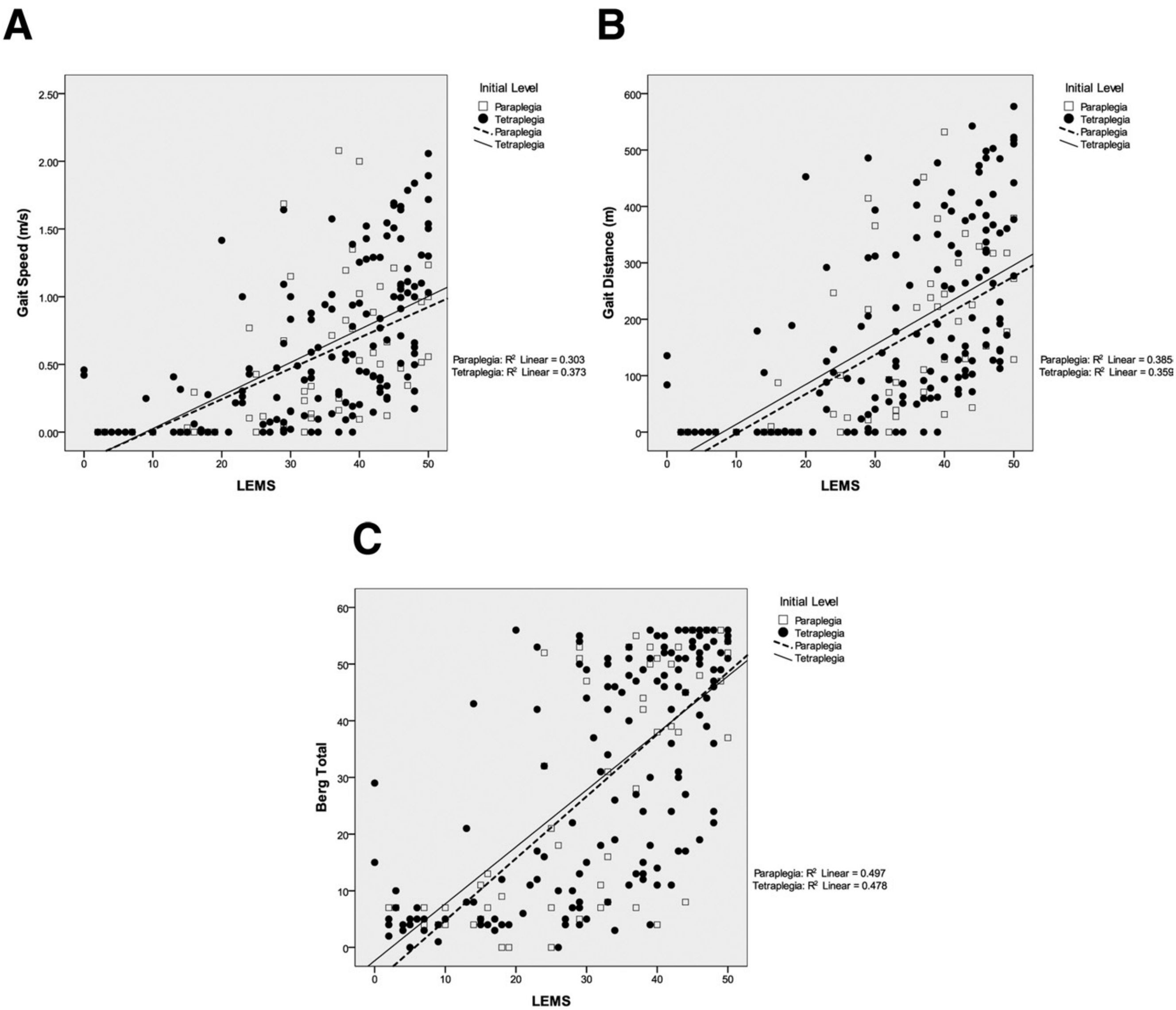

Fig 5. LEMS at enrollment compared with (A) maximum ten-meter walk test gait speed, (B) maximum six-minute walk test gait distance, and (C) Berg Balance Scale scores at discharge for tetraplegic and paraplegic subsets. Note moderately strong significant correlations between LEMS and Berg Balance Scale scores.

$P<.05$; tetraplegia: $r^2=.35$, $P<.05$) and gait speed (paraplegia: $r^2=.30$, $P<.05$; tetraplegia: $r^2=.37$; $P<.05$; Bonferroni-adjusted values for 18 comparisons: .05/18=.003) (see fig 5). While significant correlations occurred for tetraplegia, their strength was extremely poor ($r^2=.065$–.179) and did not warrant further consideration.

Gait speed significantly improved for most participants (70%) after training ($P<.001$) (fig 6; see table 2). For those showing improvement, LEMS ranged from 0 to 50 with the greatest change in gait speed (≥1.0m/s) in participants with initial scores of 20 to 50 (see fig 6). For participants who remained nonambulatory after training, 50% (n=21) had initial LEMS below 15. Nine percent of participants showed declines in gait speed after training and had initial LEMS ranging from 14 to 50 (see fig 6). Of the participants classified as AIS grade C that increased gait speed with training, gains were typically below 0.5m/s, while those classified as AIS grade D demonstrated gains from .05 to over 1.6m/s (see fig 6).

Influence of Strong Versus Weak Lower Extremity Muscles on Recovery

We examined whether the effect of locomotor training was dependent on the proportion of muscles with good strength within AIS grade C and D groups for each gait speed classification (table 4). Nonambulatory participants classified as AIS grade D that converted to ambulators after training typically had at least 6 to 8 muscle groups (out of 10) that scored 4 or 5, which equates to 60% to 80% of muscle groups with good strength. Nonambulatory participants classified as AIS grade C that became ambulators typically had few muscle groups with strength scores of at least 4 or 5 (~8%) and significantly more paralyzed muscle groups (53%) compared with AIS grade D (0%–12%; $P<.05$). By comparison, AIS grade C participants that never regained ambulation had even greater paralysis with 72% of muscle groups scoring 0 or 1.

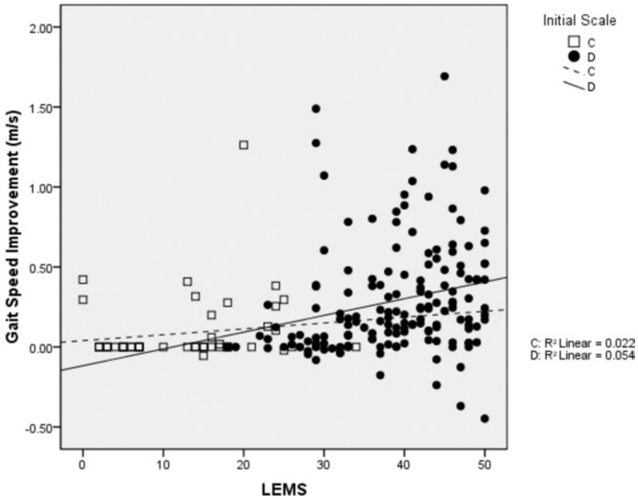

Fig 6. LEMS at enrollment compared with change in maximum ten-meter walk test gait speeds from pre- to posttraining. Note that the highest gains in speed were associated with initial LEMS in the mid- to high range (≥20). Note that declines in speed also occurred about this same LEMS range.

Individual Muscle Groups and Recovery

For the overall sample, strength of individual lower extremity muscles significantly increased with locomotor training ($P<.05$) (table 5). The most common muscle group with fair to normal strength at enrollment was the knee extensors (L3) (83.8%), which was not typically combined with good strength in the hip flexors (L2) (65.4%) (see table 5). Before locomotor training, paralysis or trace movement occurred in ankle dorsiflexors (L4) more often than any other muscle (40%). The greatest return to near normal strength after locomotor training occurred in the knee extensors (L3), and the greatest recovery from paralysis (ie, decrease in number of muscles scoring 0 or 1) occurred in the hip flexors and ankle dorsiflexors (13.1% and 11.5%, respectively; $P<.05$). Across the lower extremity, the greatest strength recovery occurred proximally in hip flexors and quadriceps (~14% increase in 4s and 5s; $P<.05$) compared with ankle dorsi- and plantarflexors (8.5% increase in 4s and 5s). Despite improvements in strength for individual muscles, more than a quarter of the overall sample (28.5%) continued to have paralysis/trace movement of the ankle dorsiflexors (L4) at discharge (see table 5).

DISCUSSION

To our knowledge, this cohort study is the largest to date examining the relationship between ISNCSCI examination parameters and functional outcomes after standardized activity-based therapy (locomotor training) in chronic incomplete SCI. Overall, 70% of participants improved gait speed with locomotor training, while 21% remained nonambulatory. For those with gait improvements (n=148), gait speed increased by 0.4±0.3m/s and distance ambulated in 6 minutes was 99.4±101.0m. Based on gait speed categories validated by van Hedel,[34] these gains in gait speed induced by locomotor training likely support conversion to home or community ambulation. Increased strength (21% overall improvement) and some resolution of paralysis in certain lower extremity muscle groups accompanied the improvements in ambulation. These gains were accompanied by a modest rate of AIS conversion and no improvement in lower extremity sensation. Thus, improvements in locomotion and balance induced by locomotor training may not be detected using broad classification measures of AIS, but muscle-specific scores may hold promise.

Conversion of AIS Classification

Locomotor training influenced the conversion of AIS classification in chronic SCI. Only a 21% conversion rate from AIS grade C to AIS grade D is expected between 1 and 5 years post-SCI,[21] but NRN locomotor training in chronic SCI produced a 28% conversion rate. Interestingly, AIS conversion from grade C to grade D (n=9) occurred with an average of 82 training sessions over 6.5 months, which is noteworthy given that 50% of the NRN sample was greater than 1 year postinjury at enrollment with 13% greater than 5 years post-SCI. Furthermore, locomotor training appeared to lessen regression for chronic SCI (3% vs 17%–21%),[21] although these lower regression rates may reflect the shorter time period (5mo vs 4y) and selection bias of those patients that were eligible for and interested in pursuing NRN locomotor training.

Recently, van Middendorp[19] studied 273 participants with acute (<1y postinjury) SCI AIS grade A through D and found that return to walking as measured by the Timed Up & Go test and the ten-meter walk test did not mirror conversion rates. Approximately 25% to 50% of those that converted from AIS grades A, B, or C to AIS grade D remained nonambulatory at 1 year. Likewise, in chronic SCI, AIS conversion is not sensitive to functional improvements produced by locomotor training. Indeed, 33% of nonambulators became walkers and 47% of slow walkers improved to faster walkers, whereas AIS conversion from grade C to grade D was 28% and no one classified as AIS grade D converted to AIS grade E. Therefore, in acute SCI, AIS conversion outpaces

Table 4: Overall Initial LEMS and Number of Lower Extremity Muscle Groups With Good Strength (4 or 5 muscle score) or Paralysis (0 or 1 muscle score) for Functional Stratifications as Determined by van Hedel's Cutoff (.44m/s)[34]

Speed Category		Observations		LEMS		No. of 4 or 5 LEMS		No. of 0 or 1 LEMS	
Initial Ten-Meter Walk Test	Final Ten-Meter Walk Test	AIS Grade C	AIS Grade D	AIS Grade C	AIS Grade D	AIS Grade C	AIS Grade D	AIS Grade C	AIS Grade D
0	0	32	12	10.7±7.8	28.2±7.0	0.7±1.3	4.1±2.1	7.2±2.8	2.2±2.0
	<.44	7	11	14.6±7.3	35.1±6.7	0.8±1.2	6.4±2.3	5.3±2.6	1.2±1.3
	≥.44	0	4	NA	41.0±2.7	NA	8.2±1.2	NA	0.0±0.0
<.44	0	1	1	25.0	29.0	4.0	3.0	4.0	2.0
	<.44	6	38	22.2±7.0	35.7±7.5	3.4±1.9	6.3±2.6	4.2±1.8	1.2±1.4
	≥.44	4	37	17.0±11.5	39.4±6.4	1.8±1.2	7.7±2.1	4.5±3.8	0.6±0.9
≥.44	<.44	0	2	NA	42.0±7.1	NA	8.0±1.4	NA	0.5±0.7
	≥.44	0	57	NA	43.1±6.5	NA	8.6±2.1	NA	0.3±0.9

NOTE. Values are mean ± SD and number of observations.
Abbreviation: NA, not applicable.

Table 5: Number and Percentage of the Overall Sample With Good or Poor Motor Response in at Least 1 Lower Extremity During LEMS Testing (n=130)

	Initial Evaluation		Discharge Evaluation	
Muscle Groups	Fair to Normal Resistance 4 or 5 MMT	Trace Mvt or Paralysis 0 or 1 MMT	Fair to Normal Resistance 4 or 5 MMT	Trace Mvt or Paralysis 0 or 1 MMT
Hip flexors L2	86 (66.2)	36 (27.7)	103 (79.2)*	19 (14.6)*
Quadriceps L3	109 (83.8)	16 (12.3)	117 (90)	12 (9.2)
Ankle DF L4	92 (70.8)	52 (40)	101 (77.7)	37 (28.5)*
Ankle PF S1	97 (74.6)	25 (19.2)	106 (81.5)	15 (11.5)*
Hip flexors and quadriceps	85 (65.4)	15 (11.5)	103 (79.3)*	11 (8.5)
Ankle DF and PF	84 (64.6)	22 (16.9)	95 (73.1)	14 (10.8)

NOTE. Values are number (%).
Abbreviations: DF, dorsiflexors; MMT, manual muscle test; Mvt, movement; PF, plantarflexors.
*McNemar test: Bonferroni adjusted *P* values ≤.05 versus proportion at initial evaluation.

gains in walking; yet after locomotor training, in chronic incomplete SCI, gains in walking outpace AIS conversion. While AIS conversion has been used in clinical trials to determine treatment efficacy,[17,47,48] our data suggest that it may be a relatively poor indicator for recovery of walking ability in both acute and chronic SCI.

Conversion Between Functional Stratifications

We used a gait speed of .44m/s to stratify patients into functional categories,[34] similar to the European Multicenter Study for Human Spinal Cord Injury,[49] and following trends reported in other studies.[31,32,41,50] Locomotor training significantly increased conversion between functionally stratified groups, as 47% of slow ambulators (<.44m/s) converted to fast ambulators (≥.44m/s). Equal proportions of participants in AIS grades C and D converted to fast ambulators. Also, although a large proportion of initial nonambulatory participants classified as AIS grade D (56%; 15/27) converted to ambulators after locomotor training, 18% (7/39) of initial nonambulatory AIS grade C participants converted to ambulators as well. Thus, classifying participants based on functional ambulation criteria, rather than AIS classification, may be more valuable in determining the appropriateness of and responsiveness to locomotor training, although future studies may be required to validate the functional strata used here.

Gains in Strength After Locomotor Training

Locomotor training induced significant gains in the LEMS (see table 2). Such improvement has been reported during the first year postinjury.[18,51] From 1 to 5 years, however, the rate of strength recovery slows. Only 58% of patients have strength gains in this period and few (28%) had gains more than 6 points in the lower and upper extremities combined.[21] Whether strength gains in our study are because of simple resistance training or result from neuroplastic changes in the central nervous system, increased motor unit recruitment or changes in muscle fiber type remains unknown.

Gains in Balance After Locomotor Training

Berg Balance Scale scores significantly improved with locomotor training (43% of the overall sample), which supports the theory that standing balance improves as lower extremity strength improves. Not evident from this study was whether locomotor training improves trunk control and strength given that LEMS do not assess core strength. It seems logical that because locomotor training improves the LEMS and balance, that improvement in trunk strength would also occur. With new trunk assessments, future studies may determine the role of trunk strength and motor control in recovery of ambulation in chronic incomplete SCI.

Pin Prick and Light Touch

Both pin prick and light touch scores can be sensitive predictors of motor recovery after acute and chronic SCI.[19,27,52] Our study found that below-level sensation had no relationship to locomotor recovery (neither gait speed, endurance, nor balance) after locomotor training in chronic incomplete SCI. This agrees with Winchester et al[35] who identified predictive factors of gait speed after manual and robotic training in incomplete SCI and found that lower extremity pin prick did not contribute significantly to the model. It may be that locomotor ability after locomotor training is less dependent on conscious perception of sensation and more dependent on the interaction of sensation with interneuronal networks at the cord level or at subcortical levels such as the cerebellum or basal ganglia.[53] Also, although those that ambulated after locomotor training showed a wide range of light touch and pin prick scores, it may be that particular dermatomal segments in the lower extremities, such as the plantar surface of the foot, are more related to locomotor ability than the overall lower extremity score. Future exploration of the relationship between specific lower extremity dermatomes or dermatomal patterns and ambulation ability after locomotor training in chronic incomplete SCI is needed.

Overall LEMS Versus Gait Speed, Distance, and Balance

Overall LEMS at enrollment does not indicate responsiveness to locomotor training or final outcomes in gait speed or endurance, regardless of type or severity of injury (tetra- vs paraplegia; AIS grades C and D), as shown previously.[35] The high variability in the LEMS and ambulation ability after locomotor training suggests that there are probably other components of motor control besides strength that contribute to recovery of locomotion, such as coordination, timing, spasticity, or tone.

Higher initial LEMS were associated with greater recovery of balance. However, lower extremity strength at enrollment accounted for only 33% of the variance in final Berg Balance Scale scores for AIS grade D. Balance performance likely depends on other variables, like trunk control or the ability to initiate movements quickly.[54] Balance synergies may be markedly impaired when requisite individual muscle groups, like ankle dorsiflexors or hip extensors, are paralyzed. Interestingly, participants with paraplegia or tetraplegia showed significant positive correlations (see fig 5) between initial LEMS and postintervention Berg Balance Scale scores. The similarity between groups could reflect subgroups of tetraplegia, which display ranges and patterns of trunk motor control as in paraplegia. Further study is warranted into the relationship of individual lower extremity or trunk muscle groups and balance after locomotor training.

Influence of Strong Versus Weak Lower Extremity Muscles on Recovery

The ability to respond to locomotor training may relate to the degree of strength and paralysis of individual lower extremity muscle groups rather than the overall LEMS. For AIS grade D, the degree of strength appears to delineate nonambulators from ambulators, whereas for AIS grade C, the degree of paralysis or severe paresis delineates walking ability. There is no particular number of muscle groups, which separates walkers from non-walkers. However, a study is currently underway to determine if muscle strength, paralysis, or the ratio of the 2 criteria can be used to predict the extent of locomotor and balance recovery for participants with AIS grades C and D.

Individual Muscle Groups and Distribution Patterns of Strength Recovery

Locomotor training increased individual muscle strength as evidenced by more muscle groups scoring in the near normal range (4 or 5) and fewer muscle groups with paralysis or severe paresis (0 or 1). The greatest return of near normal strength occurred in the knee extensors, while the greatest persistence of weakness or paralysis occurred in ankle dorsiflexors. Accordingly, Kim et al[55] showed that proximal muscle strength was more highly correlated than distal muscles with ambulation distance and speed after chronic incomplete SCI.

Further, the number of training sessions needed to improve locomotion seemed to depend on the extent of paralysis at enrollment. Delivery of an average of 50 sessions was associated with a 20% reduction in paralysis for AIS grade C and 20% increase in strength for AIS grade D. Hence, a check of the LEMS at or before 50 sessions for nonambulatory patients may indicate whether further training will be effective. Overall, recovering gait speed sufficient for community ambulation occurs faster for AIS grade D with greater muscle strength but may also be attainable for a subset of individuals with AIS grade C that train longer.

Relationships Between Patient Categories, AIS Measures, and Gait Measures in the NRN Locomotor Training Program

In this study, there was an extensive overlap in functional ability between participants with paraplegia and tetraplegia. Clinically, we predict greater locomotor and balance recovery with paraplegia than tetraplegia because more of the neural axis is spared and more motor function in the upper extremities and trunk may be preserved. These assumptions are not supported here. Trunk motor control may differ greatly within the same SCI classification and level of injury, which may explain why the responses of participants with paraplegia or tetraplegia to NRN training were indistinguishable. Further research is necessary to identify the contribution of trunk motor control and arm function to recovery of gait and balance, which could predict which patients will benefit most from locomotor training.

Study Limitations

Improvements in strength, gait speed, and balance may be due, in part, to natural recovery and not solely induced by locomotor training. While the longitudinal, pre-post design of our study has the advantage of controlling intersubject variability, it does not provide an untrained control group. In lieu of an untrained control group, the degree of natural recovery was estimated to be quite low from previous studies, but the possibility exists that the current nature of SCI severity and recovery differs from these older studies.[19,24,56]

CONCLUSIONS

Manual-facilitated locomotor training is related to improvements in gait speed, distance, balance, and functional ambulation ability in individuals with chronic motor incomplete SCI. Outcomes derived from the ISNCSCI examination and AIS classification may be poor indicators for recovery of walking ability, and care should be taken when using them to determine treatment efficacy or functional improvement after locomotor training. Functional classification based on gait speed may be a more sensitive indicator of treatment efficacy or functional improvement after locomotor training.

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