ORIGINAL ARTICLE

Assessment of Functional Improvement Without Compensation Reduces Variability of Outcome Measures After Human Spinal Cord Injury

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ABSTRACT. Behrman AL, Ardolino E, VanHiel LR, Kern M, Atkinson D, Lorenz DJ, Harkema SJ. Assessment of functional improvement without compensation reduces variability of outcome measures after human spinal cord injury. Arch Phys Med Rehabil 2012;93:1518-29.

Objective: To develop a scale (Neuromuscular Recovery Scale [NRS]) for classification of functional motor recovery after spinal cord injury (SCI) based on preinjury movement patterns that would reduce variability of the populations' level of function within each class, because assessment of functional improvement after SCI is problematic as a result of high variability of the populations' level of function and the insensitivity to change within the available outcome measures.

Design: Prospective observational cohort with longitudinal follow-up.

Setting: Seven outpatient rehabilitation centers from the Christopher and Dana Reeve Foundation NeuroRecovery Network (NRN).

Participants: Individuals (N=95) with American Spinal Injury Association Impairment Scale (AIS) grade C or AIS grade D having received at least 20 locomotor training treatment sessions in the NRN.

Interventions: Intensive locomotor training including stepping on a treadmill with partial body weight support and manual facilitation and translation of skills into home and community activities.

Main Outcome Measures: Berg Balance Scale, six-minute walk test, and ten-meter walk test.

Results: Individuals classified within each of the 4 phases of the NRS were functionally discrete, as shown by significant differences in the mean values of balance, gait speed, and walking endurance, and the variability of these measurements was significantly reduced by NRS classification. The magnitude of improvements in these outcomes was also significantly different among phase groups.

Conclusions: Assessment with the NRS provides a classification for functional motor recovery without compensation, which reduces variability in performance and improvements for individuals with injuries classified as AIS grades C and D.

Key Words: Outcome assessment (health care); Rehabilitation; Spinal cord injuries.

THERE IS A CRITICAL need for the development of valid, reliable, and sensitive outcome measures[1] for use in the rehabilitation of individuals with spinal cord injury (SCI) and in conducting meaningful clinical trials. The International Standards for Neurological Classification of Spinal Cord Injury (ISNSCI) is often used as a measure of neurologic status and recovery after SCI both clinically and in research.[2] The scale classifies the consequences of SCI according to the severity of motor and sensory impairment and whether the injury is complete or incomplete. In rehabilitation studies, the ISNSCI is used to describe the specific population being studied, and the American Spinal Injury Association Impairment Scale (AIS) classification implies a relative homogeneity within the population. The effect of an experimental therapeutic intervention is then tested on this presumptive, homogeneous population. The AIS is an effective classification tool at the body structures and function levels,[3,4] but the considerable heterogeneity in activities, participation, and functional outcomes after SCI undermines the effectiveness of the AIS and other outcome measures in the assessment of functional recovery.[5-7] The degree of heterogeneity is particularly apparent for individuals with motor incomplete SCI: AIS grades C and D (for further discussion, refer to the appropriate articles in this issue: Harkema et al[8] and Buehner et al[9]).

Significant variability of baseline performance on the Berg Balance Scale, the six-minute walk test, and the ten-meter walk test occurs in individuals with AIS grades C and D from months to years postinjury.[8,10] Variability in the baseline performances from a population of individuals with motor incomplete SCI may diminish the capacity to test the therapeutic effectiveness of an

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List of Abbreviations

AIS	American Spinal Injury Association Impairment Scale
ISNSCI	International Standards for Neurological Classification of Spinal Cord Injury
mph	miles per hour
NRN	NeuroRecovery Network
NRS	Neuromuscular Recovery Scale
SCI	spinal cord injury

intervention. Specifically, baseline performances that span a broad range of scores will mask improved performance scores associated with an intervention of interest.[11] Recovery is the restoration of the neuromuscular system to regain function using preinjury motor behaviors, whereas behavioral compensation refers to the use of atypical motor patterns, behaviors, body segments, technology, and/or assistive devices to make up for neurologic deficits postinjury to accomplish functional tasks.[12-14] The degree of variability may be further increased when outcomes are based on the successful use of compensatory strategies for achieving a functional goal as compared with the recovery of premorbid movement patterns.[12] The purpose of this study was to develop a classification of functional ability based on an individual's capacity for sitting, standing, and walking in an overground environment without compensation, and to bear weight and independently stand or step using body weight support on a treadmill. We hypothesized that classifying individuals with motor incomplete SCI according to recovery of task-specific movements would (1) result in statistically significant differences among groups in balance, gait speed, and walking endurance measures, (2) significantly reduce the variability within groups for balance, gait speed, and walking endurance measures, (3) result in significant differences among groups for improvements in these measures in response to at least 1 therapeutic intervention, and (4) show that improvements in all outcome measures in response to the intervention would be significantly and positively correlated with the size of the change in phase.

METHODS

Participants

We examined 95 patients with motor incomplete SCI who completed 20 sessions or more of a standardized locomotor training program across 7 outpatient clinical sites in the Christopher and Dana Reeve Foundation NeuroRecovery Network (NRN): Boston Medical Center, Boston, MA; Frazier Rehab Institute, Louisville, KY; Kessler Institute for Rehabilitation, West Orange, NJ; Magee Rehabilitation Hospital, Philadelphia, PA; The Ohio State University Medical Center, Columbus, OH; Shepherd Center, Atlanta, GA; and The Institute for Rehabilitation and Research Memorial Hermann, Houston, TX. Enrollment criteria for patient entry in the NRN locomotor training program included presence of a nonprogressive spinal cord lesion above T11, no current participation in an inpatient rehabilitation program, and medical referral by an NRN physician. Patients also must have exhibited some lower limb movement or visible voluntary contraction and the capacity to generate a lower limb reciprocal alternating flexion/extension stepping pattern in the step training environment using body weight support on a treadmill with manual facilitation. The NRN physician also directed eventual elimination of antispasticity medications to avoid inhibiting neuromuscular activity during the training. Enrollment characteristics of the entire population are provided in table 1. Patients considered in this article were enrolled in the NRN between February 1, 2008 and June 30, 2009.

Evaluations

Therapists conducted patient evaluations at enrollment into the NRN program and a postintervention evaluation on discharge. Evaluations included the ISNSCI AIS,[15] Berg Balance Scale,[10,16,17] six-minute walk test,[18-21] and the ten-meter walk test.[18-20] The AIS, Berg Balance Scale, six-minute walk test, and ten-meter walk test were performed and scored according to standard procedures.[22]

Neuromuscular Recovery Scale

The Neuromuscular Recovery Scale (NRS) was developed by clinicians and researchers between 2000 and 2008 based on their collective research efforts and clinical experience and the on-going program evaluation conducted within the NRN. The clinicians were primarily physical therapists working in collaboration with basic scientists and clinical researchers. The NRS was designed as a classification tool and is divided into 4 phases of neuromuscular recovery after SCI based on the individual's ability to perform task-specific movements relative to the preinjury capability, with phase 1 representing the lowest degree of functional recovery and phase 4 designating full recovery of function. Subphases (eg, 1A, 1B, 1C) delineate incremental improvements in recovery. The focus of the current work was in comparing the numeric phases (ie, 1–4) with respect to functional outcomes. The NRS uses 11 functional tasks that are related to mobility, standing, and walking, which are evaluated in the body weight support treadmill and overground environments. Overground is a term used to delineate the everyday environment for the NRS testing, in contrast to use of the treadmill environment for testing.

The scale includes 7 tasks tested in the overground environment including sit, sit-up, reverse sit-up, trunk extension, sit-to-stand, stand, and walk (appendices 1 and 2). For the overground tasks, physical assistance is only given when helping a patient achieve a position but not during the scoring of the task. For example, the patient is not allowed to use their arms when evaluating the ability to move from supine to sitting. The ability to attain and maintain sitting, to

Table 1: Demographic and Clinical Characteristics at Enrollment of the NRN Sample

Demographic and Clinical Characteristics	N=95
Sex	
Male	75 (79)
Female	20 (21)
Age (y)	43±17
AIS grade	
C	31 (33)
D	64 (67)
Injury level	
Cervical	72 (76)
Thoracic	23 (24)
Mechanism of injury	
MVC	31 (33)
Fall	19 (20)
Sporting accident	20 (21)
Nontrauma	8 (8)
Medical/surgical	11 (12)
Violence	6 (6)
Assistive walking device	
Nonambulatory	31 (33)
Walker	35 (37)
Cane(s)/crutch(es)	27 (28)
None	2 (2)
Time since SCI (y)	1 (0.1, 25.8)
<1y	47 (49)
1–3y	24 (25)
≥3y	24 (25)
Treatment and enrollment characteristics	
Time of NRN enrollment (d)	96 (30, 447)
Cumulative treatment sessions received	40 (20, 220)
Cumulative number of evaluations	3 (2, 12)
Treatment intensity (Tx/evaluation)	19±4

NOTE. Values are counts (%) for categorical variables and mean ± SD or median (minimum, maximum) for continuous variables.
Abbreviations: MVC, motor vehicle collision; Tx, treatments.

transition from sitting to standing, to stand, and the ability to independently execute the components of standing and walking are all evaluated without the use of compensation. Physical assistance may be provided at the legs and pelvis, while evaluating independence and proper trunk posture. However, once a body segment is evaluated as independent, assistance is not provided at any other subsequent phase of evaluation. Progression overground entails the ability to perform tasks of increasing difficulty or challenge to neuromuscular demands (eg, able to sit with proper posture advances to reaching forward and laterally outside of base of support).

Four tasks occur in the body weight support treadmill environment and include stand retraining, stand adaptability, step retraining, and step adaptability. Retraining (stand or step) uses therapist/trainer manual facilitation, while adaptability (stand or step) does not use physical assistance. The body weight support treadmill environment provides a means to quantify characteristics (ie, body weight load and achievable treadmill speed during retraining) that are reflective of recovery needed for the eventual achievement of standing and walking. During adaptability, the neuromuscular system's ability to independently achieve the components of standing and walking is assessed.

Briefly, a patient whose recovery is classified as phase 1 requires 50% to 60% body weight support and significant manual facilitation at the trunk, pelvis, and legs to generate the optimal position/pattern during step retraining on the treadmill and ≥40% to 20% body weight support for stand retraining. During this phase, the patient gains the ability to independently maintain proper trunk kinematics during step adaptability with body weight support <60% and >20% and treadmill speed between 0.27 to 0.54m/s (0.6–1.2 miles per hour [mph]). Patients are unable to perform tasks overground (eg, sit-up) without the use of compensation strategies. With an attempt to sit-up from a supine position, only the head is lifted. Often the individual experiences symptoms of multiple secondary conditions related to neurologic injury, and the primary focus of rehabilitation is retraining posture and increasing endurance. On classification of recovery as phase 2, patients require less body weight support during stand (<20% and ≥10%) and step retraining (<50% and ≥35%). During adaptability, the ability to control the trunk is assessed at <20% body weight support at 0.27 to 0.54m/s (0.6–1.2mph) and if achieved, then trunk and pelvis independence is observed at body weight support <40% and ≥20% at 0.27 to 0.54m/s (0.6–1.2mph). The patient has regained mobility overground and, for sit-up, the patient is able to lift head, shoulders, and scapulae inferior angles off of the mat. Rehabilitation focuses on retraining the nervous system to stand. At the phase 3 level of recovery, the optimal pattern is achieved with body weight support during stand (0%–9%) and step retraining (<35% and ≥0%). During adaptability, trunk, pelvis, and leg kinematics are independently maintained during standing (<10% body weight support), and trunk and pelvis leg kinematics are maintained during stepping at <20% body weight support and speeds of 0.58 to 0.89m/s (1.3–<2.0mph). If achieved, trunk, pelvis, and leg kinematics and independence are observed at <10% body weight support and at speeds of 0.89m/s (>2.0mph). Overground mobility is substantial, but the patient still needs significant compensation for ambulation in the home and community. With arms crossed over the chest, the patient is able to sit-up while raising head, shoulders, and trunk off the mat, although with significant effort. Rehabilitation focuses on retraining the nervous system to walk. Phase 4 recovery is characterized by independent stepping or running (step adaptability) with best pattern achieved using <10% body weight support and at 1.52m/s (>3.4mph) (eg, running). Independent standing with proper posture and position of pelvis and legs is demonstrated with 0% body weight support. Overground, a complete sit-up is achieved with arms across chest from supine to sitting without significant effort. Compensation is not required and rehabilitation focuses on increasing endurance and speed and adapting to environmental challenges, while returning to preinjury physical activities. Detailed descriptions of test administration and scoring are provided in appendices 1 and 2.

Intervention

Locomotor training is an activity-based therapeutic intervention using the body weight support treadmill environment with manual facilitation as a means to provide optimal kinematic and kinetic sensory input to the nervous system, with the aim of facilitating neuroplasticity and recovery of normative movement and function in individuals with SCI. The locomotor training protocol is standardized across NRN centers.[22] A session consists of 20 minutes of step retraining on the treadmill, 55 to 60 minutes total time on the treadmill (includes both step/stand retraining and stand/step adaptability), and 15 to 30 minutes of translation of skills to home and community ambulation and activities.

Data Analysis

Demographic and clinical characteristics and outcome variables were summarized with counts and percentages for categorical variables and with means and SDs and/or medians, minima, and maxima for continuous variables. The purpose of our analyses was to demonstrate the variability in performance and recovery shown on 3 functional outcome measures—the Berg Balance Scale, six-minute walk test, and ten-meter walk test—and to assess whether the variability of outcomes is significantly reduced with classification of patients using the NRS. The distributions of the outcome measures at enrollment were compared across the phase groups with Kruskal-Wallis tests. Comparisons of the corresponding variances were conducted with the nonparametric Fligner-Killeen test, and the variability in outcome measures accounted by phase grouping was examined through the R^2 statistics from a least-squares linear model. Enrollment to discharge changes for each outcome measure were compared with the Wilcoxon signed-rank test, both for the full sample and within each phase group. These changes were compared among the phase groups with the Kruskal-Wallis test. All analyses were performed in the open-source R software package,[23] and all hypothesis tests were conducted at the .05 significance level.

RESULTS

Demographic and Clinical Characteristics

Demographically, our study sample was largely men (79%) and exhibited a wide range of ages, times since SCI, and mechanisms of injury (see table 1). Most patients had AIS grade D classification (67%), but there was representation of AIS grade C as well. Patients with cervical lesions outnumbered those with thoracic lesions 3-to-1. The injury mechanisms were variable, with motor vehicle collisions, falls, and sporting accidents being most common. Ambulatory patients used a variety of devices for compensation during walking; 31 were nonambulatory at enrollment. Patient enrollment varied considerably as measured by number of treatment sessions received, length of time enrolled, and number of evaluations conducted. However, treatment intensity per evaluation was relatively consistent, as measured by sessions per evaluation. At enrollment in the NRN, 40 (42%) of 95 patients under consideration were classified as being in phase 1 of recovery, 42 (44%) as phase 2, and 13 (14%) as phase 3.

Outcome Measure Performance Magnitude and Variability at Enrollment: Classification by the NRS

There was a substantial amount of variability in the Berg Balance Scale (SD=16), six-minute walk test (SD=97), and ten-meter walk test (SD=0.35) at enrollment among the full NRN sample, which was substantially accounted for by consideration of the phase groups (fig 1). Specifically, enrollment assessments of the outcome measures significantly differed among the 3 phase groups (Kruskal-Wallis test, $P<.001$ for each measure), and were ordered naturally—Berg Bal-

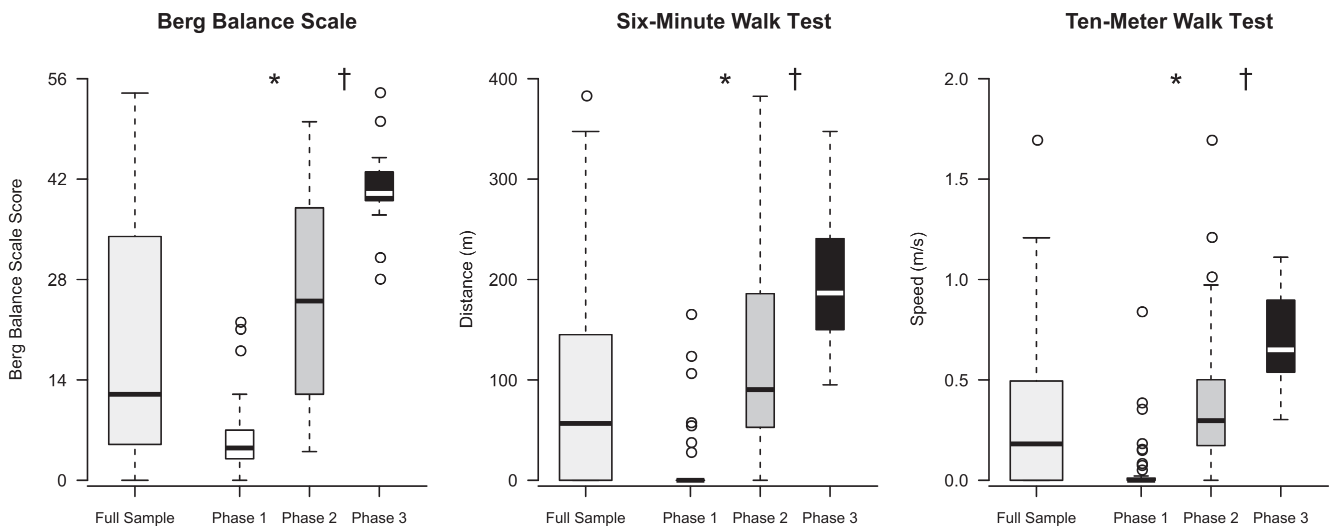

Fig 1. Boxplots of NRN enrollment measurements of the Berg Balance Scale (left panel), six-minute walk test (center), and ten-meter walk test (right) at NRN enrollment for the full sample and by phase at enrollment. *Phases significantly differed on outcome measure, Kruskal-Wallis test, *P*<.001. †Variances significantly differed among phases, Fligner-Killeen test, *P*<.001.

ance Scale scores (mean ± SD, 5.8±4.8, 24.7±14.0, 41.0±6.7 for phases 1, 2, and 3, respectively), six-minute walk test distance in meters (mean ± SD, 14±37, 121±92, 196±74 for phases 1, 2, and 3, respectively), and ten-meter walk test speeds in meters per second (mean ± SD, 0.06±0.15, 0.42±0.35, 0.68±0.27 for phases 1, 2, and 3, respectively) were lowest for patients in phase 1 and increased up to phase 3, respectively. Further, accounting for patient phase substantially and significantly reduced the variability in the measurements. In linear models of the outcome measures with phase number as a 3-level factor, phase accounted for 60%, 47%, and 42% of the variability in the Berg Balance Scale, six-minute walk test, and ten-meter walk test, respectively. We also noted that the amount of variability in the outcome measures within each phase group significantly differed (Fligner-Killeen test, *P*<.001 all measures). Patients in phase 2 tended to exhibit the most variability in measurements at enrollment, and patients in phase 1 exhibited the least. The NRS classification was further able to discriminate patients with respect to functional performance within AIS grade C and AIS grade D groups (table 2, fig 2). Specifically, phase groups significantly differed with respect to performance at enrollment on the outcome measures within AIS grade C (Kruskal-Wallis test, *P*<.001 all measures) and AIS grade D groups (*P*<.001 all measures). In addition, among phase 2 patients, AIS grades C and D patients did not significantly differ on enrollment evaluations of the Berg Balance Scale, six-minute walk test, and ten-meter walk test (Wilcoxon rank-sum test, *P*=.81, .73, .61, respectively).

Improvements in Functional Outcomes: Comparison of Enrollment to Discharge Evaluation

There was significant improvement in each outcome measure for each phase group (Wilcoxon signed-rank test, *P*<.01 for all measures and phases), and there was considerably less within-phase variability than full-sample variability (fig 3). The phase groups exhibited significantly different magnitudes of improvement for each measure (Kruskal-Wallis test, *P*<.01 for all measures). Improvements in Berg Balance Scale scores were lowest among patients classified as phase 1 (mean ± SD, 6.4±12.9) and substantially higher among those classified as phase 2 (mean ± SD, 10.9±10.4) and phase 3 (mean ± SD, 10.5±6.1). Improvements in the walk tests were ordered according to the phases; six-minute walk test distances improved 43±88m, 72±92m, and 107±77m for patients classified as phase 1, 2, and 3, respectively, and ten-meter walk test speeds improved 0.11±0.25m/s, 0.25±0.31m/s, and 0.30±0.20m/s in phases 1, 2, and 3, respectively. Patients classified as phases 1 and 2 for neuromuscular recovery exhibited similar magnitudes of improvement for the outcome measures (*P*>.14, all measures), with patients classified as phase 1 generally exhibiting substantially smaller improvements.

NRS Improvement and Outcome Measures Improvement

We observed a strong relationship between the improvement in NRS classification and the improvement in the outcome measures from enrollment to discharge (fig 4, table 3). Consider the improve-

Table 2: Summary Statistics for 3 Outcome Measures at the Initial Evaluation by AIS Grade and Phase at Enrollment

	AIS Grade C			AIS Grade D		
Outcome	Phase 1 (n=26)	Phase 2 (n=5)	Phase 3 (n=0)	Phase 1 (n=14)	Phase 2 (n=37)	Phase 3 (n=13)
Berg Balance Scale	4.10±2.20	23.00±11.00	NA	8.90±6.60	24.90±14.50	40.80±6.90
Six-minute walk test (m)	2.00±11.00	143.00±108.00	NA	37.00±55.00	118.00±91.00	196.00±74.00
Ten-meter walk test (m/s)	0.01±0.04	0.35±0.27	NA	0.15±0.24	0.42±0.36	0.68±0.27

NOTE. Values are mean ± SD. Phase groups significantly differed on all outcome measures within AIS grades C and D groups (*P*<.001, Kruskal-Wallis test).
Abbreviation: NA, not applicable.

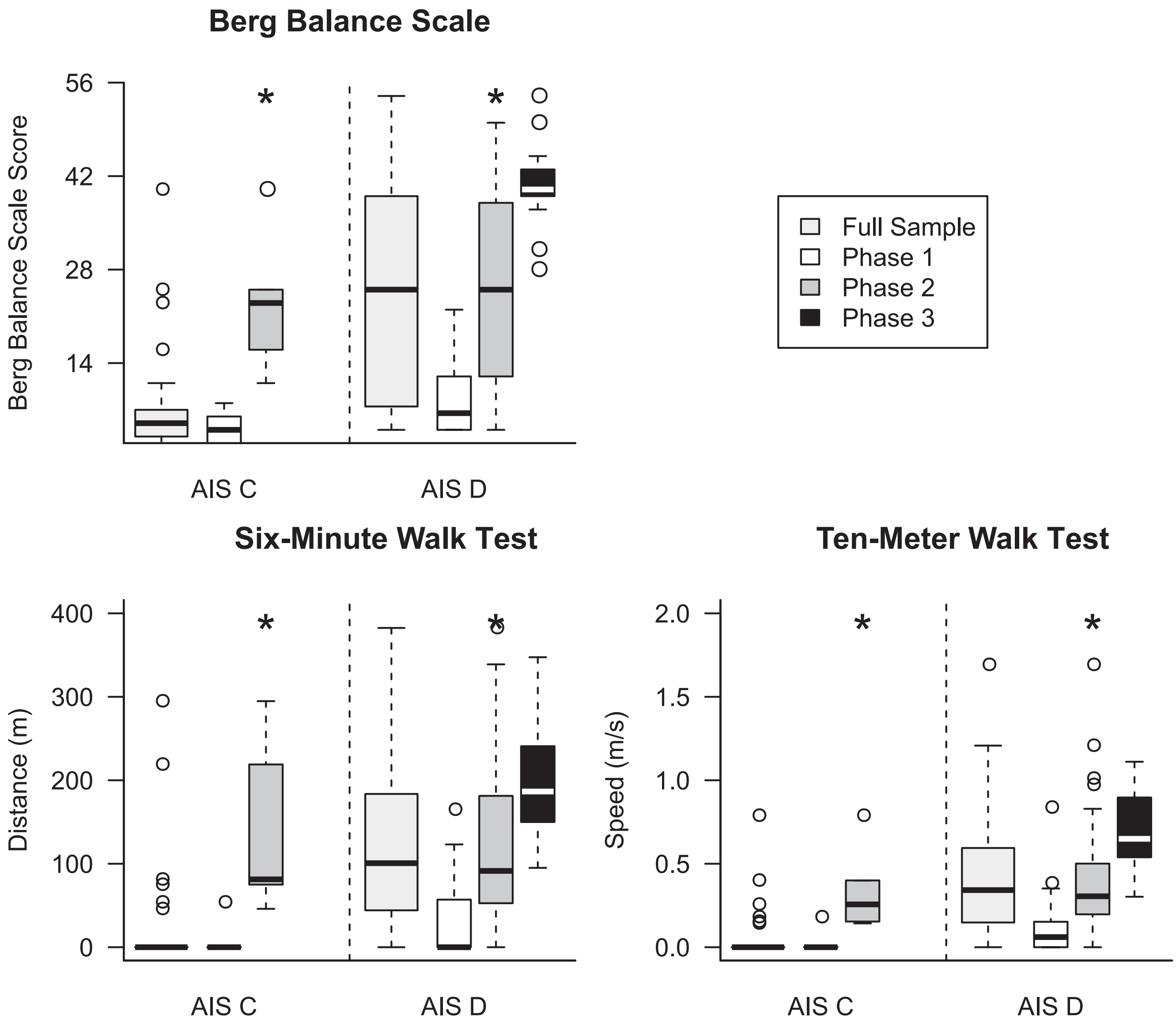

Fig 2. Boxplots of outcome measures at enrollment by phase classification and AIS grade at enrollment. Outcome measures significantly differed among the phase groups within groups of AIS grades C and D. *Phase groups significantly differed, Kruskal-Wallis test, $P<.001$ all measures.

ments in the six-minute walk test among patients classified as phase 2 at enrollment (see the middle cluster of boxes, bottom left plot, fig 4). Patients that dropped to phase 1 by the final evaluation also exhibited shorter walk distances at the final evaluation (mean decrease, −12m, white box). Patients that remained in phase 2 showed average distance improvements of 34m (light gray box), patients that advanced to phase 3 increased distance by an average of 114m (dark gray box), and patients that advanced to phase 4 improved by an average of 165m (black box). This relationship was consistent for each of the 3 measures, with the notable exception of those patients who improved from phases 2 and 3 to phase 4 when comparing improvements in the Berg Balance Scale, and for those patients who moved from phase 3 to phase 4 when comparing improvements in the ten-meter walk test. We categorized patients by the number of phase classes by which they improved (−1, 0, 1, or 2) and noted that improvements in the outcome measures were significantly different among these groups (Kruskal-Wallis test, $P<.01$ for all measures). Further, improvements in all outcome measures were significantly positively correlated with the size of the change in phase ($\rho>.36$, $P<.001$ for all measures). Of the 40 patients classified as phase 1 at enrollment, 19 (48%) remained in phase 1, 17 (43%) progressed to phase 2, and 4 (10%) progressed to phase 3 before exit from the NRN. Among patients classified as phase 2, 2 (5%) dropped to phase 1, 21 (50%) were stable, 17 (40%) progressed to phase 3, and 2 (5%) progressed to phase 4. Of the 13 patients classified as phase 3 at enrollment, 10 (77%) remained in phase 3, and 3 (23%) progressed to phase 4.

DISCUSSION

The NRS, a new scale that assesses functional improvement without compensation and classifies patients with motor incom-

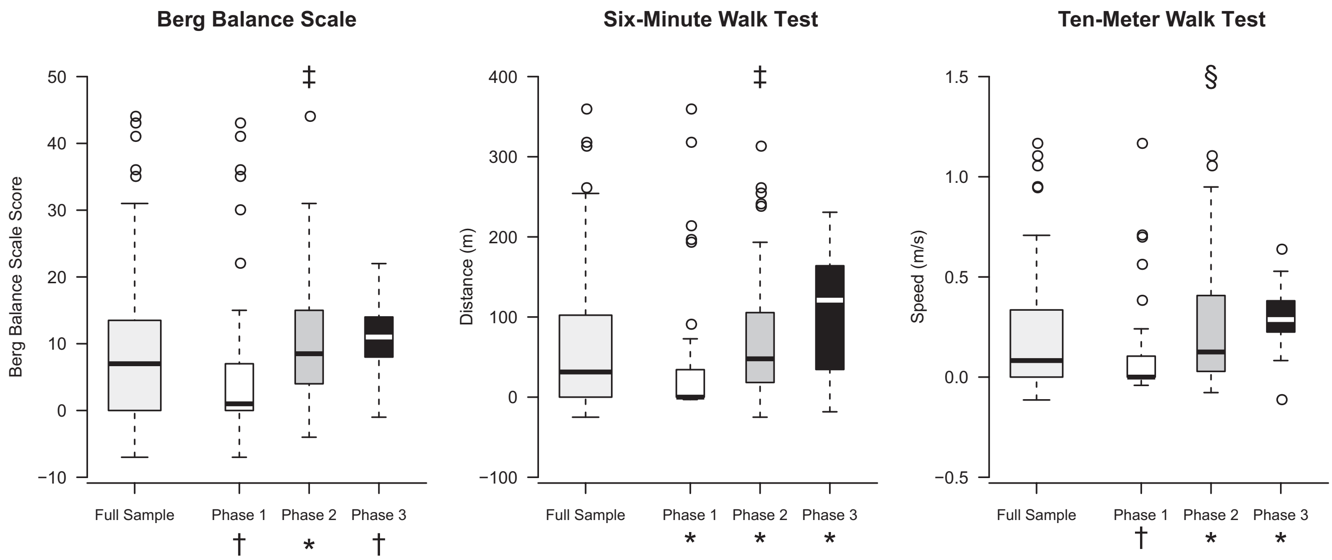

Fig 3. Boxplots of changes in the Berg Balance Scale (left panel), six-minute walk test (center), and ten-meter walk test (right) from enrollment to final evaluation for the full NRN sample and each phase group. Significant improvement on each measure was observed for the full sample and within each phase group (Wilcoxon signed-rank test; **P*<.001; †*P*<.01). Improvements were significantly different across the phase groups (Kruskal-Wallis test; ‡*P*<.001; §*P*<.01).

plete SCI into groups, effectively discriminates performance and reduces variability of walking and balance outcome measures. Consistent with our hypotheses, the NRS effectively discriminated initial evaluation abilities by determining significant differences in the magnitude and variability of each outcome measure (eg, balance, gait speed, and walking endurance) among the phase groups defined by the NRS (see fig 1). Classification by functional recovery can provide clinicians with more homogeneous patient groups to effectively set specific goals and develop treatment plans and report progress for third-party payers.

Further supporting our hypotheses is our finding that the NRS improved the distinction of people with motor incomplete SCI into groups with respect to function (see table 2, fig 2), as compared with AIS grade. This provides a tool to select more homogeneous groups than with the AIS grades C and D, potentially reducing the required sample sizes for clinical research and randomized controlled trials. The differences between the stratification of patients by the NRS and AIS grade can, in part, be attributed to the components used in the evaluations. The AIS is based on sensory testing of all dermatomes and manual muscle testing of only 10 extremity muscles, while the NRS consists of functional tasks that use synergistic muscle groups and may better relate to the outcome measures we selected for this study. In addition, the NRS has assessments related to trunk motor function that are not used during the AIS examination. There is a population of individuals who have been classified as either AIS grade C or AIS grade D with similar outcomes on the Berg Balance Scale and overground walk tests. These results indicate that the functional capacities of individuals within AIS grades C and D are highly variable.[9]

As hypothesized, the NRS classification was shown to be responsive when patients underwent an activity-based therapy for recovery of mobility, standing, and walking. The magnitude of functional improvement among the 3 phase groups was significantly different on all 3 outcome measures, indicating that within incomplete SCI patients there are cohorts that can now be predicted to have very different levels of improvement (see fig 3).

Finally, consistent with our hypothesis, improvements in NRS classification strongly corresponded to improvements in the func-

Table 3: Summary Statistics for Enrollment to Final Evaluation Changes in the Berg Balance Scale, Six-Minute Walk Test, and Ten-Meter Walk Test Phase by Enrollment and Final Phase

Outcome Measures (change scores)	Enrollment Phase	Final Phase			
		1 (n=21)	2 (n=38)	3 (n=31)	4 (n=5)
Berg Balance Scale	1 (n=40)	0 (−0.5 to 1)	1 (0 to 7)	38.5 (34.5 to 41.5)	NA
	2 (n=42)	−0.5 (−1.2 to 0.2)	7 (3 to 11)	15 (8 to 24)	9.5 (9.2 to 9.8)
	3 (n=13)	NA	NA	11 (9.5 to 13.5)	5 (3.5 to 10)
Six-minute walk test	1 (n=40)	0 (0, 0)	10 (0 to 54.6)	265.5 (208.3 to 328)	NA
	2 (n=42)	−12.5 (−18.8 to −6.2)	46 (12.2 to 71.7)	82.3 (39.3 to 193.2)	165.1 (117.2 to 213)
	3 (n=13)	NA	NA	118 (50.6 to 125.8)	183 (82.3 to 206.9)
Ten-meter walk test	1 (n=40)	0 (0 to 0)	0 (0 to 0.1)	0.7 (0.6 to 0.8)	NA
	2 (n=42)	0 (0 to 0)	0.1 (0 to 0.1)	0.3 (0.1 to 0.6)	0.7 (0.5 to 0.8)
	3 (n=13)	NA	NA	0.3 (0.2 to 0.4)	0.2 (0.1 to 0.4)

NOTE. Values are median (interquartile range).
Abbreviation: NA, not applicable.

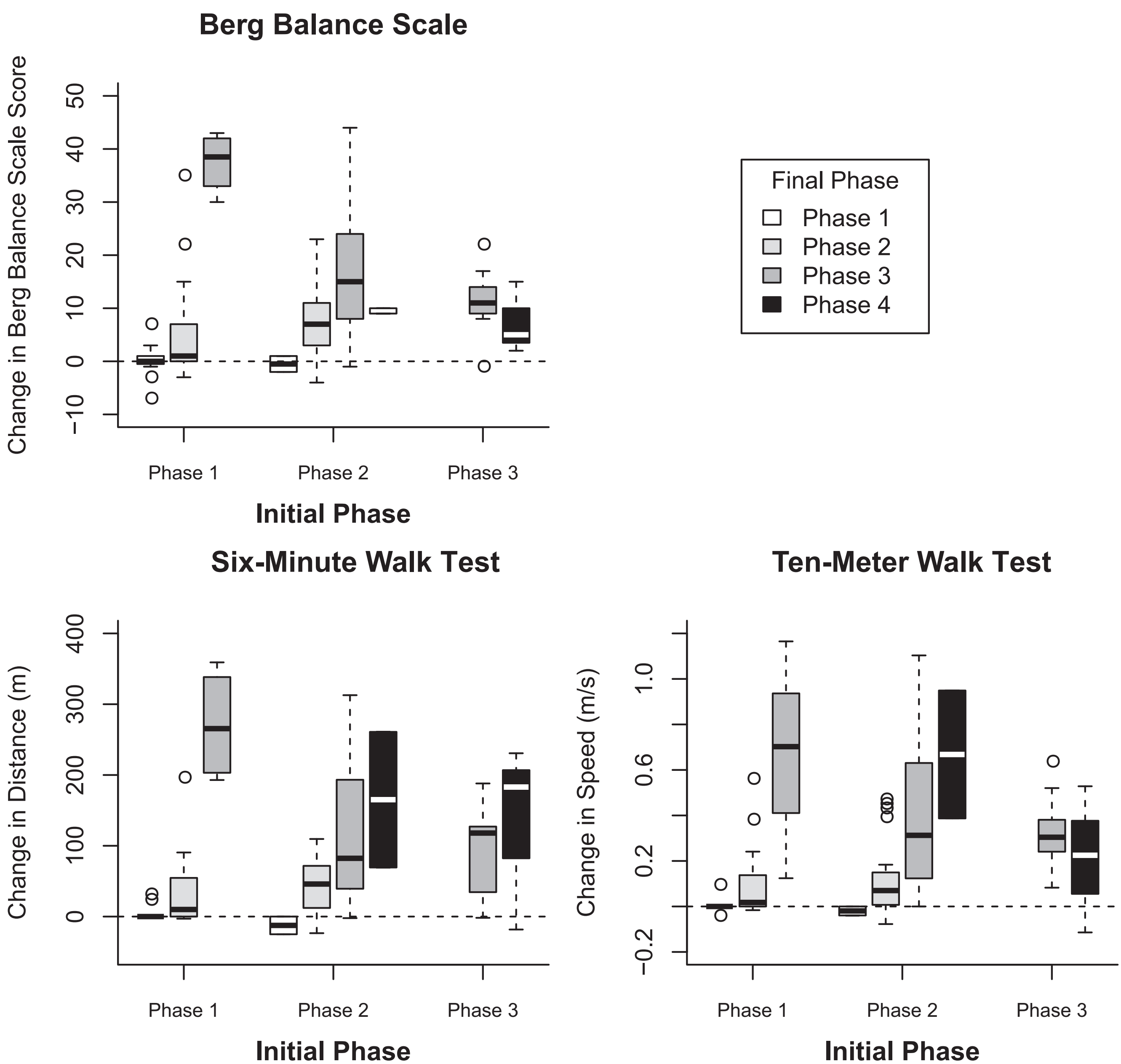

Fig 4. Boxplot of changes in outcome measures from enrollment to final evaluation for each enrollment/final evaluation phase group. Box plots are clustered with respect to the initial phase, and different shaded boxes represent different final phases. Improvements in the outcome measures were significantly different among these groups (Kruskal-Wallis test, *P*<.01 for all measures).

tional outcome measures we measured (see table 3, fig 4). This suggests that the NRS may have potential value as an outcome measure itself, rather than only as a tool to classify individuals with clinically incomplete SCI into functionally homogenous groups, especially when considering subphases.

The NRS is a practical tool that can be administered in the clinic and may provide clinicians with valuable information for patient assessment, treatment planning, and progression. In comparison with other currently available outcome measures, for example the FIM,[24] the Spinal Cord Independence Measure,[25-27] walking tests,[21,28] and recommended clinical trial outcomes,[1] the NRS uniquely assesses recovery of function to achieve a specific task goal, without allowing overt behavioral compensation. Common SCI outcome measures do not distinguish between compensation and true recovery to achieve functional goals.[12] For example, compensation using wrist tenodesis for grasp would score relatively high on most outcome measures because a functional goal was attained, but some return of normative hand function would not likely change the score. Similarly, standing with long leg braces and a walker for support achieves the task of standing via compensation, but does not demonstrate a return to the preinjury manner of standing. Thus, compensatory-based measures generally have less sensitivity to change and responsiveness than scales, which gauge performance relative to normative, preinjury movement patterns. Other measures examine the relative burden of care required to achieve a functional goal.[24-27] Independence may be achieved, but without regard to achieving the functional goal as performed prior to injury. The capacity to measure return to normative movement patterns with the NRS, demonstrating a reduction in outcome variability and sensitivity to a therapeutic intervention, is particularly relevant at this time when recovery post-SCI has become a predominant focus of rehabilitation research and an emerging paradigm shift in rehabilitation practice.[14,22,29]

Study Limitations

The findings of this study are limited to persons with motor incomplete SCI (AIS grades C or D) in outpatient rehabilitation clinics. Future studies should include assessment of individuals classified as AIS grades A and B and those receiving inpatient rehabilitation. In addition, the NRS currently assesses trunk and lower extremity function, but does not address upper extremity function. The results examining the responsiveness of the NRS relative to the outcome measures were of limited scope because of sample size constraints, and further studies should include a greater number of individuals to allow for formal hypothesis testing, intra- and interrater reliability, and continued exploration of this phenomenon. The NRS used in this study requires a body weight support treadmill system and rehabilitation specialists trained in locomotor training. Future studies should address the value of the NRS when used only with the overground tasks to allow its use in a larger number of clinics and research studies.

CONCLUSIONS

Findings from this study provide a classification scale focused on task-specific recovery without compensation after SCI, which can be used in clinical and research settings. The NRS differentiates individuals into distinct performance groups with reduced variability of the measures and is capable of demonstrating change from initial evaluation to discharge after a standardized activity-based therapy program.

Development of measures, such as the NRS, is particularly relevant because rehabilitation strategies are encompassing activity-based therapies and will soon partner with regenerative medicine[30] to advance neuromuscular recovery postinjury. This instrument will be as valuable as other activity-based therapies or combined interventions targeting plasticity and recovery are tested and translated into clinical practice because it provides an improved mechanism to test the efficacy and effectiveness of these interventions. Development of this instrument is an ongoing process, which includes expansion of the phase hierarchy to encompass the full spectrum of recovery; testing patients with AIS grades A and B SCIs; development of an upper extremity component; and further validation, reliability, and sensitivity testing.

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APPENDIX: 1: ADMINISTRATION AND SCORING OF THE PHASES

Administering the NRS

The administration of the phasing tool should take place during 1 evaluation period. The testing should begin with the first of the overground items, sit, continue through the overground items, and then follow with the items in the body weight support treadmill environment. Each item is tested and scored separately. The score of the item is the highest phase in which the patient can complete the item according to the description without any compensation. The examiner then calculates the overall phase based on the combined phase scores of each of the individual items. The continuum of scores proceeds from unable to complete the task to achieving full recovery by executing the tasks as done preinjury. Assess the client beginning with phase 1A abilities and then move up the phase scoring, because the lower phases must be achieved before higher scoring can be considered. Assistance cannot be provided to the body segment being assessed. The lower of 2 debatable scores should be selected. There is no advantage to scoring higher and all assessments should be directly compared with the ability preinjury to complete the specific task. This is important because goal setting and progression will be based on the current phase scoring and if inappropriately scored higher then this ability will not be sufficiently targeted for recovery during the therapeutic intervention. Subphases that are not scored are designated as not applicable and account for the progression of recovery within a task and across tasks.

Abilities During Overground Assessment

Overground assessment defines the capacity of the neuromuscular system without the benefit of the body weight support treadmill or manual facilitation to execute specific motor tasks.

Sit

The patient is positioned in an unsupported sitting position at the edge of a firm mat. The patient's feet should be flat on the floor. The patient is then asked to sit without upper extremity support, in a proper posture position (ie, head and shoulders in alignment, neutral pelvis position). If the patient is unable to attain this position, the examiner may assist the patient into this position, and then ask the patient to maintain the posture. The patient is then assigned a phase based on their ability to maintain the proper posture, in an unsupported position. If the patient is able to attain and maintain the proper posture (ie, phase 2), then the patient is asked to elevate their upper extremities, as described in the chart, and reach forward and laterally. The patient is assigned a phase based on these abilities. If the patient is incapable of elevating the upper extremities because of complications of the neuromuscular system, the patient may be graded on their ability to lean their trunk forward and laterally.

Scores are categorized as follows: unable (phase 1A); unable to attain, able to sit with inappropriate posture (phase 1B); unable to attain, able to sit with appropriate posture (phase 1C); able to attain and maintain appropriate position for at least 1 minute (phase 2A); able to attain and maintain appropriate position indefinitely (phase 2B); able to sit and hold arms parallel to legs for at least 30 seconds (phase 2C); able to sit and complete a lateral reach $<$12.7cm (5in) (phase 3A); able to sit and complete forward and lateral reaches between 12.7 to 25.4cm (5–10in) (phase 3B); able to sit and complete forward and lateral reaches $>$25.4cm (10in) (phase 3C); and not applicable (phase 4).

Reverse Sit-Up

The patient is positioned in an unsupported sitting position at the edge of the mat, with the feet flat on the floor. The patient is asked to slowly lower his/her trunk down to the mat, until his/her back and head are flat on the mat, without using the upper extremities for support and while maintaining a 90° angle in the knees. The examiner scores the patient based on how controlled the patient can lower the trunk, the position of the upper extremities, the compensatory use of the lower extremities, and the amount of effort required to complete the task. Manual assistance is not provided unless needed to avoid striking the mat with excessive force.

Scores are categorized as follows: not applicable (phase 1A–1C); unable (phase 2A); patient shows control through the first 45°, but loses control during the lower half of the movement (phase 2B); not applicable (phase 2C); patient is able to complete task with arms elevated in order to provide a counterbalance (phase 3A); not applicable (phase 3B); patient is able to complete task with arms held across chest, but displaying considerable effort (phase 3C); and patient is able to complete task with arms held across chest without considerable effort (phase 4).

Sit-Up

The patient is positioned in a supine position on the mat, with the lower extremities off the edge of the mat. The patient is asked to return to a sitting position without the use of his/her upper extremities, manual assistance, or momentum, while maintaining the knees at a 90° position. The examiner scores the patient based on how much of the trunk is able to be raised off of the mat, the position of the upper extremities, the compensatory use of the lower extremities, and the amount of effort required to complete the task.

Scores are categorized as follows: not applicable (phase 1A); unable (phase 1B); patient is able to raise head (phase 1C); patient is able to raise head and initiate shoulder lift (phase 2A); patient is able to raise head, shoulders, and scapulae (phase 2B); not applicable (phase 2C); patient is able to sit up, but with inappropriate position (arms elevated and/or hip/knee flexion/extension (phase 3A); not applicable (phase 3B); patient is able to sit up properly, but displaying considerable effort (phase 3C); and patient is able to sit up properly without considerable effort (phase 4).

Trunk Extension in Sitting

The patient is positioned in sitting with the feet flat on the floor, with his/her chest resting on the lap. The patient is asked to return to an upright sitting position, without the use of the upper extremities or manual assistance. The examiner grades the patient based on how much of the trunk is raised into sitting, the position of the upper extremities, and the amount of effort required to complete the task.

Scores are categorized as follows: unable (phase 1A); patient is able to initiate thoracic spine extension (phase 1B); patient is able to initiate and maintain thoracic spine extension (phase 1C); patient is able to initiate and maintain thoracic and initiate lumbar spine extension (phase 2A); patient is able to initiate and maintain thoracic and lumbar spine extension but displays considerable effort (phase 2B); not applicable (phase 2C); patient is able to initiate and maintain thoracic and lumbar spine extension without considerable effort (phase 3A); not applicable (phase 3B); patient is able to complete task with arms behind head, but displays considerable effort (phase 3C); and patient is able to complete task with arms behind head without considerable effort (phase 4).

Sit to Stand

The patient begins seated at the edge of the mat with feet flat on the floor. The patient is asked to stand up from the mat, without the use of the upper extremities. The examiner first assesses how high the patient can raise his/her body off of the mat without any assistance from the examiner. If the patient is able to raise the body approximately 50% off of the mat, then the examiner may provide assistance to the patient's pelvis and/or lower extremities, and assess the patient's control at the trunk and pelvis, as appropriate. If the patient is able to transition from sit to stand without physical assistance from the examiner, the patient is scored according to his/her kinematics during the task and the position of the upper extremities during the task.

Scores are categorized as follows: not applicable (phase 1A–1B); unable (phase 1C); patient is able to initiate weight bearing (phase 2A); the patient's body is raised off the mat, but patient reaches <50% full upright stand (phase 2B); patient is able to complete the task while maintaining proper kinematics of the head, shoulders, and trunk, and manual facilitation may be provided at the pelvis, knees, or ankles if needed (phase 2C); patient is able to complete the task with proper kinematics of the head, shoulders, and trunk, and manual facilitation may be provided at the knees or ankles if needed (phase 3A); patient is able to complete the task with proper kinematics of the head, shoulders, trunk, and pelvis, inappropriate kinematics at the knees and ankles, and no manual facilitation (phase 3B); patient is able to complete the task with proper kinematics, no manual facilitation, and uses the arms as a counterbalance (phase 3C); and patient is able to complete task properly, without using the arms as a counterbalance (phase 4).

Stand

The patient begins in a standing position, with physical assistance provided by the examiner as needed. The patient is asked to stand with a proper posture (ie, head, shoulders, and trunk extended, pelvis properly positioned under the head and shoulders, with the knees extended to adequately maintain body weight without hyperextension). The patient is assigned a phase based on his/her ability to maintain appropriate kinematics at each body segment. Please note that when the trunk is assessed (ie, phases 1C–2A), assistance may be provided to the lower extremities and pelvis by the examiner and other trainers. Likewise, assistance may be provided to the lower extremities in phase 2 to assess the kinematics of the pelvis. To be assigned phase 3, the patient must be able to maintain standing balance without physical assistance.

Scores are categorized as follows: not applicable (phase 1A–1B); unable (phase 1C); patient is able to stand with inappropriate posture and manual facilitation at the pelvis, knees, or ankles provided as needed (phase 2A); patient is able to stand with appropriate posture for <1 minute, and manual facilitation provided at the knees and ankles as needed (phase 2B); patient is able to stand with appropriate posture for >1 minute, and manual facilitation provided at the knees and ankles as needed (phase 2C); patient is able to stand with appropriate posture and without manual facilitation for <1 minute (phase 3A); patient is able to stand with appropriate posture without manual facilitation for >1 minute (phase 3B); and patient is able to stand with appropriate posture and without manual facilitation indefinitely (phase 3C).

Walking

The patient begins in standing position, with physical assistance as needed by the examiner at pelvis and lower extremities. The patient is asked to shift weight laterally. If the patient is able to shift weight without assistance at the trunk, the patient is then asked to shift weight forward and back in a stride position (left and right). The patient is assigned a phase based on ability to assume stride right and stride left positions while maintaining appropriate kinematics at each body segment. If the patient is able to independently assume stride positions and perform weight shifts independently while maintaining appropriate kinematics at all body segments, the patient is assigned a phase based on ability to perform repetitive steps with appropriate kinematics.

Scores are categorized as follows: not applicable (phase 1A–1C); unable to shift weight (phase 2A); patient is able to shift weight laterally with inappropriate kinematics at the head, shoulders, and trunk (phase 2B); patient is able to shift weight laterally with appropriate kinematics at the head, shoulders, and trunk, but is unable to initiate the stride position (phase 2C); patient is able to shift weight laterally with appropriate kinematics of the head, shoulders, and trunk, but inappropriate kinematics of the legs (phase 3A); patient is able to shift weight laterally with appropriate kinematics, but not in stride (phase 3B); patient is able to shift weight laterally and in stride with appropriate kinematics (phase 3C); and patient is able to walk with appropriate kinematics (phase 4).

Abilities During Treadmill Assessment

Once the overground assessment has been concluded, the patient is positioned in a body weight support treadmill system. The step-training environment uses the body weight support treadmill and manual assistance to assess the capacity and independence of the nervous system to stand and generate steps in a safe environment. The capacity of the nervous system is assessed by identifying the treadmill speed, body weight support, and facilitation needed to generate the optimal stepping pattern. This capacity of the nervous system is referred to as retraining. The independence of the nervous system is referred to as adaptability, and is assessed by identifying the treadmill speed and body weight support where independence from manual assistance occurs. There are 4 areas of assessment during step training: (1) stand retraining, (2) stand adaptability, (3) step retraining, and (4) step adaptability.

Stand Retraining

In this area, the capacity of the nervous system to bear weight in static standing is assessed, recorded as body weight support. The patient is positioned in the body weight support treadmill environment, in an upright posture, with head, shoulders and trunk extended, the pelvis properly positioned under the head and shoulders, with the knees extended to adequately maintain body weight without compensation. The patient should initially be supported with 75% body weight support (or the maximum amount of body weight support with the patient's feet remaining flat on the treadmill). The body weight support is then lowered as far as possible for the patient to maintain proper posture and positioning of the head, trunk, pelvis, and legs for at least 5 minutes, with the trainers providing as much physical assistance as needed to maintain the patient in an upright standing position. The lowest body weight support that is achieved is then noted, and the patient is assigned a phase level based on this amount of body weight support.

Scores are categorized as follows: body weight support ≥40% (phase 1A); body weight support 20%–39% (phase 1B); not applicable (phase 1C–2A); body weight support 10%–19% (phase 2B); not applicable (phase 2C–3B); body weight support ≤10% (phase 3C); and not applicable (phase 4).

Stand Adaptability

In this area, the patient's ability to independently maintain appropriate kinematics at each body segment, without physical assistance, is assessed, reflected by body weight support required. The patient begins at the lowest body weight support achieved during stand retraining, in an upright posture with head, shoulders, and trunk extended, the pelvis properly positioned under the head and shoulders, and the knees and ankles positioned at neutral to adequately maintain body weight. The body weight support is then adjusted, until the patient is able to independently maintain an upright posture at the trunk, with assistance provided at the pelvis and lower extremities. If the patient is able to maintain an upright posture at the trunk with less than 20% body weight support, then the body weight support is adjusted until the patient can independently maintain an appropriate position of the pelvis. If the patient can independently maintain an appropriate position of the pelvis at less than 10% body weight support, then the body weight support is adjusted to assess independence at the lower extremities. The assessment of independence follows this order: (1) trunk; (2) pelvis; and (3) legs with physical assistance only for the body segments that are not being evaluated. The patient is assigned a phase based on body weight support, where body segments were maintained independently with proper kinematics.

Scores are categorized as follows: body weight support ≥60% and manual facilitation of the pelvis, knees, and ankles (phase 1A); body weight support 40% to 59% (phase 1B); body weight support 20% to 39% (phase 1C); body weight support <20% (phase 2A); body weight support 40% to 59% without manual facilitation of the pelvis, knees, and ankles (phase 2B); body weight support 10% to 39% (phase 2C); not applicable (phase 3A); body weight support <10% with manual facilitation as needed (phase 3B); body weight support <10% with no manual facilitation (phase 3C); and body weight support 0% and the ability to recover balance (phase 4).

Step Retraining

In this area, the capacity of the nervous system is to generate an appropriate stepping pattern when provided with the sensory cues associated with walking. Leg loading is maximized, as are normative walking speeds (.89–1.34m/s; 2.0–3.0mph), resulting in scores of body weight support and speed. The body weight support level is adjusted to the body weight support where the majority of the body segments were independent during stand adaptability. The patient then begins stepping at a speed of .89m/s (2.0mph), with physical assistance from the trainers to ensure the best posture and kinematics while walking. The body weight support and speed are adjusted up or down to assess the lowest body weight support and highest speed at which the patient can generate the best stepping pattern with assistance from the trainers. The patient is assigned a phase level based on these 2 variables.

Scores are categorized as follows: body weight support ≥60% (phase 1A); body weight support 55% to 59% (phase 1B); body weight support 50% to 54% (phase 1C); body weight support 45% to 49% (phase 2A); body weight support 40% to 44% (phase 2B); body weight support 35% to 39% (phase 2C); body weight support 30% to 34% (phase 3A); body weight support 20% to 29% (phase 3B); and body weight support ≤20% (phase 3C). Patients that can maintain proper kinematics with <50% body weight support while running at speeds of >1.52m/s (3.4mph) are scored as phase 4.

Step Adaptability

In this area, the patient's ability to independently step on the treadmill is assessed, reflected by body weight and speed values. Walking speeds and body weight support are adjusted to allow complete independence from manual assistance from the examiner for compensation. Complete independence of upright posture with head, shoulders, and trunk extended is the first goal. Complete independence of the pelvis rotating aligned properly with the shoulders with an independent upright trunk is the second goal. The final goal is to achieve complete independence during the step cycle of (1) hip, knee, and ankle flexion and extension with proper kinematics, (2) pelvic rotation and proper alignment with the shoulders, and (3) upright trunk at preinjury walking speeds (.89–1.52m/s; 2.0–3.4mph). Examiners use manual assistance as needed at the body segments that are not being considered for the current goal for independence and the assessment of independence follows this order: (1) trunk; (2) hips; and (3) legs. However, once a body segment has achieved independence, manual assistance is not provided again to that segment. For example, once trunk independence is achieved at full body weight support and preinjury walking speeds, the next goal is pelvis independence, but trunk manual assistance is no longer provided. Body weight support and treadmill speed are adjusted as needed for the patient to achieve independence at the body segment targeted as the primary goal. Body weight support may be raised back to the baseline level, and speed may be reduced to as low as .27m/s (0.6mph). The patient is assigned a phase based on body weight support and speed where body segments were independently maintained with proper kinematics.

Scores are categorized as follows: body weight support ≥60% and speeds between .27 to .54m/s (0.6–1.2mph) with manual facilitation of the pelvis, knees, and ankles as needed (phase 1A); body weight support 40% to 59% and speeds .27 to .54m/s (0.6–1.2mph) (phase 1B); body weight support 20% to 39% and speeds .27 to .54m/s (0.6–1.2mph) (phase 1C); body weight support <20% and speeds .27 to .54m/s (0.6–1.2mph) (phase 2A); body weight support 40% to 59% and speeds .27 to .54m/s (0.6–1.2mph) with manual facilitation of the knees and ankles as needed (phase 2B); body weight support 20% to 39% and speeds .27 to .54m/s (0.6–1.2mph) (phase 2C); body weight support 10% to 19% and speeds .58 to .85m/s (1.3–1.9mph) (phase 3A); body weight support <10% and speeds .58 to .85m/s (1.3–1.9mph) without manual facilitation (phase 3B); and body weight support <10% and speeds ≥.89m/s (2.0mph) (phase 3C). Patients that can maintain proper kinematics with <10% body weight support while running at speeds of >1.52m/s (3.4mph) are scored as phase 4.

Calculation of Overall Phase

The overall phase is calculated based on the 2 lowest observed scores of the 11 phase tasks and the number of phase tasks that achieved each of these scores.

1. If 3 or more tasks were scored at the lowest observed phase, the overall phase is the lowest observed phase.
2. If 2 tasks were scored at the lowest observed phase, the overall phase is 1 subphase higher than the lowest observed phase.
3. If only 1 task was scored at the lowest observed phase, then if either of the following conditions were met, then the overall phase is 2 subphases higher than the lowest observed phase. Otherwise, the overall phase is 1 subphase higher than the lowest observed phase.
   a. If the second lowest observed phase was 2 or more subphases higher than the lowest observed phase.
   b. If the second lowest observed phase was 1 subphase higher than the lowest observed phase and only 1 task was scored at the second lowest observed phase.

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APPENDIX 2: PHASE SCORING SHEET

Stand Retraining	Stand Adaptability	Step Retraining	Step Adaptability	Sit	Reverse Sit-Up	Sit-Up	Trunk Extension	Sit to Stand	Stand	Walking
1A	1A	1A	1A	1A	1A	1A	1A	1A	1A	1A
1B	1B	1B	1B	1B	1B	1B	1B	1B	1B	1B
1C	1C	1C	1C	1C	1C	1C	1C	1C	1C	1C
2A	2A	2A	2A	2A	2A	2A	2A	2A	2A	2A
2B	2B	2B	2B	2B	2B	2B	2B	2B	2B	2B
2C	2C	2C	2C	2C	2C	2C	2C	2C	2C	2C
3A	3A	3A	3A	3A	3A	3A	3A	3A	3A	3A
3B	3B	3B	3B	3B	3B	3B	3B	3B	3B	3B
3C	3C	3C	3C	3C	3C	3C	3C	3C	3C	3C
4	4	4	4	4	4	4	4	4	4	4

Patient ID:		Left Leg				Right Leg			
Date:		Flexor	High	Mod	Low	Flexor	High	Mod	Low
Center:		Extensor	High	Mod	Low	Extensor	High	Mod	Low
Overall Phase:		Predominant overall pattern	Flex > Ext	Balanced	Ext > Flex	Predominant overall pattern	Flex > Ext	Balanced	Ext > Flex

Abbreviations: Ext, Extension; Flex, Flexion.
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