A Multivariate Examination of Temporal Changes in Berg Balance Scale Items for Patients With ASIA Impairment Scale C and D Spinal Cord Injuries

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Objective: To provide a multivariate examination of the Berg Balance Scale (BBS) in patients with spinal cord injury (SCI) as a first step in developing a balance tool for the SCI population.

Design: Observational cohort.

Setting: The NeuroRecovery Network (NRN), a specialized network of treatment centers providing standardized, activity-based therapy for patients with SCI.

Participants: Patients (N=97) with American Spinal Injury Association Impairment Scale C or D SCI who were enrolled in the NRN between March 1, 2005, and June 12, 2007.

Interventions: All enrolled patients received 3 to 5 locomotor training sessions a week, according to NRN protocol, and were periodically evaluated for progress on functional outcome measurements.

Main Outcome Measures: Scores on the items of the BBS, six-minute walk test distances, ten-meter walk test speeds, and scores on the SCI Functional Ambulation Index. Temporal rates of change of the BBS items were examined with a principal components and correlation analysis.

Results: The first principal component accounted for nearly half of the overall variability in the BBS, correlated well with rates of change in functional mobility measures, and had good stability in its composition as verified by a resampling analysis. Further analysis showed that the composition of the first principal component varied with the patient’s level of recovery.

Conclusions: The BBS captures a significant amount of information about balance recovery in persons with SCI and may be a good foundation for a balance tool. However, the utility of BBS items may be dependent on a patient’s level of recovery. A dynamic balance instrument for the SCI population may be needed.

Key Words: Principal components analysis; Rehabilitation; Spinal cord injuries.

THERE ARE APPROXIMATELY 12,000 new SCI cases each year. In this population, the percentage of persons with a neurologically (sensory and/or motor) incomplete injury has steadily increased from 45.9% in the 1970s to 55.3% in 2005. For persons who are diagnosed with a motor-incomplete injury, 28% of the injuries were classified (as defined by the International Standards for Neurological Classification of SCI) as “motor functional” (AIS D) and 11.6% as “motor non-functional” (AIS C) at the time of inpatient discharge. It was estimated in 1990 that between one quarter and one third of persons with an SCI regain some ability to walk by the time of discharge from an inpatient rehabilitation program.

An important component of recovery from SCI is the recovery of balance function. However, there currently is no valid and reliable instrument for measuring balance in the SCI population. The BBS is a 14-item instrument originally designed to assess the risk for falls in community-dwelling elders. The test is fairly simple to implement, taking approximately 20 minutes to administer and requiring only a chair, step or stool, ruler, and stopwatch. The items of the BBS have been formulated to evaluate an individual’s ability to maintain position, adjust posture to voluntary motion, and react to external impetus (appendix 1). The scale is designed so that sequentially, each item tested increases difficulty by decreasing the base of support from sitting, to standing, to a single-leg stance. Each item is scored on a 5-point (0–4) ordinal scale.

Evaluation of the psychometric properties of the BBS has largely been restricted to the community-dwelling elderly population, those experiencing acute stroke, and those with Parkinson disease. Although the BBS has been used in SCI populations, and the items on the scale possess reasonable face validity with respect to evaluating balance in the SCI population, a formal examination of the BBS in the SCI population has yet to be conducted.

Principal components analysis is a statistical technique that is useful for visualizing and interpreting multivariate data.
and, in particular, examining the items of a measurement scale. Each item on the BBS contributes variability to the full scale. However, it is not clear that a simple sum of the 14 BBS items provides the best summary of the scale with respect to explaining the total variation in the data. Some items may contribute less variability to the full scale than others (as applied to a specific population), and consequently would be of lesser utility. For example, if patients with SCI all performed very well on the first BBS item, then its utility in measuring balance recovery would be low. Formally, the principal components of a multivariate data set are orthogonal (ie, independent) directions in the multivariate data space that explain the most variability among the subjects. Thus, the first principal component is a linear combination of the BBS scores that is most variable among the subjects, the second principal component is the next most variable combination among all directions that are orthogonal to (ie, independent of) the first, and so forth. The orthogonality of successive principal components guarantees that each principle component captures a unique component of variation in the multivariate data set. In particular, the first principal component defines the optimal way to combine the component item scores. Typically, the first few principal components explain a substantial proportion of the total variance in the data. Some items may contribute more of the full scale variability and are of greater utility in summarizing the data. Accordingly, items with large loading coefficients explain more of the total variation in the data. The data analyzed here were collected at 5 NRN centers from March 4, 2005, to June 12, 2007.

Table 1: Demographic and Clinical Characteristics

<table>
<thead>
<tr>
<th>Clinical Characteristics</th>
<th>Full Sample (N=97)</th>
<th>Phase I (n=44)</th>
<th>Phase II (n=25)</th>
<th>Phase III (n=28)</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sex</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Male</td>
<td>71 (73)</td>
<td>31 (70)</td>
<td>15 (60)</td>
<td>25 (89)</td>
<td>.04*</td>
</tr>
<tr>
<td>Female</td>
<td>26 (27)</td>
<td>13 (30)</td>
<td>10 (40)</td>
<td>3 (11)</td>
<td>.72†</td>
</tr>
<tr>
<td><strong>Age (y)</strong></td>
<td>38 ±17</td>
<td>37 ±18</td>
<td>40 ±18</td>
<td>38 ±15</td>
<td>.001†</td>
</tr>
<tr>
<td><strong>Mechanism of injury</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Motor vehicle accident</td>
<td>34 (35)</td>
<td>17 (39)</td>
<td>10 (40)</td>
<td>7 (25)</td>
<td>.11%</td>
</tr>
<tr>
<td>Fall</td>
<td>29 (30)</td>
<td>9 (20)</td>
<td>10 (40)</td>
<td>10 (36)</td>
<td>.86%</td>
</tr>
<tr>
<td>Sporting accident</td>
<td>16 (16)</td>
<td>8 (18)</td>
<td>1 (4)</td>
<td>7 (25)</td>
<td>.72†</td>
</tr>
<tr>
<td>Other nontrauma</td>
<td>8 (8)</td>
<td>6 (14)</td>
<td>1 (4)</td>
<td>1 (4)</td>
<td>.25%</td>
</tr>
<tr>
<td>Medical/surgical</td>
<td>6 (6)</td>
<td>3 (7)</td>
<td>2 (8)</td>
<td>1 (4)</td>
<td>.99%</td>
</tr>
<tr>
<td>Violence</td>
<td>4 (4)</td>
<td>1 (2)</td>
<td>1 (4)</td>
<td>2 (7)</td>
<td>.25%</td>
</tr>
<tr>
<td><strong>Assistive walking device</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nonambulatory</td>
<td>20 (21)</td>
<td>20 (46)</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td>.002†</td>
</tr>
<tr>
<td>Walker</td>
<td>42 (43)</td>
<td>18 (41)</td>
<td>21 (84)</td>
<td>3 (11)</td>
<td>.007‡</td>
</tr>
<tr>
<td>Cane/crutches</td>
<td>22 (23)</td>
<td>6 (14)</td>
<td>4 (16)</td>
<td>12 (43)</td>
<td>.25%</td>
</tr>
<tr>
<td>None</td>
<td>13 (13)</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td>13 (46)</td>
<td>.001†</td>
</tr>
<tr>
<td><strong>Time since SCI (mo)</strong></td>
<td>11.9 [0.5, 248]</td>
<td>15 [1, 248]</td>
<td>11 [2, 82]</td>
<td>14 [0.5, 242]</td>
<td>.63%</td>
</tr>
<tr>
<td><strong>NRN participation data</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NRN enrollment time (d)</td>
<td>119±99</td>
<td>129±80</td>
<td>144±145</td>
<td>76±53</td>
<td>.03†</td>
</tr>
<tr>
<td>Cumulative treatment sessions received</td>
<td>48±39</td>
<td>62±42</td>
<td>49±41</td>
<td>27±17</td>
<td>&lt;.001†</td>
</tr>
<tr>
<td>Treatment sessions per evaluation</td>
<td>14.6±7.8</td>
<td>14.6±5.9</td>
<td>16.0±11.6</td>
<td>13.0±5.5</td>
<td>.32%</td>
</tr>
</tbody>
</table>

NOTE. Values are mean ± SD, median [min, max], or counts (percentages). Abbreviation: NT, not tested for differences among phases.
*Fisher exact test.
†Analysis of variance.‡Assistive walking device refers to walking device used at tests of six-minute walk and ten-meter walk, during which physical assistance may have been provided.
‡Kruskal-Wallis test.

Aside from being a useful data reduction and visualization technique, a principal components analysis has other benefits. Often the directions computed by a principal components analysis have clinical relevance and interpretability (see, for example, Olney, et al.12 for clinical interpretation of principal components from gait data in a population of patients with stroke). Further, a correlation analysis between the principal component scores and the scores on individual items from the scale can identify items that most substantially differentiate patient recovery. In this article, we provide the results of a principal components analysis of the BBS in patients with motor incomplete (AIS C or D) SCI as an important, albeit preliminary, step in evaluating the utility of the scale for use in the SCI population.

METHODS

Subjects

Data from 97 participants in NRN with incomplete AIS C or D spinal cord injuries were analyzed (table 1). The patient population was derived from 7 rehabilitation sites that provided a standardized activity-based intervention for the recovery of posture, standing, and walking and improvements in health and quality of life. Quantitative assessment tools were administered to document changes over time in a specific patient population (table 2). The Institutional Review Board for each of the NRN centers approved the submission of demographic and outcome data to the centralized NRN database, from which the data for this analysis were gathered. Each patient signed an informed consent form prior to the collection of data. The data analyzed here were collected at 5 NRN centers from March 4, 2005, to June 12, 2007.
Table 2: Eligibility Criteria for the NRN
1. Not actively participating in an inpatient rehabilitation program.
2. Stable with no deteriorating medical condition. No pacemaker present.
3. Nonprogressive spinal cord lesion at level T10 or above; T11 and T12 may be considered in the absence of lower motor neuron signs.
5. Able to extend head voluntarily.
6. No painful musculoskeletal dysfunction or unhealed fractures.
7. Able to follow/understand verbal commands.
8. AIS C or D with upper motor neuron lesion.
9. Demonstrates capacity for generating a lower extremity reciprocal alternating flexion/extension stepping pattern.
10. Normal or hypertonicity present in the absence of antispasticity medication.
11. No use of BTX-A within the previous 3 months.
12. Compliance to eliminate or minimize lower extremity orthotics.
13. No current illegal drug use.

Procedures

Locomotor training is an activity-based therapeutic intervention for standing and walking that facilitates input to the neuromuscular system below the level of lesion to induce neuroplasticity and promote recovery of function. Based on the findings of an initial evaluation, the treating therapist establishes goals for treatment and implements a standardized plan of care. A typical locomotor training session has three components. The step training component is comprised of task-specific retraining of the nervous system for standing and walking that occurs in a controlled environment using a body weight support treadmill system with verbal and manual facilitation by trainers. The second component is overground assisted locomotion. The third component is community integration that provides instruction for the individual to perform their daily activities in the home and community environments and achieve safe, efficient mobility. The NRN treatment protocol required 3 to 5 locomotor training sessions a week, depending on therapeutic necessity. Patient evaluations, conducted by the treating physical therapist, were scheduled for every 20 treatment sessions or 30 days. At each evaluation, functional outcome measures were assessed, including the BBS, six-minute walk test,19 ten-meter walk test,20 and SCI-FAI,20 which were the measures of primary interest. A description of the methods for evaluation for each of these measurements is contained in Appendix 2. The NRN implements procedures to optimize uniform administration of treatment across all NRN centers. There are uniform procedures for locomotor training including patient selection (see Table 2), evaluation, medical management, plan of treatment, and documentation. Physical therapists from each center were trained by the NRN during a 5-day conference. The reliability of the assessments of the outcome measures by the physical therapists was monitored by the NRN via video review. Data from all centers were compiled into a centralized database.

Data Analysis

The purpose of this analysis was to examine the joint distribution of the 14 items of the BBS, and subsequently determine its capability as a measure of balance recovery for the SCI population. This was accomplished through a principal components analysis of the longitudinally collected BBS variables. Each patient had a sequence of evaluations of the 14 BBS items over time. Because the purpose of the analysis was related to the recovery of balance rather than balance (at a given point of time), preprocessing of the data prior to the principal components analysis was necessary. This was accomplished by calculating the average rate of change between successive observed evaluations for each BBS item for each patient. This is an overall measure of recovery as captured by the temporal profile of a given BBS item. Because any smooth curve can be approximated by a piecewise linear curve, this measure provided the best summary of recovery—the rate calculated between consecutive evaluations defined the piecewise linear recovery curve, and averaging over all evaluations provided the summary measure. For example, for each patient, the difference between successive evaluations was calculated for BBS item 1 (sitting to standing); these differences were divided by the number of treatment sessions received between the successive evaluations and averaged, leading to an overall measure of change in BBS item 1 per treatment session for that patient. Principal components were constructed to examine the most informative directions of average changes in successive evaluations. This type of marginal analysis has several technical advantages. Each individual contributes 1 multivariate observation in the analysis irrespective of how many potentially dependent temporal evaluations the patient had. Furthermore, in the marginal model, these multivariate observations are independent and identically distributed across the patients, and hence, the usual inferential calculations are valid. This does not require the modeling of the data mechanism for the number of temporal observations, nor the modeling of the dependence structure between the temporal observations for a given individual.21,22

In the remainder of the article, we omit the phrase “rate of change” in describing these variables, for simplicity. For example, “BBS item 1 for patient 5” will refer to the average per treatment session change in BBS item 1 scores for patient 5 during the enrollment period.

The principal components were examined empirically, by consideration of the loading coefficients and variance accounting. The principal component scores were correlated with scores on the individual BBS items through a nonparametric (rank-based) correlation analysis to identify BBS items that most substantially differentiated patient recovery. The stability of the first 3 principal components was analyzed by repeatedly computing the first 3 principal components over pseudo-samples generated using a resampling scheme described in detail in the Results. The interpretation of the first 3 principal components was augmented by a nonparametric correlation analysis between the principal component scores and the average rates of change on 5 different measures of walking function—six-minute walk distances, ten-meter walk speeds, and the 3 subscales of the SCI-FAI instrument: Gait Parameters, Assistive Devices, and Walking Mobility.

Finally, we also conducted principal components analyses within (temporally varying) subgroups of our data set to determine whether the utility of the BBS items varied as a function of the patients’ level of recovery. To this end, 3 phases of recovery for patients with SCI were defined: I, II, and III. Patients in phase I were unable to stand or walk, were highly dependent on caregivers for mobility and activities of daily life, and experienced a multitude of symptoms from secondary complications. Phase II included patients who were able to stand for limited periods with assistive devices and physical
assistance; however, they primarily used wheelchairs for mobility at home and in the community. Phase III patients were able to ambulate but needed assistive devices and were limited in speed or endurance or had significant gait deviations. At each evaluation, each patient was classified as being in 1 of the 3 phases, so that a patient’s phase could change as the patient recovered. Then, the same calculation of the average rates of change on the BBS items and functional measures of walking were conducted within each of the 3 phase-specific data sets obtained by the current phase at the first of the 2 successive evaluations. A principal components analysis was then conducted on each of the 3 data sets. All statistical analyses detailed were conducted using the open-source R software.  

RESULTS  

Demographic and Clinical Characteristics  

A brief examination of the demographic and clinical characteristics of our data set preceded the analysis (see table 1). We noted representation from both sexes and a wide array of ages, mechanisms of injury, times since injury, and assistive walking devices at enrollment in NRN. The distribution of these characteristics in our sample roughly corresponded to that in the SCI population, which was important to note because these characteristics were observed rather than fixed (ie, it was not possible to randomize patients with respect to these characteristics).

On average, patients were enrolled in NRN for approximately 4 months and received just fewer than 50 treatment sessions over the course of enrollment. The median number of evaluations contributed by the patients to this analysis was 3. In terms of the processing of the data described, the average rate of change calculated for each patient involved averaging a median of 2 rates of change. Between consecutive evaluations, patients received an average of 14.6 treatment sessions, although there was a fair amount of variability in the number of treatment sessions per evaluation (SD = 7.8).

General Description of Changes in BBS Items  

As a first step of our multivariate examination of the BBS item scores, we investigated the relationships between each pair of BBS items graphically and through a nonparametric correlation analysis. Because there are 91 possible pairings of the 14 BBS items—which is a rather large number—we provide a general discussion of the relationships among the BBS items and focus on selected key aspects of the data. With the exception of correlations involving BBS item 3 (sitting with back unsupported), all correlation coefficients (Spearman rank correlation) were positive, which presumably suggested that a higher rate of change in each of these BBS variables indicated faster recovery for a patient. The size of the correlation coefficients ranged from very small ($\rho = .03$ for items 1, sitting to standing, and 14, standing on 1 leg) to very large ($\rho = .85$ for items 9, pick up object from the floor from standing position, and 10, turning to look behind or to the right shoulder while standing). This indicated varying strengths of association among the items.

The pairs of BBS items plotted in figure 1 were chosen to illustrate both strong and weak correlations and describe important phenomena in the BBS data. In the first column, BBS item 3 (sitting with back unsupported) was plotted against other BBS items. The observed weak correlations ($\rho = .01$ for all 3) were largely a product of the lack of variability in item 3—note that most of the data points fell on the vertical line at 0.0, indicating that most patients exhibited little change in item 3. BBS item 3 was also weakly associated with the other items not shown in figure 1. This characteristic of item 3 will be revisited. It is interesting to note that item 3 was the only item in BBS that assessed static sitting balance.

The second column plotted pairs of BBS items to illustrate weak associations. In particular, each plot of the second column paired an early BBS item, such as item 1 (sitting to standing), with a late BBS item, such as item 14 (standing on 1 leg). The weak relationships between early and late items were sensible, because the BBS was designed so that items escalate in difficulty as one progresses through the scale. Hence, we gathered that recovery of function for simpler balance tasks (early BBS items) was not closely related to the recovery of function for more advanced balance tasks (late BBS items).

The final column plotted pairs of BBS items to illustrate strong correlations. Contrasting the plots in the second column, the selected pairs of BBS items in the third column were displayed close proximity—for example, items 9 (picking up object from floor while standing) and 10 (turning to look over each shoulder while standing). Again, these strong relationships were sensible given the escalating difficulty of the component items; items in close proximity were of comparable difficulty, and recovery of function on closely related items would be expected to be closely associated. This pattern among the correlations, in which the strength of the correlation varied as a function of the proximity of the items, was generally apparent in the pairwise combinations of BBS items not shown here.

Principal Component 1  

The first principal component accounted for 48% of the total variability in the BBS, which clearly dominated the remaining principal components (see Principal Components 2 and 3 below). The loading coefficients for each BBS item detailed the composition of the first principal component (table 3), but very small coefficients were omitted from table 3 because a very small coefficient signaled a minimal contribution of an item to the given principal component. All items except BBS item 3 loaded onto the first principal component. Among the remaining items, item 14 was a minimal contributor (coefficient = .16), and item 10 contributed maximally (coefficient = .37). The loading coefficients were all positive and of comparable size (with the exception of items 3 and 14), indicating a fair amount of homogeneity among the BBS items with respect to the first principal component.

The correlations between first principal component scores and scores on individual BBS items were calculated to determine items that best differentiated recovery (see table 3). All BBS items were significantly correlated with the first principal component scores ($\rho$ ranged from .38 to .64) except for BBS item 3. The lack of correlation between first principal component scores and BBS item 3 was presumably a result of the fact that most patients exhibited little change in this item over time (see, for example, the first column of figure 1).

Principal Components 2 and 3  

The second principal component accounted for 12% of the total variability, a precipitous drop from the variability explained by the first principal component. The second principal component exhibited a lower degree of homogeneity than the first—the items loading on the second principal component did not all have the same sign, and the variability in the size of the coefficients was higher (see table 3).

In general, BBS items that loaded onto the second principal component correlated well with the second principal compo-
ent scores (see table 3), with the exception of items 1, 9, and 10. The 2 items that did not load onto the second principal component (3 and 5: transfers) did not correlate with the corresponding scores.

The third principal component also accounted for 12% of the total variability. The composition of the third principal component—4 of the 8 items loaded negatively, and items 9 through 13 (standing unsupported with 1 foot in front) loaded positively (see table 3). Neither the second nor third principal component seemed to capture a significant amount of variability in the BBS nor define an underlying data construct.

Concordance Plots: Stability of Principal Components

The principal components we observed were not based on population quantities but rather were estimated from a sample. Consequently, it was important to examine how sensitive our results were with respect to sampling before recommendation for clinical use. To that end, we created concordance plots (fig 2) for each of the first 3 principal components. We selected 10 patients arbitrarily from our sample. We then created an artificial sample by adding to these 10 patients a randomly selected collection of 40 patients sampled from the remaining 87 patients. This process was independently replicated 5 times, resulting in 5 reduced data sets, each with 50 patients and each

Fig 1. Scatterplots of average changes in selected pairs of BBS (Berg) items along with their rank correlations $\rho$ and the least-squares lines of best fit.

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containing the same original 10 patients. We then looked at the relative ranks of the initially selected 10 patients using each of the first 3 principal components, calculated from each of the 5 reduced data sets. The concordance plot provided a visual comparison of these rankings for each of these reduced data sets, together with the rankings of the scores derived from the principal components for the full data set. Ideally, the line segments joining the rank coordinates would be horizontal straight lines indicating perfect agreement and stability.

As can be seen from figure 2, the degree of agreement among the rankings for the first principal component was high, indicating that the first principal component was stable as an instrument measuring the rate of improvement of the BBS activities (basic motor skills). The level of stability was much worse for the second and third principal components, as shown by the jagged concordance lines. Such instability is an indicator that a principal component is compounded by chance variation rather than being a systematic construct of the data.

### Association With Temporal Changes in Clinical Measures

In an attempt to provide an interpretation for the first principal component, we performed a correlation analysis with the 5 clinical measures of walking: six-minute walk distances, ten-meter walk speeds, and the 3 subscales of the SCI-FAI. The Kendall $\tau$ was used in addition to the Spearman rank correlation as a measure of association. By definition, these measures technically exemplify different characterizations of association. While the Spearman measure is an ordinary correlation between the 2 vectors of ranks, the Kendall measure is based on the number of pairs that are concordant in terms of the 2 variables. Nevertheless, both measures are appropriate for discrete data and for measuring nonlinear associations, and both perform generally similarly with respect to measuring association (both will tend to have high values when associations are strong and low values when associations are weak). We present both correlations to provide a more complete picture of the relevant associations, but will generally refer to the Spearman correlation coefficients when citing specific relationships.

The first principal component correlated significantly with all measures of functional mobility except the SCI-FAI Assistive Device subscale (table 4). Hence, improvement on the BBS corresponded well with improvement on 4 of the functional measures—that is, those improving rapidly on the BBS also improved rapidly on the 4 walking measures, and those improving slowly or even getting worse on the BBS improved slowly or got worse on the walking measures.

The longitudinal plots in figure 3 provided visual evidence of the relationships between the first principal component and the 4 functional measures of recovery, suggesting that the first principal component did a reasonable job of differentiating patients on the degree of their recovery as measured by these 4 measures of walking function. Three patients with high scores and 3 with low scores on the first principal component were selected, and their measurements on the six-minute walk test, ten-meter walk test, SCI-FAI Gait Parameters subscale score, and SCI-FAI Walking Mobility subscale score plotted longitudinally. The 3 patients with high first principal component scores, represented by dashed lines, exhibited dramatic improvement in each of these parameters—sharp increases in six-minute walk distance, ten-meter walk speed, and SCI-FAI Gait Parameters and Walking Mobility subscale scores. Conversely, the 3 patients with low first principal component scores (solid lines) exhibited little, varied, or no improvement on these 4 measures.

### Principal Components by Phase of Recovery

Before proceeding with the analysis by phase of recovery, we compared the demographic characteristics of the patients in each of the phase groups. Because phase was time-varying, we conducted these comparisons relative to the patient’s phase at enrollment. Patient ages and times since injury did not significantly differ across the phases, whereas sex did (see table 1). Patients earlier in recovery tended to remain enrolled in the NRN for longer periods and hence to receive more treatment sessions and undergo more evaluations, but the number of treatment sessions per evaluation (an indicator of treatment intensity) did not significantly vary across the phases at enrollment.

The principal components analysis of the BBS in the phase subgroups indicated that the utility of BBS items in measuring balance recovery was dependent on the patient’s phase of

### Table 3: Composition of the First 3 Principal Components

<table>
<thead>
<tr>
<th>BBS Variables</th>
<th>Loading Coefficients</th>
<th>Rank Correlations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>First PC</td>
<td>Second PC</td>
</tr>
<tr>
<td>1. Sitting to standing</td>
<td>.22</td>
<td>-.16</td>
</tr>
<tr>
<td>2. Standing unsupported</td>
<td>.25</td>
<td>-.33</td>
</tr>
<tr>
<td>3. Sitting with back unsupported but feet supported</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>4. Standing to sitting</td>
<td>.31</td>
<td>-.11</td>
</tr>
<tr>
<td>5. Chair transfers</td>
<td>.30</td>
<td>NS</td>
</tr>
<tr>
<td>6. Standing unsupported with eyes closed</td>
<td>.27</td>
<td>-.12</td>
</tr>
<tr>
<td>7. Standing unsupported with feet together</td>
<td>.22</td>
<td>-.10</td>
</tr>
<tr>
<td>8. Reaching forward with outstretched arm while standing</td>
<td>.24</td>
<td>.35</td>
</tr>
<tr>
<td>9. Pick up object from floor from standing position</td>
<td>.33</td>
<td>-.18</td>
</tr>
<tr>
<td>10. Turning to look over left and right shoulders while standing</td>
<td>.37</td>
<td>-.27</td>
</tr>
<tr>
<td>11. Turning 360°</td>
<td>.25</td>
<td>.22</td>
</tr>
<tr>
<td>12. Placing foot on step or stool while standing unsupported</td>
<td>.28</td>
<td>.27</td>
</tr>
<tr>
<td>13. Standing unsupported with 1 foot in front</td>
<td>.34</td>
<td>.15</td>
</tr>
<tr>
<td>14. Standing on 1 leg</td>
<td>.16</td>
<td>.68</td>
</tr>
</tbody>
</table>

NOTE. The left column contains the loading coefficients for the first 3 principal components. The right column contains Spearman rank correlation coefficients for the observed BBS item scores and principal component scores. Abbreviations: NS, BBS item had a small loading coefficient and was not a significant contributor to the principal component; PC, principal component.

* $P<.05$. 

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recovery (table 5). The composition of the first principal component was clearly different in each of the 3 phase groups. In phase I patients, BBS items 1, 3, and 5 loaded onto the first principal component, which accounted for 53% of the total variability in the scale. BBS item 3 clearly dominated the first principal component, in stark contrast with its absence from the first principal component in the full data set. A further inspection of the data provided additional details on this phenomenon. As mentioned, 376 of the 429 unique assessments of BBS item 3 were given the highest score of 4. Of the 53 assessments not scored a 4, 48 occurred in phase I patients. Any variability in BBS item 3 almost exclusively occurred among phase I patients. Further, the remaining BBS items did not vary greatly in phase I patients (most could not complete them and scored 0), hence their absence from the first principal component in phase I patients.

Among phase II patients, the first principal component accounted for only 29% of the total variability. The items that loaded onto the first principal component were scattered across the scale, and BBS item 3 did not load on the first principal component. The loading coefficients were of differing signs, and the magnitudes varied quite a bit. While the principal component in phase II patients clearly differed from that in the full sample, the scattering and variability of the coefficients and the limited variance accounting made interpretation of this component difficult. The first principal component for phase III patients most closely mirrored that of the full sample, and accounted for 44% of the variance in the full scale for phase III patients. All BBS items except 3 and 8 (reaching forward while standing) loaded onto the first principal component in phase III patients, and the loading coefficients were uniformly positive. There was more variability in the magnitude of the coefficients than in the full sample, because coefficients ranged from .11 to .46. Items later in the scale tended to have higher loading coefficients than items earlier in the scale.

DISCUSSION

The first principal component of the full data set had several desirable properties—homogeneous loading coefficients, high variance accounting, stability with respect to sampling variability, and association with other clinical measures of recovery. Because the loading coefficients (except the third) were of the same sign and of similar magnitude, we conclude that recovery was fairly consistent across all BBS items. This inference is supported by the signs of the pairwise correlations between BBS items, namely that all were positive except those involving the third item. We can then interpret the first principal component as an overall measure of balance recovery in the general SCI population. We can be reasonably confident of the composition of the first principal component given its stability with respect to sampling variability as shown in the concordance plots.

The analysis by phase of recovery seemed to demonstrate that the utility of the individual BBS items in measuring balance recovery varied with the patient’s phase of recovery. Earlier BBS items played an important role in phase I (early stages of recovery) patients, and BBS item 3 (sitting with back unsupported) was the dominating contributor to the first principal component. This confirmed intuition: early BBS items are designed to assess sitting and standing balance, and are least difficult to perform but a challenge to patients early in recovery.

The picture was not as clear for phase II patients. The first principal component explained a low percentage of the cumulative variance and the loading coefficients lacked homogeneity and any simple interpretation. In a way, this was a reasonable phenomenon. By definition, phase II encompasses a diverse set of patients, from those unable or barely able to stand to those just beginning to walk. Hence, BBS items relevant for patients entering phase II, who have just regained the ability to stand, may not be relevant for those soon to leave phase II, who are on the verge of walking.

Things were far clearer in phase III patients. Most of the BBS items seemed to measure balance recovery adequately, but there was a clear division with respect to relative utility. Specifically, the later items were weighted more heavily than...
earlier items, signaling a greater relative importance. Again, this made intuitive sense. Late BBS items test more advanced balance function involving motion (eg, turning 360°, stepping on a stool), changing the base of support (standing with feet staggered), and limiting the base of support (standing on 1 leg). These are precisely the items that challenge patients more advanced in recovery, and hence phase III patients exhibited considerable variability in performance on these items.

Study Limitations

The patients considered in this analysis were all part of the NRN, which involves a standardized and fairly rigorous schedule of training. Because of this, it may be the case that participants in NRN are not representative of the general motor incomplete SCI population—that is, persons that chose to participate in NRN may be characteristically different from those who chose not to participate. Hence, the results presented here may not extend to the general SCI population. In particular, the imbalance in sex across the phase groupings at enrollment may be of some concern in that the conclusions from a marginal analysis may not hold if the population demographic characteristics are substantially different from those observed in the study population.

The analysis of the average rates of change in the BBS items tacitly assumes that the method for calculating said averages provides a reasonable approximation to the true rate of change and is a reasonable estimate of the construct of balance recovery. However, if the rates of change between successive evaluations are highly variable—that is, if the rates differ substantially as a function of the number of treatment sessions accumulated—the average rate of change as calculated here may be a poor estimate of balance recovery.

The calculation of the principal components by phase suffers from small sample sizes in each of the phase groupings, par-

**Table 4: Kendall $\tau$ and Spearman Rank Correlation $\rho$ Between the First Principal Component of Change in BBS Items and Changes in Clinical Measures of Walking**

<table>
<thead>
<tr>
<th></th>
<th>Six-Minute Walk Distance (m)</th>
<th>SCI-FAI Gait Subscale</th>
<th>SCI-FAI Assistive Device Subscale</th>
<th>SCI-FAI Walking Mobility Subscale</th>
<th>Ten-Meter Walk Speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>First principal component</td>
<td>$\tau$</td>
<td>$\rho$</td>
<td>$\tau$</td>
<td>$\rho$</td>
<td>$\tau$</td>
</tr>
<tr>
<td></td>
<td>.34 (*)</td>
<td>.48 (*)</td>
<td>.22 (*)</td>
<td>.31 (*)</td>
<td>.07 (.42)</td>
</tr>
</tbody>
</table>

$^*P<.01.$

Fig 3. Longitudinal (temporal) clinical profiles for 3 patients who scored low (solid lines) and for 3 patients who scored high (dashed lines) on the first PC of the BBS items. The plots are the distances for the six-minute walk test, the speed of the ten-meter walk test, scores on the Gait Parameters component of the SCI-FAI, and scores on the Walking Mobility component of the SCI-FAI. Abbreviation: PC, principal component.
particularly in the phase I group. Hence, the results of the phase-specific analysis should be viewed as preliminary and in need of additional validation. The differences we observed across the phases in NRN enrollment statistics were expected—patients earlier in recovery at enrollment needed more treatment and were subsequently enrolled for longer periods. However, these differences were handled by the marginal rate of improvement calculations before the principal components analyses were applied.

CONCLUSIONS

The analysis presented here is a first step in developing a balance tool for the SCI population starting with the BBS. We have identified a single interpretable principal component in the BBS that accounted for 48% of the total variability for the full population. This principal component was related to overall recovery of balance and consisted of all the items on the BBS except the third. A simple sum of the BBS items (less the third) provided a reasonable approximation to the first principal component, and could be regarded as a summary measure of balance in the general SCI population. However, the usefulness of the individual BBS items seemed to vary as a function of the patient’s phase of recovery. Specifically, earlier, simpler BBS items were more appropriate for patients in later stages of recovery, and later, more difficult BBS items were more appropriate for patients in latter stages of recovery. These results suggested that use of the simple sum of BBS items (less the third) as a measure of balance recovery may not be appropriate for the entire SCI population. A dynamic balance scale for the SCI population, in which the items comprising the scale change as the patient’s level of recovery changes, may be needed. This concept needs additional research, and future work toward developing a balance tool for the SCI population will include repeating this analysis on larger data sets, and further exploring the idea of phase dependence. A good balance instrument for SCI populations may also require inclusion of additional measures of sitting balance ability. Such measures may come from other balance measurement instruments, such as the Tinetti Performance Oriented Mobility Assessment balance scale\(^{26}\) and the Modified Functional Reach,\(^{27}\) or may need to be created and developed.

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APPENDIX 1: DEFINITIONS OF BERG BALANCE SCALE VARIABLES

1. Sitting to standing: Patient attempts to stand from a seated position in an armless chair, using hands as little as possible.
2. Standing unsupported: Patient attempts to stand for up to 2 minutes with no support.
3. Sitting with back unsupported but feet supported: Patient attempts to stand with feet together and no support on floor or stool: Patient attempts to sit in a chair for 2 minutes with no support.
4. Standing to sitting: Patient attempts to sit in an armless chair from standing position, using hands as little as possible.
5. Transfers: Patient attempts to move from an armless chair to a chair with arms, placed at a 90° angle from the armless chair, with minimal use of hands. Patient then attempts to move back to the armless chair, again with minimal use of hands.
6. Standing unsupported with eyes closed: Patient attempts to stand for up to 10 seconds with eyes closed and no support.
7. Standing unsupported with feet together: Patient attempts to stand with feet together and no support for up to 1 minute.
8. Reaching forward with outstretched arm while standing: Patient reaches forward as far as possible from a standing position by bending at the waist and returns to standing position with no support.
APPENDIX 1: DEFINITIONS OF BERG BALANCE SCALE VARIABLES (Cont’d)

9. Pick up object from the floor from a standing position: Patient attempts to pick up an object on the floor 15 to 30 centimeters (6–12 in) in front of his or her feet from a standing position with no support.

10. Turning to look behind over left and right shoulders while standing: Patient attempts to look at an object behind the patient over left and right shoulders, keeping feet planted on the ground and with no support.

11. Turn 360°: Patient attempts to turn in a full circle as safely and quickly as possible with no support.

12. Placing alternate foot on step or stool while standing unsupported: Patient attempts to place each foot alternately on a step or stool of 16 to 20 centimeters (6.5–8 in) until each foot has touched the step or stool 4 times with no support.

13. Standing unsupported 1 foot in front: Patient attempts to place 1 foot directly in front of the other and hold the position for 30 seconds with no support.

14. Standing on 1 leg: Patient attempts to stand on 1 leg for longer than 10 seconds with no support.

APPENDIX 2: DEFINITIONS OF CLINICAL MEASURES AS MEASURED IN THE NEURORECOVERY NETWORK

Six-minute walk: A sitting rest period of at least 10 minutes precedes the six-minute walk, during which vital signs are measured. The patient is instructed to walk as far as possible on a level surface over a period of 6 minutes. Patients are permitted to stop and rest during the walk by standing stationary or leaning against a wall, but not by sitting; the timing of the walk continues during such rest periods. Patient is alerted of the time every minute for the first 5 minutes and every 15 seconds during the last minute, and given standardized encouragement at each time update. The test concludes after 6 minutes or when the patient sits to rest.

Ten-meter walk: A sitting rest period precedes the ten-meter walk, during which vital signs are measured. The patient is instructed to walk a distance of 14m as quickly as possible. The walk is timed in the interval from 2m to 12m in the 14-m walk.

SCI-FAI: Parameters of the SCI-FAI are measured during the first 2 minutes of each six-minute walk. The 3 SCI-FAI subscales are Gait, Assistive Device, and Walking Mobility. The Gait subscale measures the quality of a patient’s gait by evaluating the patient’s weight shift, step width, step rhythm, step height, foot contact, and step length while walking. The Assistive Devices subscale quantifies the type of assistive device a patient uses according to the amount of assistance the device provides. The Walking Mobility subscale measures the capability for and frequency with which a patient walks in everyday life.

References