Adaptation of computerized posturography to assess seated balance in persons with spinal cord injury

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Background: The ability to retain or improve seated balance function after spinal cord injury (SCI) may mean the difference between independence and requiring assistance for basic activities of daily living. Compared with assessments of standing and walking balance, seated balance assessments remain relatively underemphasized and under-utilized.

Objective: To optimize tools for assessing seated balance deficits and recovery in SCI.

Design: Cross-sectional observational study of different methods for assessing seated balance function.

Setting: Veterans Affairs Center of Excellence for the Medical Consequences of Spinal Cord Injury.

Participants: Seven able-bodied volunteers, seven participants with chronic motor-complete thoracic SCI.

Interventions: A computerized pressure-plate apparatus designed for testing standing balance was adapted into a seated balance assessment system.

Outcome measures: Seated section of Berg Balance Scale; modified functional reach test; and two posturography tests: limits of stability and clinical test of sensory integration on balance.

Results: Seated posturography demonstrated improved correlation with neurological level of lesion compared to that of routinely applied subjective clinical tests.

Conclusion: Seated posturography represents an appealing outcome measure that may be applied toward the measurement of functional changes in response to various rehabilitation interventions in individuals with paralysis.

Keywords: Spinal cord injuries, Paraplegia, Rehabilitation, Disability, Assistive technology, Berg balance scale, Limits of stability, Modified functional reach test, Posturography

Introduction

A broad range of neural and musculoskeletal components maintains body stability as we perform various activities of daily living. Proprioceptive, visual and vestibular sensory inputs are integrated within spinal, brainstem, basal ganglia and cerebellar centers, leading to changes in motor output to continuously adjust truncal and proximal limb position during

walking, obstacle avoidance, reaching and other movements.¹

Maintenance of safe and functional balance is as essential seated as it is standing.² After a spinal cord injury (SCI), the individual depends even more on seated balance function to mediate basic activities of daily living. As such, one of the highest priorities during acute SCI rehabilitation is relearning to sit. This involves compensatory patterns of muscle activation involving muscles not normally used for postural support.²⁻⁴

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Though numerous scales and tools have been used to evaluate balance function, many of these tend to focus more on standing and walking rather than on seated balance. For example, the Berg Balance Scale (BBS) has confirmed reliability and validity in measuring multiple aspects of balance in elderly subjects and individuals with incomplete SCI.^{5,6} However, 12 of the 14 domains assessed by the BBS require the ability to stand – this limits the scoring range and sensitivity for measuring changes in *seated* balance. Electromyographic (EMG) analysis provides more comprehensive understanding of patterns of muscular activity during balance perturbations, but many such studies focus predominantly on major leg muscle groups, such as the tibialis anterior and triceps surae, with only a few investigators examining trunk muscle EMG activity.^{3,7} Therefore, there is a need for more sensitive, easily applied and informative tools to quantify and track seated balance function in individuals who are paralyzed.

Computerized posturography provides a sophisticated, objective measure of balance and postural stability in persons with a history of falls, vestibular disorders and other neurological and musculoskeletal conditions.^{8,9} The center of gravity (COG) and postural adjustments to various perturbations are tracked through a combination of force plates and real-time feedback. Software modules vary the types of perturbations as subjects shift toward different on-screen targets. This provides crucial information regarding brainstem, cerebellar, proprioceptive and vestibular pathway function. However, most posturography protocols focus more on standing rather than seated balance.

With the goal of improved assessment of balance in individuals with paraplegia, a computerized posturography system (Neurocom Smart EquiTest) was adapted to allow measurement of seated balance. Preliminary findings are presented from able-bodied volunteers and individuals with chronic motor-complete paraplegia that measure seated posturography's sensitivity to injury and lesion level in comparison with routinely used clinical tests, such as the BBS and modified functional reach test (MFRT).

Methods

Subjects

Able-bodied volunteers ($n = 7$, one woman, ages 23–61 years) and subjects with chronic, motor-complete thoracic SCI ($n = 7$, one woman, ages 24–61 years) were recruited to participate (Table 1). The balance testing protocols were approved by the James J. Peters VAMC Institutional Review Board after our ongoing

Table 1 Subjects

Age	Gender	Level	Grade	Time (year)
40	M	T1	B	1.5
34	M	T4	A	9
24	M	T5	A	5
43	M	T8	A	4
59	M	T8	A	6.5
61	M	T11	A	14
32	F	T11	A	15
23	M	UI		
24	M	UI		
26	F	UI		
32	M	UI (there are two 32yo male uninjured subjects, total of 7 uninjured subjects)		
40	M	UI		
61	M	UI		

UI, uninjured.

exoskeletal gait training study (unpublished) had already begun. Therefore, several subjects were assessed after already participating in a variable number of gait training sessions.

Berg Balance Scale¹⁰

The BBS consists of 14 domains, each scored between 0 and 4, testing balance in a range of static and dynamic positions. For scoring individuals with paraplegia, we applied domain 3, the “Sitting with back unsupported” section of the scale. Subjects were seated with chair height adjusted so that hip, knee, and ankle angles were each roughly 90°. Individuals were scored on ability to maintain seated balance without back support while keeping the arms folded across the chest for up to 2 minutes (Table 2).

Modified functional reach test¹¹

Subjects were seated with hips, knees, and ankle angles at roughly 90°. In the starting position, the subject rested against the chair's back support, with the right arm folded across the chest, and the left arm extended forward at a 90° angle from the shoulder with the scapula fully protracted. The position of the ulnar styloid process was recorded against a wall-mounted tape measure (Fig. 1). While maintaining the outstretched left arm, the subject was asked to lean forward at the trunk as far as possible without losing

Table 2 Berg Balance Scale – sitting with back unsupported

0	Unable to sit for at least 10 seconds
1	Able to sit 10 seconds
2	Able to sit 30 seconds
3	Able to sit 2 minutes under supervision
4	Able to sit safely and securely for 2 minutes

Figure 1 Seated balance testing setup. (A) Arms across chest starting position for Berg Scale and LOS. (B) MFRT – the position of the ulnar styloid process is tracked as the subject leans forward as far as possible without falling. (C) Limits of stability testing – the subject leans toward on-screen targets in eight cardinal directions. (D) Clinical test of sensory interaction on balance – arms-extended/eyes-open position.

balance. The position of the ulnar styloid process was recorded while the subject held the forward position for 3 seconds. Two practice trials and three test trials were recorded in this manner. The average displacement of the styloid process (in centimeters) over the three test trials was scored. If during leaning forward, a subject dropped his or her hands for stabilization, or whether study personnel needed to intervene to prevent a fall, then that trial was scored zero.

Seated posturography

Setup

The tests described were performed on the long force plate of the Smart EquiTest system (Neurocom). This apparatus is in clinical use at the Audiology clinic of

our medical center. We thank Anthony Reino, Mark Warner, and Erica Weitzmann for facilitating our use of this system for research. To accommodate individuals with paraplegia, a wooden block (46 cm $W \times 43$ cm $L \times 31$ cm H) was centered on the force plate, with an overlying foam pad (13-cm thick) for subject comfort and skin protection. Note that this cushioned block system did not provide as much adjustable height flexibility as the chair used for the BBS or MFRT. One subject with femoral and tibial lengths of 42 and 46 cm, respectively, required an extra wooden block (46 cm $W \times 36$ cm $L \times 10$ cm H) to create a comfortable starting position with knees below hips. Subjects transferred onto the pad and sat with feet flat on the platform, roughly shoulder width apart. Arms were kept crossed over the

chest during testing, except for the hands outstretched portion of the clinical test of sensory integration on balance (CTSIB; see Fig. 1 and below). Two personnel were at the subject's side at all times to ensure subject safety. Once the subject was seated comfortably, the overall COG was centered by moving the padded block backwards approximately 5 cm to counterbalance the effect of the subject's feet placed in front of the block.

Limits of stability

The limits of stability (LOS) tests dynamic balance as the subject leans toward targets in eight cardinal directions while the subject's COG is displayed on a monitor in real time. Subjects were instructed to lean as far toward the indicated target as possible without losing balance. To gauge their own limits, subjects were allowed several unscored practice attempts to lean toward one or two targets prior to beginning. If during testing, a subject dropped his or her hands for stabilization, or if study personnel needed to intervene to prevent a fall, then that trial was scored zero. Subjects were not encouraged to move quickly toward the target. Therefore, the 'reaction time' and 'movement velocity' measurements were ignored. The following measures were recorded: endpoint excursion (EPE), maximum excursion (MXE), and directional control (DCL). EPE is the distance of the first movement toward the designated target, expressed as a percentage of total distance toward that target. MXE is the maximal distance relative to the target achieved during the trial. DCL is the percent of movement in the intended direction (towards the target) expressed as percentage of total movement (Fig. 2).

Clinical test of sensory interaction on balance

The CTSIB tests static balance by quantifying postural sway while the subject attempts to remain stationary

Figure 2 Example of computerized posturography output. LOS testing for one subject with T8 AIS A SCI as he leaned toward eight targets. The points on the lean trajectory of "endpoint excursion" (EPE) and "maximal excursion" (MXE) are indicated for the right-front and the right targets. EPE and MXE are calculated as percent of target distance attained. DCL is the percent of total movement that is toward the target.

under different eyes-open or eyes-closed conditions. Trials were performed in each of four conditions: (1) arms across chest, eyes open; (2) arms across chest, eyes closed; (3) arms extended forward, eyes open; and (4) arms extended forward, eyes closed. The main outcome measurement was the average sway velocity detected under each condition. If during testing, a subject dropped his or her hands for stabilization, or if study personnel needed to intervene to prevent a fall, then that trial was scored zero.

Statistics

Scores on all tests were normalized to percentage scores. For the BBS, scores were divided by 4 then multiplied by 100; for the MFRT, scores were divided by 50 then multiplied by 100 (50 cm was the approximate maximal distance achieved by able-bodied volunteers); for the CTSIB, scores were subtracted from 10, then multiplied by 10 (falls were scored 10, resulting in a zero after normalization); for the LOS, scores were already expressed as percentages. One-tailed *t*-tests were used to determine significant differences between able-bodied and SCI individuals, with the Bonferroni correction employed for multiple comparisons among different tests. Linear regression R^2 coefficients were determined for scores on each test relative to spinal lesion level as defined numerically (e.g. C1 = 1, T1 = 9, T12 = 20).

Results

Static and dynamic balance testing approach

Testing protocols are described in more detail in the Methods section, and visually in Fig. 1. Section three of the Berg Scale (sitting with back unsupported, Table 2) and the CTSIB represent the two tests of *static* seated balance function used in this study. The MFRT and the LOS tests represent the two tests of *dynamic* seated balance function used in this study. Whereas the BBS and MFRT involve subjective clinical assessments, seated posturography involves objective computerized measurements of multiple parameters of center of gravity position and movement.

Dynamic seated balance tests more sensitive to SCI

Able-bodied volunteers all achieved the maximum score on section 3 of the BBS, and each scored remarkably similarly on the MFRT and seated posturography tests. Subjects with thoracic SCI, each of whom had regained the ability to sit independently after their injuries, performed relatively better on tests of *static* balance (77.6% cumulative score on CTSIB and seated BBS) than on tests of *dynamic* balance (31.9%

Figure 3 Dynamic seated balance testing is more sensitive to SCI. Able-bodied volunteers (black bars) and subjects with chronic motor-complete thoracic SCI (gray bars) were tested on static and dynamic measures of seated balance. SCI subjects were more impaired on dynamic (average score: 31.9%) than static (average score: 77.6%) balance outcomes. BBS, seated portion of Berg Balance Scale; Chest-EO, postural sway velocity during stationary sitting as in Fig 1A; Stretch-EO, sway during sitting as in Fig 1D; Chest-EC, sway while seated as in 1A with eyes closed; Stretch-EC, sway while seated as in 1D with eyes closed; MFRT, modified functional reach test; EPE, endpoint excursion; MXE, maximal endpoint excursion; DCL, directional control. ** $P < 0.001$; * $P < 0.01$. Error bars, SEM.

cumulative score on seated LOS and MFRT) (Fig. 3). After Bonferroni correction for multiple comparisons, subjects with SCI scored significantly lower than able-bodied subjects on each of the dynamic balance tests but none of the static balance tests. Of note, the importance of visual compensation for maintaining balance after SCI was revealed by deficits in the eyes-closed conditions of static sway testing (Fig. 3).

Seated posturography more sensitive to level of lesion

To determine how well scores on each test of balance correlated with neurological deficit, scores were plotted against spinal injury level (Fig. 4). Results are visually

Figure 4 Computerized posturography is more sensitive to SCI lesion level. Seven subjects with chronic motor-complete SCI at varying thoracic levels were tested on static and dynamic measures of seated balance. Individual SCI subject scores were plotted against lesion level. The plot shows results for a subjective static balance test (BBS, gray circles), a subjective dynamic balance test (MFRT, black triangles), and a computerized dynamic balance test (DCL, black squares). Note the prominent ceiling effect for BBS, and the floor effect for MFRT. Linear regression R^2 values confirm that DCL correlated better with level of lesion than subjective scores did. See Fig. 3 legend for abbreviations.

depicted for BBS, MFRT, and the DCL component of computerized LOS testing, and listed in table format for all nine tests of balance. The ceiling effect of the seated portion of the Berg Scale was clearly demonstrated by the observation that all subjects with lesion levels at or below T4 easily obtained the maximum score.¹² Conversely, during the MFRT, SCI subjects found it extremely difficult to lean forward while keeping one arm outstretched. Moreover, examiners found it difficult to differentiate truncal leaning (the outcome of interest) from shoulder/arm stretching during the MFRT. This not only led to low scores (floor effect), but also led to unreliable correlation with level of spinal lesion. MFRT had the weakest correlation with level of lesion ($R^2 = 0.039$), whereas the DCL parameter had the strongest correlation ($R^2 = 0.602$, $P < 0.05$) (Fig. 4). Note that if the subject with T1 SCI were removed from the analysis, then the correlation between BBS and level of lesion would be zero.

Discussion

Seated balance function represents a vital element of daily living that is usually taken for granted until a life-altering event such as SCI. We were interested in optimizing tools for assessing seated balance deficits and recovery. Of the balance tests used in this study, the BBS is by far the easiest to perform. It also has extensive supporting evidence for its validity and reliability as a clinical balance outcome measure.^{6,10,13} However, this validity depends on conducting the full BBS, which comprises 14 domains. On a practical level, subjects with motor-complete paraplegia cannot perform most of these components, limiting the effective range of scores that can be obtained. For seated balance, these data confirm that the BBS demonstrates a significant ceiling effect

that makes it difficult to discern individuals with SCI from able-bodied individuals using this tool.^{12,14}

The MFRT requires only slightly more equipment than the seated BBS, specifically a wall-mounted ruler or tape measure (a video camera is optional). It also clearly differentiates able-bodied individuals from those with SCI. However, due to the difficulty of the task, individuals with motor-complete SCI scored within a limited range (0–8 cm) that roughly overlapped with the uncertainty arising from the tendency of subjects to extend their shoulder as they attempted to lean forward at the trunk. This occurred despite subjects being specifically instructed to extend the shoulder as far as possible at the starting point rather than during the leaning phase of the MFRT. These factors likely explain the unreliable correlation of MFRT performance with level of spinal lesion in our cohort.

Another study used a different set of clinical scales (motor assessment scale (MAS) item 3 and sitting balance score) to assess seated balance in individuals with SCI.¹⁵ These investigators found modest correlation ($R^2 = 0.51$) of MAS item 3 with level of lesion, but levels were grouped into three bins (C5–C8, T1–T7, T8–L1) rather than single levels, and the patient population included motor-incomplete as well as complete injuries. Seated posturography was not utilized in this study.

Intriguingly, posturography automatically breaks down balance function into multiple quantifiable components, such as excursion, directional control, sway, angular velocity, and others. This breakdown not only could assist therapists to focus on their patients' specific deficiencies, but it could also potentially provide further insight into the neural underpinnings of each component. The expense of purchasing posturography equipment is a drawback.⁹ However, many such systems, including the one at our medical center, are already in routine clinical use within otolaryngology departments. This makes it more feasible to adapt these systems within academic medical centers, both for research use and for clinical referral.

The fact that some participants with SCI were assessed *after* the initiation of an exoskeletal gait training program represents a confounding factor in our correlation of results to lesion level. However, this is mitigated in two ways: one, the possible effects of gait training on balance are likely outweighed by the effects of the SCI lesion level itself; and two, any cross-sectional population of individuals with chronic SCI will already have a varying range of home exercise programs to begin with. In any case, until a larger number of subjects are tested, the effect of exoskeletal

gait training may remain a confounding factor. Furthermore, because repeat testing of the same individuals *without* intervention over time has not been performed, conclusions regarding seated posturography's within-subject test–retest reliability cannot be made. In addition, our experience with individuals with motor-complete thoracic SCI does not allow us to generalize the results to individuals with incomplete or cervical injuries at this time.

Although the work presented here suggests the utility of a seated posturography system to test seated balance, only a small number of subjects have been studied to date, which precludes making more definitive conclusions. As further subjects are tested, a normative database for seated balance function based on each level of spinal injury will be developed.

A small number of other studies have performed seated posturography in subjects with paraplegia, each with differences in testing protocols, outcome variables, and/or patient population.^{16–18} The report by Field-Fote and Ray finds that multidirectional seated reach distance serves as an acceptable correlate for center of pressure posturography measurements (in subjects with motor-incomplete SCI). The findings of Kim *et al.*¹⁹ and Chen *et al.*¹⁷ confirm our conclusion that posturography offers advantages over subjective clinical tests for assessing seated balance.

Conclusion

Optimal outcome measurements should be objective, accurate, and sensitive over a broad range of function. For testing seated balance in individuals with paraplegia, seated posturography better fulfills these criteria than conventionally applied clinical balance tests, such as the BBS or MFRT.

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