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Objectively assessing balance deficits after TBI: Role of computerized posturography

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Abstract—Balance impairment, or postural instability, is a common source of residual physical disability after severe traumatic brain injury (TBI). Standardized functional measures such as the Functional Independence Measure (FIM) do not specifically assess balance. Furthermore, no agreement exists as to the optimal way to objectively measure balance problems in the TBI population. Technological advances have led to force-plate balance measurement known as computerized posturography testing (CPT). Published CPT data for severe TBI are lacking, and the feasibility of using CPT during rehabilitation has not been described. This study described CPT findings in 21 ambulatory patients with severe TBI who were undergoing inpatient rehabilitation at a Defense and Veterans Brain Injury Center. Results demonstrated the utility of CPT in detecting and quantifying postural instability. Comparisons with the normative database indicate that the sample had a high degree of balance impairment despite some participants having reached the ceiling of the FIM ambulation scale at discharge from the acute rehabilitation setting. The quantitative CPT measures are a promising way to characterize postural instability in severe TBI populations.

Key words: assessment, balance, computerized posturography, mobility, posttraumatic amnesia, postural instability, rehabilitation, traumatic brain injury, vestibular dysfunction, visual cues.

INTRODUCTION

The annual incidence of all severities of traumatic brain injury (TBI) in the United States is estimated to be between 500,000 and 2 million cases. Of these, the approximately 44,000 people with moderate to severe TBI have significant residual physical or neurobehavioral sequelae [1]. The National Institutes of Health report that 2.5 million to 6.5 million Americans have TBI-related disabilities [2]. For many, balance impairment, or postural instability, is a source of residual physical disability.

While published data on the functional impact of postural instability after TBI are limited, investigations by Duong et al. [3] and Greenwald et al. [4] have shown an association between early balance deficits after TBI and late functional recovery. Other investigations have shown that dizziness and imbalance are frequent long-term symptoms after severe TBI [5]. Hillier et al. interviewed 67 subjects with TBI of mixed severity (mostly

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Abbreviations: CPT = computerized posturography testing, FIM = Functional Independence Measure, PREF = preference (ratio), PTA = posttraumatic amnesia, SD = standard deviation, SOM = somatosensory (ratio), SOT = Sensory Organization Test, TBI = traumatic brain injury, VAMC = Department of Veterans Affairs medical center, VEST = vestibular (ratio), VIS = visual (ratio).

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severe) at 5-years postinjury and found that, after headache, balance deficit was the second-most frequent self-reported physical symptom [5].

Postural imbalances as long-term sequelae of severe TBI may not be surprising given that balance involves a complex interaction of sensory, motor, and musculoskeletal systems. Even minor impairments in integration of this information could lead to significant long-term disability [6]. Postural instability after TBI can interfere with the higher level mobility skills necessary for a full return to leisure and/or vocational activities. Thus, objective methods of quantifying balance impairment may aid the tracking of mobility recovery and formulation of recommendations for disability, job restrictions, and leisure activity.

Currently, no agreement exists on the best objective measure of balance after TBI. Standardized functional measures commonly used in TBI rehabilitation, such as the Functional Independence Measure (FIM), do not specifically assess balance [7]. Quantitative tests to assess balance that have been described for the TBI population include variations of the Romberg test [8], the test of sway [9], the Berg Balance Scale [10], and other more subjective tests. Lehmann and colleagues were the first to use force platforms to document abnormal center-of-pressure parameters (i.e., test of sway) in persons with TBI [9]. They found a statistically significant difference between persons with TBI and controls in nearly all stance parameters, particularly when visual cues were either absent or indistinct. They also found that the persons with TBI had decreased stability compared with controls when somatosensory input was distorted (standing on a foam versus solid surface) [9]. Geurts and colleagues also used dual-plate force-platform testing to evaluate static and dynamic postural instability in individuals with mild TBI [11]. They found that compared with controls, the individuals with TBI had a more than 50 percent increase in anterior-posterior and lateral sway, which worsened with visual deprivation [11].

Technological advances have led to the next generation of force-platform balance measurement devices: computerized posturography testing (CPT) [12]. Research on CPT in the mild TBI population (sports-related concussion) has demonstrated that significant balance deficits are seen acutely postconcussion but normalize within 1 week [13–14]. A gap in the literature exists regarding CPT assessment among moderate-severe TBI cohorts. Some studies investigating CPT in TBI participants did not control for TBI severity. For the moderate and severe TBI populations, published CPT data is lacking and the feasibility of CPT during rehabilitation has not been described. This pilot study described CPT findings in an ambulatory severe TBI population undergoing inpatient rehabilitation.

METHODS

The study setting was an acute comprehensive brain injury rehabilitation unit (accredited by the Commission on Accreditation of Rehabilitation Facilities) at a Department of Veterans Affairs medical center (VAMC) in the Defense and Veterans Brain Injury Center [15–16]. The local VAMC institutional review board approved the study. The participants were 21 consecutive individuals (**Table 1**) with severe TBI (20 men and 1 woman, mean ± standard deviation [SD] age of 23.7 ± 4.2 years) who met the following inclusion criteria: (1) a documented severe TBI, (2) at least a supervision level of ambulation, and (3) CPT receipt during their inpatient program. Severe TBI was defined as posttraumatic amnesia (PTA) lasting longer than 7 days [17–18]. We chose PTA as the primary method because it was usually available from records at our center and has been shown to predict outcome better than initial Glasgow Coma Scale scores [19–20]. Patients who emerged from PTA before transfer to our center or who had indeterminate PTA measurements were categorized as having severe TBI if their documented initial Glasgow Coma Scale score was ≤8 [21–22]. Duration of unconsciousness was not used because acute care records were inconsistently available for our sample. **Table 2** summarizes the participants' injury characteristics.

Table 1.
Subject demographics.

Variable	Subjects	
	No.	%
Sex		
Male	20	95.2
Female	1	4.8
Race/Ethnicity		
White	19	90.4
African American	1	4.8
Native American	1	4.8
Injury		
Blast	4	19.0
Motor Vehicle Accident	8	38.1
Gunshot Wound	5	23.8
Shrapnel	1	4.8
Blunt Trauma	1	4.8
Assault	2	9.5

Table 2.
Participants' injury characteristics

Variable	*n*	Mean ± SD	Range
Age (yr)	21	24.0 ± 4.2	20–39
Initial GCS	13	6.5 ± 2.4	3–10
PTA (wk)	18	4.4 ± 2.9	1.5–12.0
Time Postinjury (mo)	21	1.9 ± 1.3	1–7
FIM Motor at Admission	21	27.1 ± 8.5	5–35
FIM Motor at Discharge	21	34.8 ± 0.4	34–35

GCS = Glasgow Coma Scale, FIM = Functional Independence Measure, PTA = posttraumatic amnesia, SD = standard deviation.

After the participants achieved at least a supervision level of ambulation, we used a dual-plate force platform called the NeuroCom Smart Balance Master® (NeuroCom International, Inc; Clackamas, Oregon) to assess their postural stability [23]. We analyzed CPT, injury severity, and demographic data with SPSS statistical software (SPSS, Inc; Chicago, Illinois) [24]. Participants completed six conditions on the NeuroCom Smart Balance Master. These six conditions compose the Sensory Organization Test (SOT) (**Figure 1**) and yield quantifiable data about postural stability. Participants were tested on the dual-plate force-support surface that moved under computerized control. We assessed the vertical ground reaction forces, which are produced by the body's center of gravity and move around a rigid base of support [13]. The SOT eliminates orientation information that is useful to the eyes, feet, and joints by "sway referencing," which involves tilting the support surface and/or visual surroundings to precisely track the participant's center of gravity and anterior-posterior sway [13,23]. Sway referencing causes orientation of the support surface or surroundings to remain constant relative to body position. The SOT is designed to evaluate the participant's ability to ignore inaccurate information from the sway-referenced sense(s).

Using the series of six SOT conditions that presents participants with conflicting sensory information, one may determine how visual, somatosensory, and vestibular input affect the participants' balance [23] (**Figure 1**). The six conditions are—

1. Eyes open with a fixed surface and visual surroundings.
2. Eyes closed with a fixed surface.
3. Eyes open with a fixed surface and sway-referenced visual surroundings.
4. Eyes open with a sway-referenced surface and fixed visual surroundings.

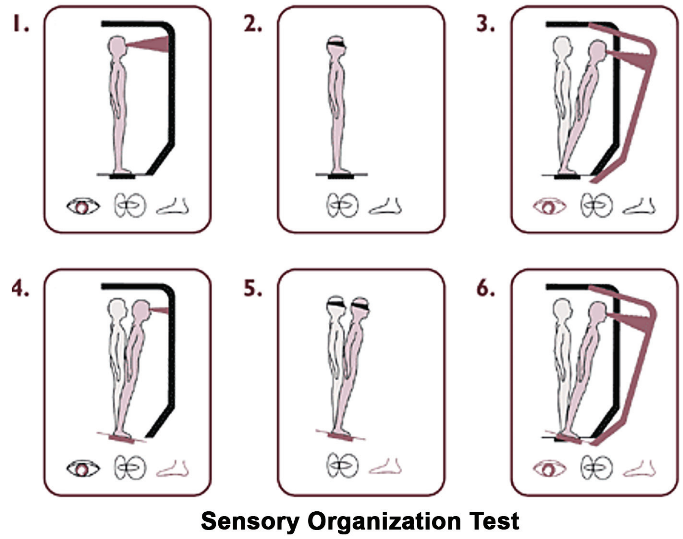

Figure 1.
Sensory Organization Test conditions. 1 = eyes open with fixed surface & visual surroundings, 2 = eyes closed with fixed surface, 3 = eyes open with fixed surface & sway-referenced visual surroundings, 4 = eyes open with sway-referenced surface & fixed visual surroundings, 5 = eyes closed with sway-referenced surface, 6 = eyes open with sway-referenced surface & visual surroundings. Reprinted by permission from NeuroCom® International, Inc (Clackamas, Oregon).

5. Eyes closed with a sway-referenced surface.
6. Eyes open with a sway-referenced surface and visual surroundings.

The test protocol consists of 18 total trials (20 seconds each). Participants are asked to stand as motionless as possible with their feet shoulder-width apart. Three trials are completed for each of the six conditions presented in **Figure 1**.

Three different visual conditions (eyes open, eyes closed, sway-referenced visual surrounding) are crossed with two different surface conditions (fixed, sway-referenced). During the sway-referenced support-surface conditions, the force plate tilts synchronously with the participants' anterior-posterior sway. A composite equilibrium score is calculated that describes the overall level of performance during all the SOT trials. This score is a weighted average of the equilibrium scores from the 18 trials (3 for each of the 6 conditions). Higher scores indicate better postural stability. Equilibrium scores from each of the trials represent a percentage in which peak amplitude of anterior-posterior sway is compared with a theoretical anterior-posterior limit of stability. Estimates of participants' peak amplitude of anterior-posterior sway are based on their height and the size of the base of support. This amplitude represents the angle at which participants can lean in any direction before the center of gravity moves beyond a point that allows maintenance of balance. Lower percentages result in a higher (better) composite score. As part of the SOT, relative differences between the equilibrium scores of various conditions are calculated from ratios to reveal specific information about each of the sensory modalities involved with maintaining balance. These ratios are useful in identifying sensory integration problems, since lower ratios indicate an inability to compensate for disruptions in selected sensory inputs.

The vestibular (VEST) ratio is computed from scores obtained in condition 5 and condition 1. This ratio indicates the relative reduction in postural stability when visual and somatosensory inputs are simultaneously disrupted. The visual (VIS) ratio is obtained by comparing condition 4 with condition 1. The VIS ratio reflects a participant's ability to use input from the visual system to maintain balance. The somatosensory (SOM) ratio compares condition 2 with condition 1 and reflects the participant's ability to use input from the somatosensory system to maintain balance. The preference (PREF) ratio compares conditions 3 and 6 with conditions 2 and 5. The PREF ratio indicates the extent to which the participant relies on visual information to maintain balance, even when this information is incorrect [25].

RESULTS

The SOT is a composite index that defines abnormalities across somatosensory, visual, and vestibular systems. Six equilibrium scores corresponding to the six sensory condition tasks were calculated from the participants' scores on the three trials for each condition.

The scores ranged from 0 (touching a support surface, shifting feet, or falling) to 100 (little or no sway). Normative data for the NeuroCom Smart Balance Master are available for three age groups: 20–59, 60–69, and 70–79 years.* Since the age of participants in this study ranged from 20–39 years, we used the normative data for the 20–59 group as comparative controls.

The SOT provides four ratio scores and an index of overall performance. The composite equilibrium score, a measure of overall performance on the SOT, is a weighted average of the six equilibrium scores (0–100). To isolate individual sensory impairments, we used the following sensory analysis ratios: SOM, VIS, PREF, and VEST (**Table 3**). We computed the SOM, VIS, and VEST ratios by dividing the equilibrium scores for conditions 2, 4, and 5, respectively, by the score for condition 1. The PREF ratio demonstrates the degree to which the participants rely on visual information for balance, even when the visual cues are not accurate. We computed the PREF ratio by dividing the sum of scores for conditions 3 and 6 by the sum of scores for conditions 2 and 5. **Table 4** displays the participants' mean composite equilibrium score, six equilibrium scores, and four sensory analysis ratios.

One-sample *z*-tests were conducted for each measure with the age-matched normative data just described. Bonferroni corrections were applied to adjust for multiple comparisons ($\alpha = 0.0045$). The mean composite equilibrium score was significantly lower in the TBI group than the normative sample (74.43 vs 79.79, respectively; $z = -4.36$, uncorrected $p < 0.001$), indicating that the TBI group had greater body sway. Four of the participants with TBI had scores in the abnormal range (less than –2 SD) and another seven scored between –1 and –2 SD based on the normative sample.

Of the six sensory conditions, the TBI group scored lower on conditions 2, 3, and 5 (**Table 4**, **Figure 2**). Statistical significance for condition 1 was lost after Bonferroni correction. Two of the four one-sample *z*-tests for the sensory analysis ratios were abnormal, as well (**Table 4**, **Figure 2**). The mean VEST ratio was lower for the TBI group than the normative sample (0.62 vs 0.73, respectively; $z = -4.91$, uncorrected $p < 0.001$), indicating that the TBI group had more difficulty using information from the vestibular system to maintain balance. In addition, the mean PREF ratio was higher for the TBI group than the normative sample (1.06 vs 0.98, respectively; $z = 5.23$, uncorrected $p < 0.001$), indicating that the TBI group relied more on visual information to maintain balance, regardless of the accuracy of that information. Difference on the SOM ratio was lost after Bonferroni correction.

DISCUSSION

This pilot study demonstrated the utility of CPT for detecting and quantifying postural instability in a sample

*Dr. Lewis Nashner, NeuroCom International, Inc, personal communication, March 2006.

Table 3.
Description of Sensory Organization Test sensory ratios. Reprinted by permission from NeuroCom® International, Inc (Clackamas, Oregon).

Ratio	Comparison	Functional Relevance
Somatosensory (SOM)	Condition 2 / Condition 1	Patient's ability to use input from the *somatosensory system* to maintain balance.
Visual (VIS)	Condition 4 / Condition 1	Patient's ability to use input from the *visual system* to maintain balance.
Vestibular (VEST)	Condition 5 / Condition 1	Patient's ability to use input from the *vestibular system* to maintain balance.
Preference (PREF)	Condition 3 + 6 / Condition 2 + 5	The degree to which a patient relies on visual information to maintain balance, even when the information is incorrect.

Table 4.
Mean Sensory Organization Test results for study sample with traumatic brain injury.

Test	Mean ± SD	*z*-Value*	95% CI
Equilibrium			
Composite	74.43 ± 7.50	–4.36†	± 2.41
Condition 1	92.63 ± 2.55	–2.65	± 1.01
Condition 2	88.84 ± 3.37	–3.49†	± 1.80
Condition 3	88.56 ± 3.70	–4.02†	± 1.43
Condition 4	79.51 ± 7.60	–1.78	± 3.23
Condition 5	57.24 ± 19.35	–5.25†	± 4.46
Condition 6	63.37 ± 15.21	–1.51	± 4.95
Sensory Analysis Ratio			
SOM	0.96 ± 0.03	–2.09	± 0.02
VIS	0.86 ± 0.07	–1.15	± 0.03
VEST	0.62 ± 0.21	–4.91†	± 0.05
PREF	1.06 ± 0.21	5.23†	± 0.03

*One-sample *z*-test.
†Significantly different from normative samples after Bonferroni correction.
CI = confidence interval, PREF = preference, SD = standard deviation, SOM = somatosensory, VEST = vestibular, VIS = visual.

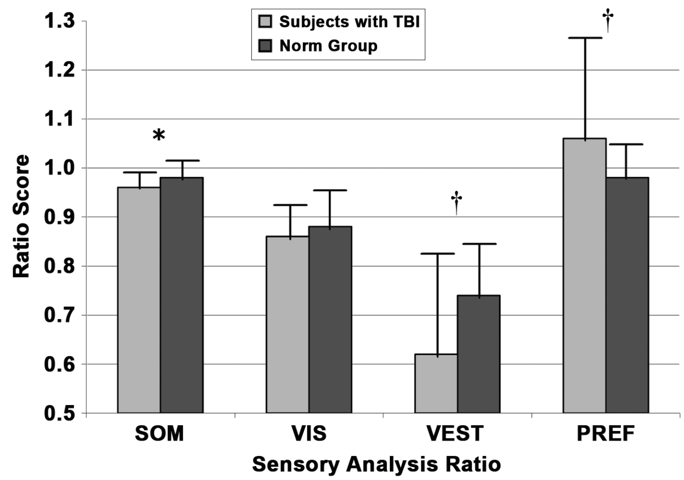

Figure 2.
Sensory analysis ratio scores for 21 subjects with traumatic brain injury (TBI) vs established normative data (Norm Group) provided by NeuroCom® International, Inc (Clackamas, Oregon). Error bar represents one standard deviation. *Significant difference between groups at $p < 0.05$. †Significant difference between groups after Bonferroni correction. PREF = preference, SOM = somatosensory, VEST = vestibular, VIS = visual.

of patients with severe TBI who were undergoing rehabilitation. Comparisons with the normative database indicated that our sample had a high degree of balance impairment despite some participants having reached the ceiling of the FIM ambulation scale at discharge from the acute rehabilitation setting. The quantitative CPT measures appear well suited to providing information on impairment severity and tracking improvement over time.

Although various altered sensory conditions were simulated with the SOT, overall postural stability deficit was also analyzed in relation to visual, somatosensory, and vestibular input. Balance is defined as the process of maintaining equilibrium and center of gravity within the body's base of support. The sense of balance is regulated within the central nervous system by a complex integration of various peripheral pathways including visual, somatosensory, and vestibular [4–5,26]. The abnormal sensory ratios found in our study indicate that the vestibular system was the primary source of our sample's postural instability. Additionally, the sensory ratios indicated that our sample was overreliant on visual compensatory strategies. In other words, these subjects used visual cues to compensate for vestibular dysfunction and maintain balance, but they were unable to completely compensate.

Our localization to vestibular dysfunction concurs with CPT research findings in subjects with mild TBI [11,26] but differs from findings in subjects with Parkinson's disease [27]. Guskiewicz postulated that two possible mechanisms cause vestibular dysfunction after TBI: peripheral versus central [13]. Alteration of peripheral receptors may provide inaccurate information or central integration of sensory input may be impaired. Basford et al. proposed that impairments in the vestibular system may result from tethering of the vestibular nerve as it passes through the internal acoustic meatus during shearing and from the acceleration/deceleration forces often sustained during TBI [6]. For this reason, follow-up studies investigating the effects of blast injury on postural stability are indicated.

Limitations of the current study include the small sample size, the retrospective design, and the between-group comparisons based on normative data from the manufacturer. Another potential limitation is that information on specific injury-related factors (e.g., fractures in lower limbs or inner ear damage) was unavailable to researchers. Despite the assumption that we employed clinical judgment when using the Smart Balance Master with the participants, some non-TBI-related variables may have contributed to the postural instability findings. Finally, as is typical of most TBI samples, demographics were skewed toward young males. More research will be needed to generalize these findings to other populations, such as females and older adults.

Our findings may provide rehabilitation therapists with treatment insights. In our sample, the steepest performance decline occurred when participants could not use visual strategies to compensate and had to maintain their balance by using the vestibular system alone. This finding suggests that persons with severe TBI may overrely on visual cues, even when this strategy is ineffective. One possibility is that rehearsing nonvisual strategies may yield greater treatment returns in this population. Studies investigating the comparative effectiveness of various "sensory-specific" treatments are needed.

CONCLUSIONS

The study findings complement and expand existing research on balance impairment after TBI. They provide evidence that CPT safely and effectively assists the diagnosis of balance impairments and provides quantitative data to track changes over time and/or assess the efficacy of treatment interventions. Similar to findings in mild TBI, vestibular dysfunction appears to underlie postural instability after severe TBI. Further research on CPT in moderate and severe TBI samples is recommended, particularly studies on longitudinal changes and correlation with markers of central or peripheral vestibular impairment.

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The authors have declared that no competing interests exist.

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