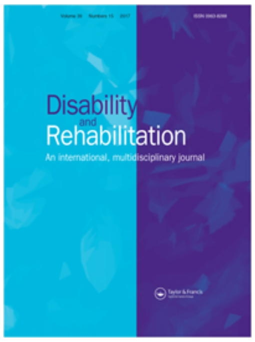

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SPECIAL ISSUE

Assessing subacute mild traumatic brain injury with a portable virtual reality balance device

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ABSTRACT

Purpose: Balance impairment is a common sensorimotor symptom in mild traumatic brain injury (mTBI). We designed an affordable, portable virtual reality (VR)-based balance screening device (Virtual Environment TBI Screen [VETS]), which will be validated relative to the Neurocom Sensory Organization Test (SOT) to determine if it can replace commonly used postural assessments.

Methods: This preliminary study examines healthy adults ($n = 56$) and adults with mTBI ($n = 11$). Participants performed six upright postural tasks on the VETS and the SOT. Analysis of variance was used to determine between-group differences. Pearson's correlations were used to establish construct validity. Known-groups approach was used to establish classification accuracy.

Results: The mTBI cohort performed significantly worse than the healthy cohort on the new device ($p = 0.001$). The new device has 91.0% accuracy and an ROC curve with a significant area-under-the-curve (AUC $= 0.865$, $p < 0.001$). Conditions with dynamic visual stimulation were the most sensitive to health status. The SOT had an 84.8% accuracy and AUC $= 0.703$ ($p = 0.034$).

Conclusions: The new VR-based device is a valid measure for detecting balance impairment following mTBI and can potentially replace more expensive and cumbersome equipment. Assessments that test visual-vestibular processing, such as VETS, increase sensitivity to mTBI-related balance deficits, which can be used to guide rehabilitation.

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Visual-vestibular processing; virtual reality; concussion; posture; sensory organization test

➤ IMPLICATIONS FOR REHABILITATION

- Emerging technology using virtual reality can be economically integrated into the clinical setting for easy testing of postural control in neurologically impaired populations.
- Tailoring postural assessments to include tasks that rely on visual and vestibular integration will increase the accuracy of detecting balance impairment following mild traumatic brain injury.

Introduction

Traumatic brain injury (TBI) affects over 2 million people per year in the United States with the largest percentage of these being mild TBI. Mild traumatic brain injury (mTBI), often referred to as concussion, can occur following a head impact or blast exposure, and though the injury is usually not life-threatening, the effects may be serious. Some of the common symptoms of concussion are headache, cognitive deficits, blurry vision, dizziness, and postural deficits.[1,2] Postural assessment is one means to determine if a concussion victim is recovering, and common tests include subjective clinical measures using the balance error scoring system (BESS) or a more objective measure, such as the Neurocom sensory organization test (SOT [3]). Although there is plenty of evidence that suggests both of these measures can be sensitive for concussion screening, there are drawbacks to each, thus, there is room to improve these postural assessment measures that could be used to improve clinical decision-making ability.

The SOT and BESS have both been found to be reliable and sensitive to postural deficits during the first 3–5 days post-injury,[3–9] however, a number of recent studies suggest there are postural and motor symptoms that last well beyond the typical 7–10 day recovery period.[10–12] One of the reasons numerous concussion signs and symptoms often go undetected is because patients can learn to compensate when tested in a controlled setting using single-task clinical measurement techniques. This highlights one of the limitations of standard clinical assessment measures as well as computerized posturography. In order to identify persistent, subacute symptoms, the assessment tool should be tailored to challenge the specifically deficient neural processes. We propose to use dynamic virtual reality (VR) scenes in a way that specifically challenges the visual-vestibular processes that help control posture. This approach builds on and refines the SOT, which is accepted by many as the "gold standard" for postural control testing, but shows only modest accuracy in concussion assessment and is very limited in sensitivity beyond the acute phase of injury.[13]

Previous evidence using VR to detect balance changes following a head trauma show that dynamic visual motion poses particular difficulties for this population.[12,14,15] It has been shown

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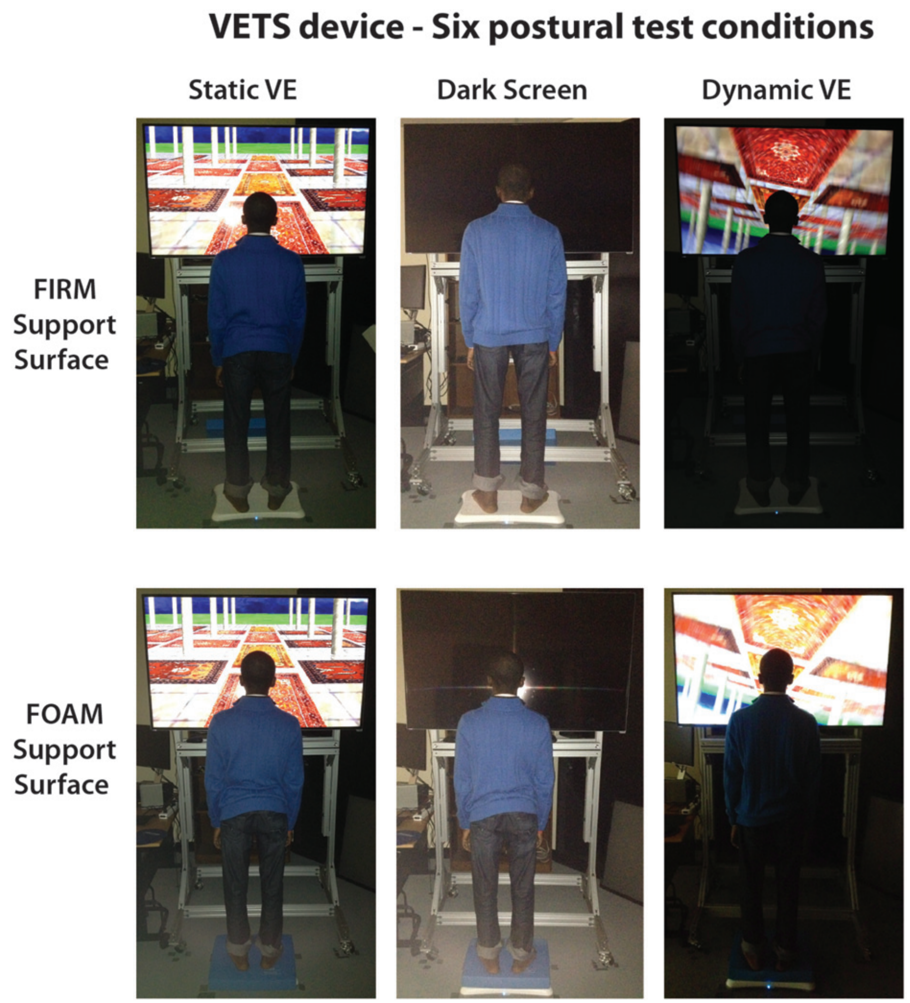

Figure 1. VETS – A VR-based balance device tests six conditions. Top row shows firm support conditions and the bottom row shows the foam support conditions. From left to right, the three columns are EO viewing a static VE scene, EC in front of a dark screen, and EO viewing a dynamic rotating scene.

that individuals subjected to a series of subconcussive head impacts using a soccer-heading paradigm showed significantly worsened balance relative to controls. However, the deficit was only uncovered when the experimental group was subjected to the most challenging VR condition, which included dynamic visual roll rotation while standing on an unstable sway-referenced surface.[14] In another balance study performed using VR, it was found that visual roll motion, more so than pitch or yaw, was the most sensitive condition for detecting both acute and longer lasting balance deficits in concussed subjects.[12] Visual roll stimulation has been known to cause postural instability for decades [16,17] and optic flow in general is an important sensory cue for maintaining balance [18]. Moreover, symptom reports for concussed individuals often include sensitivity to visual motion and vestibular processing issues,[5,19–21] therefore, testing visual-vestibular processing to detect whether concussion symptoms are present may prove to be more sensitive than assessments that do not.

In an attempt to apply this understanding of sensorimotor processing deficits concomitant with concussion, we developed a new portable virtual reality based postural assessment device for detecting the type of balance deficits specific to concussion. The custom-designed user-interface simulates and displays a virtual visual environment (Virtual Environment TBI Screen – VETS), which can be viewed on a large commercially available flat screen television while postural data is collected on a custom programmed Wii™ Balance Board (WBB – Nintendo, Kyoto, Japan) (Figure 1). To change the stability of the support surface, we used a standard foam pad, which are often used for balance testing in clinics. Traditional center-of-pressure (COP) metrics (sway area, sway velocity, and sway variability) can be calculated by the new program and were chosen because they are reliable [22] and examine important elements within the data time series that cannot be detected by sway range.

The main objectives of this effort build on our pilot work [23]: (1) to determine if there are statistical group differences between healthy and concussed participants, (2) to establish the construct and concurrent validity of the VETS relative to the criterion-measure SOT, and (3) to establish the discriminant accuracy of the VETS and SOT using "known-groups" methodology.

Methods

Subjects

Sixty-seven physically active (30 min of exercise at least three times a week) college students were recruited to participate in this study (males = 38; females = 29). Fifty-six healthy participants (22.6 ± 3.5 years of age; 1.73 ± 0.09 m; 71.1 ± 12.3 kg; females = 24) and 11 concussed (20.4 ± 1.8 years of age; 1.76 ± 0.11 m; 73.0 ± 6.4 kg; females = 5) were all active in competitive intramural (94%) or varsity (6%) sports for at least one year, and were proportionately represented in each group (intramural: healthy = 53, concussed = 10; NCAA Division I athletes: healthy = 3, concussed = 1). Participants were excluded if they self-reported having had a musculoskeletal impairment within the last month that would negatively affect balance. Healthy participants were excluded if they self-reported having had an ear infection or vestibular, oculomotor or balance issues within the past month or had experienced a concussion within the last six months. Concussion in this study was defined as sustaining a pathomechanical event that induced one or more concussion signs or symptoms.[1,2] All subjects in the concussion group were interviewed by a certified athletic trainer or physical therapist during the initial evaluation and were included if they reported having an event within three months in addition to having experienced one or more concussion signs and symptoms (e.g., headache, dizziness, nausea, balance problems, difficulty concentrating, drowsiness, irritability. See Zurich Consensus Statement for complete list of symptoms [2]). All individuals in the concussion group had experienced symptoms for 2 to 90 days with six of them being subacute (>10 days post-injury).

All subjects signed a Temple University IRB approved consent form in accordance with the guidelines of the Helsinki Accords. All subjects received monetary compensation for participation in the study. Participants completed the concussion questionnaire, which included background information such as history of concussion and general medical history including headache, vestibular, and visual issues. If recently concussed, then a description of injury, location of impact, and immediate and current signs and symptoms were also collected.

Instrumentation

Virtual environment TBI screen (VETS)

VETS is a novel postural assessment measure that employs the use of VR technology to simulate movement within a visual environment, which is viewed on a large screen commercially available television (e.g., VIZIO E-Series Razor LED 60 inches) while center-of-pressure (COP) data is collected on a custom-programmed user interface from a WBB communicated via wireless Bluetooth technology.

The WBB has been shown to be a valid tool for collecting reliable COP data during human postural assessment.[24,25] The software interface and WBB, collected COP data at 100 Hz sampling rate and the data was validated in-house relative to the SOT force plate ($r = 0.90 - 0.99$, $p < 0.001$). Our visual stimulus uses a high-resolution digital snapshot taken of an immersive VR scene (VRCO, Virginia Beach, VA), which depicts a three dimensional scene of an outdoor temple with Greek columns, marble flooring, Persian rugs, and a mountain range in the distance. The VR scene was passively rotated about the subject's roll axis at 60°/s to create a sense of self-motion in the dynamic visual conditions. The postural data collected by the user interface includes COP velocity, standard deviation in anterior-posterior (AP) direction and the mediolateral (ML) direction, and COP sway area. COP sway area was found using a principal component analysis, which approximates an ellipse around the AP-ML COP data using the first two eigenvectors. COP velocity is calculated using the COP path length traveled in the AP-ML plane per time epoch (0.01 s). An instantaneous COP velocity was calculated for each sample and the average instantaneous COP velocity per trial was reliably found to be equal to the quotient of the total path length divided by total trial time.

All VETS testing was performed in a dark room. The physical set-up places the front edge of the WBB placed at a distance of 40 cm from the television screen in a completely dark room.

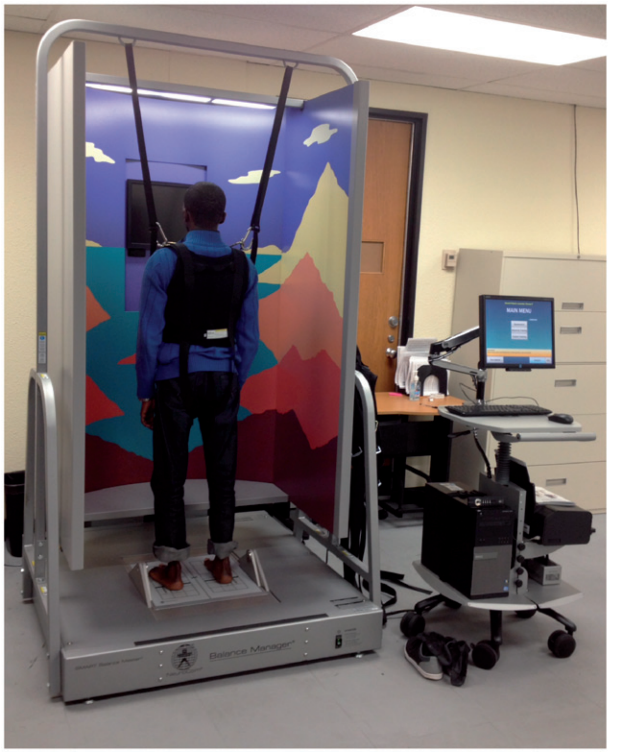

Figure 2. Neurocom Smart Balance Master (Natus Medical, Inc.).

The VETS testing involves six conditions during which participants are instructed to look straight ahead and maintain an upright stance as stably as possible. The six conditions are (1) EO Firm – eyes open with stable support surface (i.e., WBB) and static visual scene, (2) EC Firm – eyes closed with stable support surface and dark screen, (3) DYN Firm – eyes open with a stable support surface and rotating scene, (4) EO Foam – eyes open with unstable support (Airex foam pad placed on top of the WBB) and stable visual scene, (5) EC Foam – eyes closed with unstable foam support and dark screen, and (6) DYN Foam – eyes open with unstable foam support and rotating scene (Figure 1).

Sensory organization test (SOT)

All SOT testing was performed using the Neurocom Smart Balance Master System (Figure 2), Natus Medical Inc., Pleasanton, CA). The SOT was designed to objectively identify abnormalities in an individual's ability to use the three sensory systems that contribute to postural control: somatosensory (proprioception), visual, and vestibular. The SOT measures the vertical ground reaction and shear forces produced from the body's center of gravity moving around a fixed base of support. The test systematically disrupts the sensory selection process by altering availability/reliability somatosensory and/or visual information while measuring the ability to minimize postural sway in the AP direction.[26]

During the SOT, participants were required to stand upright as stably as possible for 20 s under six different testing conditions each repeated three times for a total of 18 trials: (1) eyes open with stable support surface and visual surround, (2) eyes closed with stable support surface, (3) eyes open with sway-referenced visual input with stable support surface, (4) eyes open with unstable, sway-referenced support surface, (5) eyes closed with unstable, sway-referenced support surface, and (6) eyes open with both a sway-referenced support surface and a sway-referenced visual surround.

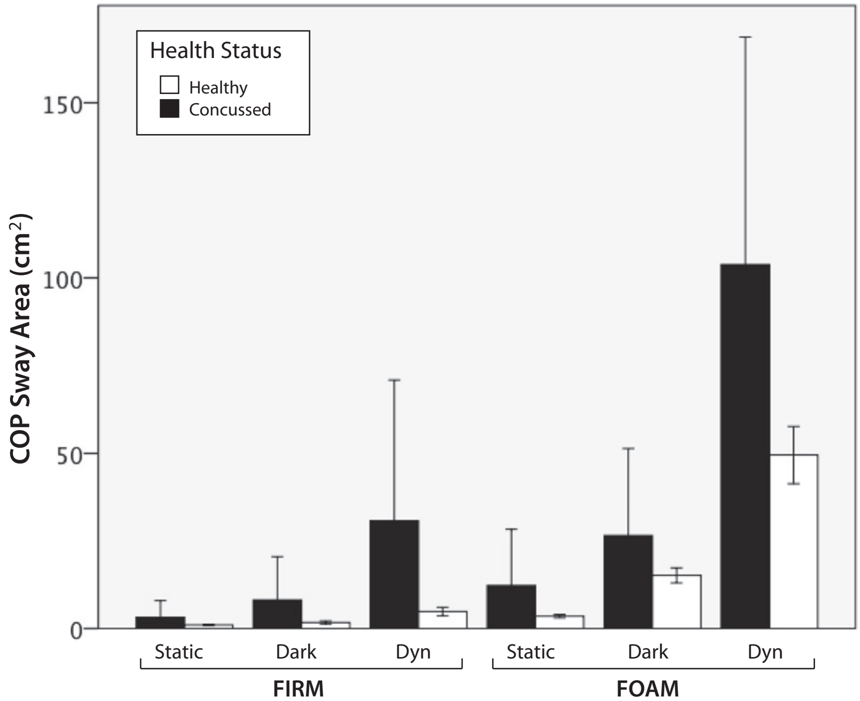

Figure 3. VETS COP sway area. Comparison of healthy (white) versus concussed (black) cohorts show significantly greater COP sway area in the concussion group. Error bars represent 95%CI.

Procedure

All participants performed the VETS then the SOT, respectively. Pilot testing revealed that there was no order effect ($n = 8$, $p > 0.25$, NS), therefore we subsequently tested VETS first for all subjects. The VETS involves testing the six conditions described earlier, in order, repeating each condition three times before proceeding to the next condition. This blocked sequential ordering was chosen since it has been validated as a part of the standard protocol used by the SOT. Each condition lasts 30 s with 5 s between trials, except when switching from Firm to Foam conditions. Switching from Firm to Foam requires approximately 1 min for the participant to step off the WBB, add the foam pad, then adjust and re-measure the stance of the participant before condition 4 (EO Foam) can commence. The participant stood barefoot on the WBB with feet comfortably at shoulder width apart and the heel-to-heel (middle calcaneus) distance was measured (22–25 cm). The participants were instructed to look at the center of the visual scene during eyes open and dynamic visual conditions. During dark conditions, participants stood with their eyes closed while maintaining a similar head position as the other conditions. During all the testing, participants were instructed to stand with their arms resting by their sides while maintaining a stable, upright position. An experimenter stood behind them at all times to guard against falls.

The SOT testing required participants to stand barefoot on the Smart Balance Master System with feet placed in a standardized position, as suggested by the manufacturer's testing guidelines. The medial malleolus was lined up with the AP rotational axes of the support surface and visual surround. The lateral calcaneus was positioned in accordance with the Neurocom guidelines prescribed by the participants' height. For heights <165 cm, a stance width 26 cm was used; for heights >165 cm, a stance width 30 cm was used (these measurements made between the left and right lateral calcaneus are comparable to the stance widths used in the VETS protocol, wherein stance width was measured between middle of the left and right calcaneus). The standard testing conditions 1–6 were run with each condition repeated three times. During all testing, participants were asked to rest their arms by their sides and maintain a stable, upright position being as still as possible for the duration of the 20 s trial. The participant wore a safety harness, which was secured to the frame of the Neurocom device.

Data analysis

Group differences in demographics were analyzed using independent sample two-tailed *t*-tests. Each of the six VETS conditions was tested three times for each participant from which an average was calculated. These within-subject, within-condition averages were used in mixed model repeated-measures analyses of variance (ANOVA), which were separately performed for each dependent variable (COP sway area, COP velocity, standard deviation of AP COP, and ML COP) to compare groups and within-subject visual and surface conditions ($2 \times 3 \times 2$). Violations of sphericity were checked by Mauchly's test, and in cases where a large violation of sphericity occurred a MANOVA was used [27]. A similar mixed model ANOVA was used on the SOT.

Pearson's correlations were used to establish the construct validity by comparing each comparable condition in the VETS and the SOT.

Known-groups methods, whereby group assignment was based on the aforementioned concussion criteria, was used to establish the classification accuracy of both the VETS and SOT. Two separate binary logistic regressions for dichotomous outcomes ("Enter Method" and "Forward Conditional") were run for each device (VETS and SOT) and "accuracy" was calculated as the sum of the true positives and true negatives divided by the total sample size. Logistic regression provided weighted coefficients (beta weights) for defining a regression model for each measure. Each regression model was then tested using receiver operating characteristic (ROC) curve analyses, from which area under the curve (AUC) was calculated. The AUC is an indicator of the overall value of a variable for accurate discrimination among all possible cut points for dichotomous categorizations of health status (i.e., concussed versus healthy). For SOT testing, we used the standard dependent variables provided by the Neurocom clinical output report, which are based the total AP COP sway range. The variable is defined relative to a theoretical maximum sway range of 12.5 cm. The calculation is a percentage ranging from 0–100%. A score of 100% is the best performance corresponding to AP sway range equal to zero. A score of 0% equates to a large sway (12.5 cm) or a fall. Three trials are collected for each SOT condition and the Neurocom software automatically averages them to generate the equilibrium score for that condition. All statistical analyses were conducted using SPSS software (version 22.0; IBM Corporation, Armonk, NY) and significance was set at 0.05. Bonferroni's corrections to the alpha-level were applied as appropriate.

Results

Between-group comparisons

Demographics: The age, height, and weight of the healthy and concussed groups were not statistically different ($p > 0.10$, NS).

VETS: COP sway area was highly sensitive to health status group (Figure 3) showing a significant between-group effect ($F_{1,60} = 3.97$, $p = 0.002$, $\eta_p^2 = 0.28$). There was also a group-by-visual-by-surface condition interaction ($F_{2,64} = 3.36$, $p = 0.041$, $\eta_p^2 = 0.10$) due to the DYN visual conditions, which showed the largest between-group effect sizes (see Table 1).

COP velocity showed a significant between-group effect ($F_{6,60} = 2.35$, $p = 0.042$, $\eta_p^2 = 0.19$). A significant group-by-visual condition interaction was found in the firm support condition ($F_{2,64} = 4.62$, $p = 0.013$, $\eta_p^2 = 0.13$) due to the DYN Firm condition.

COP standard deviation in the ML direction showed only a nonsignificant trend in the interaction of group-by-visual condition ($F_{1,} = 2.75$, $p = 0.072$, $\eta_p^2 = 0.08$). The largest between-group effects sizes involved the DYN visual conditions.

COP standard deviation in the AP direction showed a significant between-group effect ($F_{1,64} = 7.02$, $p = 0.01$, $\eta_p^2 = 0.10$) and group-by-visual condition interaction ($F_{2,63} = 3.46$, $p = 0.038$, $\eta_p^2 = 0.10$), which was due to the DYN Firm condition.

SOT: The results of the SOT ANOVA did not show a significant between-group effect ($F_{1,64} = 2.01$, $p = 0.16$, $\eta_p^2 = 0.03$) or group-by-condition interactions ($F_{2,63} = 1.20$, $p = 0.31$, $\eta_p^2 = 0.04$). Because the surface conditions are inherently different tasks, we also explored each one separately, wherein only a group-by-visual condition interaction ($F_{1,64} = 9.47$, $p = 0.003$, $\eta_p^2 = 0.13$) was found to be significant, which was due to between-group differences in Condition 3 (Firm surface, Sway-referenced visual – see Table 1). The SOT composite score was not sensitive to health status ($t(64) = 1.34$, $p = 0.185$, *Cohen's d* $= 0.45$, Student's *t*-test for independent samples).

Concurrent and convergent validity of VETS relative to SOT

Sensory organization evidence in SOT and VETS: As has been well-established and again replicated in the current study, postural performance on the SOT gets progressively worse from Condition 1 to 6, in accordance with the established norms of this device. This was found for both healthy and concussed groups. Fixed surface conditions (Conditions 1–3) were significantly better than surface sway-referenced (Conditions 4–6) conditions ($F_{1,65} = 577$, $p < 0.001$). As visual input was removed (EC – Conditions 2 and 5) or became less reliable (sway-referenced visual in Conditions 4 and 6) postural performance decreased ($F_{2,64} = 69.7$, $p < 0.001$).

Table 1. Means and standard deviations for healthy and concussed participants.

	Healthy	Concussed	Between-group comparisons	
VETS	Mean ± SD	Mean ± SD	*p* Values	Effect size (η_p^2)
COP sway area (cm^2)				
EO – Firm	0.98 ± 0.91	3.19 ± 7.06	0.024*	0.076
EC – Firm	1.73 ± 1.55	8.13 ± 18.4	0.011*	0.097
DYN – Firm	4.86 ± 4.50	30.7 ± 59.9	0.002*	0.143
EO – Foam	3.53 ± 1.78	12.3 ± 1.77	0.007*	0.106
EC – Foam	15.2 ± 7.99	26.6 ± 7.99	0.037*	0.065
DYN – Foam	49.5 ± 30.5	104 ± 96.7	0.001*	0.158
COP sway velocity (cm/s)				
EO – Firm	2.54 ± 1.30	2.73 ± 1.22	0.676	0.003
EC – Firm	2.74 ± 1.40	2.82 ± 1.22	0.864	0.000
DYN – Firm	3.70 ± 2.12	5.18 ± 4.56	0.094	0.042
EO – Foam	2.83 ± 1.37	3.17 ± 1.47	0.469	0.008
EC – Foam	5.21 ± 2.76	5.09 ± 2.35	0.894	0.000
DYN – Foam	9.89 ± 6.20	10.7 ± 5.23	0.677	0.003
COP ± ML (cm)				
EO – Firm	0.25 ± 0.28	0.37 ± 0.52	0.284	0.018
EC – Firm	0.25 ± 0.26	0.37 ± 0.50	0.250	0.021
DYN – Firm	0.42 ± 0.28	0.83 ± 0.89	0.006*	0.112
EO – Foam	0.39 ± 0.25	0.68 ± 0.86	0.032*	0.070
EC – Foam	0.66 ± 0.30	0.86 ± 0.66	0.328	0.041
DYN – Foam	1.37 ± 0.66	1.90 ± 1.22	0.042*	0.063
COP ± AP (cm)				
EO – Firm	0.38 ± 0.31	0.46 ± 0.24	0.441	0.009
EC – Firm	0.50 ± 0.31	0.69 ± 0.48	0.093	0.043
DYN – Firm	0.63 ± 0.24	1.09 ± 0.97	0.002*	0.138
EO – Foam	0.55 ± 0.24	0.81 ± 0.56	0.014*	0.090
EC – Foam	1.13 ± 0.27	1.43 ± 0.77	0.020*	0.081
DYN – Foam	1.50 ± 0.27	1.88 ± 0.81	0.023*	0.078
SOT equilibrium scores				
Condition 1	95.4 ± 1.46	95.1 ± 1.27	0.515	0.007
Condition 2	92.8 ± 2.56	90.8 ± 5.68	0.067	0.051
Condition 3	92.0 ± 2.84	88.7 ± 5.16	0.004*	0.123
Condition 4	85.9 ± 8.55	82.0 ± 7.46	0.170	0.029
Condition 5	68.2 ± 8.57	67.7 ± 8.70	0.862	0.000
Condition 6	67.1 ± 10.4	65.2 ± 14.1	0.599	0.004
Composite	80.1 ± 5.34	77.5 ± 7.17	0.185	–

All *p* values are Bonferroni's adjusted for multiple comparisons.
SD: standard deviation; SOT: sensory organization test; VETS: virtual environment TBI screen.

On the VETS device, we found a similar pattern, in that, conditions without foam were more stable than with foam ($F_{1,66} = 148$, $p < 0.001$). Also, as visual input was removed (EC) or made less reliable (DYN) postural stability decreased compared to the EO conditions ($F_{2,65} = 42.9$, $p < 0.001$). This pattern of behavior was evident in all four COP-dependent variables (sway area, sway velocity, AP-SD, and ML-SD) in the VETS device.

VETS-SOT correlations: The Pearson product-moment correlations revealed the expected negative relationships between the SOT conditions and the comparable VETS conditions (i.e., SOT Condition 1 compared to VETS Condition 1, SOT Condition 2 compared to VETS Condition 2, etc.). VETS COP sway area showed the strongest relationships with SOT conditions (Table 2). Only SOT Condition 1 (eyes open, stable support) and VETS Condition 1 (EO Firm) showed no significant correlations for any VETS COP metrics, which is likely due to the low between-subject variance in this easiest postural condition. The most challenging condition SOT and VETS condition (i.e., Condition 6) showed the highest *r* values for all four VETS COP metrics. COP sway velocity was not significantly correlated with any of its comparable SOT conditions, which is likely due to the construct differences in COP sway velocity (VETS) and AP COP sway range (SOT).

Table 2. Correlations between VETS COP metrics and SOT.

	SOT					
VETS	Condition 1	Condition 2	Condition 3	Condition 4	Condition 5	Condition 6
COP sway area	−0.146	−0.358**	−0.398**	−0.251*	−0.331**	−0.497**
COP sway velocity	−0.003	−0.023	−0.140	−0.085	−0.120	−0.211
COP SD ML	−0.015	−0.066	−0.257*	−0.057	−0.181	−0.383**
COP SD AP	−0.129	−0.211	−0.377**	−0.051	−0.308*	−0.441**

SD: standard deviation; SOT: Sensory organization test; VETS: Virtual environment TBI screen.
*$p < 0.05$,
**$p < 0.01$.

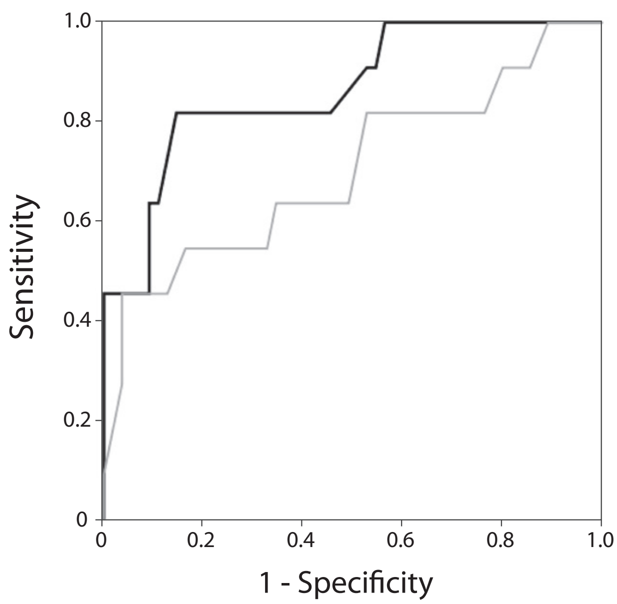

Figure 4. ROC curves generated using a logistic regression model. VETS COP sway area (thick black) shows greater discrimination than the SOT (thin gray), but both had a significant AUC with sensitivity and specificity better than chance (dotted diagonal line).

Discriminant accuracy of VETS and SOT

For VETS, since the ANOVA's for COP sway area were found to be most sensitive, we report the logistic regression results for this variable only. Using the "Enter" method, the logistic regression that included all six VETS posture conditions had the greatest accuracy (91.0%). Using the beta weights from the logistic regression, this linear model was used to generate a single value for each participant from which an ROC curve was calculated which was found to have an AUC $= 0.865$ ($p < 0.001$) (Figure 4). This model has very good ability to discriminate with a sensitivity of 81.8% and specificity of 85.7%. A second logistic regression for COP sway area using the forward stepwise conditional method found a significant beta weight ($p = 0.015$) for the DYN Firm condition, which resulted in a model with overall accuracy of 88.0%.

For SOT, a logistic regression using all six conditions was found to have 84.8% accuracy. The ROC curve derived from this linear model had an AUC $= 0.703$ ($p = 0.034$) (Figure 4), which has a sensitivity of 54.5% and a specificity of 83.6%. Condition 3 by itself was found to be the only significant predictor ($p = 0.011$) using the forward stepwise conditional method, but this resulted in a regression model with no greater accuracy than a null model with no predictors (i.e., 83.3%).

Discussion

This study reports the first step in the validation process of a new VR-based instrumented postural assessment (VETS). Our custom-designed user interface successfully collects high-resolution COP data via wireless connectivity to a Wii balance board while visual and somatosensory input is altered across conditions. The new device showed very good discrimination in detecting concussed versus healthy individuals. Unlike the SOT and other VR postural assessment devices that have been reported in the literature, our device uses only affordable, commercially available electronic equipment and can be set up quickly and used with minimal training. The WBB has been shown to be reliable and robust for measuring posturography,[24,25] and can be purchased new or used for less than $100. The use of a commercially available large flat screen television is the most expensive piece of equipment in our device, however, the price of electronics invariably drops overtime; the television used here is already 35% cheaper than when it was purchased 2 years ago. The custom-designed software allows for wireless acquisition of a high-resolution and high sampling rate (>100 Hz) data time series. Although the spatial resolution and the inability to collect shear force with the WBB does not qualify this equipment as research grade, it has been shown here that using the appropriate COP sway metrics together with well-chosen visual stimuli allows for very high assessment accuracy. A total cost of our device at under $1000 USD is one or two orders of magnitude cheaper than other specialized posturography equipment available on the market.

Establishing validity of the new VR balance device

We used a known-groups method to establish the classification accuracy (i.e., group discrimination) of the VETS by generating a logistic regression model that was then used to calculate ROC curves to discriminate between individuals who reported a recent concussion with those who reported no concussions in the last 6 months. Overall, for the sample tested the VETS showed better discrimination than the SOT. Analysis of both devices revealed the most accurate models required that all six conditions be included. Moreover, the models showed that the two conditions with unreliable visual input (i.e., VETS DYN Firm and SOT condition 3) had the best discriminability. How this relates to deficient visual and vestibular processing will be discussed below.

The Pearson product-moment correlations were also applied to help determine construct validity (i.e., convergent and discriminant validity). Before comparing the VETS to the SOT, we tested the spatial and temporal resolution of the WBB when placed on top of the Neurocom forceplate. These tests showed that positional sway detection was highly correlated ($r = 0.904$–0.999) when both devices simultaneously collected COP data at 100 Hz sampling rate. Next, we compared the conditions of the VETS with those of the SOT. The VETS and SOT were significantly correlated for all conditions except condition 1. This suggests the VETS device successfully accomplishes its design objective of quantifying postural sway metrics similarly to the SOT. Other evidence of the convergence of the VETS device with SOT is suggested by the fact that as the availability and reliability of the visual and somatosensory input was reduced, balance progressively worsened. In other words, Condition 1 SOT performance was significantly better than Condition 2, which was better than Condition 3 and so on, while in the VETS, EO Firm was better than EC and DYN and Firm support surface conditions were significantly better than Foam conditions. These findings suggest that manipulation of the sensory integration process underlying postural control is occurring in the VETS, much as the SOT has been shown to do, which provides evidence of its construct validity.

Despite this convergent evidence, the correlations, albeit significant, can at the most only account for 25% of the variance between devices (i.e., $r_{max}<0.497$, see Table 2, SOT Condition 6 versus VETS DYN Foam). This divergence may, in part, be due to the fact that the VETS system manipulates the reliability of visual (i.e., dynamically rotated scene) and somatosensory (i.e., foam pad) input differently than the Neurocom SOT (i.e., sway-references the visual surround or support surface). This point will be discussed further in the next section. Another factor contributing to the discrimination of VETS from the Neurocom test is that the latter device uses the built-in algorithms to quantify the SOT equilibrium scores, which are based on only one aspect of postural sway, i.e., AP sway range. Whereas, the VETS device evaluates both AP and ML sway metrics. The choice of these COP metrics allowed us to more thoroughly quantify the time series signal. It was also necessary to run the VETS trials 10 s longer than the SOT trials to allow for the full effect of vection on postural stability to take effect.[16] These longer trials may have had the added benefit of getting at even lower frequency postural effects than with the SOT. Thus, although VETS shows comparable accuracy in its current application, it also separates itself from the Neurocom test in some important and beneficial ways.

Pathomechanisms underlying mTBI symptoms

The SOT has been shown to detect postural deficits following an mTBI,[5,13] however, the results found using our VETS suggest that an assessment tool for detecting mTBI symptoms may achieve greater sensitivity and specificity if it can specifically challenge the visual and vestibular processing deficits that seem to be concomitant sequelae of mTBI. It has been known for some time that vestibular processing deficits may be involved in the symptomatology of mTBI.[28–30] Reliable clinical tests of vestibular function, such as the gaze stabilization test (GST), the dynamic visual acuity test (DVAT) and the dizziness handicap inventory (DHI) have all revealed reduced performance post-injury.[21,28,30,31] Further evidence for the involvement of the vestibular system comes from how responsive it is to specialized treatment. Unremitting symptoms that do not resolve within one or two weeks following a head injury have been found to improve with vestibular rehabilitation.[30,32,33,34] In the visuomotor system, oculomotor tests of smooth-pursuit, convergence, saccadic control, and visuo-spatial attention are also known to be affected by an mTBI.[35–37] In fact, some of these visual and oculomotor deficits require as much as six months to completely return to normal.[38]

Visual and vestibular processes are tightly linked via the vestibulo-ocular and optokinetic reflexes. Previous studies using the SOT have shown a significant decrease in the SOT visual ratio for up to 2 days post-injury, before returning to pre-injury levels.[5,13] More recent evidence from a study that evaluated postural control using the SOT across several months of recovery in a large military cohort who had suffered an mTBI from blast exposure, found that their postural instability was primarily a result of impaired visual and vestibular integration.[39] In a complex multisensory task like postural control, the integration of visual and vestibular inputs are highly dependent on one another, so even a minor alteration of the input from individual sensory channels or a deficiency in the sensory integration process can negatively affect postural stability.[40] By comparing performance in specific conditions, we were able to rule out the effects of individual sensory channels on balance. Specifically, by comparing performance to the baseline condition (i.e., eyes-open firm condition), the concussed group could effectively use, (1) somatosensory input in the eyes-closed firm surface condition (2) visual input in the eyes-open foam surface condition (or EO sway-referenced surface in the SOT), and (3) vestibular input in the eyes-closed foam surface condition (or EC sway-referenced surface in the SOT). However, the dynamic visual conditions, especially on a stable support surface, were found to be most affected. This points to a deficit in visual-vestibular processing.[16] It is notable that this also held true for those who were subacute in our sample. In five participants who were more than 10 days post-injury, we found this condition still discriminated between groups.

This potential visual-vestibular processing deficit raises an important distinction between the conditions in the SOT and VETS with unreliable visual feedback, which was first mentioned in the previous section. Visual sway-referencing used in the SOT has the effect of minimizing optic flow by stabilizing the visual scene relative to the movement of the test participant (i.e., participant-fixed visual frame of reference), whereas the dynamically rotating visual scene used in VETS increases optic flow. Since it has been reported in a number of studies now that individuals with brain injury are sensitive to visual motion,[12,20,21,34] exposing these individuals to dynamic visual stimulation likely has a more disturbing effect on postural control than visual sway-referencing. It has more specifically been shown that roll-plane motion seems to be the most destabilizing for this injured cohort.[12] Although roll-plane motion has also been shown to be more posturally destabilizing than other directions of motion in healthy individuals,[17] the reason roll stimulation in general is most provocative remains unclear. We can only speculate that it perhaps derives from the regularity of exposure to pitch and yaw optic flow relative to roll during the normal process of moving about in one's environment. However, why this differentially affects brain injured individuals is also unclear. We suggest that it is related to the areas of the brain commonly injured in concussion, such as the midbrain and temporo-parietal regions,[41] areas that are integral to oculomotor control and visual motion processing, respectively. Visual-vestibular processing regions such as the parieto-occipital and parietal insular vestibular cortex are thought to be reciprocally innervated and connect to the vestibular nuclei, which have descending tracts that play an important role in maintaining upright dynamic postural stabilization.[40,42]

Limitations and future plans

So far our study has only tested eleven concussed individuals and this was a rather heterogenous concussed population. Only half of the participants fell within the acute period (<2 weeks), while the rest were greater than three weeks post-injury and were possibly suffering from post-concussive syndrome. As we build a larger test sample of brain injured subjects, we hope to be able to stratify our groups according to time-since-injury. Similarly, lack of homogeneity may also be affecting the normative healthy baseline. Individuals in the healthy cohort were excluded only if they had not had a concussion in the last 6 months and reported no more than three diagnosed concussions ever. Although the medical history interview specifically asked participants if they knew what a concussion was, at least a few participants said they had been hit hard enough to be dizzy and get a headache on a number of occasions while playing their sport, but still reported never having had a diagnosed concussion. This represents a known problem in establishing a normative baseline in concussion research, in that getting accurate subjective report data from the "normal" population is not only difficult for the lay population to define, but it is also difficult for the experts to operationalize. Despite these limitations, our early results show the new VR-based device has good concurrent validity relative to the SOT, it detects the significant between-group differences, and it has very good discriminability (accuracy = 91%). Because our findings show that similar deficits of balance control and visual-vestibular processing may be present in both the acute and subacute phases of injury, this helps shed light on the timeline of underlying pathomechanisms, which helps to generalize the findings across stages of recovery.

In conclusion, this study provides promising evidence of how emerging technology can be easily integrated into the clinical setting and made accessible and user friendly. The new VR-based device is a valid measure for detecting balance impairment following mTBI and can potentially replace more expensive and cumbersome equipment. Additionally, we found evidence that using tests specifically focusing on visual-vestibular processing may increase sensitivity to mTBI-related symptoms. By increasing sensitivity and specificity of our assessment tools, we also increase the clinician's decision-making accuracy and ability to guide rehabilitation. Future steps will involve incorporating these new balance assessments with tests that incorporate cognitive and emotional assessments, in order to maximize sensitivity and specificity with a multifaceted approach to mTBI assessment.

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