University of Cincinnati

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I, Tara D Rhine M.D., hereby submit this original work as part of the requirements for the degree of Master of Science in Clinical and Translational Research.

It is entitled: Applying a Novel Balance Technology to Evaluate Postural Instability following Pediatric Mild Traumatic Brain Injury

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UNIVERSITY OF CINCINNATI

3527
Applying a Novel Balance Technology to Evaluate Postural Instability following

Pediatric Mild Traumatic Brain Injury

A thesis submitted to the
Graduate School
of the University of Cincinnati
in partial fulfillment of the
requirements for the degree of

Master of Science
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by

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Abstract

Objective: To demonstrate the utility of a novel, objective tool, the Nintendo™ Wii Balance Board (WBB), in identifying postural instability acutely following mild traumatic brain injury (mTBI) in children.

Design: Prospective case-control study over a twelve month period

Setting: Emergency department (ED) of a pediatric level-one trauma hospital

Participants: Cases included children aged 11-16 years presenting to the ED within six hours of sustaining a witnessed mTBI and who were simultaneously enrolled into a parent study evaluating biomarkers predicting post-concussion syndrome. Controls, matched on gender, height, and age, consisted of children presenting to the ED for a minor chief complaint.

Methods: In the ED, all children rated their perceived level of postural instability using two questions from the validated Post-Concussion Symptom Scale, yielding a balance subscore (PCSS-B). WBB measurements were then obtained using four different stances (single limb eyes open, single limb eyes closed, double limb eyes open, double limb eyes closed). Cases had repeat WBB measurements and PCSS-B scores taken within 72 hours and again at one week post-injury.

Results: Seventeen mTBI cases were enrolled, four of which were too dizzy to complete balance testing in the ED so were excluded from this analysis. Of the remaining thirteen, cases were mostly male (92.3%), white (61.5%), and had been injured while playing sports (69.2%). The average age was 12.8 +/- 1.5 years. One case had incomplete demographic data; for each of the remaining twelve, two controls, matched on age, height, and gender, were enrolled. In the ED, one of the WBB measurements (double limb eyes open) was significantly higher in cases
than in controls (p=0.03), reflecting increased postural instability. The PCSS-B did not predict performance on any of the WBB stances in cases or controls. By one week post-mTBI, there was not a significant change among the four WBB measurements.

**Conclusions:** Children demonstrate postural instability following mTBI when performing a simple standing balance task with two legs and their eyes open. This postural instability remains present at one week post-injury. An objective measure of postural instability would be useful in the ED to ensure safe return to activities. The WBB may be a tool which can modernize the ED physician’s examination and improve anticipatory guidance.
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Over half a million children are medically evaluated each year for traumatic brain injury; the vast majority is classified as mild traumatic brain injury (mTBI) or concussion.[1, 2] Following a mTBI, symptomatology can range from mild and transient to severe and persistent, consisting of physical, cognitive, and emotional impairments.[3] Physical impairments of dizziness and postural instability have been described in 40-50% of young athletes following mTBI.[4-6] This is likely an underestimate since TBI patients tend to under-report imbalance.[7-9] Identifying imbalance following mTBI is important for physicians to provide accurate guidance about safe return to activities, especially sports. Additionally, given that dizziness and imbalance have been correlated with a prolonged concussive recovery in children, early identification of these symptoms may provide prognostic utility.[4, 10]

Balance is a complex mechanism that utilizes the visual (eyes), vestibular (vestibular apparatus located within the inner ear), and proprioceptive (brain and spinal cord) systems. This complex motor-sensory circuit reaches maturity between 7-10 years of age.[11, 12] For adults, balance control seems to be most reliant on proprioception.[11] however, research has shown that young patients with TBI exhibit more of a reliance on visual input.[11, 13, 14] Literature suggests females exhibit superior postural stability,[12, 15] although there are likely additional factors that complicate the picture such as athletic ability and morphologic somatotype. Conflicting data has been published regarding the confounding effects that height, weight, and body mass index have on balance[15, 16] although recent literature suggests that height is the only anthropometric factor that significantly affects balance.[17, 18] The expected recovery for postural instability in young athletes with mTBI is around 3-5 days post-injury.[6, 17]

In the pediatric emergency department (ED), physicians lack an objective tool that can quickly and accurately assess a patient’s balance. The gold standard of balance testing is
posturography, an objective, validated tool which requires an electronic force platform. During posturography, the patient performs a series of movements on the platform while it dynamically records the patient’s center of pressure and the distance of the center of pressure’s sway. The larger the distance measured reflects more sway and therefore more postural instability. Posturography is an expensive method, often not portable, and it is reserved for research purposes.[7, 11, 13, 14, 19] Commonly performed physical balance measures such as gait, tandem walking, or Romberg test can be inaccurate, insensitive, and administrator dependent.[7-9, 13, 14, 20, 21] The Balance Error Scoring System test is a simple inexpensive tool that has been shown to correlate with force platform measurements, although concerns about scorer subjectivity and patient practice effects should be considered when interpreting results.[14] A new simple to use, relatively inexpensive device, the Nintendo™ Wii Balance Board (WBB) has been compared to a laboratory-grade force platform and demonstrated both good to excellent test-retest reliability (ICC= 0.66-0.94) and construct validity (ICC = 0.77-0.89)[22]. Evidence has also been published regarding the WBB’s utility in postural rehabilitation in both the adult and pediatric populations for both traumatic[23, 24] and non-traumatic[25, 26] postural instability.

The purpose of this pilot study is to use a novel, objective tool, the WBB, to demonstrate postural instability in children following mTBI. Additionally, we will assess if subjective complaints of postural instability predict poor WBB measurements.
Methods

Study Population: We prospectively identified children presenting to the Cincinnati Children’s Hospital Medical Center (CCHMC) ED from March 2012-March 2013. Cases were comprised of children aged 11-16 years presenting to the ED within six hours of sustaining a witnessed mTBI. For study inclusion, the injury had to meet the American Congress of Rehabilitation Medicine’s definition of a concussion: a blow to the head or acceleration/deceleration movement of the head resulting in one or more of the following: (1) loss of consciousness <30 minutes, (2) amnesia, (3) or any alteration in mental state at the time of the injury.[3] This age group was used since cases were only eligible if simultaneously enrolled into a larger mTBI study evaluating the use of biomarkers as a predictor of neurocognitive performance using a test which has an 11-16 year age cutoff. We defined exclusion criteria for cases as having a Glasgow Coma Scale of 13 or less at the time of ED presentation, altered mental status due to toxin ingestion, >2 extracranial injuries, history of concussion or baseline neurologic impairment, or non-English speaking. The control patients were comprised of healthy children presenting to the CCHMC ED for a minor complaint and who matched a case in age (+/- 365 days), gender, and height (+/- 10 cm). Exclusion criteria for controls, in an attempt to exclude children that may have poor baseline balance testing, included prior history of concussion, pre-existing neurologic impairment (e.g. stroke), pre-existing cognitive disorder (e.g. developmental delay), or a physical reason that would inhibit the testing of balance. “Minor complaints” were identified by lower CCHMC triage system levels (4 or 5) and confirmed by the patient’s ED clinician.

Research Design: Children were identified in the ED and enrolled by either the primary investigator or a trained clinical research coordinator. At time of enrollment, patient demographics, chief complaint for controls, and injury clinical variables (e.g. physical exam
findings, mechanism of injury) for cases were obtained. All patients filled out the Post-Concussion Symptom Scale (PCSS), a validated 22 item questionnaire designed to measure the severity of concussive symptoms.[27] Each item is scored using a 7-point Likert scale ranging from zero (symptom absent) to six (symptom severe). The scores from two questions specifically related to imbalance (dizziness and balance problems) were computed together to create the PCSS Balance subscore (PCSS-B) to reflect the patient’s perceived level of postural instability. This self-reported PCSS-B score ranged from 0 to 12.

Patients then underwent balance testing by using the WBB interfaced with specialized software (Labview 8.5, National Instruments). The WBB testing protocol was based on a previously documented protocol using four balance stances: single limb standing (on the dominant limb) with eyes closed, single limb standing with eyes open, double limb standing with eyes closed and feet together and double limb standing with eyes open and feet apart.[22]. Various orders of balance stances were distributed throughout numbered envelopes and then randomly assigned to cases, keeping the stance order consistent across subsequent testing sessions. Controls used the same order of WBB stances that their matched case had been assigned. Each balance measurement obtained yielded the subject’s center of pressure’s path length: the distance (centimeters) that a subject’s center of pressure was displaced during balance testing, relative to a neutral stance. Data were collected for 30 seconds during single limb trials and for 60 seconds during double limb trials. A total of three successful trials were performed for each of the four stances. The three successful trial measurements were averaged to obtain the stance’s mean WBB measurement. A fifteen second break was given between each trial, and a sixty second break was given before moving on the next balance stance.[22]
After being evaluated in the ED (time 1), cases returned to the hospital within 72 hours (time 2) and again at one week (time 3) post-injury to repeat the WBB and PCSS-B measures.

**Outcome and Predictor Variables:** Our primary outcome variables were the four mean WBB measurements obtained in the ED. The type of patient (cases vs. controls) and the PCSS-B score in the ED were the predictor variables. Secondary outcomes were WBB mean measurements for only the cases at time 2 and time 3.

**Sample Size Calculation:** An estimated sample size was calculated based on previously published WBB measurements obtained from healthy youth.[22] Using estimates of means and standard deviations from this published data, a sample size of 13 cases and 26 controls would result in having 80% power at an $\alpha = 0.05$, to detect a significant difference in means between the cases and controls that ranged 30 to 78 centimeters depending on the stance.

**Statistical Analysis:** Descriptive statistics including means, medians and standard deviations were generated for demographic and injury characteristics. Graphical methods were used to visually examine the distribution of the WBB measurements. T-tests were used to evaluate for significant differences among the four WBB mean measurements between cases and controls. We then built four general linear models to evaluate if the PCSS-B score was a significant predictor of the WBB mean measurements in the ED, including an indicator variable to denote patient’s study arm (case/control) and an interaction term between PCSS-B score and study arm. Thirdly, for each case we built models for each of the four WBB mean measurements to evaluate the association between the initial WBB mean measurement at time 1 and their subsequent WBB mean measurements at times 2 and 3. We did this by conducting a repeated measures analysis using the initial WBB measurements as the independent variables and the WBB measurements at times 2 and 3 as the dependent variables.
Results

Seventeen mTBI cases were enrolled, but four were excluded from this analysis since they were too dizzy to complete the WBB balance testing in the ED. The remaining thirteen cases were mostly male (92.3%), white (61.5%), and had an average age of 12.8 years (Table 1). The majority of cases had a GCS of 15 upon ED arrival (92.3%), although about half (53.9%) were noted to be acting confused per MD report (Table 2). The majority of the cases had a minor mechanism and had been injured while playing sports (69.2%) (Table 2). The four children excluded looked similar to the rest of our sample with 100% being male, 75% being white, and having an average age of 13 years. All four (100%) of these children had a GCS of 15 upon ED and were thought to be acting normal per MD report. There were no significant differences between cases and controls with respect to age, gender and height. The control group’s chief complaints varied among categories, including injury (29.2%), gastrointestinal (29.2%), pulmonary (16.7%), ENT (8.3%) or other (16.7%).

The mean, medians, and standard deviations for the WBB measurements obtained in the ED are shown in Table 3. For the four balance stances (single limb eyes open, single limb eyes closed, double limb eyes closed, double limb eyes open), there was no significant difference between cases and controls (Figure 1-4). For the WBB stance double limb eyes open, the difference trended towards significance (0.06). Due to two outliers for this stance, a nonparametric Wilcoxon Rank Sum test was conducted, resulting in double limb eyes open being significantly different between groups (0.03).

The PCSS-B score ranges from 0 to twelve; in the ED the PCSS-B mean score for cases was 5.2 +/- 3.7 and the mean score for cases was 0.1 +/- 0.3. Table 4 displays the results from the analysis evaluating the ability of the PCSS-B score to predict WBB measurements in the ED by
using generalized linear models after adjusting for study arm. The interaction term between PCSS-B score and study arm was not significant so excluded from the model. We confirmed that the distribution of the residuals for each of the models did not violate any assumptions. After adjusting for study arm, the PCSS-B scores were not significantly predictive of the WBB measurements for any of the four stances.

Lastly, the association between the initial WBB mean measurement at time 1 and subsequent WBB measurements at times 2 and 3 are graphically displaced in Figures 5 through 8. Eight children had measurements taken at all three time points. Three children were missing data for time 2, one child was missing data for time 3, and one child was missing data for time 2 and 3. There was no significant change in WBB measurements between time 1 and time 2 or between time 1 and time 3 for any of the four WBB stances.

**Discussion**

This prospective pilot study evaluated postural instability in children with mTBI acutely following injury in the ED using a novel instrument, the WBB. After accounting for outliers, children with mTBI had significantly higher (worse) measurements relative to non-injured controls on one of the four WBB stances tested, double limb eyes open. Children’s subjective complaints of imbalance did not predict performance on WBB testing. Lastly, there was no difference in WBB measurements for any of the four WBB stances by one week post-injury. Prior studies have shown that children demonstrate postural instability using objective balance testing following mTBI, however, initial testing often occurs within days to weeks following injury.[6, 20, 28] This study contributes to the literature demonstrating that postural instability is present immediately after injury. Furthermore, the instability in children with mTBI was demonstrated in a balance stance as simple as standing with two legs with eyes open.
Incorporating a test with the WBB for acute balance assessment is advantageous over routine physical exam testing or conventional balance testing, in the ED that it is objective, portable, inexpensive, and takes only minutes to perform.

In our study, the mTBI cases only performed significantly worse than the controls on the easiest balance stance, double limbs eyes open, to perform. Hypothetically, if there was an absence of postural instability within our mTBI group or if the WBB did not have enough sensitivity to detect postural instability, double limb eyes open is the stance we would least expect to see a difference in between groups. As evident by the large variability we detected within the groups’ standard deviations, there is a degree of natural variability in balance and coordination that occurs between each child. This may have contributed to the inability to detect differences in the other three stances between cases and controls. Additionally, each child likely demonstrated variation among the three attempts that had been averaged, so perhaps a protocol where the best of the three attempts is used for analysis, similar to the protocol used for the Star Excursion Balance Test, would improve WBB sensitivity.[29] Given none of the children had baseline testing, it is impossible to know how different each child was from their own baseline. Poor balance at baseline in the controls would contribute to poor performance on the more complex balance stances using one limb or eyes closed, but would be unlikely to alter performance on the simple stance, double limb eyes open.

It is not surprising that the PCSS-B was not predictive of performance on WBB testing in cases and controls. Adult literature is conflicting whether subjective complaints correlate with objective measurements of postural instability.[7, 30] The field of pediatric mTBI continues to lack a questionnaire that is both validated and sensitive enough to detect imbalance in this population, although experts agree that regardless, symptoms should be put in context of
objective testing to improve management.[11, 20] This further supports the need for objective balance testing for children to properly diagnose postural instability, in addition to continued work towards validating a pediatric inventory to assess symptoms of imbalance. There has been conflicting literature about when postural instability resolves following pediatric mTBI, ranging from 3-5 days[6, 11, 21] up to weeks.[20] The fact that WBB testing did not significantly improve in mTBI cases over a week time period is consistent with more recent literature, suggesting that postural instability may persist beyond one week post-mTBI. The lack of difference between groups on the more complicated balance stances argues for the fact that there is only so much one can control for with regards to balance testing, and that each child should serve as their own control in order to improve the accuracy of objective post-concussive symptom diagnosis.[6, 11, 31] This explanation is supported by the 2012 consensus statement from the International Conference on Concussion in Sport, which recommends that baseline pre-participation balance testing should be performed to help assist with return to play decisions following injury[32]. Baseline testing would improve research focused on describing the recovery trajectory of postural instability following mTBI, especially for those involved in activities with an increased risk of injury to the head.

Limitations
The most obvious limitation to our pilot study is the small sample size decreasing the power of our study. There was also large variation among mean measurements for both cases and controls, likely contributing to insignificant differences between the groups. This study also faced a problem common the pediatric mTBI literature, which was the majority of our patients were injured while playing sports, so the generalizability of the results may be limited when
applied to injuries sustained by more severe mechanisms. Finally, since the children did not have baseline WBB measurements, there is a natural coordination issue with balance testing that cannot be controlled for between the two groups, although we attempted to minimize this by controlling for age, gender, and height.

**Conclusions**

The WBB stance, double limb eyes open, was significantly worse in children with mTBI acutely following injury in the ED, suggesting the presence of postural instability. Using the PCSS-B, children could not accurately predict their performance on WBB testing. Postural instability is important to assess in children following mTBI and it is essential to diagnose in order for a safe return to activities. By one week post-injury, WBB measurements had not significantly improved in cases only, suggesting persistence of this symptom. Future research evaluating acute postural instability after mTBI incorporating objective baseline measurements that can be trended over time would significantly contribute to this area of research.
References


<table>
<thead>
<tr>
<th>Variables</th>
<th>Cases (N=13)</th>
<th>Controls (N = 24)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>12.8 +/- 1.5</td>
<td>13.1 +/- 1.6</td>
</tr>
<tr>
<td>Sex (M/F)</td>
<td>12/1</td>
<td>22/2</td>
</tr>
<tr>
<td>Race (W/B)</td>
<td>8/5</td>
<td>16/8</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>162.1 +/- 14</td>
<td>163.9 +/- 10.8</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>56.1 +/- 16.7</td>
<td>57.1 +/- 13.6</td>
</tr>
</tbody>
</table>

*W= White, B=Black
### Table 2. Mild Traumatic Brain Injury Descriptor Variables

<table>
<thead>
<tr>
<th>Clinical Variable</th>
<th>N (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loss of Consciousness</td>
<td>5 (38.5%)</td>
</tr>
<tr>
<td>Amnesia</td>
<td>5 (38.5%)</td>
</tr>
<tr>
<td>Seizure</td>
<td>0 (0%)</td>
</tr>
<tr>
<td>Not acting normal per parent</td>
<td>6 (46.2%)</td>
</tr>
<tr>
<td>Confusion per MD</td>
<td>7 (53.9%)</td>
</tr>
<tr>
<td>Initial ED GCS of 15</td>
<td>12 (92.3%)</td>
</tr>
<tr>
<td>Headache</td>
<td>11 (84.6%)</td>
</tr>
<tr>
<td>Vomiting</td>
<td>5 (38.5%)</td>
</tr>
<tr>
<td>Dizziness</td>
<td>5 (38.5%)</td>
</tr>
<tr>
<td>Palpable Skull Fractures</td>
<td>0 (0%)</td>
</tr>
<tr>
<td>Signs of a Basilar Skull Fracture</td>
<td>0 (0%)</td>
</tr>
<tr>
<td>Scalp Hematoma</td>
<td>4 (30.8%)</td>
</tr>
<tr>
<td>Sports related mechanism of Injury*</td>
<td>9 (69.2%)</td>
</tr>
</tbody>
</table>

*Other mechanisms of injury: 2 (15.4%) fall from standing height, 1 (7.7%) fall from elevation, 1 (7.7%) object struck head
Table 3. Comparing WBB measurements between Cases and Controls in the Emergency Department

<table>
<thead>
<tr>
<th>WBB Stance</th>
<th>Cases: Displacement of Center of Pressure (average in cm +/- SD)</th>
<th>Cases: Displacement of Center of Pressure (median in cm)</th>
<th>Controls: Displacement of Center of Pressure (average in cm +/-SD)</th>
<th>Controls: Displacement of Center of Pressure (median in cm)</th>
<th>p-Value for WBB mean T-test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double Limb</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eyes Open</td>
<td>84.9 +/- 33.9</td>
<td>69.8</td>
<td>64.0 +/-17.2</td>
<td>62.3</td>
<td>0.06*</td>
</tr>
<tr>
<td>Double Limb</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eyes Closed</td>
<td>121.3 +/- 40.4</td>
<td>114.8</td>
<td>124.4 +/-36.9</td>
<td>125.3</td>
<td>0.82</td>
</tr>
<tr>
<td>Single Limb</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eyes Open</td>
<td>132.7 +/- 30.2</td>
<td>127.2</td>
<td>126.1 +/-31.2</td>
<td>131.1</td>
<td>0.55</td>
</tr>
<tr>
<td>Single Limb</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eyes Closed</td>
<td>266.7 +/- 83.6</td>
<td>243.1</td>
<td>247.2 +/-56.5</td>
<td>229.6</td>
<td>0.47</td>
</tr>
</tbody>
</table>

*Due to two outliers, the Wilcoxon Rank Sum test was performed resulting in a significant difference between groups with a p-value of 0.03
Table 4. Evaluating the Significance of the PCSS-B Score as a Predictor of Mean Wii Balance Board Measurements in the Emergency Department after Adjusting for Patient’s Study Arm

<table>
<thead>
<tr>
<th>p-Value</th>
<th>WBB stance: Double Limb Eyes Open</th>
<th>WBB stance: Double Limb Eyes Closed</th>
<th>WBB stance: Single Limb Eyes Open</th>
<th>WBB stance: Single Limb Eyes Closed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.18</td>
<td>0.28</td>
<td>0.66</td>
<td>0.77</td>
</tr>
</tbody>
</table>
Figure 1. Comparing Mean Measurements for WBB Stance: Single Limb Eyes Closed between Cases and Controls in the Emergency Department

p = 0.57
Figure 2. Comparing Mean Measurements for WBB stance: Single Limb Eyes Open between Cases and Controls in the Emergency Department

Center of Pressure Displacement (cm)

Cases

Controls

p = 0.69
Figure 3. Comparing Mean Measurements of WBB stance: Double Limb Eyes Closed between Cases and Controls in the Emergency Department

$p = 0.81$
Figure 4. Comparing Mean Measurements of WBB stance: Double Limb Eyes Open between Cases and Controls in the Emergency Department

*p = 0.03*

*Calculated using Wilcoxon Rank Sum Test*
Figure 5. WBB stance: Single Limb Eyes Closed
Mean Measurements over One Week Post-mTBI

Case ID
- 37
- 54
- 29
- 47
- 44
- 58
- 36
- 52
- 40
- 39
- 26
- 32
- 33
Figure 6. WBB stance: Single Limb Eyes Open Mean Measurements over One Week Post-mTBI

Case ID
- 37
- 54
- 29
- 47
- 44
- 58
- 36
- 52
- 40
- 39
- 26
- 32
- 33
Figure 7. WBB stance: Double Limb Eyes Closed Mean Measurements over One Week Post-mTBI

Case ID

- 37
- 54
- 29
- 47
- 44
- 58
- 36
- 52
- 40
- 39
- 26
- 32
- 33
Figure 8. WBB stance: Double Limb Eyes Open Mean Measurements over One Week post-mTBI

Center of Pressure Displacement (cm)

Case ID
- 37
- 54
- 29
- 47
- 44
- 58
- 36
- 52
- 40
- 39
- 26
- 32
- 33

Time 1  Time 2  Time 3