BALANCE ACCELEROMETRY MEASURE VS. BALANCE ERROR SCORING SYSTEM IN CHILDREN AFTER CONCUSSION

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Concussion, also known as mild traumatic brain injury, can cause dizziness and impaired balance. Sports-related concussions are very common in the U.S., especially in high-school and college. An assessment of balance can provide useful information for estimating prognosis following concussion. Low-technology methods of assessing balance such as the Balance Error Scoring System (BESS) are fast, inexpensive, and easy to use in children, but not very precise. Recently, a low-cost, higher-technology, accelerometer system called the Balance Accelerometry Measure (BAM) has been used to study high-school aged children with concussion. This study tested the hypothesis that the BAM is more sensitive to change over time than the BESS as children recover from concussion. This study also tested the hypothesis that the BAM has context validity based on correlations with the BESS and with subjective measures of dizziness and balance. Subjects included nine persons between the ages of 13 and 17 years who had experienced a concussion between 1 and 16 days prior to their initial evaluation and who were tested twice at about a 2-week interval. The acceleration data from the BAM were processed to compute the normalized anterior-posterior path length of sway. BESS testing was videotaped for later scoring. Subjective measures included the Dizziness Handicap Inventory, the Activities-specific Balance Confidence Scale, Global Rating of Change and the Post-concussion Symptoms Score from the ImPACT test. Results indicated that effect sizes for the BESS were larger than they were for the BAM. The effect size for the easiest BAM conditions was negative, indicating

greater sway on the second evaluation. The BAM had good context validity regarding the BESS and poor context validity regarding subjective measures of dizziness and balance. This small n study of postural sway using the BAM suggested that an easily administered, low-cost test could be used in children to monitor recovery from concussion. A potentially novel finding using the BAM was that children with concussion may increase their exploratory sway behavior as they recover from concussion.

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1.0 INTRODUCTION

1.1 OVERVIEW OF BALANCE IN CONCUSSION

A concussion has been defined by the Centers for Disease Control as: “a type of traumatic brain injury, or TBI, caused by a bump, blow, or jolt to the head that can change the way your brain normally works.(Centers for Disease Control and Prevention, 2014a) The term “concussion” is often used synonymously with the term “mild traumatic brain injury (mTBI).” Mild TBI, which may or may not cause a loss of consciousness, causes abnormalities in one or more domains including physical, cognitive, and emotional aspects and sleep. Symptoms associated with mTBI vary from person to person and may last from several minutes to days, weeks, months, or years.(Reddy, Collins, & Gioia, 2008) Concussions can occur in numerous circumstances including sports activities, military encounters, motor vehicle accidents, and work-related injuries.(Langlois, Rutland-Brown, & Wald, 2006)

Typical symptoms of concussion include headache, dizziness, impaired balance, mental fogginess, emotional problems and difficulty sleeping.(McCrory et al., 2009) Most current theories of the pathophysiologic mechanism of concussion include the concept of abnormal metabolic changes in the central nervous system (CNS).(Barkhoudarian, Hovda, & Giza, 2011) Sports concussion is especially important to public health because this problem primarily affects children and teenagers.(Centers for Disease Control and Prevention, 2014b)

Sports-related concussions are very common in the U.S., especially in the high-school and college age groups because of the large number of sports teams.(Langlois et al., 2006) Incomplete records and under-reporting of concussions lead to inaccurate estimates of the actual number of sports-related concussions.(Langlois et al., 2006) According to the CDC, the rate of concussion is highest in football (0.47 per 1000 athlete exposures) and girls' soccer (0.36 per 1000 athlete exposures) with more than 170,000 sports concussions each year.(Centers for Disease Control and Prevention, 2014b) Although 90% of persons with a sports concussion recover within seven to ten days, at least 10% of persons with a sports concussion experience prolonged symptoms.(Yang, Hua, Tu, & Huang, 2009) Sports-related concussions represent a serious health condition because of their impact on academic performance in students and work performance in employees.

In 1996, Guskiewicz, Perrin, and Gansneder suggested that an evaluation of balance should be considered in persons with sports concussion.(Guskiewicz, Perrin, & Gansneder, 1996) Davis et al. also suggest that balance function be assessed in the context of a group of objective medical tests such as neuroimaging, electrophysiology, and blood work.(Davis, Iverson, Guskiewicz, Ptito, & Johnston, 2009) A recent international consensus statement from the 4th International Conference on Concussion in Sport recommends that all aspects of concussion be evaluated including dizziness and balance problems.(McCrory et al., 2013)

For bipeds like humans, maintaining balance represents a surprisingly difficult task. To maintain balance, the CNS processes information from three senses, namely vision, touch, and vestibular (the balance mechanism of the inner ear).(Guskiewicz, 2011) In persons with concussion, the most commonly injured portions of the balance system include the CNS and the vestibular apparatus of the inner ear.(Reddy et al., 2008)

Many persons with concussion experience dizziness. The symptom of dizziness represents a subjective complaint and may be associated with functional limitations, emotional changes and cognitive deficits.(Maskell, Chiarelli, & Isles, 2007) An impairment of balance, which represents a physical abnormality and can be measured objectively, may or may not accompany dizziness. Both dizziness and impaired balance can result in functional limitations, can have a negative impact on emotional health, and can adversely affect cognition.(Yardley et al., 2001)

Predicting the time course and extent of expected recovery represents one of the most challenging aspects of caring for a person with a sports concussion. Students need to know when they can return to academic activities and when they can return to their sports team. McCrea et al. found in a group of 570 athletes with concussion that loss of consciousness, amnesia, and severe symptoms acutely predicted a prolonged (> 7 days) recovery.(McCrea, Guskiewicz, et al., 2013) Several scientific studies have suggested that a balance assessment provides highly useful information for estimating prognosis.(Lau, Kontos, Collins, Mucha, & Lovell, 2011; Sheedy, Geffen, Donnelly, & Faux, 2006; Yang et al., 2009) Sheedy et al. in a study of 29 persons with concussion determined that symptoms from a concussion were worse overall in persons who complained of dizziness at the time of initial evaluation.(Sheedy et al., 2006) Lau et al. studied a group of 107 male high school students to see whether a complaint of dizziness shortly after a concussion predicted prolonged symptoms.(Lau et al., 2011) Lau et al. confirmed the findings of Yang et al. that a complaint of dizziness was a negative prognostic indicator for a quick recovery from a concussion.(Lau et al., 2011; Yang et al., 2009) The results of these studies provide a justification for balance assessments in all persons with sports concussion.

1.2 HEAD IMPACT FORCES AND CONCUSSION

Recently, methods have been developed to monitor head movement during football. These biomechanical studies have enabled researchers to categorize the types of impacts that can lead to concussion. Broglio et al.(Broglio et al., 2010), in a study of 78 high school athletes with a mean age of 16.7 years, recorded 54,247 impacts which included 13 concussions. A statistical analysis indicated that a rotational acceleration of greater than 5,582.3 radian/sec/sec, a linear acceleration of more than 96.1 g, and an impact location on the front, top, or back of the head correlated with the highest likelihood of a concussion. Using *in vivo* head impact biomechanical monitoring (Broglio et al., 2010), the authors determined that a typical high school football player sustains more than 650 impacts during a season and that the tolerance for high-intensity impacts appears to be greater in collegiate athletes as compared to high school athletes. The mean linear acceleration for concussion in college athletes was 102.8 g and mean rotational acceleration 5311.6 radian/sec/sec whereas in high school athletes these values were 86.3 g. and 6111.4 radian/sec/sec, respectively (Broglio et al., 2010). In a study of 1,208 players from eight college and 6 high school football teams, Beckwith et al.(Beckwith et al., 2013a) determined that there were a larger number of impacts and impacts with more force on days when players were diagnosed with concussion. Peak linear acceleration was the most sensitive biomechanical measure with an area under the ROC of 0.983. The authors identified that peak rotational acceleration was less sensitive than other biomechanical measures such as linear acceleration. A further analysis of these data by Beckwith et al.(Beckwith et al., 2013b) showed that concussions diagnosed immediately following an impact were characterized by players sustaining the largest forces. Interestingly, players diagnosed with concussion later on the day of concussion or within a few days of the concussion were found to have a larger number of impacts on the day of injury and within 7 days of the injury.

In a recent review article, Broglio et al.(Broglio, Eckner, Paulson, & Kutcher, 2012) hypothesize that as persons age, their cognitive ability and motor performance, such as balance, will decline at a steeper rate if there is a history of concussion. This hypothesis is based on changes in their encephalogram and motor control patterns in otherwise healthy individuals who have experienced a concussion.

1.3 TECHNIQUES FOR ASSESSING BALANCE IN SPORTS CONCUSSION

Both low-technology and high-technology methods can measure balance function.(Guskiewicz, 2011) Low-technology methods as compared with high technology methods are usually faster, less expensive, and easier to use, especially in children (Gagnon, Swaine, Friedman, & Forget, 2004; Kleffelgaard, Roe, Soberg, & Bergland, 2012; Riemann, Guskiewicz, & Shields, 1999); but have the disadvantage of being less precise. High-technology methods have the advantage of providing precision and high reliability. Interestingly, the earliest studies of balance function in sports concussion used high-technology methods to demonstrate the usefulness of balance assessments (Guskiewicz et al., 1996), whereas more recent studies have suggested low-technology methods to demonstrate wider applicability.(Guskiewicz, 2011)

The most common high-technology balance assessment method uses a computer to record and analyze how persons stand on a moving floor.(Guskiewicz et al., 1996) Computerized dynamic posturography has shown that some persons with sports concussion sway more than healthy persons.(Guskiewicz et al., 1996) Riemann and Guskiewicz (Riemann & Guskiewicz, 2000) first described the most common low-technology balance assessment tool for persons with sports concussion, namely the Balance Error Scoring System (BESS). Results from the BESS have shown that balance is impaired for several days following a concussion.(Guskiewicz, Ross, & Marshall, 2001; Riemann & Guskiewicz, 2000) High-technology methods show that on a population basis balance problems may last up to 30 days after a second concussion.(Slobounov, Slobounov, Sebastianelli, Cao, & Newell, 2007)

1.3.1 Low technology studies of balance in concussion including the BESS

In a cohort study of balance using low technology measures that included two groups of 38 children aged 7-16 years, Gagnon et al.(Gagnon et al., 2004) found that children with mTBI showed balance deficits at 12 weeks following the injury. Measures included the Bruininks-Oseretsky Test of Motor Proficiency (BOTMP), the Pediatric Clinical Test of Sensory Interaction for Balance, and the Postural Stress Test. Differences between the two groups on the BOTMP were larger at one week as compared to 12 weeks. The authors concluded that even though subjects has a normal neurologic examinations and lack of obvious motor abnormalities following mTBI, many continued to manifest postural instability at least during the first three months following concussion. In another study using low technology measures, which included the Dynamic Gait Index (DGI) and gait speed, Kleffelgaard et al.(Kleffelgaard et al., 2012) evaluated balance four years following mTBI in a cohort of 52 persons age 16-65 (mean 40 years). The authors concluded that balance abnormalities were a long-term consequence of mTBI in one third of the subjects. The authors also noted a correlation between post-concussion symptoms and balance measures.

The most widely used low technology measure is the BESS described in 1999 by Riemann et al..(Riemann et al., 1999) The BESS includes three stance conditions, including double leg stance, single-leg stance, and tandem stance (feet heel to toe), and two surface conditions including a firm surface and a medium density foam surface. For each of these six conditions, a 20 second trial is performed wherein subjects are asked to stand as motionless as possible with hands on hips and eyes closed. Subjects receive a score for each condition that reflects their ability to stand without changing their position or opening their eyes.(Riemann et al., 1999)

In one of the earliest studies of the BESS, Guskiewicz et al.(Guskiewicz et al., 2001) found that college athletes who experienced a concussion had worse BESS scores one day following concussion as compared to baseline with a return to normal at three days. The findings of this study were strengthened by the presence of a control group, which did not show any change in BESS scores.

Valovich-McLeod et al.(Valovich McLeod, Barr, McCrea, & Guskiewicz, 2006) used a repeated measures design to assess test-retest reliability of the BESS. In their study of 50 healthy young athletes between the ages of 9 and 14 there was moderate test-retest reliability for the BESS with an intra-class correlation coefficient was 0.70. Test-retest reliability, as reflected by the intra-class correlation coefficient, was lower in the younger subjects and in female subjects. They reported an adjusted reliable change index for a 90% confidence interval of 9.4 for the BESS.

Several studies have evaluated change over time in BESS scores in the absence of concussion. Four of these studies showed improved BESS scores over time whereas one study showed a postseason worsening of scores despite the absence of concussion. In a study a 46 male college football players, Gysland et al.(Gysland et al., 2012) found that there was an improvement in the BESS score after the season in a group of 46 male college football players. The authors attributed this improvement to possible practice effects. Valovich et al.(Valovich McLeod et al., 2004) evaluated the BESS in 50 subjects repeatedly over a period of 60 days. The authors found a significant practice effect. Burk et al.(Burk, Munkasy, Joyner, & Buckley, 2013) studying a group of 58 college-aged female athletes found a significant improvement in BESS scores pre- vs. post-season. These authors cautioned that a practice effect must be taken into account when determining whether or not a change in BESS score is meaningful. Mulligan et al.(I. J. Mulligan, Boland, & McIlhenny, 2013) in a study of a convenience sample of 84 college students found that BESS scores improved at one, two, and four weeks based on a learning effect. In a study of 45 college football players, Mulligan et al.(I. Mulligan, Boland, & Payette, 2012) found that a significant number of subjects had worse BESS scores after the season even though they had not had a concussion. Notably, persons who had a concussion showed more of a change in BESS scores. In summary, there appears to be a possible practice effect based on multiple administrations of the BESS test.

In a study of 296 athletes with concussion, Covassin et al.(Covassin, Elbin, Harris, Parker, & Kontos, 2012) found that high school male athletes showed worse performance on the BESS then college male athletes whereas college female athletes scored worse on the BESS than high school female athletes. The authors did not have an explanation for the statistical interaction between age and sex but advised that the interpretation of BESS scores should take into account age and gender. The authors also found that the BESS scores were higher, i.e., worse one day following head injury as compared with scores two and three days after injury. Covassin et al.(Covassin et al., 2012) were unable to determine if scores on the third day following concussion were better or worse than pre-concussion scores, which were not available.

Wilkins et al.(Wilkins, Valovich McLeod, Perrin, & Gansneder, 2004) determined that BESS scores increase in fatigued subjects. In a study of 27 male college athletes divided into two groups, half the subjects performed a fatigue protocol between a pre-test and a post test of the BESS. In the non-fatigued group, there was a significant improvement in performance on the BESS test. In the fatigue group, however, there was a worsening of balance performance. The fatigue group and control group were the same on pre-test scores, yet following fatigue there was a difference between the two groups. The authors cautioned that the BESS should not be performed without approximately 20 minutes of rest in athletes who have experienced a suspected concussion during a sporting event.

In a retrospective study of 247 athletes with concussion, Register-Mihalik et al.(J. Register-Mihalik, Guskiewicz, Mann, & Shields, 2007) determined that there was no significant effect of headache on BESS scores. Also, the BESS has also been applied to the adult population. Iverson and Koehle (Iverson & Koehle, 2013) found that BESS scores declined in persons over age 50.

Two recent studies have suggested a modification of the standard BESS to improve its reliability. Broglio et al.,(Broglio, Zhu, Sopiarz, & Park, 2009) in a study of 48 subjects age 20.4+/- 2.1 years, reported that the reliability of the BESS was significantly improved when the mean score of 3 BESS tests were obtained, which added about 10 to 15 minutes to the testing protocol. Hunt et al.,(Hunt, Ferrara, Bornstein, & Baumgartner, 2009) in a study of 144 high school football players, found that the intraclass correlation coefficient increased from 0.60 to 0.71 with removal of the double leg stance conditions. These authors also advocated using three trials of the four remaining BESS conditions as this improved the intraclass reliability coefficient.

1.3.2 High technology studies of balance in concussion including the BAM

There are several types of higher technology methods of recording balance including wearable accelerometers and force plates. In an early study of accelerometer-based motion detection, Alderton et al. in 2003 (Adlerton, Moritz, & Moe-Nilssen, 2003) using a triaxial piezo resistant accelerometer found a moderate correlation between trunk acceleration and center of pressure (COP) movement as measured by a force plate in the assessment of 23 healthy women with a mean age of 26.8 years. The authors concluded that the use of accelerometers was a potentially valuable technique for assessing balance. In a review of wearable motion detectors, Yang and Hsu (Yang & Hsu, 2010) discuss the technical details of accelerometers. Optimally, a wearable accelerometers should accurately record body movements without interfering with the subject's own movements. At the time of their review, there were 7 commercially available accelerometers systems whose weight ranged from 20 to 82 grams. In 2011, Whitney et al.(Whitney et al., 2011) compared an accelerometer monitoring system with force plate recordings of postural sway. In this study, the authors used a dual-axis accelerometer system like the one used in this research project. Using a subject population of 81 persons, age 19-85 years, the authors reported that the accelerometer system had a test-retest reliability of 0.63 to 0.80. There was a significant correlation between measures from the accelerometer system and that from the force plates. The authors concluded that a wearable accelerometer system has potential value for the assessment of balance function in adults.

In a small study, Seimetz et al.(Seimetz, Tan, Katayama, & Lockhart, 2012) evaluated 5 young adult subjects with a triaxial accelerometer and a force plate. The authors concluded that recording postural sway with a triaxial accelerometer was a feasible means of assessing postural stability. Mancini et al.(Mancini et al., 2012) evaluated a 3-axis accelerometer mounted on the trunk to assess movement of body center of mass. The accelerometer measures were compared with center of pressure recordings from a force plate. Subjects included individuals with Parkinson's disease and healthy controls subjects. The authors found that accelerometer measures were able to distinguish between patients with Parkinson's disease and controls subjects and showed a highly favorable test-retest reliability, i.e., 0.89, using path length.

In an application of accelerometer-based motion monitoring in patients with vestibular neuritis, Kim et al.(Kim, Kim, Kim, Hwang, & Han, 2013) determined that patients with vestibular neuritis had more postural sway than control subjects and that the accelerometers could be placed at the head, pelvis, or either leg with nearly equal ability to distinguish between groups. This study included 17 patients with vestibular neuritis and 18 controls subjects.

In a seminal paper, Rine et al.(Rine et al., 2013) described the development of a low-cost accelerometer system that they named the Balance Accelerometers Measure (BAM). This technology is comparable to that described by Whitney et al.(Whitney et al., 2011) and is the same technology used for the current research. In their study of 208 individuals ranging in age from 3-85 years, they included 6 postural conditions based upon combinations of stance, vision, and support surface. The authors found high reliability based on intraclass correlation coefficients in most age groups. In the 8.6-17 year age group, which is most relevant to the current study, reliability ranged from 0.73 to 0.97 depending upon the specific postural condition being measured.

Furman et al.(Furman et al., 2013) reported the use of the BAM to evaluate balance in adolescents who had a sport-related concussion. The authors assessed 43 high school students and 27 healthy controls and compared results from the BAM with scores on the BESS. Subjects were tested once. Subjects were divided into those with an acute injury (less than or equal to 2 weeks since concussion) and a sub-acute group (greater than 2 weeks since concussion). Results indicated that the BAM was not able to discriminate between healthy and concussed adolescents whereas the BESS, especially the tandem conditions, could discriminate between healthy and concussed adolescents. The authors concluded that the BAM was not as effective as the BESS in identifying abnormal balance in adolescents following sport-related concussion. The research reported in the current project aims to determine whether or not the BAM as compared to the BESS can provide useful information about change in balance over time.

In a now widely cited study, Guskiewicz et al.(Guskiewicz et al., 1996) in 1996 described the use of a static force plate system to assess balance in athletes. Subjects included 10 persons with concussion who were prescreened along with another 60 college and high school football players without concussion. The authors found a significant difference between subjects with head injury and control subjects one day following injury. This difference in sway resolved 3 days following the injury. This was the first study to indicate abnormalities in balance immediately following mild head injury. In a subsequent study, Riemann et al.(Riemann et al., 1999) studied 111 male athletes using the BESS while subjects stood on a force platform. Results of this study indicated a favorable intra-class correlation coefficient to assess inter-tester reliability but found a poor correlation between BESS scores and sway as measured by the force plate. The authors attributed the poor correlation between BESS scores and postural sway, especially in the more challenging balance conditions, on postural strategies used by the subjects. Overall, this study suggests that combining the BESS with force plate measures may not be a useful technique.

In a recent paper, Chang et al.(Chang, Levy, Seay, & Goble, 2013) studied 30 healthy young adults using a low-cost force plate manufactured by Nintendo under the trade name Wii Balance Board (WBB). The authors compared the inexpensive force plate with a more expensive force plate and recorded postural sway during the BESS. These authors corrected the center of pressure data when subjects stepped off of the WBB or force plate during testing using an approximation of how much additional sway would have been expected for such a movement. These authors also assessed inter-rater reliability for the BESS using video recordings. In their study of 30 subjects with an average age of 24.4 years, these investigators found an overall low inter-rater reliability among raters and relatively low test-retest reliability for individual conditions of the BESS. However, the authors concluded that the WBB was as good as the force plate in terms of reliability for the BESS composite score (ICC = 0.88) and that this test-retest reliability exceeded that of the BESS, which had an ICC of 0.61-0.78.

The most sophisticated balance measuring device currently is the computerized dynamic posture platform system that uses a testing sequence known as the Sensory Organization Test (SOT).(Figure 1) Riemann et al.(Riemann & Guskiewicz, 2000) in an evaluation of 16 athletes with a mean age of 19.2 years and 16 age matched control subjects found that postural sway increased one day following concussion and this increase in sway resolved three days following concussion. The same pattern was found for the BESS scores. Of note, using BESS scores for the three stance conditions on a foam surface, balance remained abnormal up to 5 days following concussion. In a study of 36 college athletes who had a concussion (mean age 19.5 years) and an age matched control group, Guskiewicz et al.(Guskiewicz et al., 2001) confirmed that both the SOT and the BESS showed increased postural instability one day following injury with resolution by three days after injury. In a recent retrospective study by Broglio et al.(Broglio, Ferrara, Sopiarz, & Kelly, 2008), data from 63 athletes with concussion revealed decreased postural stability using the SOT within 24 hours of injury. The authors concluded that balance assessment was an important component of evaluating persons with concussion. In a study of 32 college athletes with concussion with a mean age of 19.7 years, Broglio et al.(Broglio, Sosnoff, & Ferrara, 2009) reported a significant correlation between SOT scores and symptoms of dizziness or imbalance. Register-Mihalik et al.(J. K. Register-Mihalik, Mihalik, & Guskiewicz, 2008) in a retrospective study of 108 concussed athletes with a mean age of 18.8 years found that persons with posttraumatic headache manifested more difficulties with balance than persons without headache.

Figure 1. Smart Equitest™ for performing Sensory Organization Testing (SOT)

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Sosnoff et al.(Sosnoff, Broglio, Shin, & Ferrara, 2011) used a sophisticated nonlinear dynamic statistic called "apparent entropy" (ApEn) that evaluates reappearing patterns of sway. These authors evaluated postural sway in 62 individuals with concussion and 162 athletes without concussion. The authors found a condition-dependent change in ApEn on a population basis for anterior-posterior sway. The more challenging conditions of the SOT showed larger apparent entropy in the concussion group as compared to the no-concussion group, which was not found in the other, less challenging conditions. The authors concluded that individuals with a history of concussion have abnormal postural control for anterior-posterior sway. The authors noted thatt he sophisticated statistical analysis was required to uncover this change in postural stability in persons with concussion who were evaluated long after their head injury, i.e., 6-151 months following injury.

Sloboundov et al.(Slobounov et al., 2007) studied postural responses to visual motion using a 3-dimenstional virtual environment that depicted a moving virtual room in persons with concussion. In a group of 38 college athletes with head trauma, changes in postural sway were noted in the absence of neuropsychological abnormalities.

1.3.3 Assessment of gait in concussion

Another means of quantitatively assessing balance in persons with concussion is to measure gait using a sophisticated gait analysis system. Catena et al.(Catena, van Donkelaar, & Chou, 2009) in a study of 30 individuals with concussion and 30 control subjects found that combining walking with a cognitive task resulted in individuals with concussion walking more slowly and allowing less motion of their center of mass. In another study by Catena et al.(Catena, van

Donkelaar, & Chou, 2011) they reported that persons with concussion adopted a more conservative gait pattern that converted to a normal balance control pattern after 28 days following concussion.

1.4 CHANGE SCORES IN THE EVALUATION OF CONCUSSION

Change scores are an important measure for concussion research and in the evaluation of persons with concussion. Reliable change refers to the amount that a measure needs to change for that change to represent a clinically meaningful difference. Valovich-McLeod et al.(Valovich McLeod et al., 2006) computed reliable change indices for the BESS and determined that a change of from -6.8 to +2.6 corresponds to a 70% confidence interval for meaningful change. The subject population included 50 healthy athletes aged 9-14 years. Broglio et al.(Broglio et al., 2008) used a sample of 66 healthy control subjects with a mean age of 20.1 years to compute reliable change scores for the SOT at various confidence intervals. Using these values, the authors computed the sensitivity and specificity of using the SOT to distinguish between concussed and healthy subjects. Largely in agreement with Valocih-McLeod et al.,(Valovich McLeod et al., 2006) Broglio et al.(Broglio et al., 2008) determined that a confidence interval of 75% provided the optimal means for separating control subject from subjects with concussion. Barlow et al.,(Barlow, Schlabach, Peiffer, & Cook, 2011) in a retrospective study of 106 persons with concussion, found a poor correlation among various post-concussion measures such as the BESS and Post-Concussion Symptom Scale. The authors concluded that there was a poor concurrent validity among BESS, post-concussion symptom score, and various scores of the ImPACT test, a widely used neurocognitive assessment tool for concussion.

1.5 SIDELINE ASSESSMENT OF CONCUSSION

Changes in balance caused by concussion may occur immediately. Several studies have endeavored to evaluate changes in balance immediately following injury, on the sideline if necessary. In a study by Onate et al.,(Onate, Beck, & Van Lunen, 2007) 21 healthy collegiate athletes were evaluated with the BESS on the sideline and in the locker room. More errors occurred on the sideline than in the locker room. The authors suggest that the BESS should be conducted in an environment comparable to that which will be used following injury so that the confounding factor of environment can be minimized. In a study by Broglio and Guskiewicz,(Broglio & Guskiewicz, 2009) the authors advocate using a criteria of a 3 or more point increase in the BESS score from baseline for removing an athlete from play. In a 2010 publication, Halstead et al.(Halstead, Walter, Council on Sports, & Fitness, 2010) discuss the Sport Concussion Assessment Tool 2 (SCAT2), which incorporates the BESS and the Standardized Assessment of Concussion (SAC)(McCrea et al., 1998) in addition to other measures such as symptom evaluation. The SAC includes assessments of orientation, immediate memory, and concentration. Jinguji et al.(Jinguji et al., 2012) provide baseline values for the SCAT2 based on data from 214 high school athletes. The authors advocate using the SCAT2 as a baseline and following injury. In a recent study by McCrea et al.(McCrea, Iverson, Echemendia, Makdissi, & Raftery, 2013), the authors recommend an assessment of balance on the day of injury. The authors note that the SCAT2 contains a modified BESS that includes only the three conditions with stance on a stable support. The authors note that further research is necessary regarding sideline assessment concussion.

1.6 TREATMENT OF BALANCE ABNORMALITIES FOLLOWING CONCUSSION

In persons with sports concussion who have complaints of dizziness and imbalance, treatment decisions may depend upon whether the concussion has injured the inner ear balance mechanism or the CNS Camiolo-Reddy et al.(Reddy et al., 2008) introduce the concept of “individualized management” of persons with sports concussion (247). Each person with a sports concussion represents a unique case and characterizing this uniqueness requires the assessment of several different types of functional abilities, including balance. In a retrospective review of 114 patients including 67 children age 18 years in younger and 47 adults age 19-73 years, who underwent vestibular rehabilitation following concussion, Alsalahee(Alsalaheen et al., 2010) found that children improved more than adults in terms of symptom severity. Overall, balance performance measures improved in all age groups.

2.0 AIMS OF THE CURRENT STUDY

The overall aim of the current study was to further evaluate the Balance Accelerometry Measure (BAM) regarding its value in assessing persons with concussion. As noted above, the BAM was developed as part of the National Institutes of Health NIH toolbox project to provide an inexpensive lightweight device suitable for assessing balance in a wide range of ages and balance disorders. The focus of the present research was to estimate how scores on the BAM change over time in a group of high school age students who had experienced a concussion.

The first specific aim is to test the hypothesis that the BAM is more sensitive to change over time than the BESS as children recover from concussion. This hypothesis will be addressed by evaluating individual BAM and BESS conditions and appropriate combinations of the BAM and the BESS.

The second specific aim is to test the hypothesis that the BAM has context validity based on correlations with other objective measures, i.e., the BESS, and with subjective measures such as balance confidence, dizziness handicap, postconcussion symptom scores, and global rating of change.

3.0 METHODS

3.1 SUBJECTS

The subjects for this study included persons between the ages of 13 and 17 years who had experienced a concussion between 1 and 16 days prior to their initial evaluation plus who consented to being evaluated twice. Thirteen subjects were enrolled. Two of these subjects did not return for a second evaluation. The data from two subjects could not be evaluated for technical reasons. Data from the remaining nine subjects were analyzed. The 9 subjects included 5 females and 4 males with a mean age of 14.9 ± 1.5 years. The first evaluation occurred at 8.3 ± 5.8 days following concussion. The second evaluation occurred between 5 and 27 days (mean 16.8 +/- 7.4 days) following the initial evaluation. Subjects were enrolled in the study only after informed consent was obtained from their parent or legal guardian and assent was obtained from each subject. The study was approved by the Institutional Review Board of the University of Pittsburgh. The subjects were recruited from the concussion program at the University of Pittsburgh Medical Center.

The demographics of the subjects are presented in Table 1. Note that 2 of the subjects had prior concussions, 2 had a prior history of migraine, 3 had a family history of migraine, one had a loss of consciousness at the time of concussion, and 6 of the subjects had a concussion related to athletic activity.

Table 1. Demographics of subjects (n=9)

Subject	Age	Gender	Days Concussion to Balance Testing	Days Between Balance Tests	History of Prior Concussion	History of Migraine	Loss of Consciousness	Cause of Injury
1	16	F	5	5	*	Yes	No	Gym Class
2	15	M	10	16	Yes	*	No	Struck by door
3	13	M	15	19	No	No	Yes	Sports
4	17	F	6	6	No	No	No	Physical Impact during play
5	16	F	16	23	*	*	*	Fall while skateboarding
6	13	F	2	19	*	No	No	Sports
7	16	M	1	27	No	No	No	Sports
8	13	M	5	22	Yes	Yes	No	Sports
9	15	F	15	14	No	No	No	Fall from Horse

*Data not available

3.2 THE BALANCE ACCELEROMETRY MEASURE (BAM)

The Balance Accelerometry Measure (BAM) was designed to measure pelvic acceleration using a system that consisted of a dual-axis accelerometer, a battery, and a Bluetooth transmitter (Figure 2). The accelerometer was manufactured by Analog Devices (Norwood Massachusetts; model ADXL213AE). Data were transmitted wirelessly using Bluetooth at a sampling rate of 50 Hz to a laptop computer. The accelerometer was attached anteriorly at the midline at the level of the pelvis using a gait belt. The BAM protocol consisted of six conditions, which are illustrated in Figure 3. and included: 1) standing with feet side-by-side on a firm surface with eyes open, 2) standing with feet side-by-side on a firm surface with eyes closed, 3) standing with feet side-by-side on a foam surface with eyes open, 4) standing with feet side-by-side on a foam surface with eyes closed, 5) tandem stance on a firm surface with eyes open, and 6) tandem stance on a foam surface with eyes closed. For all conditions, subjects crossed their arms on their chest. Each subject was allowed three attempts to perform each condition. If a subject failed after the third attempt, testing was advanced to the next condition in the protocol and the score for the failed condition was assigned the maximum standard score. Each condition was performed for 30 seconds. Acceleration data from the BAM was used to compute a normalized path length of only the anterior-posterior component of the acceleration using the 30 seconds of each trial. The medial-lateral data were not processed. The acceleration data were processed with a fourth order, low-pass, Butterworth filter with a cutoff frequency of 1.25 Hz. The acceleration data were processed to compute the normalized path length (NPL) in mG/sec using the following formula:

$$NPL = 1/t \sum_{j=1}^{N-1} |ACC(j+1) - ACC(j)|$$

where t equals 30 seconds, and ACC equals the anterior-posterior acceleration, and N equals the number of samples, which was 1,500. The anterior-posterior normalized path length was then used to generate sway scores for each subject in each condition. The NPL's from the individual BAM conditions were standardized using an established method (Marchetti et al., 2013), which was developed to account for the effect of age on static balance and to account for changes in the within-subject variance between conditions. Previous work demonstrated that standardizing the NPL sway on each condition using the mean and SD of sway for healthy young adults on the Firm EO condition provided a valid scoring method for detecting changes in static postural sway performance,(Whitney et al., 2011) and allowed an estimation of a composite score of BAM performance. The total composite BAM score and BAM subscores were computed by adding several combinations of standardized scores from individual conditions. Using the sum of standardized scores is considered a superior approach to summing raw scores as a composite when there are large differences in standard deviations among test conditions in the raw scores.(DiStifano, Zhu, & Mindrila, 2009) The use of standard scores describes the performance on all conditions in a consistent metric. This method allows a consistent interpretation of scores between test conditions and provides a method to score subjects who may fail complete any particular test condition. A composite of raw scores would not be possible if a subject failed to complete all test conditions given the wide inter-test variance. Scores were standardized to the mean and standard deviation from a previous study of 18-34 year-old healthy participants for condition 6, i.e., 9.4 ± 2.2 mG/sec.(Whitney et al., 2011)

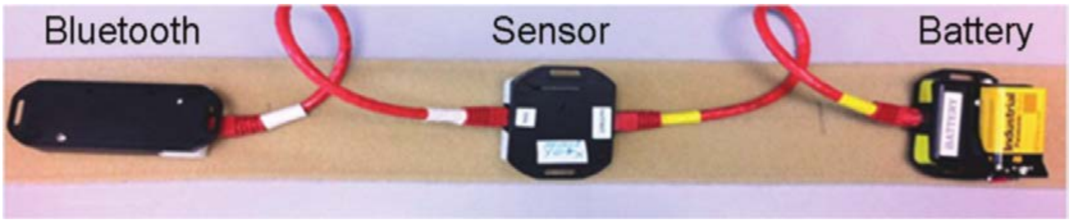


Figure 2. The National Institutes of Health Toolbox devices

The sensor (middle) is shown along with its power supply (right) and Bluetooth wireless device (left).(Furman et al., 2013)

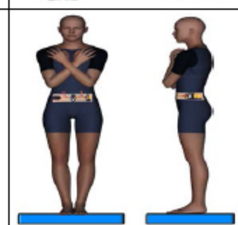
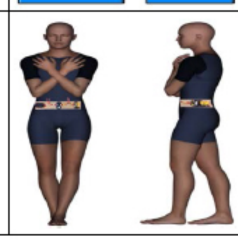
Condition	Pictures	Description	Condition	Pictures	Description
1		Eyes Open, Feet Together, Solid Support Surface	2		Eyes Closed, Feet Together, Solid Support Surface
3		Eyes Open, Feet together, Foam Support Surface	4		Eyes Closed, Feet together, Foam Support Surface
5		Eyes Open, Tandem Stance, Foam Support S urface	6		Eyes closed, Tandem Stance, Foam Support Surface

Figure 3. Balance Accelerometry Measure testing positions

(1, 2) Feet together while standing on a firm surface used for conditions 1 and 2. (3, 4) Feet together while standing on a compliant foam surface used for conditions 3 and 4. (5, 6) Feet in tandem stance while standing on a firm surface use for conditions 5 and 6.(Marchetti et al., 2013) Used with permission from the Journal of Vestibular Research.

3.3 BALANCE ERROR SCORING SYSTEM (BESS)

The Balance Error Scoring System (BESS)(Riemann et al., 1999) protocol consisted of having each subject stand for 20 seconds during each of 6 stance conditions with eyes closed and hands on the hips (Figure 4). The BESS testing was videotaped for later scoring by one experienced physical therapist. The six stance conditions are illustrated in Figure 3. The BESS conditions consisted of 1) double-leg stance on a firm surface, 2) single-leg stance on a firm surface, 3) tandem stance on firm surface, 4) double-leg stance on a foam surface, 5) single-leg stance on a foam surface, and 6) tandem stance on a foam surface. The foam surface consisted of an Airex (Somersworth, New Hampshire) pad that was 6 cm thick. The score for each BESS condition was calculated by adding up the number of errors that occurred. Simultaneous errors were counted as a single error. The maximum total score for any condition was 10. An error was considered: 1) moving hands off of the iliac crests, 2) opening the eyes, 3) a step, stumble, or fall, 4) abduction or flexion of the hip beyond 30°, 5) lifting the forefoot or heel off of the testing surface, and 6) remaining out of the proper testing position for more than 5 seconds.

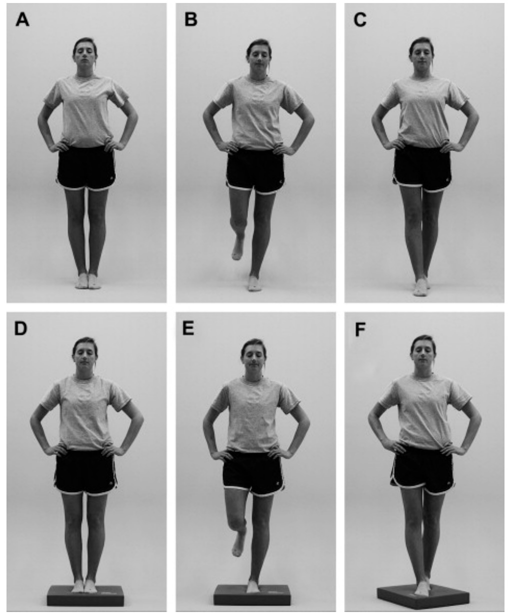


Figure 4. The positions for the Balance Error Scoring System (BESS) performed on a firm surface (A-C) and foam surface (D-F).(Guskiewicz, 2011)

Used with permission from the Journal of Clinical Sports Medicine

3.4 QUESTIONNAIRE DATA

3.4.1 Dizziness Handicap Inventory (DHI)

The Dizziness Handicap Inventory (DHI)(Jacobson & Newman, 1990) is a questionnaire used to assess disability caused by dizziness. The questionnaire contains 25 questions that are divided into three categories, i.e., physical, emotional, and functional. The highest overall score on the DHI is 100. Higher scores mean greater disability from dizziness.

3.4.2 Activities-specific Balance Confidence (ABC) Scale

The Activities-specific Balance Confidence (ABC) scale (Powell & Myers, 1995) is used to assess a subject's level of confidence about loss of balance while performing 16 functional activities. The highest possible score is 100. A higher score indicates greater balance confidence.

3.5 GLOBAL RATING OF CHANGE

Global Rating of Change was assessed using a numerical rating scale that ranged from -7 to +7. The scale ranged from "a very great deal worse" to "a very great deal better."(Jaeschke, Singer, & Guyatt, 1989)

3.6 ImPACT

The Immediate Post-concussion Assessment and Cognitive Test (ImPACT) (Collins et al., 2003) used a computer to assess cognitive function in the areas of verbal memory, visual memory, reaction time, and visual motor speed. For each area, each subject is given a percentile score. Also included in the ImPACT is a postconcussion symptom score based on a 22-item questionnaire, which will be used for this study.

3.7 PROCEDURES

Each of the subjects was recruited from the UPMC concussion clinic after they underwent a clinical evaluation including ImPACT testing. Following informed consent, testing consisted of the BAM and the BESS in random order using the protocol described above.

Each subject also completed the DHI and ABC questionnaires. Subjects were invited to be retested approximately two weeks following the initial assessment. The second assessment consisted of the BAM, the BESS, the DHI, the ABC, and an assessment of Global Rating of Change. Clinical information was obtained from the subjects' medical records.

3.8 STATISTICAL TECHNIQUES

Statistical analysis included descriptive techniques such as mean and standard deviation for age and initial postconcussion ImPACT scores and frequency counts for categorical variables. BAM scores were standardized as described above so that a total BAM score could be computed as well as three subscores as follows: Firm-EO/EC equaled the sum of standardized scores for conditions 1 and 3, Foam/Tandem-EO equaled the sum of the standardized scores for conditions 3 and 5 and Foam/Tandem-EC equaled the sum of scores for conditions 4 and 6. These combinations of BAM conditions were combined to yield a subscore for the easiest conditions, those on a firm surface with feet together, and a subscore for the most challenging conditions, those with a difficult surface condition (foam or tandem) and eyes closed. The subscore that combined scores for the challenging conditions with eyes closed was comparable to the foam subscore for the BESS, which is performed with eyes closed.

The BESS scores for individual conditions were added to compute a total BESS score and two BESS subscores, one for the three firm conditions and one for the three foam conditions. The SCAT-2 uses the BESS firm subscore.(Halstead et al., 2010) We computed the firm subscore which combines the less challenging conditions and the foam subscore, which combines the more challenging conditions in addition to the total BESS score.

Aim 1

To assess sensitivity to change during recovery from concussion, effect sizes were described using Cohen's d for each of the BAM measures and for each of the BESS measures. Cohen's d is estimated by subtracting the scores for the second assessment from the scores from the initial assessment and dividing this difference by the standard deviation for the initial assessment.(Cohen, 1988) The difference between the proportion of subjects showing improvement from initial to final assessment on two of the BAM subscores was estimated using McNemar's test for correlated proportions with exact binomial probability.(Breslow & Day, 1980)

Aim 2

To assess context validity, correlations using the Spearman non-parametric correlation coefficient were estimated between the change scores for the four BAM composite scores and 1) the change scores for each of the three BESS composite scores, 2) the change score for the Dizziness Handicap Inventory, 3) the change score for the Activities-specific Balance Confidence scale, 4) the change score for the postconcussion symptom score from the ImPACT test, and 5) the Global Rating of Change.

4.0 RESULTS

In this group of nine children evaluated twice following concussion, most of subjects improved between the first and second visits. Seven of the nine subjects improved on the global rating of change, six of nine subjects improved on the DHI, six of nine subjects improved on the ABC and seven of the seven subjects for whom data were available improved on the postconcussion symptom score from the ImPACT test.

To address the hypothesis of Aim 1 regarding whether the BAM or the BESS is more sensitive to change over time, effect sizes were computed for the BAM total score and BAM subscores. For comparison, effect sizes were computed for the BESS total score and the BESS subscores. These effect sizes are shown in Table 2 for the BAM and Table 3 for the BESS. Note that the effect sizes for the BESS are larger than they are for the BAM except for the BAM Firm-EO/EC subscore, which was actually negative, indicating greater sway on the second evaluation. Because of the small number of subjects, the changes for each subject are shown in Figures 5-8 for the BAM and in Figures 9-11 for the BESS. These case plots illustrate further that the BESS more consistently shows improvement over time than the BAM. However, the effect size for the BAM Firm-EO/EC and the case plots for this BAM subscore illustrate that for most subjects and for subjects overall there was more sway rather than less sway recorded using accelerometry during the second visit. To further evaluate this potentially novel finding, the change in BAM

Firm-EO/EC subscores was compared with the change in BAM Foam/Tandem-EC subscores on a subject-by-subject basis. Using the McNemar test, illustrated in Table 4, there was a trend (p=.125) for a disagreement between improvement vs. worsening on the two BAM subscores. This trend was based on four subjects whose sway was worse on the easiest conditions but was less on the most challenging conditions.

Table 2. Effect Size of Change Visit 1 to Visit 2 for the Balance Accelerometry Measure (BAM)

Effect Size = (Mean Visit 1 – Mean Visit 2)/ SD Visit 1

BAM Test/Condition	Mean Change	Visit 1 Standard Deviation	Effect Size of Change
Firm - EO/EC	-0.84	1.79	-0.47
Foam/Tandem - EO	1.68	6.11	0.27
Foam/Tandem - EC	0.54	4.87	0.11
BAM Total	1.37	10.18	0.13

EO: Eyes Open; EC: Eyes Closed

Table 3. Effect Size of Change Visit 1 to Visit 2 for the Balance Error Scoring System (BESS)

Effect Size = (Mean Visit 1 – Mean Visit 2)/ SD Visit 1

BESS Test/Condition	Mean Change	Visit 1 Standard Deviation	Effect Size of Change
Firm	0.89	2.91	0.31
Foam	2.00	4.82	0.41
BESS Total	2.88	6.80	0.42

EO: Eyes Open; EC: Eyes Closed

Table 4. Number of subjects whose sway increased on both the BAM Firm-EO/EC and the BAM Foam/Tandem-EC subscores, decreased on both subscores or changed in opposite directions on the two subscores

Subscore		BAM Foam/Tandem-EC		
	Change	Less sway on second visit	More sway on second visit	Total
BAM Firm-EO/EC	Less Sway on second visit	2	0	2
	More Sway on second visit	4	3	7
	Total	6	3	9

P = .125 using McNemar's test

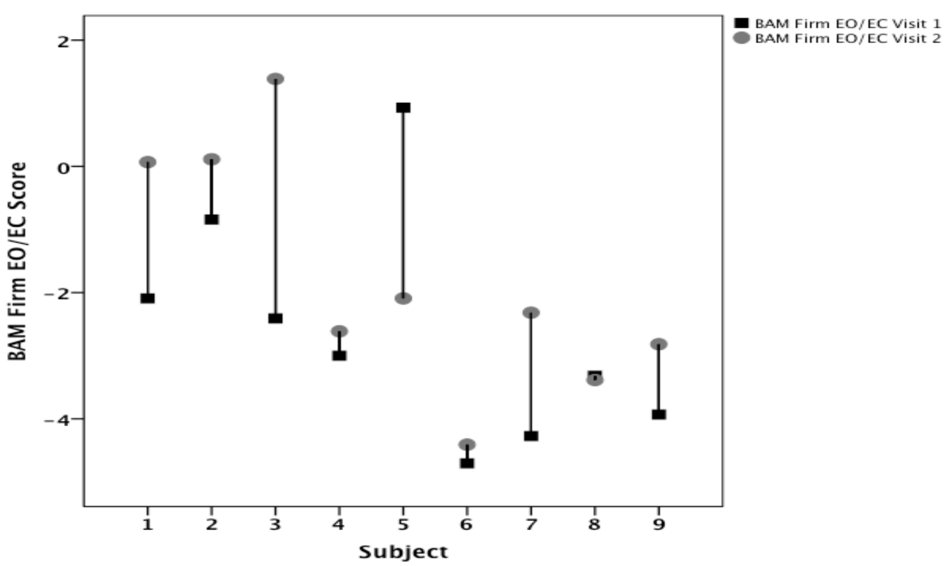


Figure 5. The plots for each person for the Balance Accelerometry Measure (BAM) Firm – EO/EC score, which was computed by adding the standardized NPL scores for conditions 1 and 2

EO: eyes open; EC: eyes closed

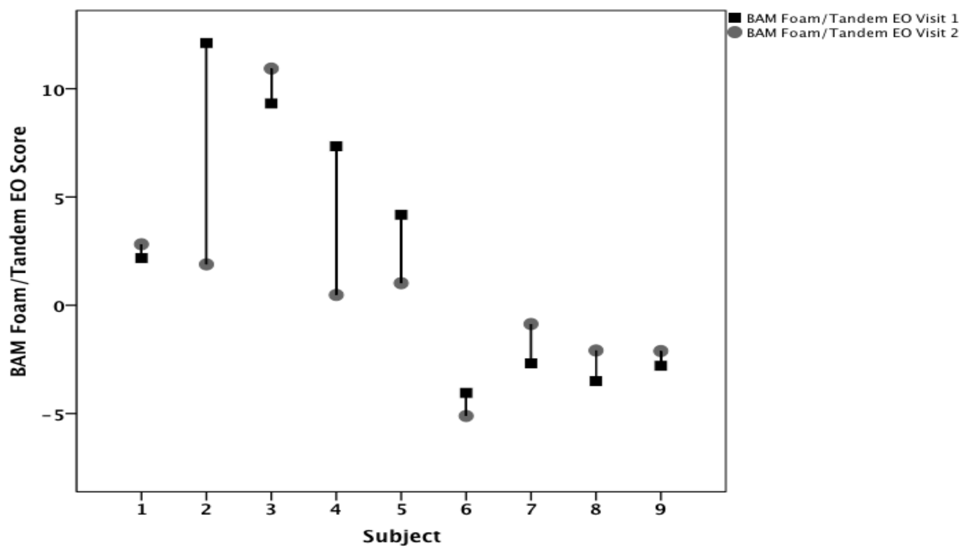


Figure 6. Case plot for the Balance Accelerometry Measure (BAM) Foam/Tandem - EO score, which was computed by adding the standardized NPL scores for conditions 3 and 5

EO: eyes open

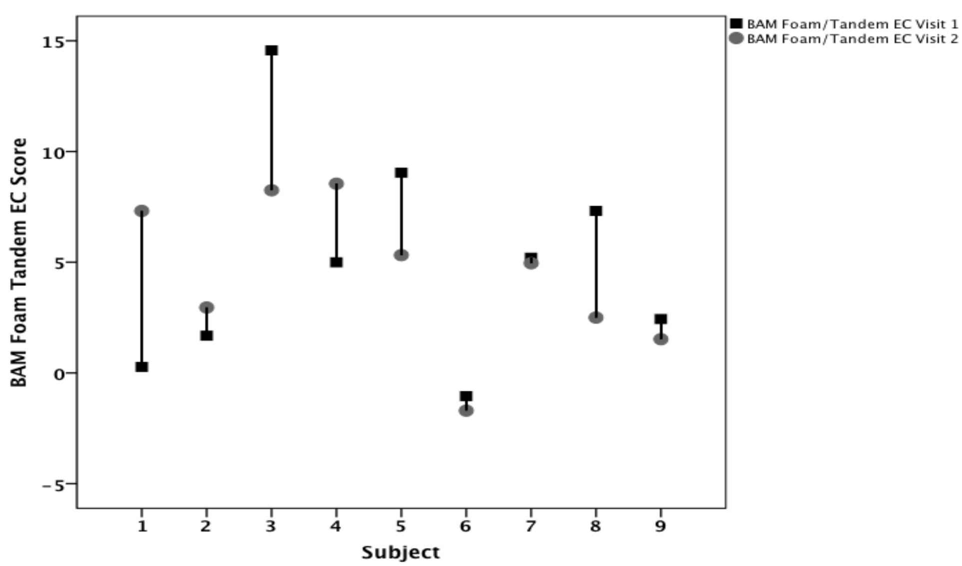


Figure 7. Case plot for the Balance Accelerometry Measure (BAM) Foam/Tandem - EC score, which was computed by adding the standardized NPL scores for conditions 4 and 6

EC: eyes closed

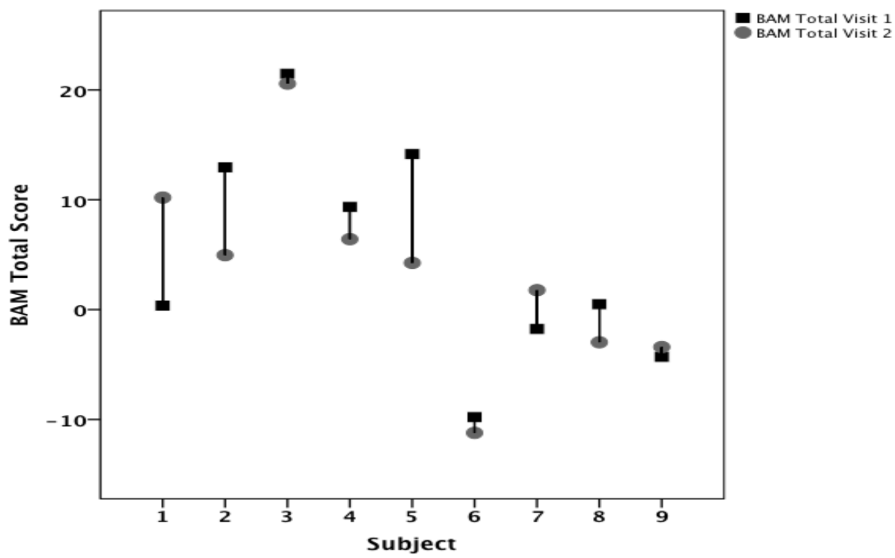


Figure 8. Case plots for the Balance Accelerometry Measure (BAM) total score

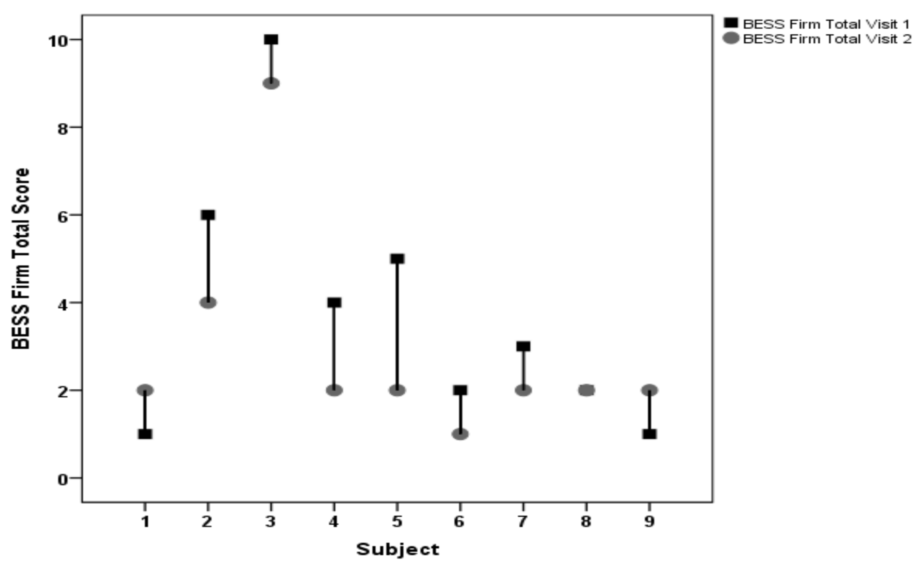


Figure 9. Case plots for the Balance Error Scoring System (BESS) Firm score

This score was computed by adding the scores from the three firm surface conditions.

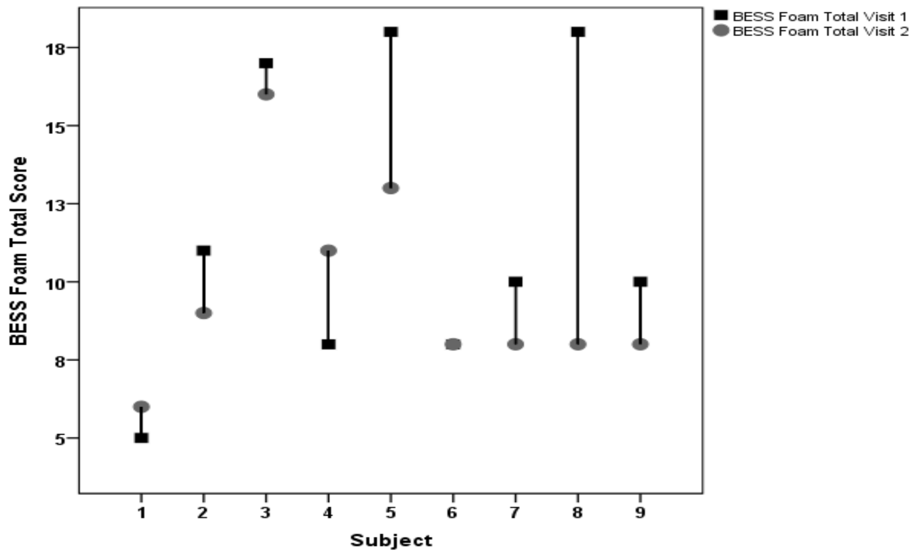


Figure 10. Case plots for the Balance Error Scoring System (BESS) Foam score

This score was computed by adding the scores from the three foam surface conditions.

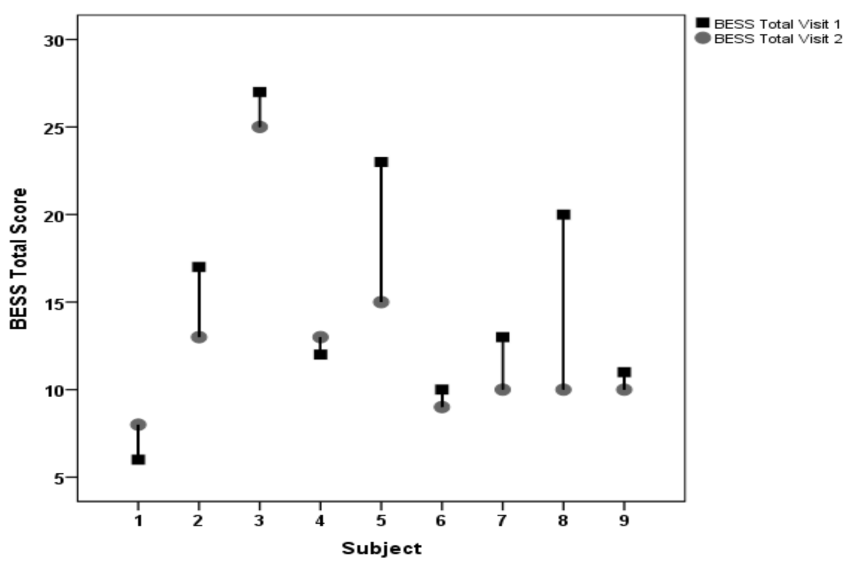


Figure 11. Case plots for the total Balance Error Scoring System (BESS) score

To address aim 2 regarding the hypothesis that the BAM has context validity, correlation coefficients were computed for change in the composite BAM scores vs. change in composite BESS scores, the change in the subjective measures, and the Global Rating of Change. Table 5 provides the correlation coefficients for BAM change scores vs. the BESS composite scores. Five correlations were selected as the most relevant measures of context validity for the BAM relative to an established measure of balance following concussion, the BESS. The two BAM subscores and the BAM total score was compared with the BESS total score. Also, the easiest BAM conditions subscore was compared with the easiest BESS conditions subscore and the most challenging BAM conditions subscore was compared with the most challenging BESS conditions subscore. These included BAM Total vs. BESS Total, BAM Firm-EO/EC vs. BESS Total, BAM Foam/Tandem-EC vs. BESS Total, BAM Firm-EO/EC vs. BESS Firm, and BAM Foam/Tandem-EC vs. BESS Foam. These correlations are illustrated in Figures 12-16. The correlation between both the total BAM change score and the BAM Foam/Tandem-EC change score vs. the total BESS change score indicated that the BAM has relatively high context validity as a measure of balance. The relatively high correlation between the BAM Foam/Tandem-EC change scores and the BESS Foam change scores is logical because this comparison is between the eyes closed challenging BAM conditions and the eyes closed challenging BESS conditions. Interestingly, in agreement with the analyses for aim 1, the BAM Firm-EO/EC change scores do not correlate with either the total BESS change scores or the BESS Firm change scores. To further probe this finding, the direction of the change in the BAM Firm-EO/EC was compared with the direction of the change in BESS Firm scores, illustrated in Table 6, indicated a trend toward a disagreement in these two measures ($p=.22$). This finding further suggests that the accelerometry-based BAM scores in the easier, feet together, firm surface conditions reflect a different aspect of the subject's balance.

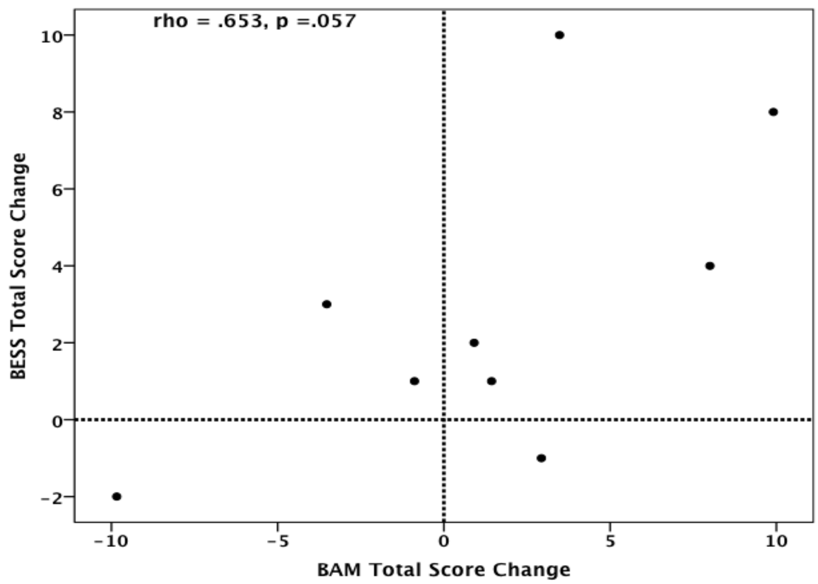


Figure 12. Change score plot (all subjects) for the Balance Accelerometry Measure (BAM) total score vs. the Balance Error Scoring System (BESS) total score

The horizontal dotted line indicates the boundary between improvement (positive values = lower error score on the second visit as compared with the first visit) and worsening (negative values = higher error score on the second visit as compared with the first visit) for the BESS. The vertical dotted line indicates the boundary between less sway (positive values = less sway on the second visit) and more sway (negative values = more sway on the second visit) for the BAM.

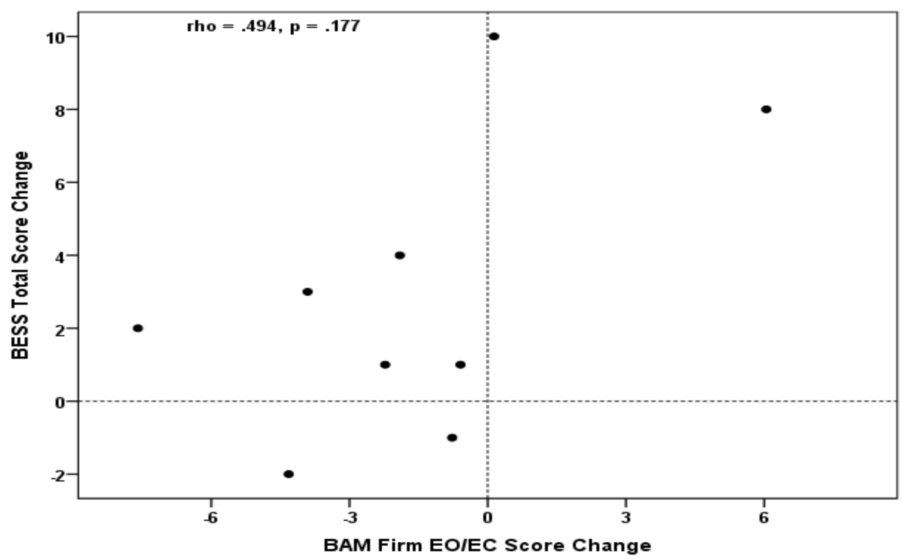


Figure 13. Change score plot for the Balance Accelerometry Measure (BAM) Firm – EO/EC score vs. the Balance Error Scoring System (BESS) total score

The Balance Accelerometry Measure (BAM) Firm – EO/EC score was computed by adding the standardized normalized path length scores for conditions 1 and 2 (Feet together on a firm surface). The horizontal dotted line indicates the boundary between improvement (positive values = lower error score on the second visit as compared with the first visit) and worsening (negative values = higher error score on the second visit as compared with the first visit) for the BESS. The vertical dotted line indicates the boundary between less sway (positive values = less sway on the second visit) and more sway (negative values = more sway on the second visit) for the BAM. EO: eyes open; EC: eyes closed.

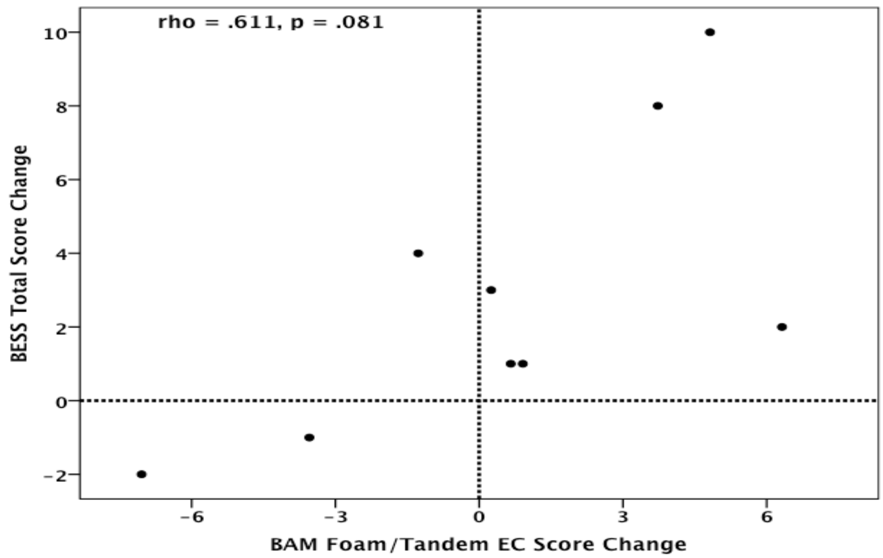


Figure 14. Change score plot for the Balance Accelerometry Measure (BAM) Foam/Tandem – EC score vs. the Balance Error Scoring System (BESS) total score

The Balance Accelerometry Measure (BAM) Foam/Tandem – EC score was computed by adding the standardized normalized path length scores for conditions 4 and 6 (Foam surface or tandem stance with eyes closed).The horizontal dotted line indicates the boundary between improvement (positive values = lower error score on the second visit as compared with the first visit) and worsening (negative values = higher error score on the second visit as compared with the first visit) for the BESS. The vertical dotted line indicates the boundary between less sway (positive values = less sway on the second visit) and more sway (negative values = more sway on the second visit) for the BAM. EC: eyes closed.

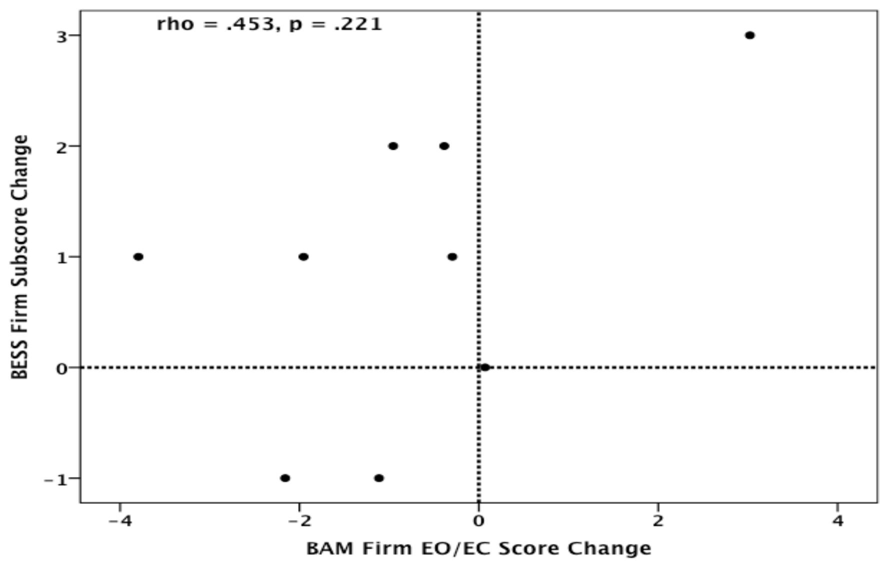


Figure 15. Change score plot for the Balance Accelerometer Measure (BAM) firm surface – EO/EC score vs. the Balance Error Scoring System Firm surface score

The BAM firm – EO/EC score was computed by adding the standardized normalized path length scores for conditions 1 and 2 (Feet together on a firm surface). The BESS firm subscore was computed by adding the scores for the three firm conditions. The horizontal dotted line indicates the boundary between improvement (positive values = lower error score on the second visit as compared with the first visit) and worsening (negative values = higher error score on the second visit as compared with the first visit) for the BESS. The vertical dotted line indicates the boundary between less sway (positive values = less sway on the second visit) and more sway (negative values = more sway on the second visit) for the BAM. EO: eyes open; EC: eyes closed.

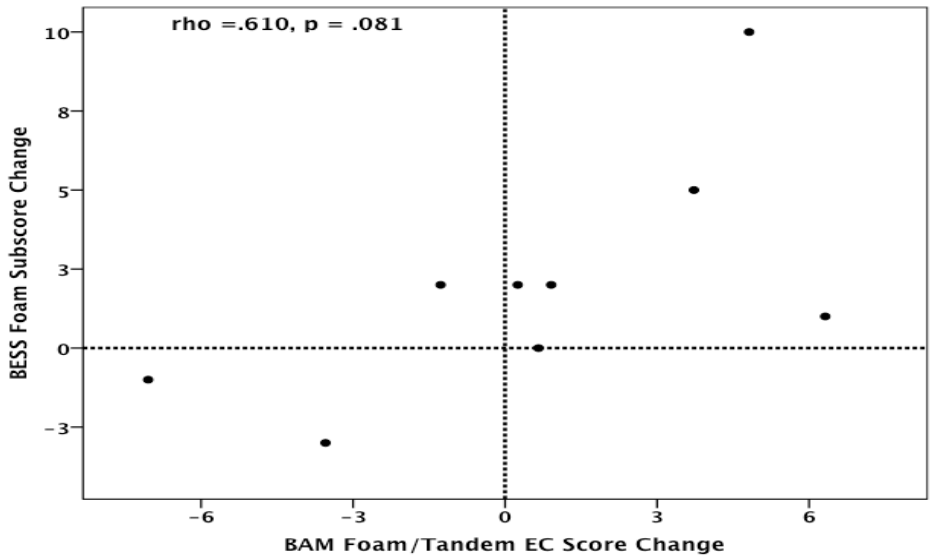


Figure 16. Change score plot for the Balance Accelerometer Measure (BAM) foam/tandem – EC score vs. the Balance Error Scoring System (BESS) foam score

The BAM foam/tandem – EC score was computed by adding the standardized normalized path lenght scores for conditions 4 and 6 (Foam surface or tandem stance with eyes closed). The BESS Foam subscore was computed by adding the scores for the three foam conditions. The horizontal dotted line indicates the boundary between improvement (positive values = lower error score on the second visit as compared with the first visit) and worsening (negative values = higher error score on the second visit as compared with the first visit) for the BESS. The vertical dotted line indicates the boundary between less sway (positive values = less sway on the second visit) and more sway (negative values = more sway on the second visit) for the BAM. EC: eyes closed.

Notably, there was no apparent correlation between the change score for the BAM and change scores for the DHI, ABC, postconcussion symptom score from ImPACT, or GRC. These results, shown in Table 7, suggest that the context validity for the BAM is good in terms of a balance measure but that the BAM does not have good context validity regarding non-balance measures, suggesting that the BAM is measuring something different from the other non-balance measures of concussion.

Table 5. Correlation coefficients and p-values for change in the Balance Accelerometry Measure (BAM) vs. change in Balance Error Scoring System (BESS)

	BESS Firm	BESS Foam	BESS Total
BAM Firm - EO/EC	rho = 0.45 p = 0.221	rho = 0.44 P = 0.235	rho = 0.49 P = 0.177
BAM Foam/Tandem - EO	rho = 0.56 P = 0.113	rho = -0.24 P = 0.539	rho = -0.12 P = 0.764
BAM Foam/Tandem - EC	rho = 0.00 P = 1.000	rho = 0.61 P = 0.081	rho = 0.61 P = 0.081
BAM Total	rho = 0.74* P = 0.024	rho = 0.46 P = 0.215	rho = 0.65 p = 0.057

*.Correlation is significant at the 0.05 level (2 –tailed)

EO: Eyes Open; EC: Eyes Closed

Table 6. Number of subjects who showed both increased sway on the BAM Firm-EO/EC subscore and an increased error score on the BESS Firm subscore, number of subjects who showed both decreased sway on the BAM Firm-EO/EC subscore and a decreased error score on the BESS Firm, and number of subjects who changed in opposite directions on the two subscores

Subscore		BESS Firm		
	Change	Lower error score on second visit	Higher error score/No change on second visit	Total
BAM Firm-EO/EC	Less Sway on second visit	1	1	2
	More Sway on second visit	5	2	7
	Total	6	3	9

p = .22 using McNemar's test

Table 7. Correlation coefficients for change in Balance Accelerometry Measure (BAM) scores vs. change in patient reported measures of recovery

	DHI *	ABC *	GRC *	PCSS**
BAM Firm	rho = -0.23 P = 0.544	rho = -0.09 P = 0.814	rho = -0.12 P = 0.764	rho = -0.29 P = 0.535
BAM Foam/Tandem - EO	rho = 0.29 P = 0.444	rho = 0.02 P = 0.966	rho = -0.29 P = 0.444	rho = 0.29 P = 0.535
BAM Foam/Tandem - EC	rho = -0.17 P = 0.667	rho = -0.09 P = 0.814	rho = 0.12 P = 0.764	rho = -0.18 P = 0.702
BAM Total	rho = -0.16 P = 0.683	rho = 0.13 P = 0.731	rho = -0.36 P = 0.342	rho = -0.11 P = 0.819

EO: Eyes Open; EC: Eyes Closed

*n = 9; **n = 7

5.0 DISCUSSION

This research extended a prior study of the use of the Balance Accelerometry Measure (BAM) in the evaluation of children with concussion.(Furman et al., 2013) The present study addressed whether the BAM provided valuable information regarding change over time in children with concussion by testing two hypotheses, one hypothesis regarding the ability of the BAM vs. the BESS to measure change during recovery from concussion and the second hypothesis regarding the context validity of the BAM in measuring recovery following concussion. Unfortunately, the present research had a small number of subjects, which limits the inferences that can be made. However, because of the repeated measures design of the study, the sample was large enough to describe the behavior of the small group statistically, to look for trends, and to judge the number of subjects that would be required to reach statistical significance.

The first hypothesis, which stated that the ability of the BAM to demonstrate improvement in sway in children following concussion was better than that of the BESS, could not be supported by the results of this study. In fact, the BESS had a higher effect size and one of the BAM subscores actually showed a negative effect, that is, more sway on the second visit. The second hypothesis, which stated that the BAM had context validity, was supported moderately regarding its relationship to the BESS but not to subjective measures of recovery from concussion.

The subject group consisted of teenagers seen twice following concussion. About half of the subjects had a sport-related concussion. Generally, the subjects got better between the two visits based on a reduction in the postconcussion symptom score in all subjects and a positive (improved) global rating of change in seven of the nine subjects. These demographics suggest that the subject group, though small, had impairments when first evaluated and overall improved between the first and second assessments.

The BAM combines the benefits of low tech and high tech balance assessment methods because it is lightweight, can be used almost anywhere, requires minimal training to use, is entirely objective, and provides a digital recording that can be stored indefinitely.(Rine et al., 2013) The BAM has the potential to provide information about the details of postural sway and possible mechanisms of postural control. The BESS, although low tech, requires training to properly score and often includes video recordings for later scoring, which adds a technology burden to the test. Both the BAM and the BESS are functional measures of balance that theoretically should correlate with functional abilities including the ability to perform athletic activity.

Previous results for the BAM have shown its ability to discriminate among age groups,(Rine et al., 2013), its ability to discriminate between healthy control subjects and persons with vestibular disorders,(Marchetti et al., 2013) and its ability to discriminate between healthy controls and children with concussion.(Furman et al., 2013) Thus, the BAM can be thought of as having validity for assessing balance in a clinical population, especially in persons with concussion, a group that would be expected to have altered postural sway early in the recovery process.

Previous studies using both the SOT (Broglio et al., 2008; Broglio & Guskiewicz, 2009; Riemann & Guskiewicz, 2000) and the BESS (Guskiewicz et al., 2001) have shown that balance function improves in most children following recovery from concussion. The group studied in this research also showed evidence of improvement based on both BESS and questionnaire measures. Thus, measuring changes in postural sway over time in children with concussion using the BAM is logical and would be expected to show changes in postural sway expected during recovery from concussion.

Although the SOT can be considered the gold standard to assess postural sway,(Broglio et al., 2008; Broglio & Guskiewicz, 2009; Riemann & Guskiewicz, 2000) the BESS is the most widely used balance measure following concussion and has been used to assess balance over time in person with concussion.(Guskiewicz et al., 2001) So, the BAM was compared with the BESS, using effect sizes between the first and second assessments, in this group of subjects who both theoretically and by other measures was considered to be recovering from their concussions. Results indicated that the BESS is better than the BAM at documenting improvements in balance over time in this group of children with concussion. This result was somewhat surprising given prior studies of the BESS (Guskiewicz et al., 2001) and the BAM (Furman et al., 2013) in this type of population. Also both the BESS and the BAM are functional tests of balance. As subjects improve functionally, both the BESS and BAM would be expected to improve

In this study, the aggregate BAM data showed that sway actually increased for the easiest conditions as subjects recovered from concussion. This finding was somewhat unexpected but is consistent with the results of a study in which postural sway was measured on a single visit using the BAM in a group of children following concussion.(Furman et al., 2013) In that study, sway, as measured using the BAM, was actually smaller in the group of persons with concussion as compared with the sway in the control group. This finding was probed further in the statistical analysis of data related to aim 1 (effect sizes) and aim 2 (correlations). Based on a difference in the sign of the effect sizes for the BAM Firm-EO/EC and the BAM Foam/Tandem-EC, a comparison was made of changes in sway in the two easiest BAM conditions vs. the change in sway in the two most challenging BAM conditions. This analysis, illustrated in Table 4, showed a trend (p=.125) toward a discrepancy between these two subscores. A further probing of the data was based on differences in the correlation between the BAM Firm-EO/EC and BESS scores vs. the correlation between the BAM Foam/Tandem-EC and BESS scores. A comparison of the sign of the change in BAM scores vs. the sign of the change in BESS scores for the BAM Firm-EO/EC versus the BESS Firm scores, illustrated in Table 6, indicated a trend toward a disagreement in these two measures, although the p value was only p=.22. The reason for more, not less, sway as persons recovering from concussion may be related to deliberate involuntary exploratory postural sway.(Carpenter, Murnaghan, & Inglis, 2010; van Emmerik & van Wegen, 2002) Carpenter et al. have suggested three reasons for exploratory postural sway including: 1) increased sway increases the variety of sensors that are activated; 2) more receptors of each type are stimulated; and 3) information from different sensory systems can be activated simultaneously

Regarding the context validity of the BAM, the BAM total score and one of its subscores, i.e., the BAM Foam/Tandem-EC subscore, compare favorably with the BESS in terms of showing postural deficits that recovers over time. Thus, the context validity of the BAM is modest regarding the BESS, which is the most commonly used test of balance after concussion. However, the BAM does not correlate well with subjective measures of balance so the BAM is presumably measuring something different from those other measures. This finding is similar to a lack of consistent correlation between the ABC and the number of falls reported in patients with balance disorders.(Whitney, Marchetti, & Schade, 2006) Note that the DHI and ABC were not designed for children although they have been used in this age group.(Alsalaheen et al., 2010; Alsalaheen et al., 2014) Possibly, the use of the ABC and the DHI in this age group may have contributed to the low context validity between the BAM and the ABC and DHI measures. Limitations of the study include primarily the small number of subjects. Other limitations in this age group include changes in attention, fatigue, and distraction that could have increased the variability of the data and led to inconsistencies from one condition to another. Based on the data from the nine subjects in this study, assuming an alpha of .01 and a power of .80, to reach statistical significance for the correlation between BAM total score and BESS total score, the number of subjects required would be 22. To reach significance ($p<.05$) for the comparison between BAM Firm-EO/EC and BAM Foam/Tandem-EC illustrated in Table 4, the number of subjects required would be about 20.

The external validity of the results of this study cannot be assessed quantitatively at this time. Additional research will be required to determine whether the results of this study can be generalized to other groups of children with concussion. The very low drop-out rate from the first to the second evaluation suggests that these results had high external validity. It is unlikely that the subject population was biased toward subjects who did not improve.

The BAM may become a useful measure in the evaluation of children following concussion but is unlikely to replace the BESS. Because the BAM is easily administered and requires no training on the part of the examiner, in future studies, the BAM could be combined with the BESS. However, loss of balance during the BES could create large changes in sway and artifacts that could be difficult to analyze with the accelerometer. Accelerometry has recently been successfully combined with the Timed Up and Go test (Salarian et al., 2010) suggesting that the BAM could also be combined with other tests of balance.

Further research will be required to determine if children with concussion sway less in non-challenging conditions early in the recovery process and then sway more as they recover. This will require a larger number of subjects. Also, future research regarding the BAM may include an evaluation of the medial-lateral as well as anterior-posterior sway as this could provide additional insights regarding postural stability in children following concussion.

6.0 CONCLUSION

In conclusion, this small n study of postural sway using the Balance Accelerometry Measure (BAM) suggested that an easily administered, low-cost test could be used in children to monitor recovery from concussion. The BAM showed moderate context validity as compared with the BESS but did not appear to be as sensitive as the BESS in detecting change. A potentially novel finding using the BAM is that children with concussion may increase their sway over time during the least challenging conditions while decreasing their sway over time during more challenging balance conditions. This change in sway pattern may reflect an increase in exploratory sway behavior that occurs with recovery from concussion.

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