COMPARISON OF THE BALANCE ERROR SCORING SYSTEM AND THE NEUROCOM SENSORY ORGANIZATION TEST IN HEALTHY, PHYSICALLY ACTIVE ADULTS

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Concussion is a common occurrence in athletics and requires a comprehensive exam, including assessment of postural stability. The Balance Error Scoring System (BESS) is recommended by the NCAA/NATA for sideline evaluation. The NeuroCom Sensory Organization Test (SOT) is a dynamic posturography assessment tool that uses somatosensory and visual input to challenge the somatosensory, visual and vestibular systems. Due to significant negative outcomes associated with mismanaged concussions, a sideline assessment must appropriately measure each component of postural stability. **Purpose:** To examine the relationship between the BESS and the SOT clinical scores and kinetic variables. **Methods:** Nineteen healthy, physically active young adults (22.16±2.59 years, 168.56±22.24cm, 73.24±15.28kg) were tested using the BESS and the SOT in a single session. The BESS tested six-conditions, including bilateral, single leg and tandem stances, each assessed on firm and foam surfaces. The SOT tested six-conditions, including eyes open, eyes closed and sway surround, each tested on a stable and sway support surface. Overall and condition error scores from the BESS were compared to SOT composite score and somatosensory, visual and vestibular component scores. Kinetic variables of standard deviation of vertical ground reaction force (SDvGRF) and total sway were calculated for each condition of the BESS and the SOT and compared between assessments. Pearson and Spearman correlation coefficients were calculated. Significance was set at $P<0.05$ a priori. **Results:** The clinical scores of the BESS and the SOT demonstrated one significant association (SOT somatosensory component and BESS tandem on firm error score, $r=-0.493$, $p=0.032$). In contrast, significant correlations were observed between several BESS and SOT SDvGRF variables ($r=0.458 – 0.760$, $p<0.05$) and sway variables ($r=0.465 – 0.681$, $p<0.05$). **Conclusion:** Based on these results, the error scoring system of the BESS should be reevaluated to determine if magnitude of error scoring would increase association with SOT clinical scores. Additionally, there may not be a significant vestibular challenge with the BESS associated with inaccurate visual input. Future research should investigate potential modifications to improve the BESS for clinical use in concussion assessment to create a more comprehensive tool that incorporates magnitude of error scoring and a heightened vestibular challenge through inaccurate visual input.

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PREFACE

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1.0 INTRODUCTION

Concussions are a pervasive issue in the field of sports medicine and affect athletes in a variety of athletic settings. Appropriate concussion assessments are critical for optimal treatment and management of concussions. Concussion assessments include a battery of components including neurocognitive testing, symptom scores and postural stability testing. The Balance Error Scoring System (BESS) and the NeuroCom Sensory Organization Test (SOT) have been used to assess postural stability associated with concussion, and have each demonstrated significant differences in scores in concussed individuals compared to healthy controls.[11, 39, 55, 62] The correlation between the BESS and the SOT, however, has not been assessed. The purpose of this study is to determine if the BESS is able to detect deficits in each of the three components of postural stability as compared to the SOT. This study will investigate the relationship between these two evaluations of postural stability. If the results demonstrate a lack of association between the BESS and a specific component of postural stability measured with the SOT, modifications can be made to the BESS to better evaluate each component; somatosensory, visual, and vestibular.

1.1 CONCUSSIONS

Concussions affect nearly 1 million people in the U.S. annually, creating a significant public health problem.[55] A concussion is defined as a "complex pathophysiological process affecting the brain, induced by biomechanical forces".[63] There are a wide range of functional limitations and symptoms of concussion. Individuals who sustain a concussion may complain of symptoms such as pain, headache, neurocognitive impairment, hyperinsomnia, hypoinsomnia, depression, anxiety, and dizziness.[55] Due to the variety in concussion presentation, concussions are often diagnosed with a combination of clinical evaluation, cognitive evaluation, postural stability evaluation and self-reported symptoms.[101]

Langlois et al[53] performed a review of the epidemiology and impact of traumatic brain injury (TBI). TBI is a broader term that includes the specific diagnosis of concussion. According to the Centers for Disease Control, a TBI is "caused by a bump, blow or jolt to the head or a penetrating head injury that disrupts the normal function of the brain".[85] This includes, but is not limited to, concussion. They report at least 10 million TBIs of a severity requiring hospitalization or leading to death annually, worldwide. Of those TBIs, approximately 1.4 million occur annually in the United States. These reports are routinely underestimated due to the prevalence of TBIs that are treated without hospitalization, which is often the case in an athletic population. Due to the availability of athletic trainers and physicians in competitive athletics, many TBIs are treated without hospitalization. Based on hospital data, TBIs are most common in children and adolescents. Additionally, males are twice as likely to sustain a TBI compared to females. The Centers for Disease Control[32] estimate approximately 300,000 sport-related TBIs and concussions, but this estimate only includes cases in which the individual suffered a loss of consciousness. Because concussion does not require a loss of consciousness, this estimate is likely an underestimate as well. Based on an estimated 8-20% rate of loss of consciousness in sports-related concussions in addition to unreported TBIs, the CDC estimates approximately 1.6-3.8 million sports-related concussions annually.

Due to the high rate of concussion and the possible long-term effects of concussion if not managed appropriately, it is imperative to use a comprehensive and accurate clinical evaluation of this injury. Concussion can result in cognitive changes and memory loss in addition to symptoms such as chronic migraine. Lei-Rivera et al[55] conclude that multiple tests are necessary for the determination of the impairment caused by concussion and the effect this has on the patient's activity level and participation level. This array of tests includes postural stability testing due to the possible decrements to the postural stability system caused by concussion. Guskiewicz et al[39] demonstrated a decrease in postural stability following concussion in 36 concussed athletes when compared to 36 control participants. These deficits generally resolve within 3 days of sustaining the injury. Due to this demonstrated decrement in postural stability following concussion, an objective measure of postural stability is necessary to properly diagnose and treat an individual who has sustained a concussion.

1.2 POSTURAL STABILITY

Postural stability is defined as the process of coordinating corrective movement strategies and movements at selected joints to remain in postural equilibrium.[37] Postural equilibrium is the balanced state of forces and moments acting on the center of gravity resulting in minimal motion,[57] or when the body is maintaining the center of gravity within the base of support though and equalization of forces and optimal alignment of body segments.[37] The center of gravity is defined as an imaginary point in space about which the sum of the forces and moments is zero.[100] The center of pressure is defined as the point on the support surface where the resultant vertical force vector would act if it were to have a single point of application.[6] Postural stability requires an individual to maintain the center of pressure inside the limits of stability.[25] The limits of stability is defined as a 2-dimensional measure defining the maximum angle of displacement of the center of gravity from the central position without altering the base of support by stepping, falling or reaching.[26, 100] Postural stability is maintained through the use of three systems; the somatosensory system, the visual system and the vestibular system.[42]

1.2.1 The Somatosensory System

The somatosensory, visual and vestibular systems provide afferent information to achieve postural stability.[73] The somatosensory system is valuable for maintaining quiet stance and accomplishing activities of daily living. Two primary components of the somatosensory system are the muscle spindle and the golgi tendon organ (GTO). The muscle spindle provides the nervous system with information about the muscle length and velocity of contraction. This allows the individual to discern joint movement and position. The GTO is located in the muscle tendon and is sensitive to, and relays information, concerning the tensile forces within the muscle fibers. The activation of the GTO leads to inhibition of the muscle alpha motorneurons leading to decreased muscle tension.[34] When the GTO is desensitized, leading to a decrease in inhibitory influence, the muscle spindle sensitivity is increased, which can lead to enhanced proprioception, increasing postural stability.

1.2.2 The Visual System

The visual system involves a group of organs including the eyes, connecting neural pathways and the visual cortex. The retina performs the initial neural processing of visual information. That signal is then sent via the axons of the ganglion cells through the optic nerves. The signal is then sent through the optic chiasm to the optic tracts, the lateral geniculate nucleus and the primary visual cortex, respectively.[59] The visual system is composed of the central, ambient and retinal slip. The central component is utilized for perceiving object motion and objection recognition. Ambient vision is utilized for perception of self-motion and postural stability. This component is essential for maintaining stable quiet stance. The retinal slip provides feedback for compensatory sway and displacement of the central nervous system.[34] The visual system is heavily relied upon for postural stability, and impairments in vision can lead to an increase in postural sway and falls, specifically in an elderly population.[88, 102]

1.2.3 The Vestibular System

The vestibular system interacts with the somatosensory system and allows the brain to identify activity created by passive head movements.[34] It utilizes gravity in addition to linear and angular head and eye movements.[100] The vestibular system is encased in the temporal bone of the skull and is comprised of three semicircular canals, the utricle and the saccule. The semicircular canals contain endolymph fluid and sensory receptors. The semicircular canals are oriented at right angles relative to each other and respond to gravitational forces through the sensation of fluid movement within the canals. This signal is sent via the acoustic nerve to the central nervous system (CNS), giving information regarding the movement of the head in space. The utricle and saccule are sacs of hair cells that provide information regarding linear accelerations in the horizontal and vertical planes, respectively. The utricle and saccule provide additional information regarding the position of the head when not in movement. The information from these vestibular organs allows for the identification of head position, movement and acceleration in space.

1.2.4 Integration of Systems

Maintaining postural stability involves the use of sensory strategies, which involve the integration of sensory information from the somatosensory, visual and vestibular systems and the relative dependence on each input. For example, when standing on a firm base of support with adequate lighting, healthy individuals have demonstrated a reliance on somatosensory information (70%) over visual (10%) and vestibular (20%) input.[78] In contrast, when standing on an unstable surface, vestibular and visual information have increased importance due to altered somatosensory input.[78] The ability to utilize and appropriately weight the dependence on each input system is necessary to maintain postural stability. This organization of sensory information allows a person to orient themselves within their environment. Orientation in space involves the ability to effectively orient the body and individual body segments relative to gravity via the vestibular system, support surface via the somatosensory system, and visual surround via the visual system.[73] Control of dynamics is necessary during movement, such as gait, and requires that the individual control the moving center of mass (COM). For example, during gait, the COM moves anterior to the body and the swing limb must be placed under the falling COM.[89] Finally, cognitive processing is necessary to process the sensory information and create motor responses.

This is supported by the finding that performance on a stability task is decreased when the individual is required to perform a cognitive task simultaneously.[17]

Furthermore, a person will also need to demonstrate an effective motor strategy to maintain postural stability after the sensory information is received and processed. The use of multiple movement strategies, including movement about the ankle or the hip joint can be used. When using ankle strategy, the COM is shifted about the ankle joint, with the body as an approximately rigid mass. It is most commonly used in situations in which the support surface is firm and the perturbation is small.[42, 73] In contrast, hip strategy is most commonly used in situations in which perturbations are larger or faster or when the support surface is compliant or unstable. It involves the use of movement about the hip joint that opposes ankle joint rotations. A horizontal shear force is created using trunk inertia in the oppose direction of hip movement.[42, 73] Faraldo-Garcia et al[26] noted that healthy subjects utilized the ankle strategy more often than the hip strategy of postural stability. In order to effectively use the ankle strategy as opposed to the hip strategy requires accurate and effective use of sensory information.

Postural stability requires the appropriate and effective use of the somatosensory, visual and vestibular system, in addition to organization of the sensory information and motor execution to maintain postural equilibrium within the limits of stability. Due to the complex nature of postural stability, dysfunction of any component of any individual system can result in decrements in postural stability. Each system involved in postural stability is at risk of impairment when an individual sustains a concussion. These decrements can present differently based on the system dysfunction present. In order to assess postural stability, a comprehensive evaluation is important in order to challenge and assess each individual component of the postural stability system.

1.3 POSTURAL STABILITY TESTING

Postural stability testing is a valuable tool in both the laboratory and the clinical setting for a variety of purposes, such as assessing the effects of a training program, determining the decrements following injury and making return to play decisions. Clinical evaluations of postural stability have focused on static balance in which the participant is required to maintain a stationary center of gravity over a stationary base of support. Dynamic balance testing implements movement of the body to create a challenge that is believed to better mimic realistic scenarios.[12] Postural stability testing is utilized in a variety of settings to assess the ability of an individual to coordinate movement and maintain postural equilibrium within the body's base of support. Postural stability testing is a component of concussion protocols, used both in the initial evaluation and diagnosis, as well as in clearance for return to play. The Balance Error Scoring System (BESS) is a commonly used sideline assessment of balance following concussion. It utilizes single leg stance, double leg stance and tandem stance on both firm and foam surfaces.[55]

Posturography is the use of techniques that objectively study and quantify postural stability by measuring the movement of the body's center of pressure using force plates. Center of pressure movement from the force plate is then used to estimate COG. Center of pressure is an indirect measure of the COG, representing a vertical line projecting downward from the actual COG onto the force plate. Based on the concept that oscillations of the COG represent postural instability, COP is heavily relied upon to calculate postural stability.[25] Center of pressure is utilized in the calculation of sway variables and results in valuable variables such as total sway and sway velocity for the duration of the trial. Posturography systems allow for the isolation and quantification of the use of sensory information by isolating and manipulating visual, vestibular and somatosensory input, and measuring the ability to maintain stability under various conditions.[12]

1.3.1 Balance Error Scoring System

The National Athletic Trainer Association and NCAA have recommended the use of the BESS for on-field concussion assessment of balance as a component of a full concussion evaluation.[8, 36] The BESS is also a component of the Sport Concussion Assessment Tools (SCAT), which are commonly used, especially in a high school athletic setting for sideline concussion assessment. The SCAT3 includes evaluation of alertness, awareness, symptoms, cognition, balance and coordination. The balance assessment involves the BESS in addition to a tandem walking task.[1]

The Balance Error Scoring System (BESS) is a clinical evaluation of balance that involves three stances: double leg stance, single-leg stance on the nondominant leg and tandem stance with the dominant foot in front of the nondominant foot in a heel-to-toe position. Each stance is performed on a firm surface and a foam surface, creating six testing positions. Each stance is completed with hands on hips and eyes closed. Each position is performed for a 20 second trial in which errors are counted. Errors are defined as opening eyes, lifting hands off hips, stepping, stumbling or falling out of position, lifting forefoot or heel, abducting hip by more than 30° or failing to return to testing position in more than five seconds.[5]

The BESS has been the subject of previous literature in relation to concussion evaluation and has demonstrated the ability to identify individuals with concussion. Guskiewicz et al[39] demonstrated that individuals who have sustained a concussion have an increase in overall BESS score, with an increase in errors on the first day following concussion and a return to baseline within 3 to 5 days of concussion. On the first day following concussion, individuals scored an average of 17 errors on the BESS compared to 8 errors in a healthy population. Despite the ability to identify individuals with concussion, there are weaknesses of the BESS that have been demonstrated. The specificity of the BESS is excellent ($\geq$0.91) in the first 7 days following concussion. The BESS has, however, demonstrated poor sensitivity for detecting concussion (0.34) immediately following injury. The sensitivity continues to decrease 1 and 3 days post injury (0.24 and 0.16 respectively).[61] Although the BESS is inexpensive and easily administered, there are potential limitations, such as a ceiling effect[13] and learning effect.[68]

1.3.2 NeuroCom Sensory Organization Test

On-field balance evaluation tests such as the BESS have broad clinical utility and are easy to administer, but lab based measures such as the SOT may present clinicians with the best information on balance function.[39] An assessment of postural stability must have the ability to maximally challenge the patient's balance in order to avoid ceiling effects, which may be present with a test such as the BESS.[12] One available posturography system available is the NeuroCom Balance Master. Based on the definition that dynamic balance testing implements a moving base of support or movement of the body,[12] the NeuroCom Sensory Organization Test (SOT) would be classified as an assessment of dynamic postural stability. The NeuroCom SOT, however, does not involve the movement of the body; therefore, for the purposes of this study, the NeuroCom SOT will be defined as a static assessment of postural stability. It uses a variation of visual and somatosensory stimulation, which can be accurate, inaccurate or absent. This allows for assessment of the vestibular, visual and somatosensory systems.[105]

The NeuroCom Sensory Organization Test (SOT) measures vertical ground reaction forces projected from the center of gravity of the body as it moves around a fixed based of support. The SOT is a widely used and accepted test for the evaluation of postural stability. It utilizes visual and support sway referencing during eyes open and eyes closed scenarios. The test systematically disrupts the individual's visual and somatosensory input information to challenge the sensory selection process while measuring the ability to minimize postural sway. The SOT controls the visual and somatosensory input through sway referencing and/or eyes open/closed conditions. The test eliminates useful visual and/or support information, creating conflicting sensory situations. This protocol is intended to isolate sensory systems and determine adaptive responses to conflicting sensory information.[34]

By tracking the center of pressure throughout the test, an assessment of overall balance, each balance sensory component and the interaction between them is calculated.[12] This produces an composite score that is based on the person's limit of stability in addition to visual (VIS), somatosensory (SOM) and vestibular (VEST) component scores.[39] In addition to component and composite scores, the SOT provides a preference (PREF) score that indicates the extent to which an individual relies on visual input for postural stability, even when the visual input is incorrect.[100] Postural stability has been shown to decrease as difficulty of condition increases from condition one (eyes open and stable support) to condition six (sway surround and sway support).[12] For the purposes of this study, the SOM, VIS and VEST component scores will be used in addition to the composite score. These scores were chosen in order to compare the BESS to an analysis of each of the sensory systems, as the purpose of this study was to determine if each sensory system is adequately tested by the BESS.

Concussed individuals are expected to present with decreased postural stability when assessed with the SOT,[55] specifically abnormal sway, a lower composite score, increased dependence on visual input and ineffective use of vestibular input.[51] Additionally, the NeuroCom SOT composite score and vestibular ratio has been negatively correlated with dizziness (r=-0.55 and r=-0.50 respectively), in a concussed population.[11] The NeuroCom SOT and the BESS have both been used in previous literature regarding concussions; however, the two tests have not been compared to each other.

1.4 DEFINITION OF THE PROBLEM

In the assessment of concussion, a variety of techniques can be used to evaluate postural stability. The National Athletic Trainers' Association recommends the BESS as a postural stability assessment tool to be utilized in the clinical evaluation of concussion. The BESS could be inadequate to fully evaluate all potential deficits of postural stability caused by concussion. Concussions affect each individual differently and can manifest in a variety of ways. Changes in any of the postural stability systems are possible, exclusive of changes in other systems; therefore, changes in each individual system must be able to be isolated and detected. Vestibular deficits are common following concussion, yet the BESS does not have a component that theoretically isolates the vestibular system such as a head-shake condition. Clinicians need a tool that is a valid, comprehensive evaluation of postural stability in order to make the optimal clinical diagnosis and decisions related to concussion.

1.5 PURPOSE

The purpose of this study is to evaluate the BESS in relation to the NeuroCom SOT. By establishing or failing to establish a relationship between the NeuroCom SOT and the BESS, results may reveal components of balance not adequately examined by the BESS. If the results demonstrate a deficit in comprehensive testing of balance, the results of this study may be utilized to modify the BESS to better evaluate the visual, somatosensory and vestibular components of balance. A modified BESS would provide a more complete, specific balance evaluation tool for sideline concussion evaluation. A strong correlation would assist in validating the clinical use of the BESS test as a sideline evaluation tool.

1.6 SPECIFIC AIMS AND HYPOTHESES

Specific Aim 1: To establish the relationship between error scores of the BESS and the NeuroCom SOT output scores; composite, VIS, SOM, VEST

Hypothesis 1: There will be a significant association between the overall BESS score and the NeuroCom SOT outcome scores

1a. There will be a significant association between the overall BESS score and the NeuroCom SOT composite score

1b. There will be a significant association between the overall BESS score and the NeuroCom SOT VIS score

1c. There will be a significant association between the overall BESS score and the NeuroCom SOT SOM score

1d. There will not be a significant association between the overall BESS score and the NeuroCom SOT VEST score

Specific Aim 2: To establish the relationship between force plate variables of the BESS and the NeuroCom SOT; standard deviation vertical ground reaction force (SD vGRF) and total sway

Hypothesis 2: There will be a significant association between force plate raw data and for the BESS and the raw data from the NeuroCom SOT

2a. There will be a significant assocation between the SD vGRF of the BESS conditions and the NeuroCom SOT conditions, excluding the vestibular conditions of the SOT

2b. There will be a significant association between the total sway of the BESS conditions and the NeuroCom SOT conditions, excluding the vestibular conditions of the SOT

1.7 STUDY SIGNIFICANCE

The BESS is a commonly used clinical examination tool for assessing balance, specifically following concussion. With the frequent use of the BESS as a component of a sideline concussion evaluation, it is valuable to understand the relationship between it and the NeuroCom SOT, which challenges visual, somatosensory and vestibular feedback individually. Concussions can have significant negative outcomes if not managed properly; therefore, the most valid, comprehensive assessment of postural stability will enhance the ability of the clinician to make the best clinical diagnosis and return-to-play decisions.

2.0 LITERATURE REVIEW

The review of the literature will begin by discussing concussions, the evaluation of concussions and risks associated with concussion, indicating the need for optimal evaluation techniques. Next will be a discussion of the postural stability system including the somatosensory, visual and vestibular systems and methods for testing postural stability.

2.1 CONCUSSION AND DIAGNOSTIC EVALUATION OF CONCUSSION

The NCAA issued a memorandum in 2010,[8] stating that athletes should be required to participate in baseline concussion testing in most sports prior to the start of preseason training. This baseline testing should, at minimum, include postural stability assessment. The comparison of baseline and post-injury assessment should be utilized in diagnosis, treatment, and return to play decisions. When assessing concussion, it is recommended to use a battery approach, including neurocognitive, postural stability, self-reported symptoms and physical examinations. Each component can vary based on a variety of factors including age, sex, location of impact, and magnitude of impact. Using a complete battery approach to concussion assessment allows for the appropriate diagnosis of concussion regardless of the specific presentation.[3, 36] No individual component of the concussion assessment battery has a sensitivity greater than 70%, but when combined, sensitivity is between 89% and 96%.[10, 54] Based on this finding, it can be inferred that a battery approach controls for the wide variety of damage and symptoms possible from a concussion. Postural stability assessment should not be used in solitude, but should be a component of the assessment. Although it is not to be used in solitude, it is crucial that the postural stability assessment used in an evaluation be thorough and assesses all components of postural stability.

Broglio et al[11] performed a retrospective assessment of concussed collegiate-level athletes who were evaluated pre and post-injury. The purpose of the study was to identify the relationship between subjective symptom reports and objective clinical measures of concussion, using an inventory of concussion-related symptoms, the NeuroCom SOT and a computerized assessment of neurocognitive function, the Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT) test. Significant correlations were found between reported "dizziness" and SOT composite score and vestibular ratio, reported "balance problems" and SOT composite score and somatosensory, vestibular and visual ratios. The authors, therefore, concluded that self-reported symptoms are associated with deficits in postural stability. While the athlete may perceive postural instability, it is important that a clinician not depend solely on self-reported symptoms, as athletes often underreport symptoms in order to continue participating.[11] Self-report symptoms should be used in tandem with objective postural stability assessment.

Due to the issue of underreporting and the complexity of concussion injuries, Guskiewicz et al[38] sought to investigate alternative approaches to the assessment of mild head injuries in athletes, specifically related to recovery and return to play. The authors noted the limited quantitative information that can be used clinically to determine injury severity or recovery. Due to the complexity of the brain and responses to brain injury, the assessment of concussion is difficult and often based on subjective self-report symptoms. These self-report symptoms are unreliable as an athlete may be anxious to return to play and therefore underreport symptoms. Additionally, subjective symptoms can resolve quickly after injury, while the concussion and pathology may remain. Recommendations for return to play vary and are based on clinical observations rather than quantitative data. As cognitive and balance deficits have been noted as a result of concussion, the authors propose that testing these deficits could provide better information for return to play decisions.

The study by Guskiewicz[38] included 22 subjects, 11 Division I athletes and 11 matched controls. The Division I athletes were assessed on day 1, 3, 5, and 10 post-injury in addition to the matched control. Postural stability was tested using the NeuroCom SOT and cognitive assessment included Trail Making Test, Wechsler Digit Span Test, Stroop Test and Hopkins Verbal Learning Test. Results indicate that 7 of 11 subjects continued to report symptoms on day 3 post-injury, while only 1 of 11 subjects continued to report symptoms after day 3. There was a significant group by day interaction for the composite score of the SOT, with differences between injured and control subjects diminishing by day 3, although the author proposes that with more subjects, differences would likely be seen at day 5. There was also a significant group by day interaction for the visual ratio. Neuropsychological testing revealed no significant difference between groups and a similar learning effect between groups. This would indicate that postural stability measures could be a more significant quantitative test for return to play decisions. The significant difference in SOT score supports the importance of postural stability assessment in concussion evaluation and supports the use of the SOT as a tool to detect the effect of concussion on postural stability.

Posturography has also been supported as a tool for postural stability assessment in a study of postural sway examined by posturography in children with mild head injuries. Lahat et al[52] demonstrated significant increases in postural sway in the injured population compared to the control group of healthy children. The author concluded that posturography is a useful way to examine the effects of mild head injury immediately following (24-36 hours) injury in children.

The use of objective postural stability testing following concussion provides information about the systems disrupted by the injury. Rubin et al[93] studied postural stability following mild head or whiplash injuries. Twenty-nine subjects reporting dizziness following a mild head or whiplash injury were compared to 51 healthy subjects. Balance assessment involved force plate measures of COP movements in the anterior-posterior and medial-lateral directions in addition to the total movement displacement. Conditions involved variations in visual (accurate, absent and inaccurate) and somatosensory (accurate and inaccurate) inputs. Those with head injury presented with significantly increased anterior-posterior sway in 4 of the 6 conditions and greater total movement displacement during the conditions involving inaccurate vision and inaccurate somatosensory input. The authors concluded that patients who have sustained a head injury present with an increased reliance on accurate visual input and decreased sensory organization utilization, specifically with conflicting visual and somatosensory input.

As previously stated, concussion evaluation should contain a variety of assessments testing neurocognitive symptoms, self-report symptoms and postural stability symptoms. Self-report symptoms are valuable to the overall evaluation, but with the frequent underreporting of symptoms, it is critical to have objective measures that can be utilized to provide more accurate information to the clinician. Postural stability scores have been associated with self-report symptoms of “dizziness” and “balance problems”, and therefore may provide information to the clinician that the patient may choose to exclude from the self-report symptoms. Additionally, previous research has demonstrated that assessments following concussion demonstrate a significant decrease in postural stability when compared to a healthy population or a baseline measure. Postural stability assessment is, therefore, valuable as an objective measure of the impact of concussion that cannot be altered by patient goals of return to play.

2.1.1 Confounding Variables

There are a variety of confounding variables that could affect the results of a concussion evaluation. It is important that a clinician be aware of possible confounding variables and control for each when possible. This control leads to a more accurate comparison between a baseline evaluation and an assessment or return to play evaluation. Possible confounding variables include learning disability, lack of sleep, dehydration and training.

Collins et al[21] observed a gap in the literature concerning the interaction between concussion history and learning disability (LD) on baseline neuropsychological testing in addition to the effect of concussion on post-injury neuropsychological testing. Football players from 4 Division I university teams participated in the study (n=393). Each participated in pre-season neuropsychological testing including tests such as the Hopkins Verbal Learning Test, Trail-Making Tests and Grooved Pegboard Test. Self-report data included age, playing position, SAT/AC scores, history of LD, neurological history, history of psychiatric illness, history of drug and alcohol abuse and history of concussion. Each subject also completed a standard Symptom Checklist Scale. Those subjects who sustained a concussion during the 2-year time period of the study completed the neuropsychological examination within 24 hours of injury and at 3, 5, and 7 days post-injury. Other subjects within the study served as matched controls. No statistically significant relationship was found between a history of LD and a history of concussion. Both concussion history and LD demonstrated a main effect on neuropsychological baseline test results, with no interaction present. The authors concluded that a history of LD and a history of concussion are independently related to lower baseline neurocognitive performance. Additionally, a history of concussion is significantly associated with long-term deficits in executive functioning and speed of information processing and an increase in self-report symptoms.

A more common potential confounding factor for concussion assessment is lack of sleep. Mihalik et al[66] investigated the effects of sleep quality and quantity on concussion baseline assessment. The authors state that because sleep deprivation affects postural stability, and may affect cognitive assessment, the baseline assessment would not be an accurate evaluation of the individual at a non-concussed state if the individual did not have adequate sleep the night before evaluation. One hundred forty-four subjects were included in the study. Each completed the Pittsburgh Sleep Quality Index, CNS Vital Sign battery, NeuroCom SOT and Graded Symptom Checklist. Results showed that subjects with low sleep quality reported increased somatic and neurobehavioral symptoms. Sleep quantity had a significant effect on visual memory and somatic symptoms. Sleep quality and quantity did not have a significant effect on neurocognitive function evaluated by the CNS Vital Signs battery or balance as assessed by the SOT. The authors conclude that moderate sleep loss does not affect the validity of baseline concussion assessment, but if a subject received no sleep the night before assessment, the session should be rescheduled.[66]

Patel et al[77] the effect of dehydration on neuropsychological performance, postural stability and reported symptoms on the premise that athletes are often dehydrated following participation in competition. This would lead to post-concussion assessments in a dehydrated state. This study utilized 24 healthy, male recreational athletes who participated in counterbalanced sessions, euhydrated and dehydrated. Results showed no significant effect of dehydration on Standardized Assessment of Concussion, total BESS score, composite SOT and composite Automated Neuropsychological Assessment Metrics score. Dehydrated individuals did present with significantly deteriorated visual memory and fatigue measures in addition to an increase in number and severity of reported symptoms. Weber et al[108] also evaluated the effect of dehydration on clinical concussion measures, using a population of NCAA Division I wrestlers. Procedures mimicked dehydration due to weight-cutting techniques prior to competition. In contrast to Patel et al[77] significant effects were seen in SCAT2 measures, BESS, Glasgow Coma Scale severity scores and reported symptoms following practice in a dehydrated state.

Burk et al[16] studied the change in BESS scores following a competitive athletic season, using 58 college-aged athletes, including student athletes and recreationally active healthy adults. The BESS was administered 90 days apart, before the start of the athletic season and immediately following the end of the athletic season. Results showed no interaction between group and time, but there was a significant improvement between the pre-season and post-season test. The results indicate that repeated BESS testing leads to a practice effect. Because the recreational group also demonstrated improvements, it is likely not depended on the training involved with competitive athletics.

Collecting a full history from an individual allows the clinician to identify possible confounding variables. Those with learning disabilities can be identified. Although a LD can affect concussion assessment, it may not impact the change in assessment scores from baseline to post-injury, as the scores are compared within subject. Dehydration and sleep should be discussed prior to testing. In the case of a baseline assessment, the individual can be tested at a later date to ensure that scores are not affected by confounding variables. When performing a concussion assessment post-injury, testing cannot be delayed due to dehydration or lack of rest, but these possible confounding variables should be noted. Finally, repeated assessment, specifically using the BESS, has demonstrated learning effects. Clinicians must be aware of the frequency with which patients are tested and note a high frequency of testing in order to account for a possible learning effect in testing. Overall, a thorough history will allow a clinician to better account for possible confounding variables when completing a concussion assessment.

2.1.2 Recovery and Long-Term Effects

Concussion assessment is critically important due to the nature of the injury. There are significant effects of concussion that can lead to long-term disability or death if not managed properly. In order to minimize long-term effects, a clinician must properly diagnose a concussion in order to initiate the proper protocols for return to play. The following studies address the recovery and potential long-term effects of concussion, supporting the importance of diligent, valid and reliable assessment tools.

Powers et al[84] sought to determine if balance deficits had completely resolved in athletes who had been cleared for return to play using COP measurements. The author indicates that the BESS is commonly used, but is not reliable due to learning effects and decreased sensitivity over time. Center of pressure can be used as an objective and valid measure of postural stability deficits. Results of the study indicate that balance had not entirely recovered in a study of 9 football players compared to 9 controls. In the acute phase of injury, concussed subjects displayed greater AP COP displacement, which had recovered by return to play. In contrast, COP velocity continued to be significantly greater in the injured group following return to play, indicating that postural stability had not completely recovered at return to play. The intention at return to play is for full recovery to have occurred; therefore balance measures are critical for return to play decisions.

Neurocognitive deficits have been shown to remain up to 14 days post-injury, even when the individual does not report any symptoms.[60, 62, 98] Peterson et al[80] evaluated the recovery curve of athletes who sustained a sport-related concussion using neurocognitive and SOT repeated testing. Baseline measures were completed for all athletes participating in football, soccer, basketball, softball and cheerleading at a Division I university. Those who sustain concussions were also tested 1, 2, 3, and 10 days post-injury. The results of the study demonstrated a significant difference between the injured and uninjured group for self-reported symptoms, speed of information processing, mean stability and vestibular function. Symptoms and the vestibular ratio demonstrated significant differences through day 3, while speed of information processing and composite balance demonstrated significant differences through day 10. This study found that the vestibular system is most disrupted following injury and returns to baseline levels within 3 days. This is in disagreement with Guskiewicz's[39] findings that vestibular deficits remained for up to 5 days post-injury. Regardless of the exact recovery time, the authors are in agreement that the vestibular system is often the last to recover from concussion, and therefore must be challenged in the balance assessment used in the return to play decision-making process.

Wade et al[107] studied the effect of rehabilitation following severe traumatic brain injury on postural sway and walking parameters. The study included 13 subjects who were undergoing rehabilitation following a severe TBI. Postural sway was examined in normal stance, right foot forward tandem and left foot forward tandem stance. Two assessments were performed, 2 to 6 weeks apart. The results of this study show that postural sway decreases in TBI patients undergoing rehabilitation, indicating that rehabilitation is a tool that can be used in concussion recovery.

Concussions can also have long-term effects. Sosnoff et al[99] investigated the effects of previous mild traumatic brain injury on postural stability dynamics. Guskiewicz et al[39] demonstrated that postural stability deficits, as tested by the SOT, resolve approximately 3 days following injury, yet Sosnoff hypothesized that deficits can present 6 months postinjury. The study[99] included 224 participants with a history of concussion at least 6 months prior to testing, and testing was conducted using the NeuroCom SOT. Minimal differences were detected in the SOT scores. Raw data was also extracted from the SOT in order to calculate approximate entropy (ApEn). Approximate entropy is a measure indicating how likely a specific pattern is to be repeated within a time period. An individual with predictable sway will present with a low ApEn, indicating decreased function. Irregular sway, therefore, indicates an irregular sway pattern. Those with a history of concussion demonstrated an increase in ML ApEn and a decrease in AP ApEn as the condition difficulty increased. The findings indicate that there are changes in cerebral functioning following concussion that may persist after the resolution of the acute injury.

Ingersoll et al[46] investigated the effects of closed-head injury on postural sway in a sample of 48 subjects with varying levels of head injury, from no loss of consciousness to loss of consciousness for greater than 6 hours. All subjects were at least 1 year post-injury at the time of the study. The COP, ML and AP sway were collected using a force plate as the subjects completed 6 variations of the Romberg test. The 6 conditions were comprised of eyes open, eyes closed and a visual conflict dome in combination with a firm or foam support surface. The results indicate that closed-head injury can result in increased postural sway up to at least 1 year post-injury. The greatest AP sway was noted in the most severely injured group that had a significant loss of consciousness in the test conditions that involved lack of or conflicting visual or somatosensory input. Total sway did not differ between subjects indicating that the COP is maintained at a greater distance from the base of support in severely injured subjects, making subjects more vulnerable to loss of stability in the presence of perturbations.

Barlow et al[4] analyzed the clinical data of concussed middle and high school athletes to evaluate the concurrent and predictive validity of the Post-Concussion Symptom Scale, BESS and ImPACT test for post-concussion syndrome. Post-concussion syndrome is a condition in which concussion symptoms are prolonged for weeks or months following the original injury. The study was conducted using a retrospective chart review of individuals diagnosed with a concussion who had completed all measures of interest. The results indicate poor concurrent validity between the three concussion assessments and that no baseline score predicts post-concussion syndrome. Although use of the BESS may not be predictive of protracted recovery from concussion, it remains useful in the evaluation, diagnosis and return to play decisions as a component of a battery assessment.

Recovery and long-term effects of concussion vary between individuals. As in a concussion assessment, the use of a battery approach helps give a clinician the most comprehensive information in order to make decisions regarding concussion treatment and return to play. Due to the potential for severe long-term effects, these decisions must be made with comprehensive, valid and reliable assessments. If a balance assessment tool does not challenge each component of the postural stability system, an athlete could be returned to participation prior to full recovery, increasing the risk of damaging effects.

2.2 POSTURAL STABILITY

Postural stability, as defined by Reimann and Guskiewicz,[37] is the process of coordinating corrective movements strategies and movements at the selected joints to remain in postural equilibrium. The base of support (BOS) is defined as the area contained within the perimeter of contact between the support surface and the two feet or single foot.[72] Limits of stability is defined as the minimal distance the center of gravity (COG) can sway while maintaining the vertical projection over the BOS.[72] It is important to test postural stability in sports medicine research, as postural stability is crucial for optimal performance.[44] Postural stability is dependent on the ability of the individual to receive sensory information, appropriately integrate that information, and select and execute an appropriate response.[94] Sensory input comes from the peripheral receptors and sensory integration is dependent on the central nervous system, including the cerebellum, cerebral cortex and brain stem.[14] The three sensory systems providing peripheral input are the somatosensory, visual and vestibular systems.

2.2.1 The Somatosensory System

To maintain postural stability, the body uses input from the somatosensory system, specifically receptors in the feet and ankles, in order to sense pressure throughout the foot and joint position of the ankle. The ankle joint is comprised of the talus and the mortise, formed by the distal tibia and fibula. A synovial joint capsule surrounds the joint. The anterior and posterior talofibular ligaments are thickened portions of the joint capsule and resist anterior and posterior translation of the ankle joint. The calcaneofibular ligament crosses the ankle and subtalar joints and resists inversion of the joint. Medially, the deltoid ligament is a strong, thick triangular ligament that spans from the medial malleolus to the navicular, talus and calcaneus. The subtalar joint, comprised of the talus and calcaneus is where inversion and eversion take place. Ligamentous structures surrounding each bony articulation provide sensory information about joint position sense as well as mechanical stability to the joint. The ankle joint is innervated by tibial and deep peroneal nerves. Innervation is important for coordinating co-activation of the musculature in order to maintain optimal joint alignment, assisting in postural stability. [58]

The somatosensory system provides input regarding the external environment through proprioception and touch. The somatosensory system provides proprioceptive input regarding body position and movement through muscle and joint stimulation. Tactile stimuli involve the detection of light touch, pressure, flutter, vibration, and temperature. Touch involves contact that produces little distortion of the skin. Pressure involves a greater force that distorts the skin and underlying tissue. Flutter and vibration are related to time varying tactile stimuli. Pressure is the tactile stimuli involved in postural stability most often due to the body mass in contact with the support surface via the plantar side of the feet. Proprioceptive stimuli involve internal forces within the joints, muscles and tendons and can be subdivided into static and dynamic forces. Static forces indicate the position of a limb. Dynamic forces indicate limb movement. Based on the type of information received by the peripheral receptors, the information is transmitted along specific afferent pathways to the central nervous system where sensory organization occurs prior to a motor response.[29, 65]

Several researchers have investigated ankle joint tactile and proprioceptive input as it relates to postural stability. Sensory and motor function related to postural stability can be disrupted due to orthopedic injury. Individuals with mechanical instability of the ankle due to ligament sprains present with decreased postural stability. With the decrease in mechanical stability of the joint from the ligaments, the muscle activation needed to maintain proper alignment and postural stability increases. Additionally, mechanoreceptors within the ligament assist in joint position sense, and the injury to the ligament causes a decrement in this sense, negatively affecting the postural stability of the individual.[18] In an injured population, injury to specific structures such as ligaments or tendons may impact postural stability due to a reduction or lack of somatosensory input. Injury to the structures during the primary injury in addition to the secondary injury caused by fluid and molecules moved to the site of injury to initiate the healing process, can damage the ability of the nerves to properly detect and send sensory input to the central nervous system.[58]

Fu et al[30] investigated ankle joint proprioception and postural stability in basketball players with bilateral ankle sprains. The study included 20 healthy male basketball players and 19 male basketball players with a history of bilateral lateral ankle sprains in the past 2 years. Examinations included the SOT and passive ankle joint repositioning. A significant increase in postural sway and repositioning errors were demonstrated in the bilateral ankle sprain group. The authors suggest that mechanoreceptors are damaged during an ankle sprain, therefore decreasing somatosensory input from the ankle joint. This leads to a decrease in postural stability, as demonstrated specifically in conditions one and two of the SOT, which isolate somatosensory input in order to maintain postural stability. The study used the mean sway angle as the measure of comparison. On condition one, healthy controls had a mean sway angle of 0.7 ± 0.1 compared to the ankle sprain group with a mean of 0.8 ± 0.2 ($p < .05$). Similarly, on condition two, healthy controls had a mean of 0.9 ± 0.2 compared to the ankle sprain group with a mean of 1.1 ± 0.3 ($p < .05$).[30]

Simmons et al[97] also demonstrated that decreased somatosensory input in the foot resulted in a significant decrease in postural stability. The study investigated the effect of bilateral cutaneous sensory deficit in the feet of individuals with diabetes as compared to those with diabetes who had no sensory deficits and were matched with healthy controls on weight, gender and age. All six tests of the SOT displayed significant increase in postural sway in the sensory deficit group compared to the control group due to the decrease in somatosensory input, which is a valuable sensory input for postural stability.

Somatosensory input plays a significant role in postural stability. When damage occurs to the nervous, muscular or ligamentous structure of the ankle and foot, somatosensory input decreases, which has a significant effect on postural stability. This deficit is demonstrated significantly in conditions of the SOT in which somatosensory input is isolated. This isolation occurs by keeping the platform stable, providing accurate somatosensory input to the subject, while altering the visual input.[100]

2.2.2 The Visual System

The eye is comprised of many parts, each with a specialized purpose. The cornea is the clear front of the eye, which transmits and focuses light as it enters the eye. The iris is the colored portion of the eye and is involved in regulating the quantity of light entering the eye. The pupil is the dark center of the eye and it regulates how much light is allowed into the eye by dilating and constricting. The lens is posterior to the cornea and focuses light onto the retina. The retina is a layer of nerves that lines the back of the eye. It senses light and relays information to the optic nerve, which connects the eye to the brain. Visual information regarding how the individual is oriented relative to other objects, especially vertical and horizontal objects, is utilized to make motor responses and maintain postural stability.[86]

Postural stability decreases when visual input is impaired or lost, especially during dynamic tasks and on foam surfaces, as visual input is crucial for maintaining postural stability.[102] Additionally, following concussion, postural stability significantly decreases in conditions in which the eyes are closed.[90] Ray et al[88] studied the effect of vision loss on balance. The study compared the SOT results of visually impaired individuals and those with full vision. The results showed significant decline in scores in the vision loss group as compared to the full vision group on condition four (sway support, eyes open) and conditions six (sway support, sway surround). For condition five, in which eyes are closed with sway support, the groups had similar scores. This similarity indicates that those with visual impairment are not able to fully compensate because the vestibular and somatosensory systems are functioning similarly in both groups when vision is removed. This study demonstrates the importance of visual input and the inability of the body to fully compensate for the loss of vision with other systems to maintain balance.

Accurate visual input is necessary for postural stability. When there is a pattern of inaccurate visual input, the brain compensates by diminishing its reliance on visual input. Nachum et al[69] investigated the effect of mal de debarquement (MD) on postural stability. Mal de debarquement is a sensation of swinging, swaying, and disequilibrium after exposure to motion. As opposed to motion sickness, symptoms are present after disembarking the motion source. Individuals susceptible to MD were compared to those not susceptible using the SOT before and immediately following sailing. It is theorized that when on a ship, vestibular and visual information are unreliable due to the movement on the water and the lack of accurate visual cues when below deck. Due to this conflict, there is a sensory rearrangement in which the motion paradigms, relative dependence on each sensory input, are changed. After disembarking, the individual no longer has the appropriate motion paradigm for land and therefore experiences disequilibrium. Those with MD demonstrated a significant increase in postural sway, specifically in conditions three, four, and five of the SOT after sailing. This demonstrates that, through higher-level sensory organization, the individuals with MD minimized the influence of visual and vestibular input on postural stability, demonstrating the importance of these inputs on postural stability.

Stabilization upon landing from a jump requires many of the same mechanisms as postural stability in quiet stance, as the individual must use sensory information to make corrective changes and maintain postural stability. Chu et al[20] studied the effect of vision removal on lower extremity kinematics during a two-legged drop landing task. Significant differences were found between the groups with and without vision. With no vision, individuals landed in increased hip abduction at initial contact, decreased maximum knee flexion and had increase in maximum vertical ground reaction force, which is a less advantageous landing position, placing the individual at a potentially higher risk of injury.[96] The author suggests that the changes in biomechanics may lead to increased injury when vision is removed.

Visual input is crucial for postural stability. In a population that has had visual impairment for a significant period of time, postural stability continues to demonstrate decrements.[88] Despite some ability to compensate for decreased visual input with sensory information from the other systems, loss of vision continues to cause decreased postural stability, demonstrating the importance of this specific sense to postural stability. The visual system functions in conjunction with the vestibular system to orient the individual to the horizon and therefore determines sway and corrections that are necessary to maintain postural stability.[88]

2.2.3 The Vestibular System

Sensory information from the vestibular system detects the movement of the head in space and is crucial for postural stability. The peripheral vestibular system is located in the petrous portion of the temporal bone and is composed of five distinct organs. The three semicircular canals detect angular accelerations, whereas the two otolith organs detect linear accelerations. The vestibular-cochlear nerve innervates the vestibular nuclei. The vestibular nucleus of interest for postural stability is the lateral nucleus, which is responsible for the vestibulospinal reflexes, responding to vestibular input to maintain upright posture. Individuals with vestibular deficits, bilaterally or unilaterally, present with decreased postural stability, especially when somatosensory and visual inputs are conflicting or compromised.[56]

Nashner et al[73] studied the effects of head movement, specifically cervical flexion and extension, on postural stability. During cervical flexion and extension, somatosensory and visual inputs for postural stability have the potential to be disrupted, forcing the individual to rely on the vestibular input. The CNS is required to process the input from the three systems and determine the reliable sensory information in order to use appropriate sensory information to dictate motor responses. Individuals with severely impaired vestibular systems had decreased ability to maintain postural stability when deprived of support and visual inputs. Those with mild vestibular dysfunction were able to maintain postural stability in the absence of adequate support or visual inputs, but were destabilized when conflicting inputs were introduced. Nashner argues that the vestibular input provides the reference against which conflicting sensory input is compared. Similarly, Buckley et al[15] determined that, in an elderly population, anterior-posterior (AP) sway is increased when the head is in a flexed or extended position compared to AP sway with the head in neutral.

The vestibular system is an important component of postural stability and is often impaired following concussion. An estimated 20.8% to 58% of individuals who have suffered a closed head or whiplash injury present with vertigo or dizziness, which often presents between seven and ten days following the injury and can persist for months or years.[35, 50, 94] Vestibular input is necessary for postural stability and is proposed to be the source against which sensory organization is based. The loss of adequate vestibular input leads to decreased postural stability, and as the system that often heals the slowest after concussion, it is imperative that concussion assessment adequately detect damage to the vestibular system.

2.2.4 The Integration of Systems

All three sensory inputs – somatosensory, visual and vestibular – are necessary for postural stability. Individual senses and the combination of the three senses do not provide enough information to maintain postural stability in all situations. The central nervous system, therefore, must compare and integrate the information from each sensory input system in order to maintain postural stability. This integration process has been termed sensory organization.[70] The body of literature related to integration of systems is focused on the impaired populations rather than a healthy population. As a result, the studies presented are not of the population of interest for this study, but demonstrate the importance of the integration of sensory systems.

Hirabayshi et al[41] investigated the development of sensory organization using dynamic posturography. A total of 112 children were involved in the study, divided into age groups. Somatosensory function developed early and was comparable to adult levels at the age of 3-4 years. Visual function was the next to develop, reaching adult levels at 15 years of age.

Vestibular function was the latest to develop, continuing to demonstrate significant difference from adult vestibular function at 15 years of age. When standing on a stable surface, in a well-practiced situation, somatosensory input is the primary source for maintaining balance. Visual input is important in a novel situation or with altered somatosensory input. Finally, vestibular input is used for reference and is important to resolve inter-sensory conflict. The central nervous system, when acting effectively, suppresses input that is not in agreement with vestibular input. For example, when an individual is standing on an unstable surface, the central nervous system suppresses the somatosensory input and relies more heavily on the vestibular input.

Oliveira et al[74] investigated sensory organization deficits in a stroke population compared to a healthy population. The study demonstrated that those with sensory organization deficits have increased difficulty maintaining postural stability in conditions with altered somatosensory information and in conditions in which there are sensory conflicts. No statistically significant differences were seen in SOT condition one (study group = 94.7, control group = 94.7, p=0.63), but statistically significant differences were seen in condition three (study group = 91.3, control group = 94.0, p=0.05) condition four (study group = 74.6, control group = 82.9, p=0.02), condition five (study group = 52.9, control group = 65.3, p=0.02) and condition six (study group = 55.2, control group = 64.5, p=0.05).[74] This supports the theory that when sensory integration is affected –whether by stroke, concussion or another source – conflicting or absent sensory input is not appropriately integrated and adjusted for by the central nervous system. This lack of integration results in decreased postural stability.

Cherng et al[19] compared the standing stability of 20 children, ages 4-6, with developmental coordination disorder (DCD) to determine the influence of sensory organization and each individual sensory input. Results indicated significantly decreased standing stability in the children with DCD in all conditions (eyes open, closed, unreliable vision mixed with fixed or compliant foot support). Standing stability showed the greatest decline when the somatosensory input was unreliable (compliant foot support). The conclusion is that children with DCD have greater difficulty managing altered sensory inputs, which requires sensory organization, as opposed to deficits in individual sensory input systems. It has been suggested that altered sensory integration has an impact on postural stability following concussion.[38] This indicates that those with concussion could demonstrate decreased postural stability when somatosensory input is unreliable.

Wade et al[106] studied the effect of walking on irregular surfaces in a railroad worker population. This study was conducted based on previous research demonstrating a relationship between walking on irregular surfaces and postural instability. The study included 16 healthy male adults who walked on ballast for 0-240 minutes, then were tested using the NeuroCom Equitest System. The researchers then analyzed sway velocity and root-mean-square sway in the medial-lateral and anterior-posterior directions. Walking on ballast resulted in increased sway in each SOT condition. After long-term inaccurate somatosensory input, the sensory integration system decreases the reliance on somatosensory input as compared to visual and vestibular. The investigators concluded that walking on an irregular surface for an extended period of time impacts postural stability due to alteration in sensory integration involving somatosensory input.[106]

It has been demonstrated that athletes who have sustained a concussion demonstrate difficulty with the integration of sensory information, leading to the inability to process altered sensory information.[38] When information from one sensory system is unreliable or absent, the individual, due to the sensory integration impairment, is unable to appropriately alter the use of information from the other sensory systems to compensation for the alteration. For example, if the individual has impairment to the visual system following concussion, he may not be able to appropriately reweight the use of the vestibular and somatosensory systems in order to compensation for the altered visual sense. This can ultimately lead to decreased postural stability.[38]

2.3 POSTURAL STABILITY TESTING

Postural stability was being assessed prior to the use of postural stability tool as a component of a concussion evaluation. As early as 1853, Moritz Heinrich Romberg was examining postural stability and stated, “if the patient is told to shut his eyes while in erect posture, he immediately begins to move from side to side and the oscillations soon attain such a pitch that unless supported, he falls to the ground.” The earliest studies of postural stability did not require technology or quantitative analysis, but simply observation. Progress continues to be made in the field of postural stability assessment. Testing mechanisms can be subdivided into clinical and laboratory measures. Common clinical measures of postural stability include the Star Excursion Balance Test (SEBT) and the Balance Error Scoring System (BESS). Laboratory measures include, but are not limited to, force plate testing, the Biodex and the NeuroCom Equitest.

2.3.1 Clinical (Field) Measures of Postural Stability

Clinical measures of postural stability are often used on the sideline or in the athletic training facility to examine an individual's postural stability. This information can be used to determine the extent of an injury and the effect that the injury has had on the postural stability of an individual. Component tasks of the tests can also be used as exercises for rehabilitation and retraining of postural stability and neuromuscular control. Additionally, clinical postural stability testing can be used in return to play decisions to ensure that an athlete has returned to baseline measures of postural stability measured prior to an injury.

The SEBT is a clinical examination of postural stability used for evaluation of postural stability before and after treatment or rehabilitation and for rehabilitation of lower extremity injury as a tool to increase postural stability and neuromuscular control.[40] It has also been used to prospectively identify individuals at an increased risk of sustaining lower extremity injury.[82] The individual stands on a single leg in the center of star on the ground with eight lines, each 45 degrees from the other, surrounding the individual. The individual is instructed to reach as far as possible along each line with the non-stance limb. The distance from the center of each point reached is measured. Testing often involves multiple attempts at each angle and the furthest point or the average point is ultimately recorded. The movement involves a single leg squat at multiple angles to test the ability of the individual to maintain postural stability in a variety of positions, with movement. It requires range of motion at multiple joints, including dorsiflexion of the stance ankle and flexion of the stance knee and hip. The individual must also have adequate strength, proprioception and neuromuscular control in order to properly and successfully complete the test.[75]

The BESS test is a simple, inexpensive evaluation of postural stability that is often used in the athletic training facility or on the sideline. The only supply necessary to conduct the test is a foam pad to alter the support surface. Due to its simplicity and ease of administration, it is commonly used in evaluation of postural stability as a component of concussion assessment. The BESS involves two support surfaces and three stances, leading to six total conditions. The support surfaces are firm and foam and are combined with double leg stance, single leg stance and tandem stance. Scoring is based on the number of errors observed by the examiner during a 20 second trial. Errors are opening eyes, lifting hands off hips, stepping, stumbling or falling out of position, lifting forefoot or heel, abducting hip by more than 30° or failing to return to testing position in more than five seconds.[5]

2.3.2 Laboratory Measures of Postural Stability

Laboratory postural stability measures are often used to determine the effects of independent variables on postural stability. Static postural stability is often tested on a force plate using single leg stance. When testing using a force plate, an individual is often asked to stand on a single leg with hands on hips for a specific period of time. The individual is instructed to stand with as little sway or movement as possible. This test can be done with eyes open or closed. Variation can be added, for example, by having the individual jump onto the force plate and measuring the time to stabilization. A variety of variables can be collected during this assessment. Ground reaction forces (GRF) are the forces exerted on the subject by the support surface. The center of pressure (COP) is the net location of the vertical GRF. The center of mass (COM) is the net location of mass on the force plate. Sway is defined as the total path length of the COP throughout the test trial. Based on these variables, standard deviation of x and y COP, average sway velocity, total sway and x and y COP range can be determined.[25, 95] For each of these variables, an increased value is indicative of decreased postural stability.

The Biodex Balance Assessment is a quantitative clinical assessment often used for baseline and post-injury testing for comparison purposes. Postural sway is quantified in four conditions; eyes open with firm surface, eyes closed with firm surface, eyes open with unstable surface, and eyes closed with unstable surface. Postural stability output includes scores and standard deviations of the overall stability index, anterior/posterior (AP) index, medial/lateral (ML) index, percent time in zone (circular zones radiating from the center), and percent time in quadrant. Each variable is presented for the right and left leg. The stability index is the average position from center, rather than the sway. The AP and ML indices are the average position in the AP and ML directions, respectively.

The NeuroCom SOT is a laboratory-based assessment that uses rotating force plates and visual surround in order to assess individual components of postural stability.[100] It is most commonly used in geriatric or stroke patients to assess the functionality of each sensory system of postural stability. The test is beginning to be used in concussion patients, but due to the expense of the system and the space necessary, it is not commonly used in a clinical setting. The NeuroCom SOT assesses composite postural stability in addition to the postural stability of the subject related to the vestibular, somatosensory and visual systems individually.[100] It completes this assessment via six conditions of increasing difficulty in which visual and somatosensory input are removed or made to be unreliable. Table 1 indicates the visual and somatosensory input for each of the six conditions in addition to what sensory system is being challenged by the condition.

Table 1: NeuroCom SOT Conditions[95]

Condition	Vision	Surface	Disadvantaged	Using
1	Eyes open	Fixed		Somatosensory
2	Eyes closed	Fixed	Vision	Somatosensory
3	Sway	Fixed	Vision	Somatosensory
4	Eyes open	Sway	Somatosensory	Vision
5	Eyes closed	Sway	Somatosensory and vision	Vestibular
6	Sway	Sway	Somatosensory and vision	Vestibular

2.4 METHODOLOGICAL CONSIDERATIONS

The rationales for the methodology for this study will be presented in this section. The purpose of this study is to determine the relationship between the BESS and the laboratory based NeuroCom SOT. The association between the overall BESS score and the SOT composite and component scores will be determined in addition to the association between the kinetic data from each test. Full description of the procedures in this study will be described in Chapter 3.

2.4.1 The Balance Error Scoring System

The BESS was chosen because it is the most commonly used sideline evaluation of postural stability when assessing concussion. It has also been recommended as a good concussion assessment tool, with good reliability and validity by The National Athletic Trainers Association (NATA).[36] Due to this recommendation and the high frequency with which it is used in practice, it is imperative that this test assesses all components of postural stability. Although the NATA presents research supporting good reliability and validity, research has also been conducted presenting possible weaknesses of the study such as a learning effect and a ceiling effect. The ceiling effect could be due to the test being too simple or due to a lack of vestibular challenge. To account for possible confounding variables, healthy participants were used and instructed to maintain adequate hydration and have a typical night of sleep prior to testing.

The NATA position statement on the management of sport related concussion states that the BESS has demonstrated good test-retest reliability in addition to good concurrent validity compared to laboratory force plate measures.[36] Finnoff et al[27] investigated the intrarater and interrater reliability of the BESS. They tested three scorers using videotape of 30 consecutive individuals performing the six stances of the BESS. The scorers viewed and scored the same videotape one week later. The interrater reliability ICC was 0.57 and ranged from 0.44 to 0.83 for individual stances. The intrarater reliability ICC was 0.74 and ranged from 0.50 to 0.88 for individual stances. The author concludes that subcategories of the BESS have adequate reliability for use in clinical practice, but the overall BESS score is not reliable. When assessing concussion and making return to play decisions based on a clinical assessment, it is vital that the assessment be reliable.

Broglio et al[13] conducted a test-retest generalizability study to determine the test-retest reliability of the BESS and to provide recommendations concerning learning effects. The study was conducted using 48 healthy adults. Each subject completed five BESS trials on two testing days, separated by 50 days. The test-retest reliability was calculated to be G=0.64. Reliability was considered clinically acceptable (>0.80) when three BESS trials were administered in a single session, or two trials were conducted at different time points. Mulligan et al[68] studied the learned response to the BESS, based on the premise that the baseline testing is the benchmark to which the post-injury assessments are compared. If there is a learning effect, the results of the post-injury assessment could indicate a deceptively low error score, allowing the athlete to return to participation prior to full recovery. This study recruited healthy, college-aged adults who were divided into three groups. Group 1 was tested at baseline and four weeks. Groups 2 and 3 were also tested at one week and two weeks, respectively. The results of this study indicate that the BESS may not be able to assess balance following a concussion due to a learning effect that did not extinguish after four weeks. Due to the small change in BESS score present with postural stability deficits, the effectiveness of the BESS may be limited. Results from each study support a learning effect associated with repeated exposures to the BESS, creating a possible ceiling effect of the BESS.

King et al[49] conducted a study to determine if alterations to the BESS would improve the ability to classify an injured population as opposed to a healthy population. The study used an accelerator and gyroscope to quantify body sway during the BESS in individuals with a recent history of concussion who continued to seek treatment for imbalance and dizziness (n=13) and in a healthy population (n=13). The alterations tested were the modified BESS (mBESS), which utilizes the three standard stances on a firm surface only, and instrumentation with an accelerometer and gyroscope. Scores from the BESS and mBESS demonstrated no significant differences between groups. Scores from the instrumented BESS did demonstrate significant differences between groups, indicating that the instrumented BESS may be more sensitive to balance deficits and presenting a possible ceiling effect of the BESS.

In contrast to the findings of King et al,[49] Furman et al[31] compared a balance accelerometer measure to the BESS in an adolescent sport population. Contrary to the expected results, the accelerometer measure was not better at discriminating between a healthy and concussed population compared to the BESS, indicating that the BESS is an effective tool for discriminating between concussed and healthy individuals.

Bell et al[5] performed a systematic review of the BESS, stating that the BESS was being used outside the scope of its original purpose. In a study of 18 male NCAA Division I athletes, intertester reliability with three testers was classified as good, with ICCs ranging from 0.78-0.96.[83] The BESS was demonstrated to have moderate to high criterion validity depending on testing condition, with difficult stances having better agreement. The final conclusion is that the BESS is valid to detect large balance deficits, but may not be valid when differences in balance are subtle in nature.

The BESS has been shown to lack sensitivity for subtle deficits and to suffer from learning,[13, 68] practice[104] and fatigue[109] effects. The Balance Error Scoring System has demonstrated weakness, specifically in sensitivity, tested to be 0.34 immediately following injury, and decreasing to 0.16 to 0.24, 1 to 3 days post-injury.[61] Additionally, because vestibular dysfunction is one of the most significant delayed complication following head trauma,[43] it is imperative that balance assessments used in the diagnosis, treatment and return-to-play decisions following concussion effectively assess the function of the vestibular system.

In addition to counting errors as is traditional in a sideline assessment, this study will use a Kistler force plate (Kistler Corp., Amherst, NY) with data collected at a frequency of 200 Hz. Prior research, such as that by Fox et al[28] that studied the effect of fatigue on BESS performance, has effectively performed the BESS on a force plate. Utilization of a force plate allows collecting of vertical ground reaction force (vGRF) and center of pressure (COP) data. For the purposes of this study, vGRF and COP data will be used to calculate SDvGRF and total sway, which will be analyzed to determine the relationship between the BESS and the NeuroCom.

2.4.2 The NeuroCom Sensory Organization Test

The NeuroCom SOT will be utilized for this study due to the ability of the test to isolate the individual sensory input systems. The vestibular system is often the slowest to recover from concussion; therefore comparing the BESS to each individual sensory system ratio is valuable for clinical decision-making regarding concussion diagnosis and return to play decisions. It was also selected due to the ability to extract raw data from the system for direct comparison with force plate data collected during the BESS. Test-retest reliability has been demonstrated to be fair to good, with an ICC of 0.67 for the composite score and ICC=0.35-0.79 for the individual conditions.[110] Although confounding variables have not been specifically studied related to the SOT, possible confounding variables will be accounted for in the same manor as with the BESS, as these confounding variables are likely to affect balance during any assessment.

Reliability and validity of the NeuroCom SOT has not been reported in a healthy population. Due to the frequent use of the SOT in geriatric and stroke populations, reliability has been reported for specific populations, but has not been reported in a healthy, physically active population. Although reliability has not been reported, the SOT has been compared to other postural stability assessment tools. Broglio et al[12] determined that postural stability decreases with increased condition difficulty during the SOT. When compared to a more challenging posturography device, a possible ceiling effect of the SOT was made evident, as the results of the SOT and the PROPRIO test diverged as the difficulty of each test increased. Although there is a possible ceiling effect of the SOT, it is thought to be more challenging than the BESS test. The SOT has been shown to correlate with other balance assessments such as the Balance Rehabilitation Unit (BRU)[2] and the PROPRIO test.[12]

Pickerill et al[81] sought to compare postural stability measures between and within devices with the purpose of establishing concurrent and construct validity. A secondary objective was to determine the test-retest reliability for limits of stability (LOS) measures of the NeuroCom and the Biodex Balance System. The study used 23 healthy subjects, each were assessed using the NeuroCom and the Biodex Balance System one week apart. Each test involves the individual transferring their COG toward targets located at 45-degree intervals around the body's COG. Results of test-retest reliability ranged from ICC=0.82 to ICC=0.48, indicating high to low reliability across the different LOS measures. Pearson correlation coefficients indicated significant relationship between and within the NeuroCom and Biodex examinations. Based on the variability of reliability, the authors suggest that researchers establish their own reliability of LOS examinations. Additionally, due to the lack of concurrent and construct validity, the authors propose that the NeuroCom LOS and Biodex Balance System assess different components of postural stability.[81]

Faraldo-Garcia et al[26] sought to determine the influence of gender on SOT and LOS in a healthy population. Results showed that males demonstrated better postural stability during condition one (eyes open and stable support). In contrast, females demonstrated better postural stability during condition three (sway surround and stable support). The LOS test demonstrated that males have a faster reaction time than females in postural changes, however this did not affect the trajectory and directional control, which remained the same between genders.

Similar to the BESS, a possible learning effect was proposed related to the SOT. Wrisley et al[110] studied the learning effect associated with multiple administrations of the SOT with the secondary purpose of beginning to establish clinical meaningful change scores for the SOT. Subjects were tested five times over a two-week period in addition to one month following initial testing. Test-retest reliability was fair to good, with an ICC of 0.67 for the composite score and ICC=0.35-0.79 for the individual conditions. Analysis of the repeated-measures showed an increase in the composite and condition four, five and six equilibrium scores over the five sessions, with a plateau at the third session. The authors also concluded that a composite change score greater than eight would indicate changes due to treatment or rehabilitation. Future studies are needed to determine what a significant change in score due to concussion or concussion recovery.

For the purposes of this study, the NeuroCom Equitest system will be used to conduct the Sensory Organization Test. The clinical outcome scores calculated by the NeuroCom include the composite score, visual component (VIS), vestibular component (VEST) and somatosensory component (SOM). In addition to the analysis of the clinical outcome scores, raw force plate data from the NeuroCom will be extracted to calculate SDvGRF and total sway. These variables will be analyzed in relation to the SDvGRF and total sway from the BESS testing.

3.0 METHODOLOGY

This study employed a cross sectional study design to examine the concurrent validity of the BESS compared to the composite, visual, somatosensory and vestibular scores of the NeuroCom SOT. A correlational design was selected to analyze the strength and direction of the association between the outcome of the BESS test and the composite, visual, somatosensory and vestibular score outcomes of the NeuroCom SOT in addition to the correlation between the kinetic force plate data from the BESS and the SOT.

3.1 SUBJECT RECRUITMENT

Participants were recruited using Institutional Review Board approved recruitment material. Interested participants called the NMRL and were assessed for eligibility through the use of a screening questionnaire and provided the opportunity to voluntarily enroll based on these results.

3.2 INCLUSION AND EXCLUSION CRITERIA

In order to be considered a qualified participant, individuals were required to meet the following inclusion criteria; physically active men and women 18-35 years of age, of good health. No exclusion criteria are based upon sex, race or ethnicity. Physically active was defined as a score of 5 or higher on the self-reported Tegner Activity Level Scale. Participants were to be free of lower extremity injury in the last six months. Participants were excluded if they had a history of lower extremity surgery or fracture. Participants were also excluded if they have low back pain or a history of surgery to the low back. Participants were excluded if they have a history of concussion or vestibular dysfunction. Those who were taking medication known to affect balance or postural stability were excluded from participation.

3.3 POWER ANALYSIS

Using G*Power 3.1 sample size software, a sample size of 19 subjects was needed to achieve 81.4% power to detect a difference of -0.60 between the null hypothesis correlation of 0.00 and the alternative hypothesis correlation of 0.60 using a two-sided hypothesis test with a significance level of 0.05. To account for 10% data loss due to attrition a total of N=21 subjects are needed for study enrollment.

3.4 INSTRUMENTATION

The BESS test was performed on a force plate (Kistler 9286A, Amherst, NY) with and without an Airex Foam Pad. Data was sampled at a frequency of 200Hz and processed with an 8^{th} order low-pass Butterworth filter with a cut-off frequency of 10 Hz. The orientation of the force plate was entered into the software package so that data calculations were based on the orientation within the global system with respect to the origin. The orientation of the force plate local coordinate system was positioned so that the subject was facing the positive (Y) direction. The positive (X) direction was oriented from the subject's left to the subject's right. The origin of the global coordinate system was located at the corner of the force plate.

The NeuroCom Equitest System (NeuroCom International Inc., Clackamas, OR) was utilized for this study. The NeuroCom Equitest is a computerized dynamic posturography tool developed initially for the assessment of the effects of space flight on vestibular function in astronauts. The system utilizes two parallel force plates, each with an anterior and posterior force transducer, resulting in a total of four force transducers. Using these force transducers, the NeuroCom is able to detect ground reaction forces and AP sway, which are utilized to calculate the outcome variables of the device. The sampling frequency of the NeuroCom is 200Hz.

3.5 TESTING PROCEDURES

Prior to official enrollment, potential participants were asked to sign an informed consent form after reading through the study procedures and having the opportunity to ask any questions regarding the study.

Demographic and anthropometric measures were comprised of height, mass, sex, date of birth and leg dominance. Height was measured using a wall mounted analogue stadiometer. Mass was measured using a calibrated digital scale. Leg dominance was defined as the leg with which the participant would prefer to kick a soccer ball for distance and accuracy, complementing previous research studies.[76, 92]

Randomization for testing order was determined using Latin Squares to ensure that an equal number of subjects start with each task; the NeuroCom SOT or the BESS.

3.5.1 Balance Error Scoring System

The BESS was performed on a Kistler force plate in a laboratory setting. The sensitivity information matrix has previously been entered into the software; therefore no calibration was necessary. Prior to each of the first three stances, the force plate was zeroed to ensure validity. Prior to each of the stances involving the Airex foam pad, the force plate was zeroed with the Airex foam pad placed directly on top of it. For the tandem stances, on both firm and foam surface, the individual was standing diagonally on the force plate.

The BESS test was described to the participants including stances, surfaces and errors to be counted. Each trial was held for 20 seconds with the eyes closed and hands placed on iliac crests. Participants were instructed to stand with eyes closed, hands on iliac crests and remain as motionless as possible. They were instructed to return to the testing position as quickly as possible if they were to lose their balance. Participants were instructed to touch down on the force plate if possible, but due to the magnitude of errors on later conditions of the BESS, trials were only discarded and retested if the participant left the force plate entirely. If a touch down occurred off the force plate, but the stance foot remained on the force plate, the trial was included. Each trial was separated by 10 to 20 seconds. Conditions were separated by two minutes.

Conditions were completed in the standard order of testing used in the clinical setting. In testing order, stances include bilateral stance, nondominant unilateral stance and tandem stance in a heel to toe fashion with dominant foot in front. Each stance was performed on a firm surface followed by an Airex foam pad.

Errors included opening eyes, lifting hands off hips, stepping, stumbling or falling out of position, lifting forefoot or heel, abducting hip by more than 30° or failing to return to testing position in more than five seconds. If multiple errors occurred simultaneously, it was counted as one error. The entire procedure was repeated and scores for each stance averaged. After each participant, the foam was flipped to the opposite side to prevent wearing patterns.

Moghadam et al[67] demonstrated good test-retest reliability of COP measures on a force plate using a foam pad for AP SD amplitude (ICC=0.78), AP SD velocity (ICC=0.65), AP phase plane (ICC=0.67), ML SD amplitude (ICC=0.68), ML SD of velocity (ICC=0.86), ML phase plane (ICC=0.84), mean COP velocity (ICC=0.78), COP area (ICC=0.67) and total phase plane (ICC=0.78). Static force plate reliability reported by Goldie et al[33] demonstrated poor to moderate reliability for vertical GRF (ICC=0.49), AP force (ICC=0.31), ML force (ICC=0.41), AP COP (ICC=0.12), and ML COP (ICC=0.38).

Based on a systematic review of the BESS by Bell et al,[11] intratester reliability of the total BESS score ranged from moderate to good with an ICC of 0.60[45] to 0.92[24] and the reliability of the individual BESS scores ranged from moderate to good, 0.50[27] to 0.98.[104] Intertester reliability for the total BESS score ranged from 0.57[27] to 0.85[64] and ranged from 0.44[27] to 0.96[91] for individual stance scores. Test-retest reliability has been found to be moderate in youth participants (0.70) and young adult (0.64) populations.[103] Test-retest reliability improves when the BESS is administered three times and an average score is calculated.[5]

3.5.2 NeuroCom Sensory Organization Test

For the SOT testing, the NeuroCom Equitest was powered on and the sensory organization test was selected. A new subject was input into the system using the demographic data collected and a subject ID number. Height and date of birth were entered into the system. The participant was asked to step onto the platform with one foot on each force platform, facing the screen. The feet of the participant were placed according to the methods described by Natus Balance & Mobility.[100] The medial malleolus of each foot was lined up with the bold horizontal line on the force platforms. The midline of the calcaneus was then lined up with the appropriate vertical line, as determined by the software based on participant height. The examiner then held the rear-feet of the participant and allowed the participant to adjust the forefeet to a comfortable position.

Three trials of each of the six conditions were completed as instructed by the software. The participant was permitted to open eyes and relax between trials, but was asked to keep their feet in the proper position. In each condition, the participant was instructed to stand still with as little sway as possible for a 20 second trial. During the first condition, the participant stood with eyes open on a fixed surface, testing primarily the somatosensory system. The second condition also tests the somatosensory system as the participant stood on a fixed surface with eyes closed. The third condition tests the somatosensory system while the participant stood on a fixed surface with a sway surround. The sway of the surround is based on the sway of the individual. As the individual sways forward on the force plate, the surround tilts forward. The fourth condition challenges the visual system, as the participant stood with eyes open while the force platform sways. As with the surround, the force platform sways based on the sway of the individual. As the individual sways forward, the force platform tilts forward. The fifth and sixth condition test the vestibular system. In the fifth condition, the individual stood with eyes closed as the platform sways. In the sixth condition, the surround and the platform sway.

NeuroCom SOT output includes an overall composite equilibrium score representing the ability of the participant to remain within the theoretical limits of stability, defined as 12.5° in the sagittal plane. If the sway of the participant during testing is low, the value of sway range will be closer to zero, resulting in an equilibrium score closer to 100. NeuroCom SOT output also includes sensory analysis of the three individual sensory systems, center of gravity alignment and normative ranges. The equilibrium score in addition to the visual, somatosensory and vestibular individual scores were used for analysis in this study (Table 2). Scores range from 0 to 100. A score of 0 indicates the individual fell, and a score of 100 indicates no movement throughout the entirety of the test.

Teel et al[101] report ICC reliability measures for SOT condition one (0.611), condition three (0.345), condition four (0.845) and condition six (0.514). Wrisley et al[110] report fair to good test-retest reliability for the composite score (ICC=0.67) and the equilibrium scores for each condition (ICC= 0.35-0.79) of the SOT when subjects were tested five times over a two-week period in addition to a one-month follow up. Dickin et al[22, 23] demonstrated moderate to good test-retest reliability for the SOT when tested on a single testing day as well as when tested on separate days. Reliability data from pilot testing within the Neuromuscular Research Laboratory is available in Table 3.

Table 2: NeuroCom SOT outcome variable formulas

Variable	Formula
Equilibrium Score	$[12.5 - (\theta_{max}(ant) - \theta_{max}(post))]/12.5$
SOM	$\frac{\text{Condition 2}}{\text{Condition 1}}$
VIS	$\frac{\text{Condition 4}}{\text{Condition 1}}$
VEST	$\frac{\text{Condition 5}}{\text{Condition 1}}$

Table 3: NeuroCom SOT reliability

Score	Reliability (ICC)
Equilibrium	0.825
SOM	-0.95
VIS	0.582
VEST	0.80

3.6 DATA REDUCTION

During testing, trials in which touch-downs occurred outside the force plate were included in the analysis. If the participant left the force plate entirely, and no longer had a stance foot on the force plate, the trial was discarded and retested. Force plate data for the BESS was passed through a zero-lag 4th order low pass Butterworth filter with a 20 Hz cutoff frequency and processed using a custom MATLAB (v7.0.4, Natick, MA) script file.[51] Utilization of a force plate allows for the collection and calculation of standard deviation of vertical ground reaction force (SDvGRF) and total sway. These two force plate variables were averaged from the three trials of each condition.

The composite and equilibrium scores were exported from the NeuroCom as .sum files and saved to the lab network drive. The .sum files were then uploaded into excel using the 'Text Import Wizard'. This was opened and saved as an excel file containing the component and composite scores for each subject. Data was then imported to SPSS for analysis. Reliability information for the SOT is presented in Table 3.

Raw force plate data from the NeuroCom Balance Master was exported as a .txt file with left forefoot (lb), right rearfoot (lb), shear (lb), left rearfoot (lb), right forefoot (lb), center of force in the x and y plane (in), and center of gravity in the x and y planes (in) variables with 2000 data points per variable per condition trial. There were three trials for each of the six SOT conditions. Files were checked to ensure that all data points were present for each subject. If all data points were not present, the data was discarded. The .txt files were processed with a custom MatLab script in order to create an excel output file with standard deviation of the vertical ground reaction force (SDvGRF) and total sway (TotSway) variables for each of the six conditions. The equations for the outcome variables can be reviewed in Table 4. The output data was then imported to SPSS for analysis. The raw force plate data from the NeuroCom was used in comparison with the same variables obtained from the force plate data from the BESS testing. Total sway and SDvGRF were chosen in order to analyze data in regards to both horizontal oscillations and vertical oscillations[47] respectively. Sway during the BESS is primarily in the ML direction, whereas sway during the SOT is in the AP direction, therefore total sway allows for comparison of sway regardless of the direction.

Table 4: Outcome variable formulas

Variable	Formula
SDvGRF	SD Σ GRFz
Total Sway	$\Sigma\ [\sqrt{}(COPx_2\text{-}COPx_1)^2 + (COPy_2\text{-}COPy_1)^2\ ]/1000$

3.7 DATA ANALYSIS

Descriptive statistics, such as group means and standard deviations were calculated for the each variable. Normality of the data was assessed using a Sharpiro-Wilk test for normality. If assumptions of normality were met, Pearson correlation coefficients were calculated. If assumptions of normality were not met, Spearman correlation coefficients were calculated. Correlations were also utilized to analyze the association between the standard deviation of the vertical ground reaction force and total sway during each of the six conditions of the BESS test and the SOT. A correlation analysis was used to determine if a significant association exists between the overall BESS score and the composite, visual, vestibular and somatosensory scores from the NeuroCom SOT. A correlation was also used to determine if a significant association exists between the error scores on each condition of the BESS and the component and composite scores of the SOT. Additionally, a correlation analysis was used to determine if a significant association exists between the raw force plate data from the NeuroCom and the force plate data collected during the BESS test, as the force plate data will potentially be more sensitive to postural stability deficits throughout the various conditions of the two assessments as compared to the overall error score, SOT equilibrium score and SOT composite scores. Alpha was set at 0.05 *a priori*.

4.0 RESULTS

The purpose of this study was to investigate the relationship between the Balance Error Scoring System and the NeuroCom Sensory Organization Test clinical outcome measures and kinetic force plate data.

4.1 SUBJECTS

4.1.1 Demographic Data

A total of 21 subjects expressed interest in study participation, and 21 met all eligibility criteria outlined in the initial phone screen. Twenty-one subjects enrolled in the study and completed data collection. Power analysis for the significant correlations revealed that 19 subjects would be needed to complete data collection, and a total of 21 subjects meeting all eligibility criteria participated in all study activities. Due to loss of data from the force plate during BESS testing of two subjects, data from 19 subjects was used for analysis in this study.

Subject demographics are presented in Table 5. The age range of study participants was 20-31 years old. Of the 19 participants, there were seven males and twelve females. Fifteen subjects were right foot dominant and four participants were left foot dominant.

Table 5. Demographic Data

Variable	Mean	SD	Median	Q1	Q3
Age	22.16	2.59	21.00	20.91	23.41
Height (cm)	168.56	22.24	173.40	157.84	179.28
Weight (kg)	73.24	15.28	71.60	65.88	80.61

Q1 = First quartile
Q3 = Third quartile

4.2 BALANCE ERROR SCORING SYSTEM

4.2.1 BESS Clinical Outcome Scores

Error scores were calculated for each of the conditions of the BESS test and used to represent a clinical measure of postural stability. Descriptive statistics for the BESS error scores are presented in Table 6. The error score for tandem on firm did not meet assumptions of normality.

Table 6. Descriptive Statistics for the Balance Error Scoring System Error Scores

Condition	Mean	SD	Median	Q1	Q3
BFR	0.00	0.00	0.00	0.00	0.00
SFR	2.74	1.58	2.67	1.98	3.50
TFR	0.54	0.63	0.33	0.24	0.85
BFM	0.00	0.00	0.00	0.00	0.00
SFM	7.79	1.88	8.00	6.88	8.70
TFM	2.72	1.74	2.33	1.88	3.56
Total Error Score	13.79	4.76	13.33	11.49	16.09

BFR = Bilateral, firm
SFR = Single leg, firm
TFR = Tandem, firm
BFM = Bilateral, foam
SFM = Single leg, foam
TFM = Tandem, foam
Q1 = First quartile
Q3 = Third quartile

4.2.2 BESS Kinetic Force Plate Data

Kinetic force plate results for the BESS test are presented in Table 7. The standard deviation of the vertical ground reaction force and the total sway were calculated for each condition of the BESS. The greatest SDvGRF and total sway were observed for the single leg on foam condition. Multiple variables did not meet assumptions for normality, including SDvGRF for single leg on firm, tandem on firm, single leg on foam, and tandem on foam. Additionally, total sway for single leg on firm did not meet assumptions for normality.

Table 7. Descriptive Statistics for the Balance Error Scoring System Kinetic Data

Condition	SDvGRF Mean±SD	Median	Q1	Q3	Total Sway Mean±SD	Median	Q1	Q3
BFR	1.28 ± 0.17	1.26	1.20	1.36	1.38 ± 0.36	1.37	1.21	1.56
SFR	22.16 ± 18.71	19.24	13.15	31.18	2.16 ± 0.62	2.10	1.86	2.46
TFR	10.24 ± 10.45	5.69	5.20	15.27	1.85 ± 0.42	1.83	1.65	2.05
BFM	6.57 ± 2.82	5.71	5.21	7.93	1.44 ± 0.31	1.43	1.29	1.59
SFM	64.06 ± 47.40	41.75	41.22	86.91	2.72 ± 0.55	2.64	2.45	2.99
TFM	46.84 ± 33.34	38.03	30.77	62.91	2.62 ± 0.77	2.58	2.25	2.99

SDvGRF = Standard Deviation of the Vertical Ground Reaction Force
BFR = Bilateral, firm
SFR = Single leg, firm
TFR = Tandem, firm
BFM = Bilateral, foam
SFM = Single leg, foam
TFM = Tandem, foam
Q1 = First quartile
Q3 = Third quartile

4.3 NEUROCOM SENSORY ORGANIZATION TEST

4.3.1 SOT Clinical Outcome Scores

Descriptive statistics for the SOT component and composite scores are presented in Table 8. Scores are based on the AP sway in relation to the LOS as discussed in the methodology of this study.

Table 8. Descriptive Statistics for the Sensory Organization Test Output Data

Variable	Mean	SD	Median	Q1	Q3
SOM	97.58	1.68	98.00	96.77	98.39
VIS	87.58	7.58	89.00	83.92	91.23
VEST	72.68	8.87	74.00	68.41	76.96
Composite	79.68	5.39	80.00	77.09	82.28

SOM = Somatosensory component score
VIS = Visual component score
VEST = Vestibular component score
Q1 = First quartile
Q3 = Third quartile

4.3.2 SOT Kinetic Force Plate Data

Kinetic force plate results for the BESS test are presented in Table 9. The standard deviation of the vertical ground reaction force and the total sway were calculated for each condition of the SOT. Several variables did not meet assumptions of normality, including SDvGRF of SOT condition four, SDvGRF of SOT condition five, SDvGRF of SOT condition six, and total sway of SOT condition three.

Table 9. Descriptive Statistics for the Sensory Organization Test Kinetic Data

Condition	SDvGRF Mean±SD	Median	Q1	Q3	Total Sway Mean±SD	Median	Q1	Q3
C1	1.06 ± 0.33	1.03	0.90	1.22	0.02 ± 0.00	0.02	0.02	0.02
C2	1.03 ± 0.18	1.05	0.95	1.12	0.02 ± 0.00	0.02	0.02	0.02
C3	1.06 ± 0.17	1.05	0.98	1.14	0.02 ± 0.01	0.02	0.02	0.02
C4	1.34 ± 0.55	1.19	1.07	1.60	0.02 ± 0.00	0.03	0.02	0.03
C5	1.93 ± 0.91	1.76	1.49	2.36	0.04 ± 0.01	0.04	0.04	0.05
C6	2.95 ± 4.35	2.00	0.86	5.05	0.04 ± 0.01	0.04	0.03	0.04

SDvGRF = Standard Deviation of the Vertical Ground Reaction Force
C1 = Condition 1 (eyes open, no sway)
C2 = Condition 2 (eyes closed, no sway)
C3 = Condition 3 (eyes open, sway surround)
C4 = Condition 4 (eyes open, sway support)
C5 = Condition 5 (eyes closed, sway support)
C6 = Condition 6 (sway surround, sway support)
Q1 = First quartile
Q3 = Third quartile

4.4 RELATIONSHIP BETWEEN BALANCE ERROR SCORING SYSTEM AND NEUROCOM SENSORY ORGANIZATION TEST

The following variables violated assumptions of normality: SOT condition four SDvGRF, SOT condition five SDvGRF, SOT condition six SDvGRF, SOT condition three total sway, BESS condition three error score, BESS condition two SDvGRF, BESS condition three SDvGRF, BESS condition five SDvGRF, BESS condition six SDvGRF and BESS condition two total sway.

4.4.1 Correlation Analysis for BESS Error Scores and SOT Outcome Scores

Results of the correlation between the BESS error scores and the SOT outcome scores are presented in Table 10. One significant association was observed between the SOT SOM component score and the BESS tandem on firm error score, $r = -0.493$ ($p = 0.032$). No other significant associations were observed between the errors scores from the six conditions of the BESS test and the SOM, VIS, VEST and composite scores of the SOT. No correlation coefficient is reported for BFR and BFM of the BESS as no errors were committed during the bilateral stances.

Table 10. Balance Error Scoring System Error Score and Sensory Organization Test Output Correlation Analysis

	SOT Component Scores			
	SOM	**VIS**	**VEST**	**Composite**
BESS Condition	**r(p-value)**	**r(p-value)**	**r(p-value)**	**r(p-value)**
BFR				
SFR	-0.226(0.352)	-0.010(0.968)	-0.164(0.503)	-0.145(0.552)
TFR	-0.493(0.032)*[+]	-0.197(0.419)*	-0.104(0.671)*	-0.014(0.956)*
BFM				
SFM	-0.118(0.631)	-0.101(0.680)	-0.203(0.404)	-0.307(0.201)
TFM	-0.334(0.162)	-0.341(0.152)	-0.095(0.700)	-0.284(0.239)
Total Error Score	-0.285(0.236)	-0.186(0.446)	-0.160(0.514)	-0.273(0.258)

Correlation coefficients and p-values are not reported for bilateral stances because no errors were committed during bilateral testing; therefore, correlations cannot be produced

VIS = Visual component score

VEST = vestibular component score

SOMA = somatosensory component score

BFR = Bilateral, firm

SFR = Single leg, firm

TFR = Tandem, firm

BFM = Bilateral, foam

SFM = Single leg, foam

TFM = Tandem, foam

Q1 = First quartile

Q3 = Third quartile

* denotes the use of a non-parametric test

[+] denotes statistical significance

4.4.2 Correlation Analysis for BESS and SOT Kinetic Force Plate Variables

Results of the correlation analyses between the BESS and SOT kinetic variables of SDvGRF and total sway are presented in Table 11 and Table 12 respectively.

Table 11. Balance Error Scoring System and Sensory Organization Test SDvGRF Correlation Analysis

	SOT Conditions					
	C1	C2	C3	C4	C5	C6
BESS	r(p-value)	r(p-value)	r(p-value)	r(p-value)	r(p-value)	r(p-value)
BFR	0.307(0.201)	0.509(0.026) +	0.310(0.196)	0.477(0.039)*+	0.246(0.311)*	0.625(0.004)*+
SFR	0.426(0.069)*	0.651(0.003)* +	0.695(0.001)* +	0.482(0.036)* +	0.584(0.009)*+	0.561(0.012)* +
TFR	-0.191(0.433)*	-0.065(0.792)*	-0.328(0.170)*	-0.004(0.989)*	0.525(0.021)*+	0.760(<0.001)* +
BFM	0.140(0.568)	0.577(0.010) +	0.458(0.049) +	0.539(0.017)* +	0.556(0.013)*+	0.481(0.037)* +
SFM	0.246(0.311)*	0.584(0.009)* +	0.525(0.021)* +	0.556(0.013)* +	0.118(0.632)*	0.533(0.019)* +
TFM	0.625(0.004)* +	0.561(0.012)* +	0.760(0.000)* +	0.481(0.037)* +	0.032(0.898)*	0.337(0.158)*

BFR = Bilateral, firm
SFR = Single leg, firm
TFR = Tandem, firm
BFM = Bilateral, foam
SFM = Single leg, foam
TFM = Tandem, foam
* denotes the use of a non-parametric test
+ denotes statistical significance

Table 12. Balance Error Scoring System and Sensory Organization Test Total Sway Correlation Analysis

	SOT Conditions					
	C1	**C2**	**C3**	**C4**	**C5**	**C6**
BESS	**r(p-value)**	**r(p-value)**	**r(p-value)**	**r(p-value)**	**r(p-value)**	**r(p-value)**
BFR	0.573(0.010) +	0.343(0.150)	0.647(0.003)* +	0.252(0.298)	0.167(0.494)	-0.175(0.474)
SFR	0.625(0.004)*+	0.442(0.058)*	0.677(0.001)* +	0.644(0.003)* +	0.612(0.005)* +	0.340(0.154)*
TFR	0.420(0.073)	0.264(0.275)	0.530(0.020)* +	0.509(0.026) +	0.377(0.112)	-0.024(0.921)
BFM	0.615(0.005) +	0.378(0.110)	0.681(0.001)* +	0.352(0.140)	0.224(0.357)	-0.101(0.680)
SFM	0.587(0.008) +	0.465(0.045) +	0.544(0.016)* +	0.497(0.031) +	0.559(0.013) +	0.138(0.572)
TFM	0.265(0.273)	0.222(0.360)	0.402(0.088)*	0.543(0.016) +	0.572(0.010) +	0.283(0.240)

BFR = Bilateral, firm
SFR = Single leg, firm
TFR = Tandem, firm
BFM = Bilateral, foam
SFM = Single leg, foam
TFM = Tandem, foam
* denotes the use of a non-parametric test
+ denotes statistical significance

5.0 DISCUSSION

The purpose of this study was to investigate the relationship between the Balance Error Scoring System and the NeuroCom Sensory Organization Test clinical outcome measures and kinetic variables. Physically active, healthy individuals participated in an assessment of postural stability using the BESS and the SOT in a single session. A correlation analysis was performed to examine the association between the clinical outcome measures from each assessment and the kinetic force plate data from each assessment.

It was hypothesized that a significant association would be present between the BESS error scores and NeuroCom SOT clinical outcome scores of VIS, SOM and composite. It was hypothesized that the SOT VEST component would not have a significant association with the BESS error scores. Similarly, it was hypothesized that there would be a significant association between the SDvGRF and total sway of the BESS and the NeuroCom SOT for conditions one through four of the SOT. A significant association was not hypothesized between SDvGRF and total sway of the BESS and SOT conditions five and six, which challenge the vestibular system. Our hypotheses concerning the clinical error and outcome scores were rejected, as there was only one significant association between the clinical scores of the two tests. Our hypotheses concerning the kinetic measures of SDvGRF and total sway were partially rejected, as there were not significant associations between some of the conditions. There were, however, significant associations demonstrated between specific conditions of the BESS and the SOT when comparing the kinetic variables. The postural stability assessments, research hypotheses, limitations and future directions are discussed in the sections below.

5.1 BALANCE ERROR SCORING SYSTEM

The BESS was used for this study due to its frequent use in the clinical setting as an assessment of postural stability. In contrast to the findings by Guskiewicz et al[39] indicating an average error score of eight in a healthy population, the mean total error score observed in this study was 13.79±4.76. The findings of this study are in agreement with the mean error score reported by McCrea et al[62] who reported a mean error score at baseline of 11.89±8.09 in the concussion group and 12.73±7.57 in the control group. The studies by Guskiewicz[39] and McCrea[62] were each performed in a collegiate athlete population; however, as previously discussed, interrater reliability of the BESS is low to moderate, therefore leading to discrepancies in normative error scores reported. No errors were committed during the two bilateral stance conditions. The greatest number of errors, 7.79±1.88, was observed in the single leg, foam condition. A moderate number of errors were observed during the single leg on firm and tandem on foam, 2.74±1.58 and 2.72±1.74 respectively. Aside from the bilateral stances, the fewest errors were committed during the tandem on firm, 0.54±0.63. The results indicate that the most difficult stance is single leg on foam, followed by single leg on firm, tandem on foam, tandem on firm and bilateral on foam and firm. Single leg stance creates the smallest BOS, followed by the tandem stance. Bilateral stance is the largest BOS in the BESS test. Additionally, conditions on the foam surface are more difficult than conditions on the firm surface due to the inaccurate somatosensory input provided by the foam pad. The error scores are an indication of the difficulty of each condition and are supported by this understanding of BOS and somatosensory input.

The kinetic data from the force plate was also analyzed for the purposes of this study. Standard deviation of the vertical ground reaction force (SDvGRF) and total sway were calculated for each of the conditions of the BESS test. An increase in both SDvGRF and total sway indicate a decrease in postural stability. An increase in SDvGRF indicates increased vertical body oscillations[47] which is closely related to AP COP velocity.[47] Total sway indicates the horizontal amplitude of movement.[47] The kinetic variables are largely in agreement with the error scores observed. Based on the SDvGRF and total sway, the most difficult condition was the single leg on foam. While the error score was slightly higher for single leg on firm compared to tandem on foam, the kinetic variables indicate that there was more sway and oscillations in the tandem on foam as compared to the single leg on firm. The error scores and kinetic variables are in agreement that the bilateral on firm is the easiest, followed by bilateral on foam and tandem on firm respectively. The kinetic variables give insight to the differences between the two bilateral stance conditions. Both conditions resulted in zero errors during testing, but the SDvGRF and total sway were greater on the foam surface compared to the firm surface, 6.57±2.82 and 1.44±1.33 compared to 1.28±0.17 and 1.38±0.36 respectively. This supports the rationale that inaccurate somatosensory input results in decreased postural stability, as supported by previous literature.[30, 97] Previous literature has reported kinetic force plate variables from BESS testing including sway velocity and total sway area. Mean sway velocity in healthy individuals at baseline as been reported as 8.15±2.06cm/s and mean total sway area has been reported as

$49.14 \pm 17.56 cm^2$.[28] Fox et al[28] did not report kinetic variables for individual conditions and did not report SDvGRF, therefore results cannot be directly compared with the results of this study.

The scoring of the BESS has limitations from a clinical perspective. When scoring the BESS, there is no indication of the magnitude of an error. An error is counted when a subject gently touches down with the non-stance foot. An error is also counted when a subject completely falls out of position. A clinical error score of four can indicate a wide range in postural stability due to the lack of importance of the magnitude of errors when counting the error score. Additionally, an error is counted when a subject fails to return to the testing position within five seconds. There is no indication of how long the subject is out of position. If a subject were to fall out of position and remain out of position for the entirety of the test, the error score could be as low as two. A subject would have the same error score of two with two controlled touch-downs of the non-stance foot. An inability to hold the appropriate position and two controlled touch-downs have different clinical implications, yet are scored the same for the purposes of the BESS. While the clinical scoring has limitations, there is general agreement between the conditions with the greatest number of errors and the conditions with the highest SDvGRF and total sway.

5.2 NEUROCOM SENSORY ORGANIZATION TEST

The NeuroCom SOT was used in this study as a laboratory assessment of postural stability because it is able to isolate the visual, vestibular and somatosensory systems and detect deficits in each.[30, 69, 74, 88, 100] The SOT outcome scores are the VIS, VEST, and SOM component scores in addition to the composite score. Component scores from the SOT use condition one as a baseline reference. The closer a component score is to 100, the more optimal the use of the sensory system of interest. Condition one of the SOT serves as a baseline measure for component calculations and involves eyes open with a stable support and stable surround. The SOM component score compares condition two and condition one. Condition two involves eyes closed on a stationary support. This condition challenges the somatosensory system because the visual input is removed and the somatosensory input is accurate, and therefore should be used to maintain postural stability.[100] The VIS component score is calculated based on condition four and condition one of the SOT, comparing the eyes open with sway support condition to the baseline (eyes open with no sway) condition. With sway support and accurate visual input, the sensory integration system should rely heavily on the visual system to maintain postural stability. The VEST component score compares condition five and condition one. Condition five involves eyes closed on a sway support. This challenges the vestibular system because the visual system is removed and the somatosensory input is inaccurate.[100]

The average SOM component score was 97.58±1.68, indicating that subjects performed well, with minimal additional sway, during the somatosensory challenge when compared to the baseline condition. This supports the findings of Peterka et al,[79] which demonstrated that healthy individuals rely most heavily on the somatosensory system; therefore healthy individuals would be capable of relying on the somatosensory system effectively in a condition that challenges the this system. The VIS component mean score was 87.58±7.58, indicating a less optimal use of the visual system when compared to the somatosensory condition. The VEST component mean was 72.68±8.87. The VEST component score observed indicates that the vestibular system is least effective in maintaining postural stability when compared to the visual and somatosensory systems. The relative order of the component scores observed in this study are in general agreement with the normative findings reported by Nashner,[71] which demonstrated that the greatest component score was SOM (0.94), followed by VIS (0.78) and VEST (0.58), respectively. The study by Nashner was performed in a general population and did not require a specific physical activity level, which could explain the decreased scores compared to the findings of this study.

The kinetic variables analyzed support the finding that the conditions challenging the vestibular system present with the lowest postural stability. The greatest SDvGRF and total sway were observed in condition six (sway surround, sway support), 2.95±4.35 and 0.04±0.01 respectively. This was followed in difficulty by the SDvGRF and total sway observed in condition five (eyes closed, sway support), observed as 1.93±0.91 and 0.04±0.01 respectively. The visual challenge presented in condition four (eyes open, sway support) resulted in the next greatest SDvGRF and total sway, 1.34±0.55 and 0.02±0.00 respectively. Based on the SDvGRF and total sway values, the somatosensory challenges in conditions one (eyes open, stable support), two (eyes closed, stable support) and three (sway surround, stable support) resulted in the least sway and vertical oscillations.

These findings are supported by the theory that the vestibular system is used primarily when resolving conflicting input from sensory systems.[41, 56] This theory would imply that the vestibular system is, therefore, not the system relied upon during normal or stable conditions. The vestibular system would be used in conditions in which postural stability is inherently compromised due to lack of accurate sensory input to the other systems. Peterka et al[79] found that individuals rely most heavily on the somatosensory system in ideal conditions. This is in agreement with the findings that SDvGRF and total sway were lowest during the somatosensory challenges compared to the visual and vestibular challenges. Additionally, the SDvGRF and total sway demonstrated during condition two indicates that subjects had improved postural stability in the somatosensory challenge when compared to the baseline condition. The body is most effective when using the somatosensory system as the primary source of sensory input for postural stability, as previously discussed.[79]

5.3 RELATIONSHIP BETWEEN CLINICAL OUTCOME SCORES

One significant association was observed between the error scores of the BESS and the component and composite scores from the SOT, between the SOM component score and the tandem on firm BESS error score. As discussed previously, the error score from the BESS does not indicate the magnitude of the errors committed during the course of the test. This is in contrast to the outcome scoring of the SOT. The VIS, SOM, VEST and composite scores of the SOT indicate the anterior-posterior sway of the individual during the testing, therefore indicating the magnitude of errors performed. The scoring of the SOT encompasses magnitude, whereas the clinical scoring of the BESS does not encompass magnitude. This is one explanation for a lack of association between outcome scores of the BESS and the SOT.

A secondary explanation for the lack of significant association is that the BESS employs a variety of stances and the SOT utilizes a bilateral stance for all conditions. The single leg and tandem stance conditions of the BESS result in a decreased BOS. This decreased BOS provides a different challenge to the postural stability system. Karlsson and Persson[48] describe that single leg stance is a quasi-static posture because absolute equilibrium cannot be achieved, therefore the body is in continuous motion. During a bilateral stance, ML sway is controlled primarily through a load and unload strategy, in which load is transferred from one foot to another to minimize sway.[47] In a single leg stance and in tandem stance, ML oscillations cannot be as easily controlled with load transfer. Therefore, the narrow base of support conditions may require more strength and functional stability in order to maintain equilibrium without requiring the use of the hip strategy or falling out of position entirely.

Due to the findings of this study, it would be valuable to address the scoring system for the BESS to determine if there is a clinically acceptable way to score postural stability that would account for the magnitude of errors, and therefore have a stronger relationship with a test such as the SOT. This study observed significant associations between the kinetic variables of the two postural stability tests, suggesting that the tests, to an extent, are testing the same construct. The lack of association between clinical scores in conjunction with the significant associations between kinetic variables suggest that the primary limitation of the BESS is likely the scoring system as opposed to the challenge to each of the sensory systems of postural stability.

5.4 RELATIONSHIP BETWEEN KINETIC FORCE PLATE DATA

Significant associations were observed between similar kinetic variables on a variety of conditions from the BESS and the SOT. Standard deviation of the vertical ground reaction force and total sway will each be discussed in the following sections.

5.4.1 Relationship between SDvGRF on the BESS and the SOT

In relation to SDvGRF, the majority of BESS conditions are significantly related to conditions two (eyes closed, stable support), three (sway surround, stable support), four (eyes open, sway support), five (eyes closed, sway support) and six (sway surround, sway support) of the SOT.

Condition two of the SOT was significantly related to all conditions of the BESS, excluding tandem on firm. Condition two of the SOT is intended to challenge the somatosensory system by eliminating visual input. All conditions of the BESS are completed with eyes closed, increasing the need to rely on the somatosensory and vestibular systems. Similarly, condition three of the SOT involves inaccurate visual input, challenging the somatosensory and vestibular systems. This provides rationale for the significant association between condition three of the SOT and most conditions of the BESS, excluding bilateral on firm and tandem on firm. The BESS appears to challenge the somatosensory system in a similar manor compared to the SOT somatosensory specific conditions.

Condition four of the SOT aims to challenge the visual system by providing inaccurate somatosensory information via a sway support surface. The BESS does not have a visual challenge associated with any of the conditions because each condition involves a lack of visual input. The lack of visual input during the BESS results in no testing conditions that require the participant to rely primarily on the visual system for postural stability. While the BESS does not isolate or require the visual system, this study demonstrated a significant association between the SOT condition four and all conditions of the BESS, excluding tandem on firm. One possible explanation is that the BESS involves a smaller BOS for most conditions as compared to the SOT, therefore potentially increasing the somatosensory challenge presented and requiring more strength and functional stability of the lower leg and ankle to maintain postural stability. As the conditions of the SOT increase, the challenge to the postural stability system also increases, potentially requiring a similar increase in strength and functional stability demands. This increased demand may explain the significant association observed between the BESS and condition four of the SOT. Additionally, condition four of the SOT provides inaccurate somatosensory input, requiring the individual to rely on the visual and vestibular systems to maintain postural stability. The BESS provides no visual input, as the eyes are closed, resulting the in dependence on the somatosensory and vestibular systems to maintain postural stability. It is possible that the overlap of vestibular requirements is the reason for the significant association. Regardless of explanation for the significant association, it is evident based on the results of this study that the BESS is examining a similar construct of postural stability compared to condition four of the SOT.

Conditions five and six of the SOT intend to challenge the vestibular system by removing vision or providing inaccurate vision, respectively, in conjunction with inaccurate somatosensory information. Condition five (eyes closed, sway support) of the SOT is significantly correlated with single leg firm, tandem firm and bilateral foam. The bilateral foam condition of the BESS would theoretically challenge the vestibular system in a similar manor as the SOT. The SOT is performed in a bilateral stance and condition five involves removal of vision and inaccurate support via a sway support surface. Similarly, the bilateral foam condition of the BESS involves eyes closed on foam support surface that provides inaccurate somatosensory information. Condition five of the SOT and bilateral foam of the BESS are significantly related and both theoretically challenge the vestibular system. This is validated by studies that have used the SOT in a population with concussion or vestibular dysfunction and found significant differences when compared to a healthy group, specifically on conditions challenging the vestibular system.[7, 11] Additionally, the BESS, specifically the tandem stances, has been demonstrated to discriminate between concussed individuals and healthy controls.[31] A significant increase in error score on the BESS has been observed in concussed athletes,[39] but has not been specifically related to vestibular deficits in a concussed population.

Condition five of the SOT challenges the vestibular system through the use of sway support surface with eyes closed, therefore providing inaccurate somatosensory input and removing visual input. This is in contrast to condition six of the SOT that provides inaccurate visual input in conjunction with inaccurate somatosensory input. Condition six requires the use of the vestibular system as a reference against which inaccurate visual input is compared, which provides an additional vestibular challenge compared to condition five. While conditions five and six of the SOT demonstrate significant associations with individual conditions of the BESS, there are conditions that are not significantly related. Condition five of the SOT is not significantly associated with bilateral on firm, single leg on foam or tandem on foam. Condition six of the SOT is not significantly associated with tandem on foam. This could indicate, based on the presence of significant associations, that a vestibular challenge is present in the BESS, but due to various conditions that are not significantly associated, the BESS may not optimally challenge the vestibular system when compared to the SOT. The analysis of total sway provides further insight into the vestibular challenge associated with the BESS.

It was thought that the SOT, specifically conditions five and six, would provide a greater challenge to postural stability when compared to the BESS. On the contrary, SDvGRF was greater on the BESS for single leg foam and tandem foam when compared to conditions five and six of the SOT. Based on the results of this study, it is possible that the BESS provides a vestibular challenge as it relates to the SOT, but that the BESS is, in fact, more challenging to the entirety of the postural stability system than the SOT. This increased challenge may be due to the various stances used for the BESS, including the single leg and tandem stances, which result in a narrow base of support. A narrower base of support may increase the demands on the functional stability of the ankle as well as the strength of the hip, leg, ankle and foot. Due to the change in base of support, the BESS may provide a greater challenge to the motor response required for postural stability, rather than primarily challenging the sensory systems of postural stability. The SOT, however, may provide a more general picture of the functioning of the sensory systems involved in postural stability, as it provides inaccurate sensory information and challenges each of the systems individually.

5.4.2 Relationship between total sway on the BESS and the SOT

Total sway measures observed from the BESS and the SOT demonstrated fewer significantly related results than SDvGRF measures. When compared to condition one (eyes open, stable support) of the SOT, there were significant correlations observed with both bilateral and both single leg stances. Tandem stance is potentially a more novel task when compared to the single leg and bilateral stances. This could explain the lack of association of total sway with the base condition of the SOT, however different significant associations were observed when comparing SDvGRF. Total sway is a measure that is more related to horizontal movements, calculated using the COP movement in the x and y directions, as opposed to vertical body oscillations as is measured via SDvGRF. This would indicate that tandem stance may result in more horizontal sway as opposed to the single leg and bilateral stances.

Condition six of the SOT is a vestibular challenge and did not significantly relate to any conditions of the BESS when comparing total sway measures. The BESS conditions produced a greater total sway when compared to the SOT conditions, indicating that it is a more challenging postural stability task than the SOT, but the lack of correlation indicates that it may not stress the vestibular system in the manor that the SOT is able to isolate the specific system. The BESS has the combination of no vision and an unstable, inaccurate support surface, which provides conditions for the vestibular system to be tested, however, the SOT provides inaccurate visual information, which is a unique postural stability challenge. The vestibular system and sensory organization must be utilized optimally in order to maintain postural stability. The CNS must deemphasize the use of visual input, whereas visual input is not present for the BESS test. Suppression of the visual input reliance requires comparison against the vestibular system to determine the accuracy of the information.[41] This is a unique finding observed in this study and should be further investigated in the future. Despite the difficulty of the BESS, it may not be able to isolate the vestibular system and require the sensory organization system to reorganize the use of visual input in the manor that the SOT does.

There are differences between the SOT and the BESS that are detectable via force plate measures due to the differences in the tasks. During SOT testing, the individual is in a bilateral stance for the entirety of the test. Due to the bilateral stance, the subject has a larger base of support than a single leg or tandem stance. Additionally, inaccurate sensory input during the SOT is provided through AP sway of the surround and support surface, resulting in an increase in AP instability, and a less significant challenge to ML stability. Subjects generally presented with instability in the sagittal plane. In contrast, the BESS employs single leg and tandem stances, which creates a smaller and narrower base of support, leading to decreased stability, specifically in the ML direction. Subjects primarily lost stability in the frontal plane as opposed to the sagittal plane. This is likely due to the inability to transfer weight as a subject would in a bilateral stance.[47]

The more narrow base of support tested during the BESS creates different demands of the sensory and motor systems. A narrow stance, such as single leg and tandem stance, requires more functional stability of the ankle joint. Rather than testing solely the differences in the sensory component of postural stability, the tests differ in strength and stability demands of the lower leg and ankle. It was observed during the BESS test, that subjects utilized both ankle and hip strategy to maintain postural stability. The use of hip strategy results in greater magnitude of movement and is used in situations in which conditions are less stable, or ankle strategy is insufficient to maintain postural stability, and creates increased sway.[42, 73, 100] In contrast, subjects relied primarily on ankle strategy during the SOT testing, leading to much smaller SDvGRF and total sway. It would be valuable to conduct the SOT in a single leg stance to determine if the lack of correlation on a variety of stances is resolved by the change in BOS. Postural stability requires both sensory and motor function, but the purpose of this study was related to the sensory component of postural stability, therefore the different requirements of the motor system due to the variation in stances is a possible confounding factor.

5.5 LIMITATIONS

This study has several limitations worth mentioning. The BESS error score does not have high test-retest reliability. For the purposes of this study, scores were counted during testing and were counted by a single assessor rather than multiple assessors. This method was used for the current study to mirror a sideline concussion evaluation in which a single clinician is counting errors during the BESS test with no video feedback to confirm error scores. It would, however, improve the reliability of the BESS error score to have multiple assessors score the BESS test simultaneously, as the intrarater and interrater reliability has been shown to be only moderate to good for the individual stances and total error score of the BESS.[27]

Additionally, the BESS was conducted on a force plate for kinetic data collection of SDvGRF and total sway. Due to the difficulty of the later conditions of the BESS, multiple subjects were unable to stay on the force plate for the duration of testing. Touch-downs outside of the force plate result in a loss of data concerning sway and GRFs that cannot be accounted for in the analysis of the data. Validity would improve if all touch-downs were on the force plate, therefore allowing for assessment of total sway and SDvGRF including the touch-downs. Due to the size of the force plate used for testing and the magnitude of the errors made by participants, not all touch-downs occurred on the force plate resulting in a loss of data regarding the kinetic variables. Touch-downs outside of the force plate occurred on single leg foam and tandem foam during the testing of five participants.

Subjects used in this study were recreationally active as opposed to competitive athletes, as were used in many studies regarding the effect of concussion on postural stability.[39] This difference in demographics affects the ability to compare results between studies. For example, Guskiewicz et al[39] reported an average error score on the BESS of eight in a healthy population. This is in contrast to the findings of this study. This discrepancy may be due to the difference in activity and training level of participants. Additionally, subjects were excluded from participation if they had a lower extremity injury in the past six months. This did not exclude subjects with a history of ankle sprain prior to this time period. Those with a history of ankle sprain were, therefore, included in the study. Ankle sprains have been shown to affect postural stability due to a change in functional stability of the ankle, and may have affected the BESS test more significantly than the SOT due to the single leg and tandem stances.[18]

For the purposes of this study, the SOT preference (PREF) score was not analyzed. The PREF score is an indication of the extent to which an individual relies on visual information to maintain postural stability, even when that visual information is incorrect. Based on the aims of this study, the PREF score was not used for analysis, but would provide valuable information in future studies regarding the sensory organization system. It would be valuable to determine the effect of concussion on sensory organization represented through the PREF score.

Finally, although participants were instructed to sleep for a normal number of hours prior to testing and hydrate adequately, participants were not questioned regarding sleep schedule, hydration or prior testing using the BESS or NeuroCom prior to the study. These are all possible confounding variables affecting postural stability,[16, 66, 77] and it is not known if these variables could affect one sensory system of postural stability more than another. Scores were compared within subjects, which can partially control for this limitation.

5.6 STUDY SIGNIFICANCE

Although portions of our hypotheses were rejected as a result of the study, the results of this study contribute to the body of knowledge concerning postural stability testing, specifically as it relates to concussion assessment. To the author's knowledge, no study has assessed the relationship between the BESS and the SOT, which aims to isolate the visual, somatosensory and vestibular systems. Based on the findings of this study, the BESS error scoring system may not be adequate to assess postural stability when compared to clinical scores from the SOT. Additionally, the total sway measures from the BESS are not significantly related to the total sway measures from the SOT sway surround and sway support condition, which challenges the vestibular system. This finding indicates that the BESS may not adequately challenge the vestibular system, specifically the ability to use the vestibular system as a reference against inaccurate visual input. This study may provide a foundation for future research concerning validation and modification of the BESS to improve the postural stability component of sideline concussion assessment. Changes may be made in future research to determine a more specific and valid scoring system for the BESS that incorporates the magnitude of errors or to add a specific vestibular challenge to the BESS. Specific changes in future research are described below.

5.7 FUTURE DIRECTIONS

Future research examining postural stability testing in a sideline concussion assessment can explore many variations of the current study. The age range and inclusion criteria of the current study aimed to be generalizable to a healthy, physically active young adult population. Since age may affect postural stability testing specifically following concussion, as demonstrated by Quatman-Yates et al[87], assessments of the pediatric population would be valuable to understand the validity of the BESS test in a pediatric population. Additionally, assessment of a concussed population would provide the ability to compare the BESS and the SOT in a population with possible vestibular dysfunction. Assessing a concussed population would lead to information that is more generalizable to the population of interest. While total errors would be expected to increase in a concussed population, it is also possible that there would be fewer significant relationships between the BESS and the SOT as it relates to vestibular challenges. An impaired vestibular system, as is common following concussion, could highlight the differences between the challenges presented by the BESS and the SOT.

It is imperative that concussions be assessed in a valid and reliable manor, as mismanagement of concussion can have significant repercussions. If a concussion is not properly diagnosed or an athlete returns to play prior to full resolution of a concussion and sustains a second concussive impact, the athlete can sustain second impact syndrome, which can lead to significant disability or death.[9] Due to the significant negative outcomes of mismanaged concussions, the tools used to assess concussion, such as the BESS, must be valid. Future studies should continue to investigate the optimal scoring system for the BESS in order to create the optimal sideline postural stability assessment tool for clinicians.

Future studies can also use other assessments of postural stability known to challenge the vestibular system. The NeuroCom Balance Master has a head-shake function that could provide a greater challenge to the vestibular function. Additionally, a future study could employ a modified BESS with a specific vestibular challenge such as a head-shake condition to determine if a new condition would have a greater correlation with a vestibular challenge on the SOT as compared to the standard BESS conditions. Finally, future studies can create new scoring paradigms for the BESS that incorporate magnitude of error in the scoring. This new scoring system can be compared to kinetic variables such as SDvGRF and total sway. This would allow for validation of the new scoring system against kinetic variables that are affected by magnitude of errors. Magnitude of errors is important clinically; therefore, finding a scoring system that incorporates magnitude would give valuable information to the clinician for evaluation and decision making purposes.

5.8 CONCLUSIONS

The purpose of this study was to investigate the relationship between the Balance Error Scoring System and the NeuroCom Sensory Organization Test clinical outcome measures and kinetic force plate data. Our hypotheses regarding the clinical scoring were rejected, as results demonstrated only one significant association between the error scores from the BESS and the SOT component and composite scores. This finding indicates that the scoring of the BESS may require revisions to incorporate magnitude of error in the scoring system in order to create a more valid clinical assessment of postural stability. Our hypotheses regarding the association between kinetic variables from the two tests were partially rejected, as significant associations were observed between some conditions from the BESS and SOT and not other conditions. The most significant finding related to the kinetic variables was the lack of significant association between the total sway measures of the BESS and the sway surround and sway support condition of the SOT. This finding indicates that the BESS may not challenge the vestibular system in a similar manor as the SOT, specifically requiring the use of the vestibular system as a reference when visual input is inaccurate. Overall, this study provides a foundation for other work to be conducted regarding postural stability testing in relation to concussion assessment. Future research can explore the relationship between the BESS and the SOT in a concussed population, the effect of a modified BESS scoring system and the effect of an added vestibular challenge to the BESS.

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