BASELINE COMPARABILITY TO ACCELEROMETRY DATA AND CHANGES IN STANDING BALANCE OVER THE COURSE OF AN ATHLETIC SEASON USING A POSTURAL SWAY ASSESSMENT TOOL

By

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Abstract:

Changes in balance ability can be a sensitive measure of post-concussion changes in brain function. However there is a need to determine the most reliable, valid and practical ways to assess balance abilities (i.e. degree of postural sway). The Sway Balance™ System is a mobile software application that uses the tri-axial accelerometer located within an iOS device to quantify thoracic sway. The software relies on comparing the individual's post-concussion score to baseline scores obtained at the start of an athletic season. However, in youth athletes in particular, balance may change over the course of the season, worsening due to factors other than concussion, such as lower limb injuries, or improving as fitness improves. This study first compared baseline Sway Balance™ scores to the industry standard accelerometer data recorded from the sternum and attached externally to the iOS device in an elite youth (aged 16 to 20) lacrosse team. We found that balance scores derived from Sway Medical's algorithm had moderate to very strong validity when compared to laboratory accelerometers. We then assessed the reproducibility of the Sway Balance™ System at 5 and 10 weeks relative to baseline. Correlations ranged from weak to excellent depending on which weeks were compared. Variations were observed in some of the athletes' balance scores over the 10 weeks, and in overall group differences at different measurement points. This work indicates that while software such as the Sway Balance™ System has the validity to act as a balance measure, there is considerable work needed in protocol development to ensure that a change in score genuinely reflects a change in balance in concussed athletes.

Keywords: Balance, Postural Sway, Concussion, Baseline Testing, Mild Traumatic Brain Injury (mTBI), iOS device, smart phone

Declaration:

I, Patricia A. Riley, declare that this thesis represents my own work except as acknowledged in the text, and that none of this material has been previously submitted for a degree at the University of Ontario Institute Of Technology, or any other University. The contribution of supervisors and others to this work was consistent with the UOIT regulations and policies. Research for this thesis has been conducted in accordance to UOIT's Research Ethics Committee.

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List of Abbreviations Used:

aBESS- Abbreviated Balance Error Scoring System

ACL- Anterior Cruciate Ligament

A-P or AP- Anterior Posterior or Anteroposterior

BAM- Balance Accelerometer Measure

BSS- Biodex Balance System SD

BESS- Balance Error Scoring System

M-L or ML- Medial Lateral or Mediolateral

mTBI- Mild Traumatic Brain Injury

mBESS- Modified Balance Error Scoring System

SOT- Sensory Organization Testing

WBB- Wii Balance Board

Chapter ONE: Literature Review

Introduction

As the public becomes more aware of the potentially devastating effects that a concussion can have on a person's life, we realize the importance of prevention. If prevention fails, or was not initially implemented, then appropriate management and rehabilitation becomes the next vital step. A concussion, currently defined as "a complex pathophysiological process affecting the brain, induced by traumatic biomechanical forces secondary to direct or indirect forces to the head" (CDC, 2007), is seen predominantly in the sport's world and is becoming a growing clinical concern. Subjective measures of physical abilities by an examiner, and subjective reporting of symptoms by an injured person, are just not enough. Instead, using science to objectively identify pre-concussion abilities and current deficiencies (i.e. those that are less than ideal) are of utmost importance.

Baseline concussion testing refers to the testing of an individual's neurological, cognitive and physical abilities prior to the occurrence of a new or initial head injury. Should a concussion subsequently occur, post-injury testing could best identify deficits by comparing post-concussion scores to pre-concussion scores. Once deficits are identified, the injured person could be rehabilitated back to, or better than, their pre-concussion score(s) prior to returning to play and/or normal activity. This would expectantly reduce the incidence of a subsequent concussion and/or other physical injuries as well as long term deficits and/or persistent post-concussion symptoms.

Human balance, which can generally be described as the coordination of our sensory and motor systems along with biomechanical processes to maintain our centre of gravity within our base of support, is vital to our everyday activities of life. Identifying the most appropriate means to assess and re-assess the neural and physical components of human balance is the focus of this literature review.

The decision to return a concussed athlete to play should be based on an appropriate combination of subjective and objective measures. All too often however, return to play occurs too early, due to incomplete evaluation. Premature clearance for play is, in part, due to the use of subjective measures, in the form of symptom resolution, as a sole indicator of readiness for play. Nearly 50% of concussions sustained by athletes are not reported, (McCrea et al., 2004) making objective identification important (Guskiewicz, 2011). Objective measures improve our ability to confirm that a concussed individual is returning, or has returned, to their pre-injury status; that the injured area of brain has healed to the best of [our] knowledge. These objective assessment measures allow clinical practitioners to assess a person's cognitive, neurological and vestibular function and make appropriate rehabilitative and return to play decisions, even after all reported symptoms have resolved. In the event that an athlete encounters another concussion after being returned to full activity too early, second impact syndrome may result (Bey et al., 2009). Second Impact Syndrome (SIS) is defined as "a devastating case when an athlete is allowed to return to play before having adequate time to recover from a traumatic brain injury; diffuse brain swelling, brain herniation, and even death can occur (Bey et al., 2009)". Post-concussion syndrome refers to the cluster of symptoms that often occur after a person sustains a concussion (Ryan and Warden, 2003). These symptoms may include headaches, dizziness, visual disturbances etc. (Alexander, 1995; Gouvier et al., 1992) and can vary among individuals. Of the many signs and symptoms of a concussion, balance dysfunctions post-concussion are reported in 30% of concussed athletes (Marar et al., 2012; Guskiewicz, 2011). In 2008, a consensus statement from the 3rd International Conference on Concussion, has suggested that various aspects of a concussion be examined (McCrory et al., 2009). This evaluation should include, but is not limited to, questions of dizziness, poor sleep, headaches, emotional issues and balance (McCrory et al., 2009). It was also reaffirmed that assessing balance is a reliable and valid addition to this assessment (McCrory et al., 2009). Without proper overall management affected athletes may have prolonged recovery, experience long term cognitive deficits, and become potentially pre-disposed to a more serious subsequent injury. Published data on postural instability and concussion are on the rise, and investigations have shown that there is an association between early balance deficits post-concussion and a later functional recovery (Duong et al., 2004; Greenwald et al., 2001). Research has also demonstrated that even minor impairments in balance can potentially lead to long-term disability (Basford et al., 2003). By determining the best and most comprehensive method(s) of baseline concussion testing and of assessing and rehabilitating a concussed athlete, we (researchers, clinicians, trainers, coaches and parents) may help preserve brain function, particularly of the young who are the most commonly concussed.

With this constant growing concern, an understanding of the potential effects of a concussive injury, particularly in respect to balance loss, is necessary in order to properly assess and manage it. This initial portion of the literature review will focus on the neuroanatomy and physiology of human balance and of a mild traumatic brain injury (commonly referred to as a mTBI or a concussion). The second portion will focus on the most commonly used methods to assess balance.

1.1 Anatomy of Balance, the Brain and Concussions

1.1.1- Anatomy of Balance

The term balance can most simply be described as the ability to maintain the body's centre of gravity within its base of support, with minimal postural sway. Once thought to be a summation of static reflexes, postural control is now known to actually be a complex skill that is based upon the interaction of multiple dynamic sensorimotor processes (Horak, 2006). Horak (2006) discusses six important resources for postural stability and orientation, which include: cognitive processing (attention and learning), biomechanical constraints (degrees of freedom, strength, limits of stability), movement strategies (reactive, anticipatory, and voluntary), control of dynamics (gait, proactive), orientation in space (perception, gravity, surfaces, vision, verticality), and sensory strategies (sensory integration, sensory reweighing) (Horak, 2006). Postural instability may result from a disorder in one, or more of the above listed variables (Horak, 2006).

Small perturbations within the body, such as shifting from one foot to the other, shifting from the forefoot to the rear foot and breathing, will make a certain amount of sway inevitable, and healthy. An increase in postural sway could indicate poor coordination of input from the body's sensory systems, such as the vestibular, visual and somatosensory systems (discussed later). A deficit could be present in one or more systems, or conflicting input could exist from one system to the next. These systems can be impaired by factors such as age, disease or injury, and may have a single cause or multiple causes. If damage occurs to any one of our balance-related systems, different and context-specific instabilities will result (Horak, 2006). Our central nervous system, which is comprised of the spinal cord and the brain, will integrate the 3 sensory systems involved in balance control and will reweigh these systems as needed (in the event that one system is suppressed) in order to maintain postural control. Integration of these systems will occur within the cerebellum, which is involved heavily in movement-related functions of the body. Postural sway can occur in various planes of motion, such as medial to lateral and anterior to posterior, but studies have shown that medial-lateral deviations are a better indicator of fall risk than anterior-posterior (Park et al., 2014). This thesis will focus on standing balance on a firm surface, rather than dynamic balance (locomotion, i.e. walking).

1.1.2- Effects of Concussions

The brain is protected by cerebral spinal fluid that aids in preventing the brain's physical contact with the skull. When forces are strong enough, however, the cerebral spinal fluid is not able to prevent this contact and a concussion will result. As mentioned previously, a concussion (mild traumatic brain injury or mTBI), is currently defined as "a complex pathophysiological process affecting the brain, induced by traumatic biomechanical forces secondary to direct or indirect forces to the head" (CDC, 2007). A concussion can be the result of either a direct blow (the head contacting an object, for instance) or an indirect blow (whiplash, for instance) which causes an acceleration-deceleration type of movement, transmitting forces from an area such as the head, to the brain. This event will often lead to a focal injury with secondary physiological changes (discussed later) due to a shearing strain of the cerebral axons (nerve fibres) with subsequent changes in neurometabolism and neurotransmission (Grady et al., 2012). It is thought that this axonal stretch injury contributes to the brain dysfunctions that are evident post injury (Bergschneider et al., 2003; Yuen et al., 2009). The metabolic changes, which can range in length from minutes to months (or longer) can lead to issues with cognitive, emotional, and physical function evident in clinical signs and symptoms (CDC, 2007). Loss of consciousness is not a requirement for the diagnosis of a concussion (reported in less than 10-20% of cases) (CDC, 2007), and the injury is considered a functional rather than a structural problem; detailed imaging such as CT scans and MRI's have poor clinical value for use in concussion management (unless a cerebral bleed or fracture is suspected).

Mitochondria, the power house of the cell, are responsible for producing adenosine triphosphate (ATP -cellular energy). In normal circumstances, mitochondria can upregulate ATP when there is an increase in metabolic demand of the cell. However, during the acute phase of a concussion the energy requirements are not met due to functional impairments of the mitochondria (Grady at al., 2012), leaving injured areas of the brain compromised and susceptible. To further complicate the situation, glucose (an important fuel source for the production of ATP) becomes less available after the initial injury (Grady et al. 2012). Energy production and subsequent delivery is compromised at a time when it is needed the most- the 'metabolic mismatch phase' (Donat et al., 2010). Of important note, it has been demonstrated that this cerebral blood flow reduction is prolonged in early adolescents compared to adults (Maugans et al., 2012).

Studies on rat models have allowed for a better understanding of the physiology behind mild, moderate and severe brain injuries (Grady et al. 2012). The Lateral Fluid Percussion (LFP) brain injury model is an example of such studies, where a device is used to force fluid against the dura of an exposed area of a rat's brain (Gurkoff et al., 2006). This action (injury) creates a focal lesion (primary insult) and a secondary inflammatory response (Grady et al. 2012). This primary insult fits with a moderate or severe traumatic brain injury, but the observed secondary inflammatory response has allowed for a better understanding of the cellular changes that occur with a mild traumatic brain injury (Grady et al., 2012).

What the Lateral Fluid Percussion (LFP) Brain Injury Model has taught us

It is currently understood that the initial brain injury causes a pathological release of the excitatory amino acid neurotransmitters glutamate and aspartate (Grady et al., 2012). This release then causes widespread depolarization to occur, reducing cell wall integrity and subsequently increasing the permeability of the cell wall (Grady et al., 2012). This leads to an influx of sodium ions and an efflux of potassium ions causing alteration in the pH of the cell (Grady et al., 2012). This change in pH will allow for an influx of calcium ions, which causes axonal swelling and subsequent reduced axonal functioning, as observed days after initial insult (Smith et al., 2014; Tang-Scomer et al., 2009). Subtle white matter abnormalities, indicating a concern with neurotransmitters properties, have been observed in the early and late phases post-concussion using diffusion tensor imaging (Niogi et al., 2010; Wilde et al., 2012). While the pH of the cell is still altered the mitochondria remain impaired, preventing them from being able to produce the large amounts of ATP that are required for normal cellular function and repair (Thompson et al., 2005). This inflammatory effect can also create secondary injuries at distant sites to the initial injury, displaying signs and symptoms that relate to the area of the brain affected (Grady et al., 2012). We are now aware that after this type of injury has occurred, the metabolic needs of the cell (glucose requirements in particular) increase dramatically (Gurkoff et al., 2006; Yuen et al., 2009). With the purpose of restoring intracellular balance, mild to moderately injured cells will up-regulate the sodium potassium ATPase dependant ion membrane transport proteins- these proteins are needed for the process of healing and require glucose in order to complete their role (Schmidt et al. et al., 2005); a physiological compensation mechanism, so to speak. It is thought that this cascade of events explains why symptoms of a concussion can worsen [clinically] during the first 6-24 hours post injury (Grady et al., 2012)

Glucose delivery to an injured cerebral site (area of the brain affected) is vital to the healing process in order to restore intracellular ion balance and subsequently promote healing of cell membranes (Grady et al., 2012). Keeping cerebral blood flow to the injured area high will aid in the healing process. One of the most important mechanisms of regulating cerebral circulation involves the coupling of cerebral blood flow to metabolism; a homeostatic mechanism that can adjust accordingly at a global and regional level (Fox et al., 1986; Prins et al., 2010; Udomphorn et al., 2008). This can be promoted by limiting other activities that cause diversion of cerebral blood flow, such as over-using the visual, cognitive and muscular systems. Refer to figure 1 and 2 for a visual of the pathophysiology described above.

Although exercise can have very beneficial effects on brain function under normal circumstances (spatial memory in particular) (Gagnon et al., 2009; Lovell, 2008) it is also an activity that can impair the healing process. Exercise will cause an increase in metabolic demand, when the brain is already compromised energetically. If available, sufficient cerebral blood flow to the site of brain injury promotes restoration of energy and the production of synaptic plasticity molecules. (Crane et al., 2012). During the acute phase of a concussion, exercise appears to have the most harmful effect (Leddy et al., 2010; Griesbach, 2011; Griesbach et al., 2004), but during the subacute phase (less than 3 months duration, just prior to becoming chronic), exercise is considered both safe and beneficial (Gagnon et al., 2009; Lovell, 2008). Even in the absence of physical exertion, over-use of the visual and cognitive systems can also impair the healing process post-concussion. It has been reported that more than 80% of students who have sustained a concussion, have a significant increase in their symptom severity during school within the first 2 weeks of their injury (Gioia et al., 2010). One week of complete cognitive rest is suggested in order to allow for a reduced 'cerebral energy crisis' (Moser et al., 2012). A retrospective study on physical and cognitive exertion, found that high levels of this activity during the early post-concussive phase, has a negative impact on cognitive function and recovery (McCrory et al., 2009). This was demonstrated in both subjective symptom reporting and subjective/objective cognitive testing (McCrory et al., 2009). Reiterating what was mentioned earlier, premature neuronal activation, via cognitive or physical exertion, could have a negative effect on recovery due to the required metabolic demands of execution; even in the absence of re-injury (McCrory et al., 2009). Cognitive and physical activity may have damaging effects, short or long term, if completed within the `vulnerability window' (dependant on severity) (McCrory et al., 2009). The bottom line: "if given sufficient time and energy to recover, the cells and axons can restore intracellular function and remain viable" (Grady et al., 2012). Understanding the physiology of a concussion may help practitioners, coaches and parents rehabilitate an injured person most appropriately.

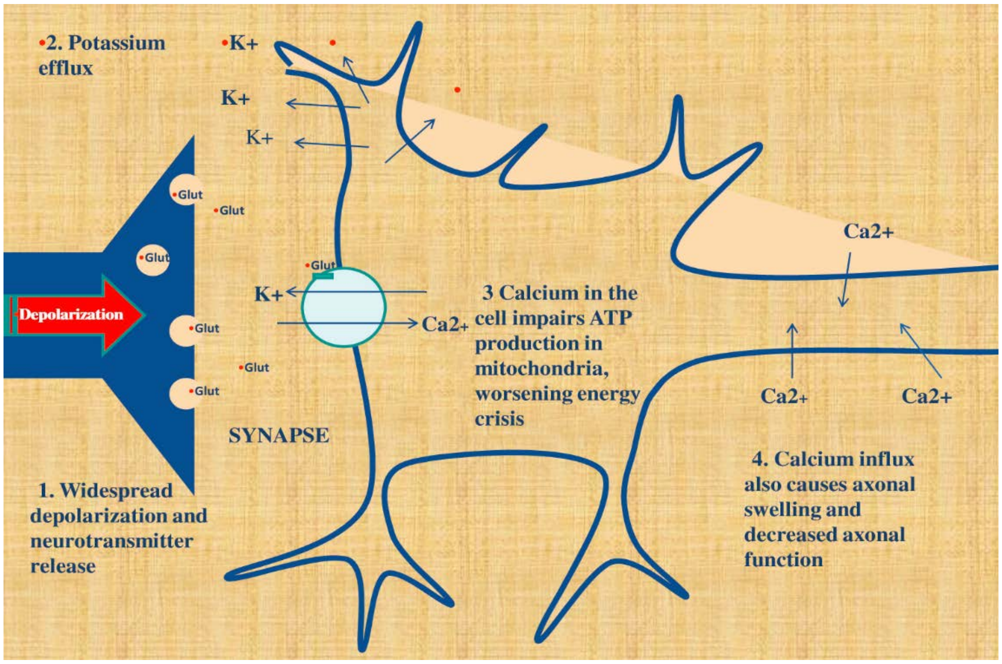


Figure 1*:* Pathophysiology of a Concussion- The 'Energy Crisis' (Grady et al., 2012)

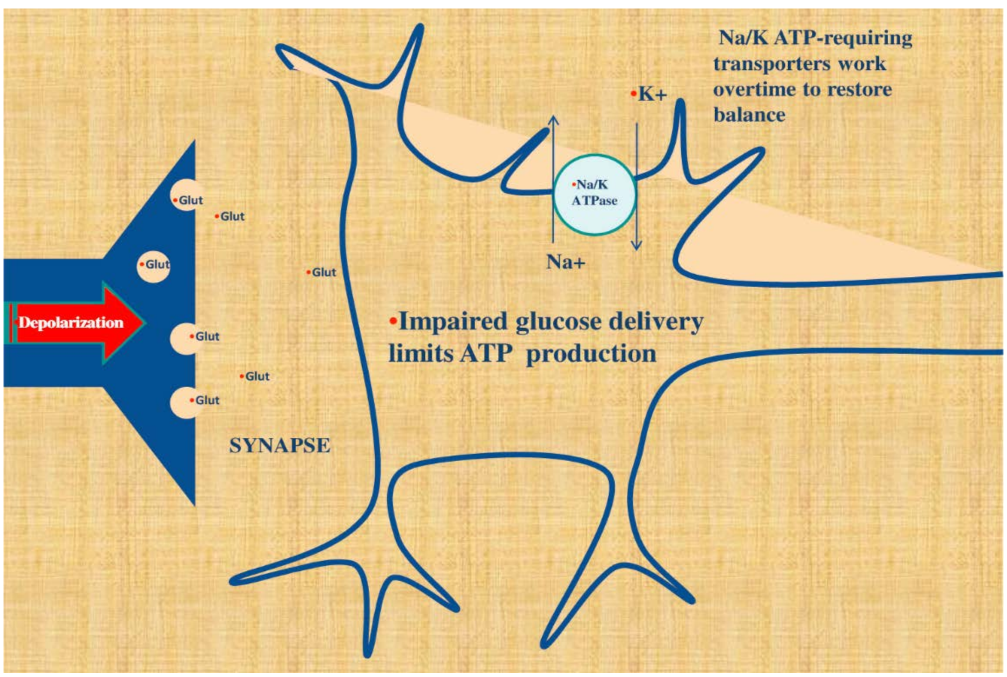


Figure 2: Pathophysiology of a Concussion- the 'Energy Crisis" (Grady et al., 2012)

1.1.3- The Vestibular System

An important entity in maintaining both postural control and the visual axis (also known as gaze), is the vestibular system (Byrne et al., 1997). This system constitutes the labyrinth of the inner ear located within the vestibulum (Byrne et al., 1997). The vestibular system is an important sensory organ that is responsible for movement and balance, and in sending signals to specific neural structures that control eye movement and muscles that allow for postural control (Byrne et al., 1997). This system will generate reflexes by detecting motion of the head and thereby assisting with activities that are crucial to human movement (Byrne et al., 1997). Anatomically, the inner ear is comprised mainly of two components/sensors: the three semicircular canals which indicate angular acceleration (rotational movements) in three planes, and the two otolith organs (the saccule and/or utricle) which indicate linear acceleration (gravitational and translational movements) (Byrne et al., 1997). Their associated receptor cells will send signals through the vestibular nerve fibers to structures that affect posture, balance and movement of the eyes (Byrne et al., 1997). Otolith crystals (octonia), found within the saccule and utricle, are made of calcium carbonate ($CaCO_3$) and after a head injury (among other causes) they can become dislodged from the gelatinous matrix that they typically adhere to (Byrneet al., 1997). Upon dislodgement, these crystals can migrate to other areas of the inner ear including the semicircular canals (Byrne et al., 1997). This re-location can cause reported symptoms of nausea, dizziness and loss of balance as our brain receives confusing signals on linear versus angular accelerations (Byrne et al., 1997). This system can be disrupted with a concussive injury.

1.1.4- The Somatosensory System

The somatosensory system is concerned with perception of pain, pressure, position, temperature, touch, movement and vibration in a conscious state (Byrne et al., 1997). This complex system contains various receptors that contribute to somatosensation, such as photoreceptors, mechanoreceptors, chemoreceptors and thermoreceptors (Byrne et al., 1997). We experience these sensations from signals returned to the brain from our joints, muscles, skin, and fascia. Signals are sent from our periphery (the foot, for example) through pathways along the spinal cord, brainstem and then to the brain to create the desired response (Byrne et al., 1997). The majority of what we accomplish during the day, including our ability to maintain good postural control, relies on both proprioceptive and cutaneous input (Seel, 2012). Proprioception (the ability to know where our body is in space by use of sensory feedback taken from the environment and the body and sent to the brain) is derived from the parietal lobe of the cerebrum, the brainstem, the cerebellum, muscles spindles (sensory receptors that detect changes of length in a muscle) and golgi tendon organs (sense changes in muscle tension) (Seel, 2012; Byrne et al., 1997). Muscle spindles are thought to be responsible for joint position sense, and it is thought that these muscle spindles are found in higher concentration (than the limbs, for instance) within the intervertebral muscles of the spine (Abrahams, 1977; Bakker and Richmond 1982). Cutaneous input, on the other hand, is derived from our skin, where hundreds of sensory nerve endings can send a message to the brain when experiencing such sensations as a simple pin prick, for instance (Byrne et al., 1997).

Assessment of other affected areas of the body is also important as balance may be affected from proprioceptive loss from the neck, an ankle, a knee, or a back injury for instance, and not from the brain itself. A common potential culprit of issues with postural control is loss of communication between the cervical region of the neck and the brain (Armstrong et al., 2008). This loss of communication can disrupt normal function of our muscles, nerves, joints and skin, which in turn can lead to reduction in normal proprioceptive input (Armstrong et al., 2008). Head and neck position sense impairments are commonly seen post whiplash injuries, but other conditions and injuries can cause this as well (Sterlinget al., 2003; Treleavenet al., 2003). Whiplash injuries are often observed in sports, and are often times coupled with a concussion injury (or the cause of a concussion injury in some cases). Often times, when the neck is affected, an individual may present with all or some of the following: an abnormal head tilt, head rotation, dizziness/vertigo, reduced range of motion, tension throughout the cervical muscles or simply a subjective reporting of neck pain; or only palpable findings are present. A practitioner trained in this area should be able to differentiate between neck and vestibular issues as the cause of dizziness or alterations in balance, by simple orthopedic tests. Neck problems are common after a concussion as the majority of these individuals will suffer a neck injury (such as whiplash) and brain injury simultaneously. Once again, correct identification of these deficits allows for appropriate rehabilitation of affected structures and their associated functions.

Understanding the actual cause (or contributor) of reduced postural control, rather than only assuming, may speed recovery by allowing for the most appropriate form of rehabilitation: a focus on vestibular rehabilitation vs ankle rehabilitation for instance.

1.1.5- The Visual System

Visual detail is processed by the visual system, a component of the central nervous system. Information from visible light is detected and interpreted in order to understand our surroundings. Of the three sensory systems involved in balance, input from the visual system is given the greatest sensory weighting (Hansson et al., 2010). Many studies have shown that there is an increase in postural sway with the simple act of closing the eyes, demonstrating the importance of the visual system on postural control (Barela et al., 2011).

Binocular vision (which enables depth perception by combining input from both eyes for vision) and monocular vision (using only one eye for vision) (Byrne et al., 1997) are also important variables for postural control. Vision disorders are common post-mTBI, with an array of different possible clinical findings (Green et al., 2010; Fox, 2005; Ciuffreda et al., 2008). Abnormalities in accommodation, visual acuity, convergence and visual field integrity are among some of these clinical findings and are collectively referred to as post-trauma vision syndrome (PTVS) (Green et al., 2010; Fox, 2005; Ciuffreda et al., 2008); referring to changes in normal binocular vision.

Although this abnormal function can improve over time, due to natural history alone, it could potentially persist and leave an individual with long lasting mild, moderate or severe symptoms (Padula et al., 1988). Children (excluding infants, as binocular vision is not completely developed at this age) and adults who suffer from impairments in binocular vision (even in the absence of a known concussion) can experience problems with depth perception, which may lead to dizziness, double vision and loss of, or reduction in, postural control (Padula et al., 1988). Reduction in binocular vision can result in trouble concentrating, eye strain, difficulty focusing on images or words, and headache-like discomfort (Padula et al., 1988). For individuals that experience abnormal posture or double vision, eye patching or prism lenses can help alleviate this issue (Padula et al., 1988)

Assessment of eye function, including binocular vision, is a component of baseline concussion testing and post-mTBI management. If deficits are detected, appropriate eye therapy (at-home, and/or in-clinic) can allow for return of normal function, and therefore reduction in symptoms (Padula et al., 1988). Individuals that have underlying or pre-existing issues with their vision may experience exacerbation of the above signs and symptoms post-concussion. Conflicts arising from our visual system can have compelling effects on postural control (Redfern et al., 2001). Healthy adults can experience postural changes, motion sickness and disequilibrium when exposed to moving visual environments, for instance (Redfern et al., 2001).

Each of the three main sensory systems involved with postural control (visual, vestibular and sensorimotor) operate at different frequency ranges (see below). These different frequency ranges will affect their influence on balance in different situations (Redfern et al., 2001). The frequencies overlap, and proper integration of these systems require that the inputs are correctly weighted in a given situation.

The visual system is reported to operate at a frequency of <0.1Hz, enabling it to respond to an object that is moving slowly in the visual field (Dichgans et al., 1976; Lestienne et al., 1977)

The vestibular system's otoliths and semicircular canals are reported to operate at a frequency of 0.5 Hz and 0.5-1.0 Hz respectively. For example, the otoliths will be activated to provide input when standing on a unstable surface with the eyes closed; whereas the semicircular canals are activated during quick head rotations, which requires integration of head and eye movement control (Nashner et al., 1989);

The somatosensory system is reported to operate at a higher frequency of >0.1 Hz, and is used to control one's head position with respect to the torso (Diener at al., 1984).

Sensory system issues, such as loss of or reduction in balance abilities, generally occur when there is conflicting information between visual and/or proprioceptive signals and vestibular information (Redfern et al., 2001). When one system functions less than optimally, adjustments needs to be made in the integration process in order to determine the correct orientation in space to create the most fitting motor response (Redfern et al., 2001). When central or peripheral vestibular disorders exist, issues with resolving these conflicts can occur (Redfern et al., 2001) which may result in increased postural sway, particularly under challenging conditions.

1.2 Postural Sway [Balance] Assessment Tools

The literature demonstrates various forms of balance testing, both subjective and objective in nature. This section of the literature review will analyze the following measures of balance abilities: self-reported loss of balance and dizziness; Sport Concussion Assessment Tool-3 (SCAT-3); The Balance Error Scoring System (BESS) and the Modified Balance Error Scoring System (mBESS); laboratory force platform technology; portable force platforms; triaxial wireless accelerometers (industry standard); the Balance Accelerometer Measure (BAM); iOS technology (accelerometer based); Romberg's test; the Balance Evaluation Systems Test (BESTest); the Clinical Test of Sensory Organization (Interaction) and Balance (CTSIB); Romberg's Test; the Tinetti Test of Balance; and the Berg Test of Balance.

Balance assessment tools are not meant to replace a medical exam. If a concussed athlete demonstrates any 'red flags' (i.e. warning signs) upon presentation, emergency referral should be given. When administering all tests of balance ability, examiners should ensure that the testing environment is appropriate to the test's requirements and that distractions or obstacles are not present. The examiner must also be present, at close distance, to spot the tested athlete in the event of a fall.

1.2.1- Self-Reported Symptoms of Loss of Balance and Dizziness

Questions regarding symptoms post-concussion should be asked immediately post-injury and on every subsequent clinical visit. In terms of balance, questions should include all or some of the following: 'are you experiencing dizziness?'; 'are you feeling off balance?'; 'are you feeling as though everything around you is spinning? ; do you feel as though you are spinning?'; 'are you having trouble focusing?'; 'do your eyes hurt?'. These questions are subjective in nature and should be asked in addition to completing objective testing (discussed below). It is important to know that even after an individual no longer reports any issues relating to their postural control, that objective balance testing (and any other required testing) should continue until the results indicate probable recovery.

1.2.2 The Sport Concussion Assessment Tool-3 (SCAT-3)

The Sport Concussion Assessment Tool-3, or SCAT-3, is a standardized method of evaluating an injured athlete for a suspected concussion. This test can be done on the sideline of a game or practice and is meant for persons aged 13 and older (McCrory et al., 2013). This assessment contains objective measures of cognitive and physical abilities and various subjective questions, including those relating to balance and dizziness (unsteadiness). This test does not confirm that a concussion has or has not occurred but is instead used as a screening tool. The scoring summary includes a brief evaluation of presenting symptoms, cognition, *balance* and coordination (McCrory et al., 2013). This test is designed for use by a qualified medical professional, otherwise a Sports Concussion Recognition Tool is available for use; if under the age of 13 the Child SCAT-3 should be used (McCrory et al., 2013).

1.2.3- The Balance Error Scoring System (The BESS)

Historically, baseline and post-concussion balance assessment has most commonly been measured with the use of the Balance Error Scoring System (the BESS), which measures postural sway using two measures: a flat stable surface (ground) and a foam pad (unstable surface) (Bell et al., 2011). The BESS requires subjects to have their eyes closed and hands on their iliac crest for each 20-second position, which includes double, single and tandem leg stances bilaterally done on a flat surface and then on a medium-density foam pad (see figure 3) (Bell et al., 2011):

1. Double leg stance- feet together with legs straight

2. Single leg stance- standing on non-dominant leg. The dominant leg is lifted at approximately 30 degrees of hip flexion and 45 degrees of knee flexion.

3. Tandem leg stance- standing heel to toe with the non-dominant foot at the back

The examiner counts the number of errors (deviations from the required position) that occur throughout each position, including: moving hand(s) off of the iliac crest (top lateral part of pelvis); opening the eye(s); step stumble or fall; abduction of hip beyond 30 degrees; lifting the forefoot or heel off of the testing surface; and remaining out of the proper testing position for greater than 5 seconds (Bell et al., 2011). Ideally this test is done prior to the start of the athletic season (at baseline) and re-tested at least one time per year. If this is a post-concussion test, final scores are compared to the individual's baseline score or established normative data (Iverson et al., 2013), depending on what is available. A maximum of 10 errors can occur for each position, and if multiple errors are completed simultaneously then only one error point is assigned (Khanna et al., 2015).

Although it is useful for baseline balance ability and post-concussion assessment, this measure may be subject to intra- and inter-examiner errors due to its obvious subjectivity.

Studies have also demonstrated that results of this test may be influenced by the type of sport played, fatigue, exertion, and previous ankle injuries or instabilities (Dziemianowicz et al. 2012). However, the BESS system has demonstrated good to moderate reliability for detecting balance differences when used by the same test administrator (Guskiewicz et al., 2001). In a randomized control trial by Mulligan et al. (2013), a learned effect (reduction in the number of errors with subsequent testing) was demonstrated in college-aged adults. This effect was seen even after 4 weeks of testing balance (with the BESS), which may limit its clinical use post-concussion (Mulligan et al., 2013). In another study by Valovich et al. (2003) a practice effect was seen with repeated administration of the BESS in high-school aged athletes, but this diminished after 3 weeks (unlike the college-aged group). This suggests that a difference exists in learned effects of the BESS between different age brackets. This brings up an important concept: is this change related to a learned effect or are balance abilities for certain age groups improving with indirect or unintentional training? In a study by Burk et al (2013), BESS performance was followed over a 90-day intercollegiate athletic season (2 assessments total; immediately pre and post season). Statistically and clinically significant differences were observed with the BESS scores post 90 day season, suggesting that a training effect occurred in the athlete's balance skills (Burk et al., 2013). This study may indicate that repeated baseline testing throughout the year should be done in order to know the athlete's true balance ability.

A systematic review completed by Murray et al. (2014), suggested that there was not published data available on the reliability or validity for the force plate Sensory Organization Test (SOT), Romberg test and the Wii Fit for assessing individuals who have sustained a concussion (these tests discussed later). The BESS however, was shown to have high reliability (but low validity) for use in concussion assessment (Murray et al., 2014).

In a study by Brown et al. in 2014, 30 young healthy physically active male and female subjects were recruited to participate in a study assessing balance by use of the Balance Error Scoring System and triaxial accelerometers (sensors that detect accelerations). The authors developed an algorithm to calculate an objective BESS (oBESS) system using data collected from small wireless sensors (Brown et al. 2014). The sensors were placed on the forehead, sternum, anterior waist, right and left wrist, and right and left shin and the subjects completed the BESS protocol (Brown et al. 2014). The authors of this study found that the oBESS was able to reliably predict total BESS scores in these healthy subjects. The results of a study by Finnoff et al. (2009) suggested that specific sub-categories of the BESS have sufficient reliability in evaluating postural sway but that the *total* BESS score of the 6 stance positions is not reliable (Finnoff et al., 2009). Furman et al. 2013 found that the tandem leg stance positions of the BESS best discriminated between concussed and non-concussed individuals. This study also found that the BESS was useful for discriminating between concussed and healthy persons beyond the 3rd day of injury (Furman et al. 2013). A study by Register-Mihalik et al. 2013 however, found that BESS scores returned to baseline 3 days after injury.

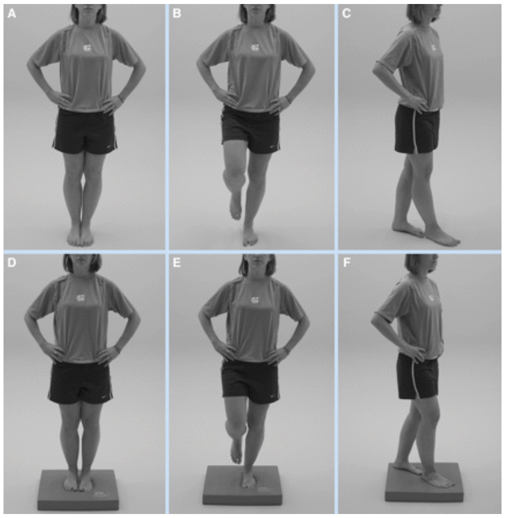


Figure 3- The BESS (Bell et al., 2011)

A *modified BESS* (mBESS) is included in the Sport Concussion Assessment Tool-3 (SCAT-3), and is meant to be a fast balance assessment completed on-field when a concussion is suspected. This test includes 3 standing positions held for 20 seconds, with the eyes closed, on a flat stable surface (rather than including the foam condition- the only eliminated variable):

1. Double leg stance- feet together and legs straight

2. Single leg stance- standing on non-dominant leg. The dominant leg is lifted at approximately 30 degrees of hip flexion and 45 degrees of knee flexion.

3. Tandem leg stance- standing heel to toe with the non-dominant foot at the back

For the modified BESS test, errors are calculated in the same fashion as the original BESS test. A 2012 study found no difference, using the modified BESS test, between high school students with and without a concussion (Valovich et al., 2012). The authors of this study reported that the modified BESS may have a ceiling affect and that the implementation of the foam surfaces to testing (the full BESS) may help differentiate between those who have suffered a concussion and those who have not (Valovich et al. 2012).

1.2.4- Force Platform Technology

In terms of terrestrial locomotion, centre of pressure (CoP) can be measured by a force plate to determine balance ability or degree of postural sway. Centre of pressure refers to the point of application of the ground reaction force vector which represents the addition of all forces that act between an object (human) and a support surface (force plate) (Rohleder, 2012; Hubbard et al., 2012).

Standard Laboratory Force Platform Technology

Laboratory Force Platform Technology, the current market gold standard for balance testing, is an objective instrument that measures ground reaction forces that are generated by a body standing on or moving across a force plate (Rohleder, 2012). It is most commonly used to analyze/quantify gait and balance in sports and medicine. This assessment tool uses centre of pressure (CoP) path length as its primary outcome measure (Hubbard et al., 2012) and will quantify ground reaction forces that are generated by a body standing on or moving across a force plate (Rohleder, 2012). Most laboratory force plates used today are advanced enough to measure: force in its three-dimensions (x, y, and z), centre of pressure, and the vertical moment of force. Specifically, these three directions are referred to as Fx (horizontal width), Fy (horizontal length) and Fz (vertical).

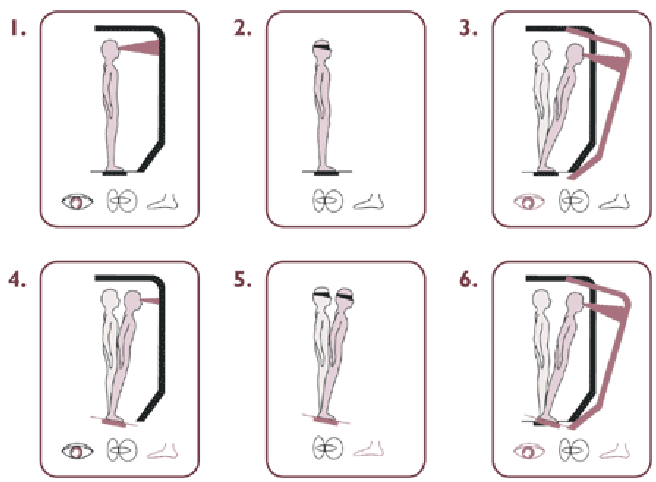
For the purpose of static balance assessment, individuals stand on the force plate with their eyes closed, and often with their shoes off. The positional protocol can be similar to the BESS, but scores are mechanically derived and therefore objective. Laboratory force platforms, such as Acuforce™ by AMTI are considered highly objective but are very expensive, with poor accessibility and portability (Rohleder, 2012). Although portable versions do exist, they are still expensive and not ideal for on-field use.

Sensory Organization Test (SOT)

Sensory Organization Testing (SOT) is an example of a complex or high technology force platform (see diagram 1). The SOT attempts to alter visual and somatosensory referencing, by placing patients under six different sensory conditions (20-seconds per condition) that involve changes in their support system (what they stand on) and their visual surround (what they see). This system will effectively remove or conflict sensory inputs. This is done through the following positions, while harnessed for safety (Nashner, 1990):

1. Eyes exposed, no change in visual surround or support system (force plate)
2. Eyes covered, no change in support system
3. Eyes exposed, visual surround altered, support system neutral
4. Eyes exposed, support system altered, visual surround neutral
5. Eyes covered, support system altered
6. Eyes exposed, visual surround and support system altered.

This technology monitors the three systems of balance: visual, somatosensory and vestibular by effectively eliminating any useful information (for balance) that would be ordinarily delivered to the patient's eyes, feet and joints. This is done through calibrated 'sway referencing' of the support surface and/or the visual surround that tilts in order to follow the anteroposterior sway of the patient. This in-depth assessment measure can help differentiate between the different causes of balance issues- visual, somatosensory or vestibular (Nashner, 1990).



Sensory Organization Test

Diagram 1- SOT (Natus Balance & Mobility 2015)

In a study by Wrisley et al. (2007), healthy young adults had their balance tested with the SOT device, with 5 repetitions over a 2 week period, to determine if a learning effect occurred. A learning effect was observed and appeared to plateau around session 3 and 4 and was primarily seen in the composite score of conditions 4 through 6 (Wrisley et al., 2007). This study suggested that multiple sessions of the SOT should be administered if used for baseline balance scores in order to account for change that occurs from practice (Wrisley et al., 2007). Another finding showed that improvements of more than 8 points in the composite score indicated recovery that was beyond what would be expected from the learning effect of the SOT itself (Wrisley et al., 2007).

As stated earlier, force platforms, the current market gold standard, are considered highly objective but are very expensive, with poor accessibility and portability (Rohleder, 2012). In addition, this type of testing using sway referencing could create sensations of nausea in concussed patients, possibly affecting test completion.

Due to the impracticality of laboratory force plate technology for clinical and side-line settings, Riemann and Guskiewicz (2000) assessed the use of the BESS and compared it to the SOT. Sixteen subjects with mild head injuries (assessed using the BESS and the SOT on day 1, 3 and 5 post-injury) and 16 matched controls (Post-test control group design with repeated measures) were recruited for the study (Riemann and Guskiewicz, 2000). Results of the study suggested that, in the absence of the force platform technology, the BESS may be a good clinical tool to assess balance and aid with return to play decisions (Riemann and Guskiewicz, 2000).

***Portable* Force Platform Technology**

Portable force platform technology allows for balance testing outside of a laboratory. Cost of this equipment will vary, as will their conduciveness for on-field assessment. Acuforce™ by AMTI and the Nintendo Wii Balance Board (WBB), offer solutions for those who require force plate use outside of a lab. The Nintendo Wii Balance Board, in particular, has gained popularity over recent years in assessing and training human balance.

Nintendo Wii Balance Board (WBB) - Portable Force Platform

A comparable alternative to laboratory force platforms, is the Nintendo Wii Balance Board (WBB). This posturography tool is commercially accessible, low-cost, and shares many similar characteristics with the more traditionally used laboratory force plates (Hubbard et al., 2012). In a study by Hubbard et al. (2012) healthy subjects without a history of vestibular problems, participated in WBB testing and matched testing on the Acuforce™ by AMTI. Post testing examination of the WBB transducers demonstrated excellent linearity ($r= .994$, $p<.0001$) (Hubbard et al., 2012). The results of study suggest that the WBB could be used for longitudinal telemetry (measurements taken remotely) and in-home testing, and its additional beneficial features include its portability, low-cost and commercial availability (Hubbard et al., 2012).

Another study by Clark et al. (2010), examined the reliability and validity of the WBB and compared it to the AMTI laboratory force platform. Thirty subjects were recruited, without having any lower limb pathology, to perform a combination of single and double leg standing balance tests with the eyes open and then closed, and in two different conditions (Clark, R et al., 2010). Intraclass correlation coefficients (ICC), Bland-Altman plots (BAP) and minimum detectable changes (MDC) were used to compare the WBB with the force plate data and for their test-retest reliability (Clark et al., 2010). The results showed good to excellent centre of pressure (COP) path length test-retest reliability of both balance devices (within-device ICC= 0.66-0.94; between-device ICC= 0.77-0.89) on each of the testing protocols. The Bland-Altman plot (BAP) did not show a relationship between the difference and the mean within any test and the minimum detectable change values for the WBB exceeded the values of the laboratory force platform in 3 of the 4 tests (Clark et al., 2010). Findings of this study suggest that the WBB is a valid standing balance assessment tool (Clark et al., 2010).

1.2.5- Triaxial Accelerometers and iOS Devices

Accelerometers are small battery operated devices used to detect accelerations-movement, and velocity of movement. Frequently, piezoelectric (electric charge generated in response to applied mechanical stress) accelerometers are used to measure movement in one to three planes. Tri-axial accelerometers, as used commonly in human movement laboratories, can be used to monitor human movement in 3 dimensions (x, y and z) within various situations (Currie et al, 1992; Evans et al., 1991; Mayagoitia et al., 2001; Kamen et al., 1988). Multiple accelerometers are commonly used at the same time on various areas of the body. Accelerometers can be found as small wearable sensors or within mobile devices and have shown to be consistent and reliable (Patterson et al., 2014; Amick et al., 2013). Accelerometers eliminate self-report bias because they do not depend on subject recall and they are of benefit for human movement because they can measure movement in all geometric planes (Riekert et al., 2014). Limitations are noted when accelerometers are used without supervision and when being used to detect dynamic movements in compared to static ones (Riekert et al., 2014). Validation studies have demonstrated that accelerometers tend to underestimate energy expenditure, and are less accurate in detecting complex activities, water activities, strength training and upper body movement (Riekert et al., 2014). However, for the purpose of testing standing balance ability in a controlled environment, this method appears to be a valuable tool. Small triaxial accelerometers are also found in iOS devices (such as an iPad, iPhone and IPod), which make their use convenient and inexpensive.

iOS Devices for Postural Sway Assessment

iOS devices, such as the Apple iPad, iPhone and iPod, are designed with a built-in triaxial accelerometer. The accelerometer is used to detect changes in device position in the x, y and z direction for use with various different iOS compatible applications. This technology utilizes the built-in low power MEMS accelerometer (MEMS- a microelectromechanical system which measures static and/or dynamic forces of acceleration) found within an iOS mobile device to estimate stability (www.swaymedical.com). iOS devices are a unique research tool because they possess numerous capabilities including the ability to store data securely and wirelessly to remote locations. They are portable and relatively low-cost devices. Some studies have demonstrated that the iOS device accelerometers have the capability to accurately measure postural sway with sufficient consistency (Lemoyne et al., 2010; Lemoyne et al., 2011), however more research needs to be done to assess the validity and reliability of the accelerometry function of smart phone devices

A 2014 pilot study by Khoo Chee Han et al. analyzed the accuracy, consistency and reproducibility of the tri-axial accelerometer found within the iPod Touch devices. After the device was calibrated it was secured to a string and dropped 100 cm, 30 times (Khoo Chee Han et al., 2014). This study showed that the iPod accelerometer displays very high accuracy and sensitivity to capture acceleration data under various conditions (Khoo Chee Han et al., 2014).

In a study Mayagoitia et al. (2001) 8 male students (aged 23-34 years) were assessed for balance abilities using a triaxial accelerometer belt (Mayagoitia et al., 2001). This belt was placed around the posterior trunk at the approximate level of the whole body centre of mass, and subjects were asked to stand on a force platform (AMTI). The participants stood in four different stance positions (Mayagoitia et al., 2001):

CPEO- Feet comfortable position, eyes open, arms at side

CPEC- feet comfortable position, eyes closed, arms at side

FTEO- feet together, eyes open, arms at side

FTEC- feet together, eyes closed, arms at side

Paired t-tests showed that the accelerometer measurements in this study were able to discriminate between the different tests conditions as well as or better than the AMTI™ force platform (Mayagoitia et al., 2001).

In a study by Soangra et al. (2014), 12 healthy subjects wore a smart phone with a built-in triaxial accelerometer on their right anterior superior iliac spine (front of pelvis) while standing on a force plate. Results from this study showed a high correlation in the centre of pressure (COP) time series between the smart phone data and the force plate data (Soangra et al., 2014). In a second study (with two of the same authors as above) by Chung et al. (2014) smart phones with built-in triaxial accelerometers were used, fixed at the pelvic region, to investigate if the non-linear information of postural sway is similar to that derived from a force plate. The study found that the smart phone accelerometer can quantify the predictability of the non-linear postural sway dynamics in a similar fashion to what the force plate can, even though the dynamics of postural sway between the two devices provide somewhat different information (Chung et al., 2014).

Triaxial accelerometers, placed on specific muscles and joints of the body, can detect changes in acceleration in these areas during positional stances such as the double, single or tandem leg stance. Having this information may allow for identifying which muscles (of the hip vs the ankle for instance) play more of a role during certain stances than others, and which muscles are used more than others to counteract imbalance.

Diagram 2- Triaxial Accelerometers (Trigno^{TM} by Delsys)

1.2.6- The Balance Accelerometer Measure (BAM)

The Balance Accelerometer Measure (BAM) is a low cost balance assessment tool that is portable and easy to administer (Furman et al., 2013; Rine at al., 2013). This balance measure uses a dual-axis accelerometer attached to a gait belt and placed on the anterior midline of the pelvis (Furman et al., 2013; Rine at al., 2013). This measure was used to evaluate an individual's balance ability while performing 6 different standing positions, for 45 seconds per stance, with the arms crossed at the level of the chest (Furman et al., 2013, Rine at al., 2013):

1. Standing with feet side by side on a firm surface with eyes open
2. Standing with feet side by side on a firm surface with eyes closed
3. Standing with feet side by side on a foam surface with eyes open
4. Standing with feet side by side on a foam surface with eyes closed
5. Tandem stance on a firm surface with eyes open
6. Tandem stance on a firm surface with eyes closed.

Subjects who could not complete a particular stance condition within 3 attempts are arbitrarily assigned the maximum standard score for that specific stance condition (higher score equating to poorer balance) (Furman et al., 2013; Rine at al., 2013).

Furman et al. (2013) evaluated balance abilities, at various time points, in 43 concussed high school students and 27 healthy controls. The purpose of this study was to compare the ability of the BAM and the BESS in distinguishing between concussed and non-concussed individuals. (Furman et al., 2013). The expectation of the researchers completing this study was that the BAM would be better at identifying concussed patients than the BESS, as the BESS scores are derived from the examiner's subjective observation and the BAM scores from objective measurement (Furman et al., 2013). This study showed that the BAM was not as sensitive at identifying a concussed person but was better at assessing balance (objective), than the BESS (Furman et al., 2013). It is important to know that this statement assumed that baseline scores were not available (Furman et al., 2013). The BAM was not specifically designed for concussion assessment (Furman et al., 2013; Rine at al., 2013) but if baseline scores were available then the BAM may in fact be useful for this purpose. The researchers in this study then re-analyzed their data using only the firm stance conditions (a modified version of the

BESS) and found that the mBESS (from the SCAT-2) did not distinguish between concussed and non-concussed individuals in this study (Furman et al., 2013). This may indicate that using the foam surface as part of the testing protocol may help distinguish between concussed and healthy persons.

1.2.7- The Sway Balance™ System by Sway Medical- iOS Device Application

As mentioned earlier, iOS devices, such as the Apple iPad, iPhone and iPod, are designed with a built-in triaxial accelerometer. The accelerometer is used to detect changes in device position in the x, y and z direction for use with various different iOS compatible applications. This technology utilizes the built-in low power MEMS accelerometer found within an iOS mobile device to estimate stability (www.swaymedical.com). A motion analysis algorithm calculates stability, by estimating total thoracic sway, while the device is held/pressed against the chest (www.swaymedical.com). In early 2013, a device called the Sway Balance™ System was introduced as tool to assess the presence of balance dysfunction pre and post-concussion, and to develop normative (baseline) balance data for an individual. Sway Medical is a software company that is focused on developing and reinventing objective measures of medical outcomes (www.swaymedical.com). Their main product, the Sway Balance™ System, is an FDA-cleared mobile software application (www.swaymedical.com). Their website states that the system allows athletes and patients to be monitored for dysfunctions in the musculoskeletal, neurological and vestibular systems by using the tri-axial accelerometer located within an iOS device (www.swaymedical.com). This assessment is administered by a qualified healthcare provider (www.swaymedical.com). For the purpose of this device application, sway is defined as: any movement detected in the thoracic planes (anterior-posterior [AP] and medial-lateral [ML]) throughout various positions without the use of the visual system. (www.swaymedical.com).

A device verification feature is available within this app that ensures accelerometer scores have not been affected by mechanical failure (www.swaymedical.com). The 3-second verification tool is used to ensure that the iOS device is not recording accelerometer values that are abnormal; outside of the sensitivity threshold (www.swaymedical.com). Multiple baseline tests will allow for a practice effect by the user and the examiner in order to yield more accurate results (www.swaymedical.com). After more than one test, the average score is automatically/mechanically calculated but individual scores per test and per condition may also be analyzed (www.swaymedical.com). An athlete's/individual's recovery can be tracked, and variations from normal/baseline can be determined by viewing simple graphs (motion data) (www.swaymedical.com). The score assigned after each test, however, is not broken down into ML and AP components, which would be of value as research has demonstrated that ML sway may be a better indicator of fall risk then AP (Park et al., 2014).

Sway Medical states that they have ensured compliance with all current medical device quality regulations and standards (www.swaymedical.com). In assuring the validity of the device, various balance conditions and foam and non-foam surfaces were studied to allow for optimal comparison between other measures such as the BESS and force platform technology (results discussed in later sections) (www.swaymedical.com). More recently, Sway Medical has extended their application's capabilities to include fall risk assessment, for the elderly and for those with Parkinson's disease (a progressive disorder of the nervous system that impacts human movement), and reaction time.

For the assessment of postural sway, an iOS mobile device is held by the patient statically and instructions are described out loud and in fine detail. Each person holds the device against their chest and follows the on-screen prompts (www.swaymedical.com). There are 5 required 10-second body positions which include the double, single and tandem leg stance, all with the eyes closed, and on a solid stable surface (www.swaymedical.com). Athletes are to be closely supervised to avoid inaccurate use by limiting the following: hip abduction, opening the eyes, bending the knees to increase stability during the double leg stance and resting an elevated leg against the planted leg or resting the foot/toes on the ground during the single leg stance (www.swaymedical.com). If the sway test was not performed correctly (i.e. errors were not corrected immediately) the athlete would have to re-start the test for the most accurate baseline or post-concussion results (www.swaymedical.com). This test mimics the BESS, however postural sway is evaluated objectively, without the use of a foam surface, and with two additional stances (both legs for the tandem and single leg stances- rather than only testing one leg in each position).

The Sway Medical website states that "studies on the reliability, validity and usefulness of the Sway Balance™ System have been verified in multiple fields of study including exercise physiology, biomedical engineering, biomechanics and neuroscience (www.swaymedical.com)." Further it states that under a research partnership with Wichita State University, verification and comparison studies of this system were performed and test-retest reliability was shown using the Sway Balance™ System (www.swaymedical.com). The website continues to state that testing of the sensitivity of the iOS device for use in postural sway estimates was completed by Wichita State University, and the department of mechanical engineering determined that the accelerometer sensitivity in random samples of iOS devices was well within manufacturer's acceptable range (www.swaymedical.com). It also demonstrated consistency through low coefficients of variation (www.swaymedical.com). It was then concluded that the downloadable Sway Medical app is expected to record acceleration values (thoracic sway) accurately (www.swaymedical.com). Interestingly, the website does not include references to this material in the peer reviewed literature, making it impossible to assess the research completely. Sway Medical also states that the Sway Balance™ System has demonstrated more accurate results than scores gathered with Force Platform Technology in some studies (www.swaymedical.com). Greater accuracy was observed with the Sway Balance™ System in differentiating between balance conditions and demonstrated within subject significant differences between foam and non-foam conditions, and unstable (one foot) and stable (two foot) conditions than with force platform technology (www.swaymedical.com).

In 2014, Patterson et al. compared the Sway Balance Application to the Biodex Balance System SD. Thirty healthy college-aged individuals were recruited and asked to perform one trial of the Athlete's Single Leg Test protocol on the Biodex Balance System SD while simultaneously measuring postural sway with the Sway Balance™ App (Patterson et al., 2014). The Athlete's Single Leg Test protocol requires the person to stand on their non-dominant foot for ten seconds (Patterson et al., 2014). It is important to note that this study measured postural sway only in the anterior-posterior plane, rather than including the medial-lateral (Patterson et al., 2014). This was a pilot study and was limited in scope, however paired t-tests revealed no significant difference between the mean sway measures between both devices (p=0.818) and a significant correlation between the two devices was found with a mean difference of 0.030 + 0.713 and a correlation of r=0.632, p<0.01 (Patterson et al., 2014)

A study by Amick et al (2015) compared the Sway Balance^{TM} System to the abbreviated Balance Error Scoring System (or, the modified BESS found within the SCAT-3 protocol). Forty-four young healthy male adults were recruited to perform the modified BESS while using the Sway Balance System to assess balance (Amick et al., 2015). This study found a significant negative and moderate correlation (high score for the Sway Balance^{TM} System represents better balance, and a high score for the BESS represents poorer balance) between the modified (abbreviated) BESS and the Sway Balance System (r=0.601, P<.0001) (Amick et al., 2015).

Diagram 3- Sway Balance^{TM} System (www.swaymedical.com; Sway Medical LLC)

In 2014 Patterson et al. compared the Sway Balance System to the Balance Error Scoring System with 21 non-athletic healthy young subjects. A strong inverse (high score for the Sway Balance^{TM} System represents better balance, and a high score for the BESS represents poorer balance) relationship was found between both methods (Patterson et al., 2014). These results further demonstrate the likely validity of iOS technology for balance assessment.

The Sway Medical website states that greater accuracy was observed with the Sway Balance™ System in differentiating between balance conditions and demonstrated within-subject significant differences between foam and non-foam conditions, and unstable (one foot) and stable (two foot) conditions than with force platform technology (www.swaymedical.com), however there were no peer reviewed references provided to substantiate these claims.

As mentioned earlier, an obvious limitation of the Sway Balance™ System is that the score assigned after each test is not broken down into medial lateral and anterior posterior components. This feature would be of value as research has demonstrated that medial lateral sway may be a better indicator of fall risk than anterior posterior (Park et al., 2014), which may help with rehabilitation strategies.

1.2.8- Romberg's Test

Romberg's Test assesses balance abilities, often to assess for possible neurological damage, by removing or reducing visual sensory input (Khasnis and Gokula, 2003; Garcin, 1969). When the visual system is removed, somatosensory and vestibular systems must compensate for this loss (Khasnis and Gokula, 2003; Garcin, 1969). The test is completed by having the individual stand quietly, and often with their shoes off. The examiner may first observe the person with their eyes open to see if loss of balance occurs with the presence of visual feedback (Khasnis and Gokula, 2003; Garcin, 1969). The individual is then asked to close their eyes and remain still for as long as possible. A positive Romberg's test occurs when the person is unable to maintain balance (Khasnis and Gokula, 2003; Garcin, 1969). This test can be made more difficult by having the examiner lightly challenge the person by external perturbation, and by having the person position their feet in a semi-tandem or tandem stance (heel to toe); or by adding a foam pad (Khasnis and Gokula, 2003; Garcin, 1969).

Upon reviewing the literature, Murray et al. (2014) reported that they were not aware of any validity or reliability data for Romberg's test in those who have suffered a concussion. Reliability data is available for use of this test with other neurological disorders, such as Parkinson's disease (ICC 0.86 in a normal vision condition and 0.84 in the reduced vision condition) (Steffen and Seney, 2008). In 2011, Jacobson et al. determined that the Romberg test could only accurately detect dysfunctions in balance ability in 60% of people suffering from vestibular dysfunction and should therefore not be used as a screen for this type of impairment (Jacobson et al., 2011).

1.2.9- The Balance Evaluation Systems Test (BESTest)

Presently, the most comprehensive balance assessment test is called the Balance Evaluation Systems Test or the BESTest (Horak et al., 2009). This test was developed in 2009 by Horak (et al.) and is designed to assess all areas, independently, that may create human balance deficits in order to identify a specific cause. According to Horak et al. (2009) the six areas impacting balance abilities are: biomechanical constraints, stability limits/verticality, anticipatory postural adjustments, postural responses, sensory orientation, and stability in gait. The BESTest assesses 27 tasks with certain sub-items, for a total of 36 items (Horak et al., 2009); items are scored out of 4 with a higher number indicating better performance (Horak et al., 2009). The completeness of this test would allow for identification of specific causes of balance deficits in order to prescribe the most appropriate rehabilitation strategies. A study done in

2009 by Horak et al. (using 2 interrrater trials) examined 22 subjects with and without balance problems (ages 50-88), assessed with the BESTest by 19 therapists, students and balance researchers concurrently. Correlation between the BESTest and balance confidence (assessed with the Activities-specific Balance Confidence Scale/ABC Scale) measured concurrent validity ($r=.636$, $P<0.01$ (Horak et al., 2009). For the BESTest as a whole, the ICC for interrater reliability was .91; the ICCs for the 6 sections ranged from .79 to .96 (Horak et al., 2009). The Kendall coefficient of concordance among the raters, for the 36 individual items, ranged from .46 to 1.00 (Horak et al., 2009).

Although this test is comprehensive, it does not appear to be practical for regular use in baseline and immediate post-concussion testing due to complexity and the time it takes to administer.

1.2.10 Clinical Test of Sensory Interaction and Balance (CTSIB)

The Clinical Test of Sensory Organization (Interaction) and Balance attempts to measure balance by assessing the 3 systems involved in postural control- Visual, Vestibular and Somatosensory. This is done by altering the visual and support surfaces which would ordinarily provide visual and somatosensory feedback. Difficulty with these tasks (when visual and support systems are manipulated) may demonstrate that deficits exist with the vestibular system. This test was developed in 1986 by Shumway-Cook and Horak and involves 6 conditions:

1- Individual stands on flat surface with arms across their chest and hands touching shoulders. Feet are kept together (ankle bones touching) and the position is held for 30 second.

2- Same as condition 1 but with eyes closed.

3- Same as condition 1 but with a visual conflict dome placed on the head.

4- Same as condition 1 but standing on a 3 inch high density foam cushion.

5- Same as condition 4 but with eyes closed.

6- Same as condition 4 but with visual conflict dome placed on head.

It is suggested, by Horak and Shumway-Cook (1986), that each test be completed 3 times and a score (per condition) is given based on degree of sway:

1= minimal sway
2= mild sway
3= moderate sway
4=fall
A study by Blatchly et al. (1993) used the CTSIB test with 22 young adults. Test-restest and interrater reliability were strong ($r=.99$, $P<.01$), and the authors found that this test was most useful in identifying vestibular disorders rather than other causes of balance disorders (Blatchly et al., 1993). However the BESTtest, also developed by Horak (2009) and discussed above, is far more comprehensive and complete for identifying causes of balance disorders when compared to the CTSIB test.

According to a literature review by Murray et al. in 2014, no sensitivity, specificity or reliability measures have been reported using the CTSIB test in young, healthy individuals or individuals with a concussion.

1.2.11- Less Commonly used Balance Assessment Measures

The Tinetti Test of Balance

An additional tool used to assess balance is called the Tinetti test of balance or the Performance Oriented Mobility Assessment (POMA). Balance is measured in a seated, sit to stand, and standing position (17 activities total) (Tinetti, 1986). Scores range from 0-2, where a higher score indicates better balance (Tinetti, 1986). This test is typically used to assess fall risk, to aid in fall prevention, in the elderly. Literature is not available on its use for the assessment of balance in the concussed athlete. A systematic literature search by Kopke and Meyer (2006) et al. identified the Tinetti Test in 37 publications (for fall risk). The results of this search indicated a very wide variation in the 'name' of the instrument, test items, scoring details/methods, cut-off values and modifications in test execution, which in turn affects the validity and reliability of the test (Kopke and Meyer et al., 2006). The subjective nature of this test makes it a less favourable option for the purpose of baseline and post-concussion management.

The Berg Test of Balance

The final test of balance that will be discussed in this review is called the Berg Test of Balance. It is Similar to Tinetti test of balance but more detailed (14 activities that are common to everyday life) scored from 0-4, with a higher score indicating better balance. This test is used mainly for fall risk, to aid in fall prevention. The Berg balance test was found to have a relative inter-rater reliability of ICC = 0.98 and an intra-rater reliability of ICC = 0.99 (Berg et al., 1989). Similar to the Tinetti Test of Balance, there are also variations in the test name and protocol. In conclusion, literature is not available on its use with baseline or post-concussion testing, and the nature of the test assessment is very subjective.

The systematic review completed by Murray et al. in 2014 suggests that there is not published data on reliability and validity of the SOT, Romberg's test, CTSIB or Wii fit for balance assessments in concussed individuals. Additional studies on reliability and validity of these balance assessment tools are needed for use with healthy individuals, and those who have sustained a concussion (Murray et al. 2014).

1.3 Understanding how Structures and Function may Impact Balance

As mentioned earlier, various body systems must interact appropriately for good postural control. Due to system redundancy, compensation strategies allow for balance maintenance even when certain systems operate less than optimal. It is important to consider the variables that may impact a person's balance because most clinical tests of balance may not detect impaired balance unless compensation strategies fail. Due to this compensation, balance impairments may go unnoticed until advanced stages are reached. Familiarization of the potential variables that may confound a person's balance is important. These variables will vary depending on the population of concern (age, for instance). In order to account for all potential contributors to increased postural sway, a questionnaire should be completed similar to the one used in our study (see appendix B). Although other variables exist, those that may affect balance abilities in our study's population of athletes are discussed below.

1.3.1- Exertion and Fatigue

Certain portable balance assessment tools, such as the Balance Error Scoring System (the BESS) and the Sway Balance^{TM} System, will endorse themselves as being a sideline concussion screening tool. This would allow for a convenient, inexpensive, and fast assessment immediately after a suspected injury. However, it is important to consider the effect that exertion and fatigue may have on balance if these athletes are being tested immediately after exerting themselves. These post-injury scores may be not indicate true ability when comparing to their baseline. In addition, it would be important to consider the effects that exertion and fatigue may have prior to baseline concussion testing, possibly skewing the person's true balance.

Halil et al. (2009) investigated whether fatiguing exercise on a treadmill would affect the use of the Balance Error Scoring System (the BESS) as a scoring tool for balance. The subjects, males and females aged 18-26 (n=19), were assessed using the BESS before and after fatiguing exercise (Halil et al., 2009). A significant effect of fatigue was evident in men (P <0.05) and women (P <0.05) with the mean difference (pre and post-test) between men and woman not different from each other (Halil et al., 2009). The results of this study suggest that a fatiguing exercise (by use of a treadmill) can increase postural sway in healthy subjects, and this effect was sex-independent (Halil et al., 2009). A study by Wilkins et al. (2004) found similar findings as above, suggesting that balance testing should not be done immediately after a concussion occurs or immediately after exertion. These findings may suggest that if balance assessments are done when an athlete underwent fatiguing exercise immediately pre balance testing, that results may be skewed thereby affecting immediate return to play decision or later re-assessment scores. It may make sense that if a person's balance is being assessed post-exertion that normative data is developed for post-exerted states. An alternative testing option may be to wait a period of time before assessing balance immediately post exertion; which is dependent on the type of activity (aerobic, anaerobic or mixed). A study by Khanna et al. (2008) demonstrated that balance recovery post exertion occurred at: 15 minutes post aerobic exercise; 10 minutes post anaerobic exercise; and 20 minutes post mixed exercise. This is an important principle to apply when assessing a patient for balance deficits post exertion (for baseline or post injury purposes). This concept, however, requires further study.

1.3.2- Dehydration

In a study by Erkmen et al. (2010) balance performance was found to decrease after prolonged exercise without fluid intake in 17 physically active men. One hour of physical exercise (75%-85% of maximal heart rate) without fluid intake was followed by 20 minutes of rest without fluid intake (Erkmen et al., 2010). Balance was subsequently assessed in eyes open and eyes closed positions on a force platform (Erkmen et al., 2010). This study found an increase in postural sway with dehydration, so fluid intake during exercise may actually prevent this deficit in balance which may have impacts both during and after exertional activity (Erkmen et al., 2010)

1.3.3- Anterior Cruciate Ligament (ACL) Reconstruction

The anterior cruciate ligament is one of the four major cruciate ligaments supporting the human knee, and it can be damaged to variable degrees in sport activity. The ACL's main purpose is to resist medial rotation and anterior translation of the tibia (medial lower leg bone) with respect to the femur (thigh bone). Pivoting types of movements may lead to minor or major tears of the ligament with or without direct contact. Due to its crucial role in stabilizing the knee during movements such as planting the foot or pivoting, an ACL injury in an athlete may lead to necessary reconstruction in order to return to, or advance in, sport. According to some studies, biomechanical changes to the tibiofemoral joint are evident after an ACL injury (Barrack et al., 1989; Co et al., 1993; MacDonald et al., 1996). Sensorimotor and proprioceptive deficits are also seen post injury (Barrack et al., 1989; Co et al., 1993; MacDonald et al., 1996) and reconstructive surgery does not appear to restore this function in its entirety (Johansson et al., 1991; Kvist et al., 2004). A study by Paterno et al. (2013) evaluated postural sway in 98 young male and female subjects (56 ACL reconstruction athletes and 42 uninjured control athletes). All ACL reconstruction subjects had already completed physical rehabilitation and were cleared for return to sport prior to testing (Paterno et al., 2013). Dynamic postural sway assessments using the Biodex Balance System (a type of force platform) were completed on all participants (Paterno et al., 2013). Increased postural sway was seen in injured vs non-injured group. It would be probable that this difference would be even greater in individuals that had not undergone adequate post-operative rehabilitation.

1.3.4- Lower Back Pain and Lower Back Fatigue

Paraspinal muscles are muscles that contribute to the support and movement of the spine. Paraspinal muscle proprioception plays a role in postural stability, so it would be probable that lower back pain/dysfunction in an athlete may reduce this ability. In a study by Brumagne et al. (2008), the lumbar spine erectors and tibialis anterior muscles of participants were stimulated with vibration in order to elicit muscle fatigue and postural sway was measured using a force plate. Individuals with lower back pain of recurring nature showed differences in postural control strategies when compared to those without lower back pain (Brumagne et al., 2008). Instead of relying on proprioceptive feedback from lumbar (low back) spine paraspinal muscles, they relied on, or favoured, ankle muscle proprioception instead (Brumagne et al., 2008). An additional study done in 2011 by Johanson et al. revealed similar findings, but also found that lower back muscle fatigue, with or without pain, led to a decrease in postural control and a greater reliance on ankle muscle proprioception when on an unstable surface. Postural sway after lower back fatigue, however, was not increased in those with low back pain vs. those without lower back pain (Johanson et al., 2011). Learning multi-segmental control may improve postural abilities if athletes are able to switch from relying on lower back vs ankle proprioception on demand and with ease. This is a concept that needs to be investigated further, but is an important consideration when assessing an individual's balance.

1.3.5- Lower Limb Stretching

As a decrease in maximum voluntary contraction is observed after the stretching of a muscle, it would seem probable that this may have an effect on postural control; should the stretched muscle(s) be involved with postural control, that is. In a study by Lewis et al. (2009), passive pain-free (45 second; 3 reps; 15 second rest) lower extremity stretching was performed on healthy young adults immediately prior to balance testing (on a force platform) and EMG (muscle activity) measurements. Muscle groups that were stretched included the plantar flexors, hamstrings and gastrocnemius bilaterally, due to their involvement in postural control. No statistically significant effect on balance was found in males or females that had postural muscles stretched immediately prior to testing (Lewis et al., 2009). An additional study by Nagano et al. (2006) of 11 healthy athletic males found that stretching can impair static postural control ability. This affect was seen to a much greater extent while the eyes were closed, making its impact during sport of less importance (Nagano et al., 2006), but relevant for balance testing. Of interesting note, the inclusion of vision appeared to nearly negate the impact that stretch has on balance (Nagano et al., 2006). These studies did not investigate the effect that stretching of spinal erector and pelvic muscles would have on postural control.

1.3.6- Plantar Flexor Muscle Fatigue

The plantar flexor muscles are located at the back (posterior) part of the leg and the sole (plantar surface) of the foot and are used to help plant the foot on the ground when walking (the action of plantar flexion) and to stand up on the forefoot. These muscles include the gastrocnemius and soleus (calf) and the plantaris, flexor hallucis longus, flexor digitorum longus, and tibilais posterior (posterior leg and foot). These muscles also contribute to postural control as they are activated during standing and walking in order to help control one's position in space. Gimmon et al. (2011) investigated the relationship between localized plantar muscle fatigue and postural control. Ten healthy subjects were recruited, and foam surfaces were used to fatigue the plantar muscles and force plates were used to assess postural sway (Gimmon et al., 2011). Impairments in balance abilities were noted when plantar flexor muscles were fatigued, mainly within the sagittal (back to front or front to back) plane and these effects were greater in eyes closed vs eyes opened conditions, which was expected (Gimmon et al., 2011). This concept is interesting when applied to the balance assessment tool the BESS, which uses foam and non-foam surfaces to assess balance abilities. Trying to balance on a foam surface would activate the plantar muscles more than standing on a solid stable surface.

In 2014 Lima et al. investigated the effect that unilateral static stretching of the plantar flexors had on postural sway. Fourteen young, healthy, non-athletic subjects were asked to quietly stand on their dominant leg for 30 seconds after a static stretching protocol [6 sets of 45s/15s, 70-90% point of discomfort] (Lima, B et al., 2014). Muscle changes and postural sway were measured using surface electromyography (sEMG) and a force plate respectively (Lima et al. 2014). The results of the study indicated that static stretching does have an impact on balance abilities during the single leg stance, seen as an increase in centre of pressure (COP) area, but the effects were no longer significant after 10 minutes of rest (Lima et al., 2014).

1.3.7- Acute Lateral Ankle (Inversion) Sprains

The ankle contains numerous ligaments that support (stabilize) the ankle and contribute to proprioception (the ability to know where our body is in space). Lateral (versus medial) ligament sprains (inversion sprains) of the ankle are most commonly seen, with obvious deficits in proprioception noted, clinically, when not properly rehabilitated.

Akbari et al. (2006) discussed two types of proprioception: unconscious (reflexive) and conscious (voluntary). Thirty male multi-sport athletes with acute unilateral ankle sprains (grade I and II) were recruited for balance assessment using the Biodex Balance System (Akbari et al., 2006). Results indicated that post-acute lateral ankle sprains led to a greater deficit in reflexive proprioception than voluntary, although both were affected (Akbari et al., 2006). This study suggested that the importance of proprioceptive rehabilitation post-ankle sprain is important to assist with return of postural control, and reduction in incidence of sprain reoccurrence (Akbari et al., 2006).

An additional study by Arnold et al (2000) found that those with ankle instability have deficits in their postural sway control in both dynamic and static assessments. However, because these participants had existing ankle instability it is difficult to know with certainty whether their balance issues were pre-existing, or caused by acquired ankle instability (Arnold et al., 2009).

It is important to document an individual's injury history when assessing and re-assessing their balance. A brief ankle assessment (strength, flexibility and joint mobility) pre-balance testing may allow for improved preventative measures and proper injury rehabilitation.

1.3.8- Degree of Lumbar Lordosis

Evolution of the human structure has allowed for the acquisition of an 's-shaped' spine when viewed from laterally (from the person's left or right side). Distinct curvatures are associated with each region: the cervical, thoracic, lumbar and sacral regions or the neck, upper back, lower back and sacrum/tailbone respectively. The cervical and lumbar spine have adopted a concave shape (referred to as lordosis) and the thoracic and [to a lesser extent] sacral regions have adopted a convex shape (referred to as kyphosis). The purpose of these features is to allow for appropriate range of motion, create shock absorption and assist with balance. Many factors can contribute to either accentuation or reduction in 'normal' spinal curvatures such as, but not limited to: age, poor posture, injury, disease and genetics.

In 2009, Johnson et al. evaluated the relationship between the curvature of the spine and balance in 25 healthy young adults. A force plate was used to measure postural sway in the sagittal (mediolateral) and frontal (anterioposterior) plane and a Microscribe 3DX Digitizer to measure degree of spinal curvature (Johnson et al., 2009). Participants were asked to stand on the force plate (30 second reading) for 15 minutes and balance measurements were taken at the beginning and end of this time period (Johnson et al., 2009). A significant positive correlation was found between degree of lumbar lordosis and anteroposterior sway at the start of the 15 minutes ($r=0.398$, $p<0.05$) and the change in mediolateral sway at the end of 15 minutes was also significant ($p< 0.05$) (Johnson et al., 2009).This study concluded that there was an increase in mediolateral sway and anteroposterior sway with increasing spinal angles in the sagittal plane and frontal plane respectively (Johnson et al., 2009).The findings of this research study suggest the possibility of identifying those at risk of falling, based on spinal curvatures measurements, and rehabilitating them to assist with injury prevention (Johnson et al., 2009).In the event that there is a distinct [visual] accentuation or reduction in spinal curvatures, it may be worth noting this during any physical examination related to balance.

Although other variables that may affect postural control (balance) exist, the above listed factors appear to be most relevant to a population of young, healthy athletes. It is important to measure all potentially confounding variable of balance in order to account for their possible impact on postural control.

1.4- Discussion

There is much more involved in concussion management than the simple statement: “you’ve experienced a concussion, take a few weeks off of sport activity”. Although this method of management is very common, it may be causing more hurt to the injured athlete, in the short and long term. Assessments post-concussion need to be thorough, and encompass all potential areas of deficit, targeting the [probable] cause and managing it effectively. It is also crucial to consider, and document, all of the possible variables that may confound a person’s true balance. Since problems with postural control are multi-factorial, it is important that all potentially affected areas are considered. This includes, but is not necessarily limited to, the vestibular, visual and somatosensory systems. Proper postural control requires accurate integration of these 3 systems, and depression of one may supress another. All three systems should be examined and treated as separate entities with consideration on how they must all work together for proper execution. Dependency lies on the health care provider managing each concussion case, as imaging and other markers are not yet advanced enough to provide important clinical information.

While research continues to elaborate on the complex nature of balance and concussions, on their own and together, there are some important future research directions to consider. It is understood that balance is affected by a mild traumatic brain injury; that balance ability is multifactorial; that it is important to document baseline balance abilities before such injury should occur; and that rehabilitation of balance, if a balance deficit exists or may exist, should be part of the recovery process. However, what is not completely understood is what variables of balance control weigh heavier than others in each individual pre and post injury. If we learn how to best identify the specific cause of increased postural sway, we may be better able to prevent and/or rehabilitate the affected person. We also understand that if one single system that controls balance fails or operates less than optimally that other systems will compensate. Identifying which systems are functioning better than [or worse than] others is an important future consideration. A concussion will vary amongst individuals, in terms of deficits and severity.

Balance is one objective measures that appears to be a sensitive measure of post-concussion deficit, however most systems are either very expensive such as laboratory force platforms, or subjective (such as the BESS). There are potentially promising new outcome measures of balance such as the use of smart phone devices, that are objective, easy to administer, relatively affordable, and appear to be a valid measure of postural sway. However, these balance measures for use in concussion management rely on comparing post-concussion scores to baseline. It is therefore critical to understand the validity of such devices, and if balance changes over the course of a sport's season in the absence of a concussion. This thesis endeavours to address this gap.

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Chapter TWO: Manuscript

BASELINE COMPARABILITY TO ACCELEROMETRY DATA AND CHANGES IN STANDING BALANCE OVER THE COURSE OF AN ATHLETIC SEASON USING A POSTURAL SWAY ASSESSMENT TOOL

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Abstract

Changes in balance ability can be a sensitive measure of post-concussion changes in brain function. However there is a need to determine the most reliable, valid and practical methods to assess balance, in order to optimize this component of concussion management. The Sway Balance™ System, by Sway Medical, is a mobile software application that uses the triaxial accelerometer located within an iOS device to quantify thoracic sway. The software relies on comparing the individual's post-concussion score to baseline scores obtained at the start of the season. However, in youth athletes in particular, balance may change over the course of the season, worsening due to factors other than a concussion, such as lower limb injuries, or improving as fitness improves. The purpose of this study was to compare balance measures obtained from a commercially available iOS device software package to industry standard accelerometers placed externally on an iOS device and the sternum. A secondary aim was to assess the reproducibility of a standing balance measure (Sway Balance™ System) throughout an athletic season in an elite youth (aged 16 to 21) lacrosse team. We found that balance scores derived from Sway Medical's algorithm had moderate to very strong validity when compared to the data gathered from the industry standard accelerometers which were placed on the sternum and externally on the iOS device. We then assessed the reproducibility of the Sway Balance™ scores at approximately 5 and 10 weeks relative to baseline. Intraclass correlation coefficients of overall balance scores ranged from weak to excellent depending on which weeks were compared. Variations were observed in some of the athlete's balance scores over the 10 weeks, and in overall group differences at different measurement points. This work indicates that while software such as the Sway Balance™ System has the validity to act as a balance measure, changes in balance occurring over the course of the season may necessitate repeated baseline testing, throughout the season, in order to have the most up-to-date score. While this software appears to have the validity to act as a balance measure, there is considerable work needed in protocol development to ensure that a change in score genuinely reflects a change in balance in concussed athletes.

1. Introduction

A concussion is "a complex pathophysiological process affecting the brain, induced by traumatic biomechanical forces secondary to direct or indirect forces to the head" (CDC, 2007). According to one study, sport-related concussions in the United States were reported to occur in 1.6-3.8 million athletes (Langlois, Rutland-Brown & Wald, 2006). Post-concussion syndrome refers to the cluster of symptoms that often occur after a person sustains a concussion (Ryan and Warden, 2003). These symptoms may include headaches, dizziness, visual disturbances etc.

(Alexander, 1995; Gouvier et al., 1992) and can vary among individuals in terms of intensity, quantity, and onset (Ryan and Warden, 2003). Nearly every day concussed athletes are being cleared for play based on subjective symptom resolution; however objective measures are a vital component in the return to play process. It is essential that clinicians, coaches, and parents do not rely solely on the concussed athlete's opinion regarding their readiness for return to play, but instead use valid and reliable measures which objectively measure concussion related outcomes. Objective measures allow clinicians to assess a person's cognitive, neurological and vestibular functions to make appropriate rehabilitative and return to play decisions, even after all reported symptoms have resolved. Objective balance assessment tools enable measurement and quantification of an athlete's specific, and sometimes less obvious, deficits. Impairments in balance and vision are examples of such deficits that are important to identify during clinical examination to avoid returning an athlete to play too early. It is possible that premature clearance for return to play is, in part, due to the use of subjective measures as a sole indicator of readiness for play.

Postural control is complex, relying on the interaction of multiple dynamic sensorimotor processes (Horak, 2006). Horak (2006) described six important resources for postural stability and orientation: cognitive processing, biomechanical constraints, movement strategies, control of dynamics, orientation in space, and sensory strategies. Postural instability may result from a disorder in one, or more of the above listed variables (Horak, 2006). Balance dysfunctions post-concussion are reported in 30% of concussed athletes (Marar et al., 2012; Guskiewicz, 2011) and nearly 50% of concussions sustained by athletes are not reported, (McCrea et al., 2004); making objective identification of deficits important (Guskiewicz, 2011). Without proper overall management, these affected athletes may have prolonged recovery, experience long term cognitive deficits, and become potentially pre-disposed to a more serious subsequent injury.

In attempt to better the future of an athlete, annual baseline testing has become an obvious necessity, and has fortunately been mandated in certain sport's associations world-wide. Baseline testing assesses an athlete's brain function on various levels, including but not limited to: neurocognitive function, visual function and balance abilities, prior to a new or initial head injury. This testing provides clinicians with baseline information (an athlete's 'normal') that can be used to assist with return to play decisions should that athlete sustain a concussion. Objective, rather than subjective, measures should improve our ability to confirm that a concussed athlete is returning, or has returned, to their pre-injury status. Numerous approaches can be used to assess balance, such as: the Balance Error Scoring System (the BESS), force plates (Guskiewicz, 2001) and accelerometers (Furman et al., 2007). Identifying the most appropriate tools (i.e. reliable, valid, objective, portable, affordable, easy to administer and interpret) to assess and re-assess the neural and physical components of human balance is a necessity for future concussion research.

Triaxial accelerometers can be used to monitor static and dynamic human movement characteristics (Amick, Patterson, and Jorgensen, 2013). Accelerometers eliminate self-report bias because they do not depend on subject recall and they can measure human movement in all geometric planes (Riekert et al., 2014). Most smartphones and tablets are designed with an ultra-low power, triaxial accelerometer that can be used to measure postural sway and estimate stability. Such devices are portable, relatively low-cost, and can store data securely and wirelessly to remote locations. It has been demonstrated that the Apple iPods are a valid and reliable measure of gait and postural sway (Kosse et al., 2015).

The Sway Balance™ System (Sway Medical LLC, Tulsa, OK) is an FDA-cleared mobile software application that assesses postural sway through the use of an iOS mobile device by a qualified healthcare provider (www.swaymedical.com). This function uses the triaxial accelerometer within the iOS device, to estimate thoracic sway (www.swaymedical.com). According to Sway Medical, the thoracic region is a stable center to precisely measure postural sway in order to adequately assess a person's balance (personal communication; Sway Medical LLC). Multiple trials are recommended to allow for a practice effect by the user and the examiner in order to yield more accurate results (www.swaymedical.com). After more than one test is completed, the average and overall score is automatically calculated, however individual test scores and positional stances may also be viewed (mediolateral and anteroposterior scores are combined and equally weighted) (www.swaymedical.com). The ability to access details from previous balance scores effectively allows a person's recovery to be tracked, and variations from normal/baseline to be determined by viewing motion data (www.swaymedical.com). At the time of this study, normative data did not yet exist for the Sway Balance™ System, but it is suggested that a score of 80 or above is considered normal (www.swaymedical.com).

To some degree, the Sway Balance™ System is similar to the commonly used subjective balance assessment measure, the BESS. The BESS involves standing in three 20-second stances with and without the use of a foam pad, and is scored subjectively by the examiner (Kleffelgård et al., 2015). In a study by Patterson et al. (2014), a strong relationship was found between the Sway Balance^{TM} System and the BESS among 21 healthy, non-athlete college-aged individuals (r=-0.767). Amick et al., (2015) tested forty-four young healthy male adults who performed the abbreviated Balance Error Scoring System (aBESS, without the use of a foam pad) while using the Sway Balance^{TM} System to assess balance. A significant correlation (r=-0.601) was found between scores from the aBESS and the Sway Balance^{TM} System (Amick et al., 2015). Literature is not available comparing the Sway Balance^{TM} System's algorithm to externally placed industry standard accelerometers. Despite the extensive use of this software for baseline concussion testing, post-concussion testing and fall-risk, available literature is limited.

Baseline concussion testing (which includes balance testing) is often performed once per year (pre-athletic season). However, there is minimal evidence available as to whether or not a person will display clinically significant changes in their balance over the course of a season, making it hard to determine if pre-season baseline scores are an accurate depiction of an athlete's future balance ability. It is quite possible that as an athlete trains throughout a sport's season that their balance might improve. Alternatively, they may sustain non-concussive musculoskeletal injuries that affect their balance. If this is true, then baseline balance testing should be performed on more than one occasion throughout the athletic season to update the athlete's score. Should the athlete sustain a concussion, a clinician could compare post-concussion scores to that of the athlete's most recent, up-to-date, pre-injury score. The aim of this study was to determine how Sway Medical's algorithm compares to measures gathered from industry standard triaxial accelerometers, placed on both an iPad and the participant's sternum. A secondary aim was to identify whether changes occur in an athlete's balance throughout an athletic season.

2. Methodology

2.1 Participants

Part one

Twenty male athletes (n=20) from a Junior B lacrosse team (ages 16-21) were recruited to participate in a baseline balance study. Testing was completed at the University of Ontario Institute of Technology (UOIT), within the kinesiology laboratory. In order to optimize performance by trying to control for variables that may impact balance (such as physical exertion and alcohol consumption), a baseline testing preparation form was provided to each participant (see appendix A). Prior to testing, all participants completed a pre-testing questionnaire to confirm their eligibility for the study and to provide examiners with other potentially useful variables (see appendix B). Athletes were eligible to participate in the study if they had not developed a medical condition that could affect their balance or been diagnosed with a concussion within the past 3 months and/or had unresolved concussion symptoms. All potential confounding variables were documented on the pre-testing questionnaire for consideration during analyses. A complete concussion screening was carried out at baseline to ensure that athletes did not have an undiagnosed concussion which might confound their balance scores.

Part two

Participants from the baseline study were then recruited for the second part of the study to identify whether changes occur in balance throughout an athletic season (baseline, mid-season, end of season; week 1, week 5 and week 10 respectively). Participants were asked to complete the same pre-testing preparation form and pre-testing questionnaire as used in the baseline study (week 1) at week 5 and at week 10. Participants were eligible to continue with the study if they had not sustained a concussion any time after the baseline testing date, and had not developed any medical condition that could impair their balance.

Study considerations

All recruited participants (n=20) qualified for participation in the baseline study (week 1). Due to absenteeism and concussions, the number of participants for the second part of the study was reduced: thirteen participants qualified to participate on all three occasions (baseline; mid-season; and end of season); eighteen qualified for comparison of baseline scores to mid-season scores; thirteen qualified for comparison of baseline scores to end of season scores; thirteen qualified for comparison of mid-season scores to end of season scores and 2 were not eligible for analysis because they had sustained a concussion post baseline. The total number of eligible participants for part one of the study was eighteen.

This study was approved by the University Research Ethics Board (REB) and both verbal and written consent was received by all participants for involvement in the study and for use of data.

2.2 Experimental protocol

Part one

The following measures were utilized for the complete baseline examination (week 1): ImPACT computerized neurocognitive testing (Immediate Post-Concussion Assessment and Cognitive Testing, Pittsburgh, PA, Lovell et al., 2000); a basic binocular vision screen questionnaire; King-Devick©® test of reading accuracy and speed (Oakbrook Terrace, IL); and a balance assessment using Trigno™ accelerometers (Delsys® inc., Boston, MA) and an Apple iPad 4th Generation with the Sway Balance™ System application (Sway Medical LLC, Tulsa, OK). Participants were assessed in a supervised and controlled environment over a 3 hour period. Results derived from neurocognitive, physical and balance testing were used to ensure that athletes did not have an undiagnosed concussion at baseline. Only the balance data was reported as the other variables were beyond the scope of this study.

Physical Assessment

A baseline balance assessment was completed using both the accelerometer system (Trigno™, Delsys®inc., Boston, MA) and an Apple iPad 4th Generation device with the Sway Balance™ System application. The balance assessment tools were used simultaneously to test an athlete's balance, specifically measuring thoracic sway. While standing on a flat surface and pressing the iPad device against their chest, accelerometers were taped to 7 different areas on the participant and 1 on the iPad; locations included: posterior superior section of the iPad, manubrium of the sternum, anterior superior iliac spine (1 per side), lateral malleoli (1 per side) and the medial mid tibia (1 per side). The body locations were chosen due to their involvement in postural control and the multiple sites were used to provide further information should we require it. Accelerometer data acquired from the sensor that was placed on the iPad and at the manubrium of the sternum were analyzed for the purpose of this study, where anteroposterior sway was observed in the ‘z’ direction and mediolateral sway in the ‘y’ direction. Each participant was asked to remove their shoes and keep their eyes closed throughout each of the 10-second stances. Prior to the onset of the test and after all instructions were given, each participant went through a practice test in order to familiarize themselves with each of the stances. On-screen prompts then directed the participant to complete the following 10-second stances: 1) feet together; 2) tandem leg stance right (TL/R); 3) tandem leg stance left (TL/L); 4) single leg stance right (SL/R); and 5) single leg stance left (SL/L). Each participant (one at a time) was closely supervised to avoid inaccurate use by limiting the following: hip abduction, opening the eyes, bending the knees to increase stability during the double and/ or single leg stance and resting an elevated leg against the planted leg or resting the foot/toes on the ground during the single leg stance. If the balance test was not performed correctly (i.e. major deviations from test protocol) the athlete would re-start the test. The iPad device was calibrated with the app’s built-in calibration tool and a complete balance test (all 5 stances) was performed twice. The iPad’s built-in triaxial accelerometer supports a maximum sampling rate of 100Hz (Mark and LaMarche, 2008).Using this information, the Sway Balance^{TM} System automatically calculates the derivative of acceleration (jerk), using the average of the two tests, to estimate total thoracic motion (anteroposterior and mediolateral) from each stance; jerk is then extrapolated onto a 100 point scale (personal communication, Chase Curtiss, Sway Medical LLC). Although individual stances can be viewed, the overall score is provided for use as the athlete’s sway score; a higher score indicates better balance, or less thoracic sway (www.swaymedical.com). The laboratory accelerometers were sampled at 256.30 Hz throughout each stance, collected using EMGWorks (Version 4, Delsys® inc., Boston, MA) and stored on a personal computer. Accelerometer data were collected at the same time as the iPad by manually starting both systems simultaneously and setting the Delsys® inc. software to run for 10 seconds. In order to identify potential confounding variables of balance, such as a weak or injured muscle, muscle strength and flexibility was assessed by a registered Chiropractor. Muscle strength was graded on a scale of 0-5, where 5/5 indicated full normal strength and 4/5 indicated reduced strength, but contraction could still move the joint against resistance (MRC, 1981). Flexibility was tested by comparing the two lower limbs and noting if the range of motion was reduced relative to normal for the hip, knee and ankle.The following muscles involved with postural control were assessed, bilaterally: hamstrings, soleus, tibialis anterior, and gluteus medius. Normal joint range of motion for the hip, ankle and knee are listed in table 1, and were used as reference (Jahn, 1979).

Table 1- Normal joint Ranges of Motion (ROM) (Jahn, 1979)

Assessed action	ROM	Muscle stretched
Hip flexion	120°	Hamstrings
Ankle plantar flexion	50°	Soleus
Ankle dorsiflexion	20°	Tibilais anterior
Hip external rotation	35-45°	Gluteus Medius

Part two

At approximately five weeks (mid-season) and ten weeks (end of season) from the baseline testing date (week one) eligible participants had their balance re-tested, prior to their practice, at their regular practice arena. For this part of the study only the Sway Balance^{TM} System was used for assessing balance. In particular, three iOS devices (iPhone 4 [n=2] and iPad 4 [n=1]) were used and each device was calibrated prior to initial use. Upon completion of the pre-testing questionnaire (see appendix B), 3 participants were separated from one another by approximately 5 feet to be tested simultaneously (one device per person). Instructions were given out loud on proper test taking, and participants were reminded that they will be supervised should loss of balance occur. The participants were asked to remove their shoes, and while standing on a flat hard surface they completed a practice test. The complete Sway Balance^{TM} test was then performed twice.

2.3 Analysis

Data Analysis

A motion analysis algorithm, for the Sway Balance^{TM} System, calculated degree of thoracic sway using the derivative of acceleration, with respect to time, called jerk (personal communication, Chase Curtiss, Sway Medical LLC). It is unclear how the raw acceleration values were processed by the Sway Balance^{TM} System, if any filtering of the data occurred, or how exactly the data was fit to the 100 point scale as this information was not provided by Sway Medical. Using MatLab (Mathworks, R2015a, Natick, MA), data from the industry standard accelerometers were low pass Butterworth filtered (2nd order, dual pass, 10Hz cut-off). Accelerometer data were measured in “g’s”, where 1g=9.81 m/s2, and was converted to m/s2. The derivative of acceleration was calculated to determine jerk and the Root Mean Square (RMS) of jerk was calculated to provide one measure for all directions. The RMS of acceleration was also calculated. These calculations were performed for the accelerometer placed on the iPad and on the sternum. Final data from the industry standard accelerometers were not adjusted for height and weight (although these variables were documented); Sway Medical reports that their algorithm does not adjust for height and weight (personal communication, Sway Medical LLC).

Statistical Analysis:

The validity of the Sway Balance^{TM} scores and accelerometer jerk measures were completed using linear regression with a 95% confidence interval. The goodness of fit for each model was assessed using pearson's product-moment correlation coefficient (r) and strength of association was classified as weak (.10 or -.10), moderate (.30 or -.30), strong (.50 or -.50) and very strong (.70 or -.70, or greater) (Rosenthal, 1996). Reproducibility of the Sway Balance^{TM} System was assessed using consecutive pairwise analysis of trials. Intraclass correlation coefficients (ICC's) with a 95% confidence interval (CI) were used to determine change in scores over the three assessment dates. ICC's were interpreted as excellent (>0.75), fair to good (0.40-0.75) and poor (<0.40) (Fleiss, 1986).

3. Results

Correlations between the Sway Balance^{TM} System score (reported as 'sway score') and the industry standard accelerometer data can be found in Table 2. Graphical depictions of these relationships for the single leg stance, which had the highest correlations (very strong) amongst all measures, can be viewed in figures 1- 3. Table 3 summarizes the scores from the feet together stance.

Table 2- Pearson Correlation (r) for each Stance (95% Confidence Interval)

Stance	r	Lower CI	Upper CI
Feet Together (FT)			
iPad Jerk and Sternum Jerk	0.42	-0.03	0.73
iPad Acceleration and Sternum Acceleration	0.14	-0.32	0.55
iPad Jerk and Sway Score	-0.52	-0.78	-0.11
Sternum Jerk and Sway Score	-0.09	-0.37	0.51
iPad Acceleration and Sway Score	-0.39	-0.71	0.06
Sternum Acceleration and Sway Score	0	-0.44	0.44
Tandem Leg Right (TL/R)			
iPad Jerk and Sternum Jerk	0.67	0.33	0.86
iPad Acceleration and Sternum Acceleration	0.6	0.22	0.83
iPad Jerk and Sway Score	-0.82	0.93	0.6
Sternum Jerk and Sway Score	-0.59	-0.82	-0.2
iPad Acceleration and Sway Score	-0.67	-0.86	-0.32
Sternum Acceleration and Sway Score	-0.69	-0.87	-0.36
Tandem Leg Left (TL/L)			
iPad Jerk and Sternum Jerk	0.75	0.46	0.9
iPad Acceleration and Sternum Acceleration	0.76	0.47	0.9
iPad Jerk and Sway Score	-0.8	-0.92	-0.55
Sternum Jerk and Sway Score	-0.67	-0.86	-0.33
iPad Acceleration and Sway Score	-0.57	-0.81	-0.16
Sternum Acceleration and Sway Score	-0.81	-0.92	-0.57
Single Leg Right (SL/R)			
iPad Jerk and Sternum Jerk	0.89	0.75	0.96
iPad Acceleration and Sternum Acceleration	0.48	0.04	0.76
iPad Jerk and Sway Score	-0.91	-0.96	-0.78
Sternum Jerk and Sway Score	-0.83	-0.93	-0.61
iPad Acceleration and Sway Score	-0.64	-0.84	-0.27
Sternum Acceleration and Sway Score	-0.82	-0.93	-0.59
Single Leg Left (SL/L)			
iPad Jerk and Sternum Jerk	0.93	0.84	0.97
iPad Acceleration and Sternum Acceleration	0.75	0.45	0.89
iPad Jerk and Sway Score	-0.9	-0.96	-0.77
Sternum Jerk and Sway Score	-0.83	-0.93	-0.62
iPad Acceleration and Sway Score	-0.8	-0.92	-0.55
Sternum Acceleration and Sway Score	-0.8	-0.92	-0.56

In the feet together stance, a strong linear relationship was seen with the iPad jerk and sway score (r=-0.52). A moderate linear relationship was observed between iPad jerk and sternum jerk (r=0.42) and between the iPad acceleration and sway score (r=-0.39). A weak linear relationship was observed between the iPad acceleration and sternum acceleration (r=0.14) and between the sternum jerk and sway score (r=-0.09). There was no relationship observed between the sternum acceleration and sway score (r=0).

Table 3- Feet Together Stance (FT) (n=20)

	Accelerometer 1 (iPad)			**Accelerometer 2 (sternum)**		
Subject	**Jerk (m/s3)**	**Acceleration (m/s2)**	**Sway**	**Jerk (m/s3)**	**Acceleration (m/s2)**	**Sway**
1	231.19	2.79	99.4	145.85	3.52	99.4
2	191.01	1	99.56	115.57	2.98	99.56
3	169.86	0.48	99.4	116.74	2.86	99.4
4	193.95	1.9	99.04	94.98	2.3	99.04
5	165.03	1.63	98.78	101.22	2.18	98.78
6	144.47	1.29	99.23	104.13	2.32	99.23
7	161.72	0.99	99.68	122.21	2.89	99.68
8	173.82	1.66	99.33	109.97	2.34	99.33
9	172.79	0.98	99.62	113.81	2.75	99.62
10	143.63	0.92	99.24	104.88	2.46	99.24
11	196.97	2.38	99.08	138.09	2.36	99.08
12	191.44	1.62	99.04	188.87	4.03	99.04
13	188.73	1.75	98.73	98.8	2.11	98.73
14	126.44	1.01	99.77	108.61	2.73	99.77
15	131.67	0.81	99.99	100.64	2.3	99.99
16	175.17	1.3	99.85	121.45	2.7	99.85
17	148.47	1.37	99.35	121.69	2.73	99.35
18	139.49	1.21	99.03	83.19	2.06	99.03
19	196.75	1.55	96.47	102.72	2.76	96.47
20	237.21	2.22	96.97	118.6	2.81	96.97

In the tandem leg stance right, a very strong linear relationship was observed between the iPad jerk and sway score (r=-.082). A strong linear relationship was observed between the iPad acceleration and sternum acceleration (r=0.60), between the sternum jerk and sway score (r=-0.59), between the iPad jerk and sternum jerk (r=0.67), between the iPad acceleration and sway score (r=-0.67) and between the sternum acceleration and sway score (r=-0.69).

In the tandem stance left, a very strong linear relationship was observed between the sternum acceleration and sway score (r=-0.81), between the iPad jerk and sway score (r=-0.80), between the iPad acceleration and sternum acceleration (r=0.76) and between the iPad jerk and sternum jerk (r=0.75). A strong linear relationship was observed between the sternum jerk and sway score (r=-0.67) and between the iPad acceleration and sway score (r=-0.57).

In the single leg stance right, a very strong linear relationship was observed between the iPad jerk and sway score (r=-0.91), between the iPad jerk and sternum jerk (r=0.89), between the sternum jerk and sway score (r=-0.83) and between the sternum acceleration and sway score (r=-0.82). A strong linear relationship was observed between the iPad acceleration and sway score (r=-0.64). A moderate linear relationship was observed between the iPad acceleration and sternum acceleration (r=0.48).

In the single leg stance left, a very strong linear relationship was observed between the iPad jerk and sternum jerk (r=0.93), between the iPad jerk and sway score (r=-0.90), between the sternum jerk and sway score (r=-0.83), between the iPad acceleration and sway score (r=-0.80), between the sternum acceleration and sway score (r=-0.80) and between the iPad acceleration and sternum acceleration (r=0.75).

Table 4 summaries the ICC's of the 3 assessment dates. An excellent correlation was observed between the sway score from week 10 and week 1; a fair correlation was observed between week 5 and week 1, and a poor correlation was observed between week 10 and week 5. Absolute percent change in overall sway score (combined score from all stances, both trials) between week 5 and week 1, week 10 and week 5, and between week 10 and week 5 can be viewed in table 5. The average absolute change between week 1 and week 5 was 13.12±12.03 (S.D.), 9.6±7.34 between week 5 and week 10 and 6.71±5.17 between week 1 and week 10.

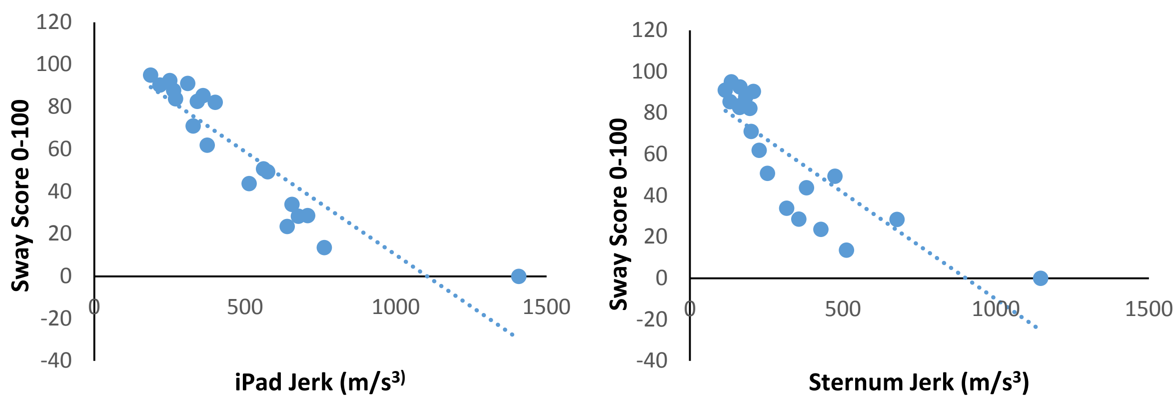


Figure 1: A) Single leg stance (left), iPad jerk vs sway score. **B)** Single leg stance (left), sternum jerk vs sway score

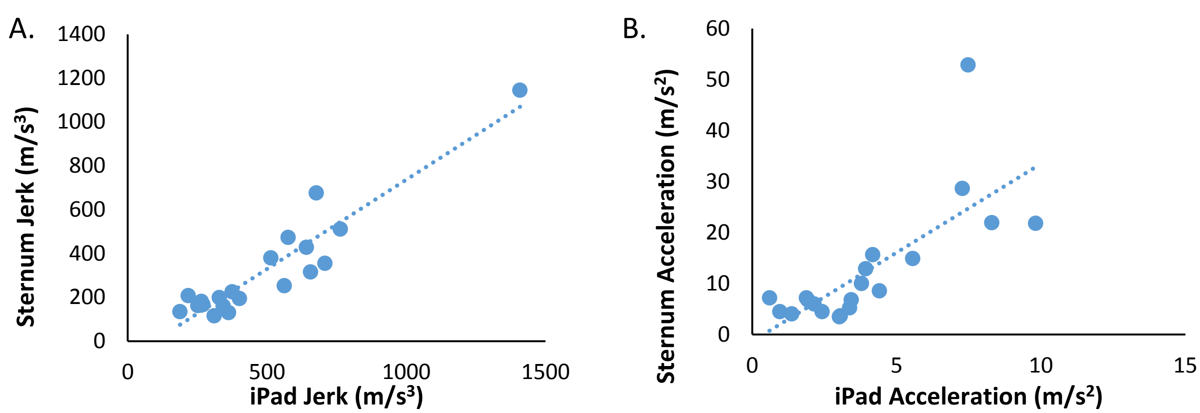
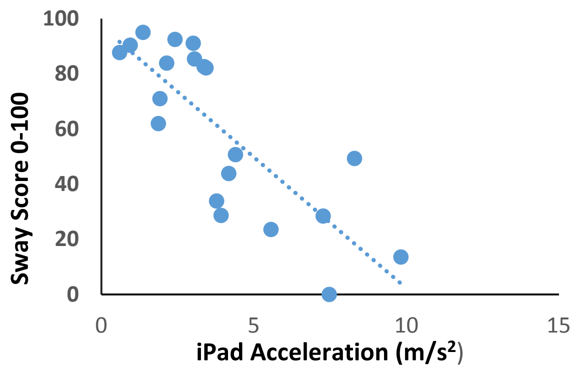


Figure 2: A) Single leg stance (left), iPad jerk vs Sternum jerk. **B)** Single leg stance (left), iPad acceleration vs. Sternum acceleration.



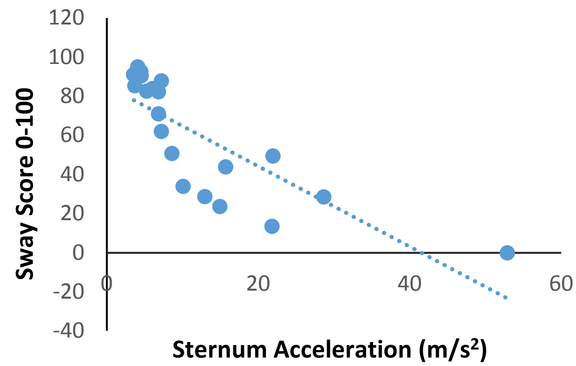


Figure 3: A) Single leg stance (left), iPad acceleration vs sway score. B) Single leg stance (leg), sternum acceleration and sway score.

Table 4-

Intraclass Correlation Coefficients (ICC) for the Sway Score (overall score) over the course of an athletic season (10 Weeks)

Weeks	Intraclass Correlation Coefficient
W5-W1 (n=18)	0.37 (95% CI= -0.10-0.71)
W10-W5 (n=13)	0.49 (95% CI= -0.05-0.81)
W10-W1 (n=13)	0.86 (95% CI= 0.60-0.95)

Table 5-
Percent change in Sway Score throughout Weeks

	% change in sway score			Absolute % change in sway score		
Participant	**w5-w1**	**w10-w5**	**w10-w1**	**w5-w1**	**w10-w5**	**w10-w1**
1	21.46	no data	no data	21.46	no data	no data
2	18.06	no data	no data	18.06	no data	no data
3	no data	no data	-0.71	18.06	no data	0.71
4	2.26	3.40	5.74	2.26	3.40	5.74
5	-1.21	-5.11	-6.27	1.21	5.11	6.27
6	16.47	no data	no data	16.47	no data	no data
7	11.41	-1.75	9.46	11.41	1.75	9.46
8	-10.14	no data	no data	10.14	no data	no data
9	-7.93	3.35	-4.85	7.93	3.35	4.85
10	-12.96	4.18	-9.32	12.96	4.18	9.32
11	11.81	-6.87	4.12	11.81	6.87	4.12
12	18.54	-22.84	-8.53	18.54	22.84	8.53
13	-10.30	18.68	6.45	10.30	18.68	6.45
14	-5.67	10.15	3.91	5.67	10.15	3.91
15	16.35	-10.08	4.63	16.35	10.08	4.63
16	-16.41	15.34	-3.59	16.41	15.34	3.59
17	0.70	no data	no data	0.70	no data	no data
18	0.92	2.82	3.76	0.92	2.82	3.76
19	53.61	-20.22	22.56	53.61	20.22	22.56
			Mean	**13.12**	**9.60**	**6.71**
			Median	**11.61**	**6.87**	**5.29**
			SD	**12.03**	**7.34**	**5.17**

Upon reviewing pre-testing questionnaires, it was identified that certain athletes either did not follow all pre-testing preparation instructions or they demonstrated potential confounding variables: four athletes engaged in physical exertion to the point of fatigue within 3 hours of their testing time; three athletes had 5 or less hours of sleep the night before testing; two athletes were suffering from a headache that they related to being “sick”; and two athletes reported having hip pain, two ankle pain and one knee pain.

4. Discussion

At baseline (week 1), this study evaluated the relationship between the Sway Balance^{TM} System and industry standard accelerometers for measuring an athlete's balance. This study also used the Sway Balance^{TM} system to evaluate baseline, mid and end of season balance in a competitive youth sports team. In assessing the validity of Sway Medical's algorithm for quantifying a person's balance when compared to the industry standard accelerometers, we observed an improvement in correlation as the stances became more difficult. The inverse (negative) linear relationship observed when comparing both jerk and acceleration from the accelerometer placed on the iPad and on the sternum to the sway score is due to differences in how each measure quantifies postural sway; that is, a higher number indicates increased postural sway with the industry standard accelerometers but reduced postural sway (better balance) with the Sway Balance^{TM} System. Our results demonstrated strong to very strong linear (negative) relationships when comparing iPad and sternum jerk to the sway score, as well as iPad and sternum acceleration to the sway score in all stances, except for the feet together stance (weak to strong). As both the laboratory accelerometers and the Sway Balance^{TM} System calculated jerk to estimate postural sway, these results are promising, because they suggest that the Sway Balance^{TM} System is quantifying postural sway accurately.

As the stances became more difficult, the Sway Balance^{TM} System provided similar information on postural sway as the accelerometer placed on the sternum and on the iPad. Although this was evident in both jerk and acceleration values, the strongest relationship between both devices was seen with jerk. These strong to very strong correlations (with the exception of a moderate correlation of 0.48 in the single leg stance right between the iPad acceleration and sternum acceleration) suggest that the Sway Balance^{TM} System is a valid option for quantifying a person's postural sway objectively, and with ease of administration. We theorize that the relatively poor correlation in the feet together stance (see table 3) may be because the Sway Balance^{TM} System assigns a maximum score of 100 (a perfect score), which would indicate that no movement was detected even though a certain amount of sway would inevitably be present. The laboratory accelerometers however, would continue to detect even small amounts of movement (at the thoracic region) even after the sway score has reached or approached its maximum. This could suggest that the Sway Balance^{TM} System's method of score allocation and/or the iOS device's triaxial accelerometer may not be sensitive enough to detect small changes in position. It is also possible that the high quality industry standard accelerometers have higher resolution and accuracy, making them more sensitive in identifying small amounts of movement, as evident in the feet together stance, compared to the Sway Balance^{TM} System and/or the iOS device. We also speculate that the variations in how a person may hold the iOS device against their chest in the different stances may contribute to the improved correlation as the stances became more difficult. This research may suggest that balance testing with an iOS device would be more accurate if the device is strapped to the person's chest, rather than held by the person being tested. Of important note, the Balance Accelerometer measure (the BAM) uses a dual-axis accelerometer attached to a gait belt which is strapped to the anterior midline of the pelvis, to objectively measure balance (Furman et al., 2013; Rine at al., 2013). The BAM requires tested persons to stand in a feet together and tandem leg stance, on a firm and then a foam surface, with the eyes open and then closed

(Furman et al., 2013; Rine at al., 2013). In 2013, Marchetti et al., assessed the test-retest reliability of the BAM and found good to excellent reliability for all conditions except for the eyes open tandem stance. The BAM was also able to discriminate between healthy subjects and those with vestibular disorders when using the composite score (Marchetti et al., 2013). A study by Furman et al. (2013) found that the BAM was not as effective as the BESS in differentiating between concussed vs non- concussed individuals when baseline scores were not available. Although the BAM was not specifically designed for concussion assessment, the technique is promising. The chosen location from the BAM is interesting and it is possible that belt usage may enhance the objective nature of this device, allowing athletes to place their hands on their hips to aid in postural control rather than focusing on holding the device correctly. Mayagoitia et al. (2002), assessed balance using a triaxial accelerometer belt (posterior trunk, at centre of whole body mass) while standing on a force plate in different conditions involving eyes open and eyes closed, feet together and feet comfortable positions. Paired t-tests ($P \leq 0.05$) showed that the accelerometer measurements were able to discriminate between different test conditions as well as or better than the force platform (Mayagoitia et al., 2002). Although this concept needs to be studied further, these studies reinforce that attaching the balance measuring device to the tested person may be of benefit.

When assessing reproducibility of the Sway Balance™ System by measuring balance on 3 occasions throughout an athletic season (baseline/week 1, mid-season/week 5 and end of season/week 10) we found that repeated baseline testing of an athlete’s balance may be necessary in order to account for changes that may occur over time. We observed an excellent correlation in balance scores between weeks 10 and 1, a fair relationship between weeks 5 and

10, and a poor relationship between weeks 5 and 1 (table 3). Variations were observed in some participants for their balance measurements throughout the 10 weeks, and in overall group differences at the different measurement points (table 5). It is conceivable that the differences observed between baseline sway scores and later season sway scores amongst certain athletes is due to either: improvements in postural control as athletes train for their sport, reduction in postural control due to musculoskeletal injuries to areas such as the ankles, or the low back, or that their baseline score was not an accurate depiction of their true ability. These results are in accordance with Burk et al. (2013) who found statistically and clinically significant differences in BESS scores over a 90 day intercollegiate athletic season, suggesting that balance does not necessarily remain the same over time, in this age group. If balance changes (improves or worsens) over a period of time it would seem important to re-test the athlete at different intervals throughout their athletic season for the most up-to-date score. This could increase the sensitivity of concussion testing by providing a more accurate baseline score against which to compare the scores of a concussed athlete. In this present study, there were no systematic changes in balance over the course of the athletic season, as some athletes improved and others got worse. It is unclear if the changes in balance are short or long term, but the potential implications on a mTBI and subsequent recovery are important to consider.

According to a pilot study by Amick et al. (2013) on the sensitivity of the acceleration outputs of multiple mobile consumer devices, low coefficients of variability demonstrated highly consistent sensitivity values across the different devices. Validity of the Sway Balance™ System is further supported by Patterson et al. (2014), who compared this system to laboratory force plate data (Biodex Balance System SD), using a 10-second single leg stance. There were no significant differences ($p = 0.818$) between the two reported balance scores (Patterson et al., 2014). It is important to note that balance was only assessed in the anteroposterior direction, so future research should include the mediolateral direction (Patterson et al., 2014).

Variability in a healthy person's balance score throughout an athletic season can be explained by many factors. In signal processing, 'noise' refers to undesirable modifications that may affect a signal while capturing data (Tuzlukov, 2010); anteroposterior and mediolateral deviations at the thoracic level, in this case. For the purpose of this study, noise in the form of breathing, test environment distractions, and compensation mechanisms (among others) will impact balance measurements, and it may explain variability in an individual's balance scores when measured at different time points. Dynamical systems theory provides a theoretical framework to understand why balance may change over the course of a season independent of concussion status. By nature a dynamical system has complexity, continuity and dynamic stability (Thelen, 2005). The pattern chosen will be stable but must be dynamically stable to adjust to the changing environment. The dynamical systems model can be used to explain why it is important to look not only at the end point of an objective, but how the system produces that endpoint (Shenoy, Sahani & Churchland, 2013). Without knowing the full algorithm used by Sway Medical it is impossible to know what aspects of balance change over the course of the season, as the Sway Balance™ System provides a single number. Taking into account what we know about dynamical systems theory and noise in signal processing, it is evident that ensuring protocol quality is as important as its validity.

This current work indicates that in the absence of laboratory force platforms and portable accelerometers, smart phone/tablet applications such as the Sway Balance^{TM} System may be a good objective clinical tool to assess balance and assist with return to play decisions, as long as baseline balance is measured at multiple time points throughout the season. This re-testing would be simple and fast and may account for the variability in balance scores seen amongst different athletes at different time points.

4.2 Future Research

Sway Medical markets their balance app as a sideline screening tool. This assessment can be done immediately after a concussion is suspected, but no obvious signs are present and the athlete is not reporting any symptoms (www.swaymedical.com). However, for all sideline assessments it is important to consider the effect that exertion leading to fatigue would have on balance, thereby potentially affecting scores. In 2009, Halil et al. determined that balance was effected immediately after aerobic, anaerobic and mixed fatigue protocols, using the Balance Error Scoring System ($p<0.05$). Recovery of balance was observed after 20 minutes of rest (Halil et al., 2009). Sway Medical suggests allowing for a 5% comparative marginal offset to account for hydration and fatigue (personal communication, Sway Medical LLC). These are important concepts that need to be studied further and a principle that needs to be considered when assessing a person's baseline balance or balance deficits immediately post exertion. Of additional importance, it would be interesting to identify whether balance would be affected by using the sideline test on different terrain (grass vs. indoor solid flat surface) and in different footwear (shoes/cleats, barefoot). However, Sway Medical states that there is only a 1-2 point difference out of the 100 total available points between a firm surface and a turf surface when wearing cleats (personal communication, Sway Medical LLC). In studies analyzing the reliability and validity of accelerometers and smart phones for assessment of human balance, location of the device has varied between the sternum, lower back, and the chest. It would be interesting to determine if location of device relative to the whole body's centre of mass has a statistically significant effect on resultant data. Detailed medical and procedural records are an important component of baseline concussion testing, which was not stressed in the reviewed literature. As literature on concussion testing has indicated, foam surfaces may be more accurate in identifying a concussed person from a non-concussed person (Valovich et al., 2012), therefore adding this into smart phone/tablet balance testing protocols may be of benefit. The addition of a foam pad could be an easy, inexpensive, and relatively portable addition to the Sway Balance™ System, but needs to be studied further. At the time of this study, normative data did not exist for the Sway Balance™ System; an important next step for Sway Medical to address concussion cases where a baseline assessment was not completed. The equal weighing of each stance in creating the athlete's overall balance score is an area where the protocol could be modified to improve the reliability of baseline scores. Further studies should analyze individual stances and their role in differentiating between a concussed versus non-concussed athlete. A study by Furman et al. (2013) revealed that the tandem leg stance was most sensitive in identifying a concussed person from a healthy one, using the mBESS.

It is important that measures of balance, for concussion assessment in particular, be objective, reliable, valid, easy to use and interpret, inexpensive and portable. Sensitivity testing on different postural sway devices to identify small changes in balance, and differentiating between a concussed versus non-concussed athlete should be an additional focus of future research in this area.

4.3 Limitations

Normative data on the Sway Balance^{TM} score would assist with creating a more meaningful score. This system's score allocation maxing out at 100 was limiting for our data analyses, in the feet together position in particular. We were also unable to determine what would be considered a clinically significant change in balance score, making it difficult to know whether the changes (+ or -) in balance score over the course of the season are enough to warrant concern. Sway Medical states that clinically significant offsets would be dependent on the medical professional's interpretation (personal communication, Sway Medical LLC). There was also a reduction in participant number from eighteen to thirteen in part two of the study, due to concussions and absenteeism, throughout the 10 weeks.

4.4 Conclusion

After a thorough review of the literature regarding balance assessment technology and its use for concussion management, it is evident that certain gaps exist. Our study attempted to address these gaps by examining new objective technology for quantifying balance. We demonstrated that the Sway Balance^{TM} System appears to be a valid alternative to conventionally used methods. We also determined that repeated baseline balance assessments may be necessary in order to allow for the most accurate baseline score to compare with post-concussion results. In a technology driven world, smart phone and tablet devices will continue to challenge the way traditional health care is administered. Those who use these devices as a clinical tool must not be blinded by device attractiveness, and instead be reminded of the importance of the application's validity.

As more athletes become injured and suffer from debilitating post-concussion symptoms, the importance of an objective and comprehensive approach to concussion management becomes clear. Balance testing for concussions shows potential as part of a multi-faceted approach, including but not limited to: a complete medical history and incident report; neurocognitive computerized testing; orthopedic testing; vestibular testing; neurological testing; ocular and binocular vision assessment; measures of postural sway; and collaboration with family physician, coaches, parents and the educational system.

Conflict of interest statement

None. The primary author has used the Sway Balance™ System within her practice but does not have any other affiliations with Sway Medical.

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Chapter THREE: Appendices

Appendix A: Test preparation form

PLEASE READ BEFORE YOUR BASELINE TEST APPOINTMENT

In order to bring you the highest standard of concussion care, we now offer the ***Shift Concussion Management Program*** – a full service concussion rehabilitative program. A vital component of concussion management involves obtaining a pre-season or “baseline” test. Baseline testing is essential for athletes at risk of concussive injury as it provides an important point of reference when managing head injury and determining readiness to return-to-play. We thank you for taking a proactive approach to concussion management and participating in our baseline program.

Your Baseline Test is scheduled for:

____-

We require a completed consent form prior to test administration. If you have been given the consent form in advance, please fill it out and bring it on testing day or forward it to us ahead of time. If you have not been given a consent form one will be provided to you at your appointment.

TIPS FOR SUCCESSFUL TEST TAKING

- Be sure to read all instructions carefully during the computer-based testing portion and give it your best effort. This will lessen the chance of you having to retake the test due to a less-than-optimal result.
- If during the test you find you do not understand the instructions, or if your computer freezes/internet connection is interrupted, and you have to re-do the test – contact us
- Let us know if you are sleepy, fatigued, rushed, distracted, emotionally distressed, or if you have been under the influence of intoxicants within the last 24 hours. We will reschedule your test for a day that you are feeling better.
- During the physical components of the test, listen to instructions carefully, focus, and give it your best effort.
- If you are testing with your teammates, please be courteous of those test takers around you
- Wear or bring comfortable/athletic clothes (eg. Shorts, T-shirt, Running Shoes)
- **If you normally wear contact lenses or glasses, be sure to bring them to the test**
- Give each task your **BEST EFFORT**
- **Please wear/bring athletic clothing and socks**

A note on our **Neurocognitive Testing Component** (Computer portion of the test):

On rare occasions, we do not obtain a successful result on the first test. Many computerized cognitive assessment tools have built-in “quality control checks” so that if performance is less than optimal or an athlete is intentionally trying to do poorly, the program will notify us. In these situations, we will ask you to complete a second test or have you return on a later date, as we do not want to *underestimate* your performance level.

Often invalid attempts are a result of the testing environment (distraction by teammates, noise, etc.) or internal factors (lack of motivation, fatigue, frustration, or failure to understand the test principles). It is important to us that we obtain an accurate baseline, and for some, this requires repeat testing or a change in environment.

If you have any questions regarding the baseline process or concussion management in general, please do not hesitate to contact us!

Balance Testing using an iOS Device

- Be sure to read all instructions carefully and give your best effort. This will lessen the chance of you having to retake the test due to a less-than-optimal result.
- If during the test you find you do not understand the instructions, please let us know.
- Let us know if you are sleepy, fatigued, rushed, distracted, emotionally distressed, or if you have been under the influence of intoxicants within the last 24 hours. We will reschedule your test for a day that you are feeling better.
- During the physical components of the test, listen to instructions carefully, focus, and give it your best effort.
- If you are testing with your teammates, please be courteous of those test takers around you
- Wear or bring comfortable/athletic clothes (eg. Shorts, T-shirt, Running Shoes)
- Please wear/bring athletic clothing and socks
- Please do not complete any physical exercise within 3 hours of your testing time (such as, but not limited to, running, swimming, weight lifting.)
- Please do not consume alcohol or any other toxicants within 24 hours of your testing time
- If an injury has occurred since your last testing date it is very important to indicate this on the questionnaire you are provided with on your testing date.
- If you have any questions or concerns prior to testing please inform your GM who can then contact us.

Appendix B: Pre-test questionnaire

Chiropractic Wellness and Rehabilitation- Baseline Testing

Pre-Participation Questionnaire:

Full name: ________________________

Team: Clarington Green Gaels- Lacrosse

Have you ever been diagnosed with (if YES to any please provide details):

- ☐ A balance disorder ____________________________________
- ☐ A condition causing dizziness ____________________________
- ☐ A recent ear infection__________________________________
- ☐ Chronic knee sprains___________________________________
- ☐ Chronic ankle sprains__________________________________
- ☐ A developmental disorder from birth______________________
- ☐ A medical condition____________________________

Are you currently experiencing any of the following (if YES to any please provide details):

- ☐ Nausea __________________________________
- ☐ Headache________________________________
- ☐ An ear infection___________________________
- ☐ Moderate or severe fatigue___________________
- ☐ Moderate or severe dehydration________________________
- ☐ Knee pain______________________
- ☐ Back pain______________________
- ☐ Ankle pain_____________________
- ☐ Lower back pain________________
- ☐ Hip pain_______________________

Have you consumed any **alcohol** within the last 24 hours? If YES, please provide details ________________

Have you taken any **medications** in the last 24 hours that may cause **drowsiness**? If YES, please provide details ____

Are you currently taking any **medications**? Y N _______________________________

How many **hours of sleep** did you get last night? ____________

Please see next page:

Have you engaged in **physical exertion** within the last 3 hours? If yes please provide details

____

Have you ever had any **surgeries** to your back, hip, knee or ankle? Please discuss:____

____

____

Current level of sport?___________ Number of years at this level______

** Please list your sport/physical activity participation for the 2-3 months prior to the start of your 2014 lacrosse season:

____

____

____

____

**Do you wish to be provided with a copy of your study results? YES NO

If YES, please provide your complete mailing address:

____

____

<u>**Consent:**</u> By Signing below, you agree to have the data that Chiropractic Wellness and Rehabilitation has collected from your baseline testing to potentially be used for analysis/ research. Any data used for research purposes will be kept **anonymous** in order to improve concussion management. Only researchers that are directly involved in the research will have access to your data.

Name: ________________________ Date:_________________

Signature:__________________________

Appendix C: consent form

Athlete Name: ___________________________Date of Birth: ____/____/______ (dd/mm/yy)

Age: _______ Phone and/or Email: _____________________________________

If Testing as part of Team, Please Indicate Team Name: Clarington Green Gaels

OR Check if Individual Testing ☐

Dear Parent, Guardian, and Athlete:

As a ***Shift Concussion Management Program*** provider, we are taking a proactive approach to the management of concussion by providing you with a comprehensive pre-participation assessment (or baseline test).

The purpose of the computerized assessment portion is to establish and store a baseline of cognitive function. Please review our entire baseline prep package for the proper administration of this portion of the testing.

A secondary *physical* component of the exam involves various measures of balance, coordination, and visual skills. Knowing your baseline level of both cognitive and physical performance gives us important information when evaluating post-injury recovery and readiness to return to play (should you or your son/daughter sustain a concussion).

We ask that you outline any previous concussive episodes here (include month/year, how it happened, symptoms experienced, and length of recovery):

____
____
____

PLEASE REVIEW BELOW, SIGN, AND RETURN

I hereby authorize *Chiropractic Wellness and Rehabilitation* to exchange my concussion testing information and results with the Coach and/or Training Staff representing the above-named team(s), and other Health Professionals involved in my current and/or future rehabilitative care.

____________________________ ___________________________ _____________

SIGNED PRINT NAME DATE