

Effects of Recurrent Subconcussive Head Impacts on Balance Control in Contact-Sport Athletes

by

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Bachelor of Kinesiology (Honours), McMaster University, 2016

A Thesis Submitted in Partial Fulfillment  
of the Requirements for the Degree of

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**Supervisory Committee**

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## Abstract

**Background:** Subconcussion, a mild traumatic brain injury, is best defined and identified by a lack of observable symptoms after axonal injury from minor head impacts. Subconcussive impacts are believed to accumulate with increased exposure over time, and are likely prodromal in the manifestation of a full-blown concussion. As evidenced by changes to changes in cerebral neurochemistry and structure, it is apparent that although individuals who have accumulated subconcussion may present as asymptomatic for motor and/or cognitive impairment using current clinical assessment tools, there is indication of long-term neurological damage which is presently going unrecognized. **Objective:** For the reasons stated above, a more sensitive and objective assessment tool is required to assess and recognize prodromal concussion manifestation in at risk populations with the intention of preventing further chronic sequelae. **Design:** Multiple baseline, time-series with repeated measures. **Methods:** Balance and bilateral reflex variability was assessed at pre-season and at post-season. **Results:** The current study identified significant changes to static balance postures (taken from the Balance Error Scoring System) through an objective postural assessment of centre of pressure (COP) and Area of Ellipse (AoE) calculations using a low-cost balance board and basic software interface after a season of accumulated subconcussion in female varsity rugby athletes. Specifically, double stance on the floor worsened by 31% in  $COP_{AP}$  ( $p=.025$ ) and by 26% in  $COP_T$  ( $p=.038$ ) and tandem stance on an unstable foam surface worsened by 180% in  $COP_{ML}$  ( $p=.014$ ), 175% in  $COP_{AP}$  ( $p=.025$ ) and 141% in  $COP_T$  ( $p=.005$ ) between pre- and post-season. Our results indicate that these outcome measures are sensitive and can discriminate underlying balance deficits associated with accumulated subconcussive impacts. An objective measurement of spinal cord excitability through bilateral fluctuations of the Hoffman (H-) reflex in the tibial nerve found significantly elevated pre-season Cross Covariance (CCV)

values which were 3x higher than those of a neurologically intact control population, suggesting prior neurological damage in study participants. **Conclusion:** The current study provides a platform for future research investigating bilateral fluctuation in spinal cord excitability after accumulated subconcussion and confirms balance decrements related to subconcussion can be identified through sensitive and specific measurement tools.

*Keywords:* Subconcussion, Centre of Pressure, Balance, Hoffman Reflex

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**Equation 1.** Centre of Pressure X ( $COP_x$ )

**Equation 2.** Centre of Pressure Y ( $COP_y$ )

**Equation 3.** Centre of Pressure medial-lateral path length ( $COP_{ML}$ )

**Equation 4.** Centre of Pressure anterior-posterior path length ( $COP_{AP}$ )

**Equation 5.** Centre of Pressure total path length ( $COP_T$ )

**Equation 6.** Total recovery time ( $t_{TOTAL}$ )

### List of Abbreviations

- COP – Center of Pressure
- SCAT-5 – Sport Concussion Assessment Tool; 5<sup>th</sup> Edition
- BESS – Balance Error Scoring System
- mBESS – Modified Balance Error Scoring System
- WBB – Wii Balance Board
- COP<sub>ML</sub> – COP Path Length in X (medial-lateral) direction
- COP<sub>AP</sub> – COP Path Length in Y (anterior-posterior) direction
- COP<sub>T</sub> – Total COP Path Length
- tTarget – Time to Target
- tCenter – Time to Center
- tTotal – Total Time
- RM-ANOVA – Repeated Measures Analysis of Variance
- SOL – Soleus
- TA – Tibialis Anterior
- VL – Vastus Lateralis
- AoE – Area of Ellipse

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**Dedication**

I dedicate this work to my grandparents, Molly and Sandy Sutherland, whose bright spirit I cherished, and whose unwavering love and support will always be remembered.

## CHAPTER ONE – Review of Literature

### 1.1 Introduction to Subconcussion

Subconcussion describes a subset of mild traumatic brain injuries (mTBIs) that is, perhaps incorrectly, considered to be on the less debilitating end of the spectrum in terms of brain injury severity. Repetitive subconcussions can also be referred to as repetitive subthreshold head injuries (RSHIs) or prodromal concussions (Lin et al., 2015). Unlike concussions, which are also included under the mTBI designation, subconcussions do not result in overt clinical symptoms, although there is known structural damage such as changes to cortical and hippocampal cytoskeleton proteins (Bailes, Petraglia, Omalu, Nauman & Talvage, 2013) and lesions to the blood-brain-barrier (BBB) after subconcussion (Laurer et al., 2001). Subconcussions can be thought of similarly to the slow accumulation of snow on the edge of a mountain. Individually, small snowfalls do not have any significant effect on the overall integrity of the mountain side. However, over time, the accumulation of snow becomes too heavy and breaks loose from the mountainside causing a disastrous avalanche. Like an avalanche, small head impacts in isolation may not cause major damage. It is the accumulation of these small insults to the brain that can cause long term neurological damage.

The lack of observable signs indicating central nervous system (CNS) damage after repeated exposure to subconcussive head impacts is a large area for concern. The absence of these symptoms may indicate clinical tests that are not sensitive enough to detect subtle, underlying changes that occur with repetitive subconcussion (Hwang, Ma, Kawata, Tierney & Jeka, 2017). With an understanding of the pathological sequelae following mild head trauma, current research suggests that the cumulative number of head impacts is the best correlate for future concussion risk and probability of chronic disease such as chronic traumatic encephalopathy (CTE), post-

concussion syndrome and mild cognitive impairment (Dashnaw, Petraglia & Bailes, 2012).

Individuals who experience an initial mTBI have a 24-hour period of vulnerability for sustaining one or more insults. This period of vulnerability is caused by a combination of changes to cerebral blood flow dynamics, dysregulation of protein channels resulting in disruption of ion homeostasis and neurodestructive microglia (Baylock & Maroon, 2011), (Farkas, Lifshitz & Povlishock, 2006). These neural changes are accompanied by transient motor deficits, which may sometimes be mistaken for fatigue, following the initial impact and increase susceptibility to sustaining a concussion (Dashnaw, Petraglia & Bailes, 2012). It is the presumed subtle changes to balance as a result of accumulated subconcussion that is the basis for this research study. Specifically focusing on balance provides more opportunity for objective analysis of head injuries, as opposed to other more subjective forms such as self-report data.

Change in balance control can be influenced by level of cognitive or physical fatigue, as fatigue is known to impair neuromuscular control (Clarke, Farthing, Lanovaz & Krentz, 2015). Individuals who exhibit postural instability as a result of fatigue usually present with alterations in spinal cord excitability measured by the Hoffmann (H-) reflex (Kim, Hart, Saliba & Hertel, 2016). Individuals with neurologic diseases or damage present an inability to modulate H-reflex amplitude, resulting hyperactive H-reflexes compared to neurologically intact individuals (Barzi & Zehr, 2008). Previous research has uncovered that presynaptic inhibition of Ia terminals to alpha motoneurone transmission is largely controlled by descending tracts (Lundberg, 1975), it is possible the reason greater H-reflex amplitudes are seen following spinal cord injury (SCI) is a result of Ia pathways experiencing a reduction in gating by the Ia inhibitory interneurons, ultimately facilitating Ia transmission (Kim, Corcos & Hornby, 2015). Katayama, Glisson, Becker and Hayes (1985) showed that suppression of sensory transmission is present following

concussive head injuries in cats. Monitoring changes to H-reflex modulation as a result of damage to supraspinal regulatory pathways may be a way to assess the subtle neurological changes that accompany subconcussion.

## **1.2 Mechanism of Concussive Injury**

The most up to date definition of a concussion is an acute event, caused by a single biomechanical force acting on the body which produces an impulsive force on the head, resulting in the brain moving inside the cranium (McCrory et al., 2017). The mechanism of concussion is believed to be a combination of shearing and tensile forces on axons as a result of the external biomechanical force (Montenigro et al., 2017). Alternatively, it is the cumulative exposure to minor head impacts that results in a subconcussive head injury. Any transfer of mechanical energy to the brain from either a direct head impact or an indirect impact to the body, with sufficient force to damage axonal integrity without any clinical concussive symptoms is considered to be a subconcussion (Bailes et al., 2013). Individual differences exist in terms of the magnitude of force necessary to produce a concussion, for this reason there is no known numeric or biomechanical threshold to which one can use to decipher a concussion from a subconcussion, consequently the concussive symptomology or lack thereof is the best indicator (Harmon et al., 2013). Subconcussion is most commonly sustained in contact sports athletes such a rugby, hockey, mixed martial arts and football, as well as non-contact sports such as soccer where heading the ball is common (Bailes et al., 2013).

## **1.3 Signs, Symptoms and Clinical Assessments**

### **1.3.1 Current Clinical Assessments**

#### *1.3.1.1 Balance Assessment*

A critical aspect of subconcussion is that no overt clinical symptoms may be detected using current clinical concussion tests, and individuals are not aware of any abnormal signs. This is a powerful indication that a more objective protocol and sensitive tools are necessary to identify these subtle neurological decrements in individuals who have sustained repetitive subconcussive head impacts. Balance testing has become an increasingly relied upon as a strategy to diagnose and manage sports related concussions, specifically used as a sideline measure directly following a suspicious head impact.

Yet, there are no specific tests which exist to measure changes in balance due to subconcussion. The Balance Error Scoring System (BESS) is one of the most widely used and researched sideline balance assessment tools for concussion, as it is easily administered in under seven minutes and is relatively inexpensive (Starling, Leong, Bogle, & Vargas, 2015). It includes a combination of three stances, each held for 20 seconds with eyes closed, performed on two surface conditions including one stable and one unstable surface (Starling et al., 2015). The BESS is limited by low interrater and intrarater reliabilities as determined by interclass correlation coefficients of  $r=0.57$  and  $r=0.74$  respectively, due to the subjective nature of the clinical evaluation (Finnoff, Peterson, Hollman & Smith, 2009). Additionally, it may be insensitive to mild impairments to balance (King et al., 2014) while limited by test sensitivity decrements in the days following injury (Harmon et al., 2013). The Sport Concussion Assessment Tool (SCAT) – 5<sup>th</sup> edition and NFL Concussion Assessment Tool use the modified BESS (mBESS) which only includes testing on a firm footing surface. The mBESS is similarly limited by poor reliability due to the highly subjective nature of outcome measures (King et al., 2014). The lack of sensitivity and interrater reliability for this measure was demonstrated when a battery of soccer ball ‘heading’ was performed by an experimental group. There were no

significant changes to individual mBESS scores, however changes to sensory integration were evident. Significantly ( $p=.007$ ) higher levels of medio-lateral trunk orientation displacement and velocity ( $p=.005$ ) were evident, contributing to variability in walking gait (Hwang, Ma, Kawata, Tierney & Jeka, 2017). Additionally, there is a high degree of variability in baseline testing, specifically in the single leg stance condition which contributes to reliability issues in the identification of a suspected concussion (Starling, Leong, Bogle & Vargas, 2015). Due to issues including test sensitivity, reliability and validity, there is a clear need for a more objective balance assessment, to properly evaluate subtle neurological decrements following subconcussion.

#### *1.3.1.2 Cognitive Assessment*

The SCAT is a multidimensional instrument that is available for sideline assessment of a sport-related concussion (SRC) to gauge symptoms and the severity of those symptoms over time (McCrory et al., 2017). There have been multiple updates and amendments made to the SCAT as new research emerges, with the most recent update being the SCAT5, published in 2017. The cognitive assessment portion of the SCAT5, known as the Standardized Assessment of Concussion (SAC) is relatively brief and includes orientation, immediate memory and concentration sections where the results are summed to obtain a total score. This section of the SCAT5, unchanged from the previous SCAT3, has been validated for detecting concussion directly after injury and differentiating concussed from non-concussed individuals (McCrory et al., 2017). The SCAT3, although heavily relied upon for evaluation of suspected concussion, has low test-retest reliability making comparisons of post-injury to baseline challenging (Hanninen et al., 2016). In a study of over 2,000 high school and collegiate level athletes, the effect size for the SAC and BESS components of the SCAT3 from baseline to post-injury testing, was small to

moderate 24 hours after injury, where they became non-significant 8 and 15 days after injury, respectively (Chin, Nelson, Barr, McCrory & McCrea, 2016). This finding implies that in as little as 8 days, one would not be able to discriminate between concussed and non-concussed athletes after employing the SAC. An example of this is evident as Gysland and colleagues found no meaningful changes on uninjured college level football players from preseason to postseason on both the SAC and BESS (Gysland, Mihalik, Register-Mihalik, Trulock, Shields & Guskiewicz, 2012). Since the update from SCAT3 to SCAT5, there have been no amendments to the SAC section, rendering it as reliable as in the SCAT3, with utility decreasing significantly 3-5 days after injury (McCrory et al., 2017). Based on the review presented above, it is clear that more objective tools are required for the diagnosis of subconcussion specifically, targeting underlying symptomology that accompanies repetitive head trauma and which cannot be detected with current clinical tools.

### **1.3.2 Clinical Assessments to Support Current Tests**

#### *1.3.2.1 Balance Assessment*

In an attempt to find a more sensitive measurement to uncover the subtleties associated with subconcussion and postural balance, Parker, Osternig, van Donkelaar & Chou (2008), investigated the role of subconcussion in ability to control sway during a walking task between non-concussed, contact-sport athletes and age matched controls. Results suggest that contact-sport athletes had a decreased ability to control sway with medio-lateral (ML) deviations of 0.041m compared to 0.032m in controls. Both athlete groups also had an increased velocity of sway at 0.145m/s compared to 0.120m/s and 0.127m/s. Additionally, both athlete groups had significantly slower gait velocity at 1.37m/s and 1.40m/s compared to controls at 1.25m/s and 1.27m/s (Parker,

Osternig, van Donkelaar & Chou, 2008). These results demonstrate that subconcussion produces gait instability and overall decreased balance control in contact-sport athletes, even in the absence of a medically diagnosed concussion or concussion symptomology.

Alterations in dynamic and static balance caused by subconcussion have been well documented. A study by Clarke, Farthing, Lanovaz & Krentz (2015) at The University of Saskatchewan simulated a university level football game to investigate the effects of neuromuscular fatigue on postural balance in athletes. The simulation consisted of 4 quarters of 12-18 high-intensity exercise stations depending on the quarter to imitate both game and training situations. Stations combined a 4.6-m shuttle sprint with an explosive upper body, agility or whole-body movement. Each bout of exercise varied in time to achieve work-to-rest intervals consistent with a typical university level football game (Rhea, Hunter & Hunter, 2006). The exercises included in the simulation were based on football game analysis (Rhea et al., 2006), and heart rate (HR) responses from the 2011 university season (Clarke et al., 2015).

Following the simulation, centre of pressure (COP) area was 95% larger, compared to pre-simulation. The lack of postural control post-match was attributed to both decreased neuromuscular activation and decreased strength measures as measured by a counter-movement jump. Based on these results, it would appear that mechanisms of central fatigue originate at the spinal level and ultimately contribute to changes in postural sway seen after a collision based sports game (Clarke et al., 2015). COP, a measurement of postural sway and overall postural stability is often affected by subconcussion and is important to understand as COP approximates centre of mass (COM). With increased postural sway, the COM is likely to move outside of the base of

support, which increases falling risk (Horak, 2006). The above findings reiterate the need for sensitive and objective balance assessments to detect the underlying symptoms associated with subconcussion to replace the current subjective assessments.

#### *1.3.2.2 Cognitive Assessment*

Neuropsychological testing is an important measurement of cognitive function and is used in current return to play protocols after concussion. Including this type of assessment in concussion evaluation can reveal cognitive changes in otherwise asymptomatic athletes. Multiple object tracking is a neuropsychological assessment tool which has the potential to detect cognitive deficits that persist after symptom recovery in concussed individuals. This tool was able to identify cognitive deficits in a pediatric population, that persisted twelve weeks post-injury, after all other symptom resolution (Brosseau-Lachaine, Gagnon, Forget, & Faubert, 2008). The King-Devick (KD) test is a reading efficiency test that has been recently used as a sideline tool to assess cognitive visual processing and performance in individuals with suspected concussion, as part of a multi-faceted approach to concussion diagnosis and recovery.

In a cohort of both male and female varsity athletes, concussed individuals performed significantly slower on the KD test compared to baseline, with an average slowing speed of 4.4 seconds, which is consistent with previous research (Leong et al., 2015). The test challenges circuits within the brain related to visuospatial integration, attention and motor planning, demanding the use of using eye saccades which are generated in areas of the brain often injured following concussion such as the dorsolateral prefrontal cortex and brainstem (King, Hume, Gissane & Clark, 2017). The KD test has high test-retest reliability of 0.97 and has significant

correlations with aspects of the ImPACT computerized concussion evaluation (King et al., 2017). The KD test is easily administered in under two minutes, and is an objective tool for monitoring symptom resolution over time (Tjarks et al., 2013).

Changes to cognitive function is a principal symptom in concussion diagnosis and recovery, so it is anticipated that there are notable cognitive deficits after sustaining repetitive subconcussion. One study found that non-concussed, contact-sport, collegiate athletes had poorer postseason cognitive testing scores on both the California Verbal Learning Test (CVLT) and the Immediate Post-Concussion Assessment and Cognitive Test (ImPACT) Reaction Time, which correlated with a greater number of head impacts (McAllister et al., 2012). The CVLT is sensitive to deficits in episodic memory while the ImPACT is a computerized neuropsychological test that evaluates one's visual memory, reaction time and oculomotor speed post-concussion. ImPACT provides information corresponding to when an athletes cognitive test score has returned to baseline from a diagnosed concussion (Terrell et al., 2014). Deficits in episodic memory and oculomotor speed can be associated with axonal damage to oculomotor neurons (Tjarks, Dorman, Valentine, Munce, Thompson, Kindt, & Bergeron, 2013).

Accelerometer data and neuropsychological outcomes for 214 Division I hockey and football players were compared with control, non-contact athletes. It was found that overall the contact-sport athletes had inferior performance on tests for novel learning post-season using the CVLT, as well as scored lower on post-season cognitive testing on the ImPACT reaction time trials compared to pre-season (McAllister et al., 2012). These differences were evident despite any of the participants experiencing a medically diagnosed concussion during the study period

(McAllister et al., 2012). Implementing assessment tools which are more sensitive to changes in cognitive function even after symptom resolution is an important step towards attaining full recovery and preventing long term neurological damage.

### *1.3.2.3 Neurological Assessment*

As evidenced by Clarke, Farthing, Lanovaz & Krentz (2015), mechanisms contributing to central fatigue originate at the spinal level and result in overt changes to postural sway after a collision based sports game. In one study by Girard, Racinais, Micallef, & Millet (2011), that looked to investigate the impact of neuromuscular fatigue in a prolonged tennis match on Hmax amplitude, it was found that Hmax was greatly reduced (~80%) over the course of the three-hour game. These plastic changes in central nervous function, namely the reduction in Hmax amplitude, is hypothesized to be the result of reduced central drive from supraspinal control centres following a fatiguing task or exercise. Reduced normalized EMG activity of the SOL and tibialis anterior (TA) confirm the central drive to working muscles was greatly reduced over the match protocol. The results of this study are indicative of central fatigue causing changes to the excitation and inhibition of the alpha-motoneurone pool, likely a result of increased presynaptic inhibition of Ia afferents (Girard, Racinais, Micallef, & Millet, 2011). In addition, studies investigating the phenomenon of variation in the time interval between individual heartbeats after head impacts, known as heart rate variability (HRV) holds promise as a potential measurement tool in subconcussion and concussion diagnosis. It is expected that in the future, HRV will provide clinically useful information that will allow practitioners to better monitor athletes and their recover after having sustained a concussion (Bishop, Dech, Guzik & Neary, 2018). It is likely that analyzing variable heart rate rhythms may provide an alternative, holistic

approach to identifying subconcussion in otherwise asymptomatic athletes, however it is still in the early stages of development. Using the H-reflex as a probe for assessment of supraspinal control may be a promising, objective measure to monitor neurological change as a result of subconcussive head injury.

### **1.3.3 Clinical Assessments for the Future**

#### *1.3.3.1 Cognitive Assessment*

Test sensitivity and objectivity are two extremely important features of concussion and subconcussion assessments. It is for this reason that medical tests and images, which are unbiased by nature, will likely become the gold standard for concussion and subconcussion diagnosis and recovery prognosis. The association between number of subconcussive head impacts and a decline in cognitive function is well supported in the literature. Downs and Abwender (2002) studied the effect of ‘heading’ in soccer on cognition and concluded that length of soccer career at a high level of play was related to poorer performance on four cognitive tests. A study which paralleled these results tracked the neurocognitive changes in high school football players over the course of a season. During a working memory task, players without concussion exhibited quantifiable functional magnetic resonance imaging (fMRI) changes from pre-to post-season, which mirrored fMRI changes that were seen in players who had sustained a medically diagnosed concussion. This finding was especially evident in linemen, who sustain helmet-to-helmet contact in almost every play in a football game (Bailes et al., 2013).

### *1.3.3.2 Neurological Assessment*

It is thought that subconcussions, as presumed prodromal manifestations of concussion, are caused by the shearing and tensile forces applied to axons of the brain during acceleration and deceleration (Montenigro et al., 2017). Although the axonal integrity is likely affected in both concussion and subconcussion, only clinical assessments for concussion are available. Changes to the neurochemistry of the brain are evident after subconcussive impacts, such as changes to specific biomarkers (Lin, Muehlmann, Koerte, Merugumala, Liao, Starr & Stern, 2015) including myo-inositol, choline (Davis, et al., 2009) and glutathione (Lin et al., 2015), as well as an increase in white matter volume (Davis, Iverson, Guskiewicz, Ptito & Johnston, 2009). These aforementioned changes are only detectible using specific imaging techniques such as magnetic resonance spectroscopy (MRS) and diffusion tensor imaging (DTI). MRS produces images based on signals from individual neurotransmitters detected within tissues (Davis, et al., 2009), and have shown increases to myo-inositol, a biomarker of glial activation and choline, a membrane biomarker in the posterior cingulate of the brain. Glutathione, an oxidative stress response to neuroinflammation, has also been seen to increase significantly with subconcussive exposure (Lin et al., 2015). A study conducted by Lin and colleagues demonstrated increases in biomarkers of inflammation, specifically in choline, and glutathione in former professional soccer players, compared to control athletes. Interestingly, goalkeepers, who are not typically involved in heading the ball, had lower levels of these biomarkers with levels closer to the control group mean. These changes in brain chemistry are significantly correlated with a lifetime estimate of repeated subconcussive head injuries in professional soccer athletes (Lin et al., 2015).

DTI produces images of axons by analyzing the direction of water molecule diffusion within the brain (Davis et al., 2009). Gray matter makes up the outer layer of brain tissue and is comprised of unmyelinated axons, cell bodies and dendrites (Budday, Nay, Rooij, Steinmann, Wyrobek, Ovaert & Kuhl, 2014). Conversely, white matter lies beneath gray matter and is made up of myelinated axon bundles, which are responsible for connecting neurons of different brain regions (Fields, 2011). Physiological changes seen through DTI techniques include changes to white matter volume in the brain from pre-to post-season. Significant differences were detected in the white matter in hockey and football athletes who had a single concussion. However, the most surprising DTI results were the significant increase in white matter in asymptomatic athletes who had sustained multiple subconcussive impacts but no diagnosed concussions (Bailes et al., 2013). Although the relationship between white matter changes and repetitive head impacts needs further investigation, it is evident repetitive subconcussive impacts produce adverse physiological changes in the athlete. These imaging techniques provide a good platform to understand the changing neurochemistry from head impacts, however they are currently not feasible diagnostic techniques due to cost.

The detection of neurologic dysfunction is important as individuals who have sustained a subconcussion may be more susceptible to sustaining a full concussion due to a period of increased vulnerability, as evidenced in highly controlled studies using rodents (Huang et al., 2013), (Vagnozzi et al., 2018). Literature on NHL players suggests that there is an increased risk for more severe injury as well as prolonged concussion symptoms if individuals with suspected concussion are not removed from play immediately. Suspected concussion was defined by the identification of one of seven visual signs, including loss of consciousness (LOC), slow to get up, motor incoordination, blank or vacant look, disorientation, clutching of head and visible

facial injury with any of the above (Echemendia, Bruce, Meeuwisse, Hutchison, Comper & Aubry, 2017).

A study on rodents demonstrated this window of vulnerability by administering two head impacts 24 hours apart. Researchers documented statistically significant increases in axonal injury as measured by presence of  $\beta$ -amyloid precursor protein ( $p < 0.01$ ), astrocytic reactivity and memory impairment after the second impact (Prins, Hales, Reger, Giza & Hovda, 2010). One other rodent study suggested there was significant tissue damage after mild, cumulative head trauma induced one or three days apart. Edema and hemorrhage in the first 24-hours following injury induction lasted for 14 days after initial impact, compared to the single impact and control rodents. Additionally, neurobehavioral impairments were seen in those groups, where they exhibited spatial learning deficits and decreased exploratory movements (Huang et al., 2013). This is suggestive of a need for more sensitive tests that are better able to detect subclinical neurological dysfunction in athletes sustaining multiple, repetitive subthreshold concussive events as a means of preventing subacute and chronic sequelae (Bailes et al., 2013).

#### **1.4 Introduction to Human Postural Balance**

Dynamic movement, which requires maintenance of postural balance, is an integral part of daily life and is especially important in sport. Postural balance is the process that maintains centre of mass (COM) within the base of support, and is a function of postural control. Postural control is the result of the interaction of many sensorimotor processes, with a functional goal of maintaining accurate body alignment for a given environment and coordination of the COM in response to external movement (Horak, 2006). The integration of information from somatosensory, visual and vestibular systems is necessary to coordinate COM. Adjusting relative

dependence on each sense becomes important for maintaining COM stability in less optimal environmental conditions (Horak, 2006). It has been suggested that, under good lighting conditions and a firm surface, humans rely on 70% somatosensory information, 20% vestibular information and 10% from visual input to maintain normal posture (Horak, 2006).

In situations where the body is set off balance, compensatory movement strategies are employed to return the COM within the base of support. For disturbances occurring on stable footing surfaces, ankle strategies are initiated, where the body moves as an inverted pendulum to allow small amounts of sway in order to maintain balance. For disturbances that are a result of a narrow surface or when COM must be moved quickly, hip strategies are initiated, where individuals exert torque at the hips to quickly move the COM (Horak, 2006). Additionally, a mixed hip-ankle strategy has been suggested in place of the pure ankle strategy, to correct postural disturbances at speed, as there is limited effectiveness of the ankle to be able to single-handedly correct movement of the entire body (Kuo, 1993).

Another strategy to regain balance is to enlarge the base of support so that the COM moves back within the base. This can be achieved two-fold. One way is to take a step in front or behind the COM to decelerate the body's movement forward or backwards, depending on the direction of the postural disturbance. The second approach is to use a support such as cane or walking stick that is extended forward and acts to widen the base of support so that the COM remains inside. The first strategy can be employed in any direction, while the second is limited to disturbances from behind (Kandel, Schwartz, Jessel, Siegelbaum & Hudspeth, 2013).

Balance is a clinical domain in the suspected diagnosis of a concussion, as it is often compromised after head injury (McCrorry et al., 2017). Studies that have investigated postural

balance in athletes after sustaining a mild head injury have provided evidence for decreased postural stability likely related to a sensory interaction deficit, where, unlike healthy individuals, the injured athlete is unable to effectively integrate information provided by the somatosensory, visual and vestibular systems (Guskiewicz, 2011).

### **1.5 Assessing Spinal Cord Excitability**

Assessing spinal cord excitability is one non-invasive method that allows researchers to evaluate supraspinal control centres. In a study conducted by Katayama, et al., (1985), looking at the effects of concussive head injuries on sensory transmission within the spinal cord in cats, it was demonstrated that in the minutes following an induced fluid-percussion head injury, there is a depression of sensory transmission from Ia fibers. This finding is important in understanding the magnitude that supraspinal input can have on spinal cord level control. Nozaki et al. (1995), looked to identify whether supraspinal centers were in fact the originating source producing the time-correlated (fractal) characteristics observed in the H-reflex sequence or if the local neuronal networks of the spinal cord could function without higher level input. Findings by Yamamoto et al., (1986) suggest fractal characteristics are present in the brain during slow-wave sleep, leading to the development of a hypothesis to determine whether supraspinal centers were involved in the generation of fractal correlation in H-reflex sequences. By comparing soleus H-reflex sequences of SCI and control participants, it was observed that SCI individuals had a weaker fractal correlation which was not a result of variability of stimulus intensity or characteristics of the nerve, but of presumed supraspinal influences acting on the reflex arc in the spinal cord. These results suggest that H-reflex modulation is associated with descending control from supraspinal centers (Nozaki, Nakazawa and Yamamoto, 1996). A secondary finding from Nozaki

et al. (1996), was that both the left and right legs of neurologically intact subjects had synchronous Ia afferent input from soleus motorneuron pools, compared to individuals with spinal cord injury (SCI) who experienced desynchronization between legs. The absence of common Ia input in SCI is apparent when looking at the varying bilateral H-reflex amplitudes in the legs (Nozaki et al., 1996).

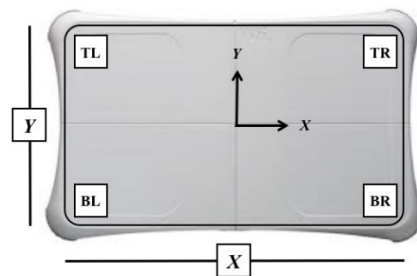
These changes to H-reflex amplitude fluctuation may be produced for one or more reasons including presynaptic inhibition of Ia terminals, changes to postsynaptic membrane potentials on motoneurons as well as homosynaptic depression in the Ia to motorneurone synapses. Analyzing the independence of these amplitudes in humans using a cross-covariance (CCV) sequence may provide information relating to synaptic inputs affecting motoneurons and spinal cord circuitry (Mezzarane & Kohn, 2002). A significant change in the CCV amplitude, calculated from bilateral fluctuations in H-reflex amplitude, is indicative of either greater modulation of bilateral alpha-motorneurone pools or a stronger modulation from common central contributions on the alpha-motorneurones (Ceballos-Villegas et al., 2017). In a study by Mezzarane, Nakajima & Zehr (2017), bilateral H-reflexes were elicited in both upper and lower limbs to assess if common drive onto bilateral pools of motorneurones influence spinal cord excitability, a CCV sequence between reflexes was used to evaluate spinal excitability between sides. The parallel bilateral fluctuation in H-reflex amplitudes seen in this study is suggestive that both limbs receive common neural commands. This echoes previous CCV peak findings at the zero-lag by Mezzarane & Kohn (2002), where there is indication of a correlated supraspinal influence to both legs at rest, with the corticospinal or reticulospinal tracts as hypothesized origins.

H-reflex fluctuations and changes in amplitude can also be a result of training and changes to physiological mechanisms such as alpha-motorneurone recruitment, presynaptic inhibition or intrinsic properties of alpha-motorneurones (Ceballos-Villegas et al., 2017). This was seen in a study by Ceballos-Villegas et al. (2017), where trained athletes had decreased H-reflex amplitude after a running intervention, while sedentary individuals who participated in the same intervention experienced an increase in H-reflex amplitude compared to baseline. The influence of activity level on spinal reflexes has previously been documented, after a study conducted by Nielson, Crone and Hultborn (1993) found smaller Hmax values in dancers from the Royal Danish Ballet than in untrained controls. A number of studies have made similar conclusions, where Hmax values are significantly reduced after training (Aagaard, Simonsen, Andersen, Magnusson, & Dyhre-Poulsen, 2002), (Gruber et al., 2010). Understanding that neural pathways are plastic and spinal reflexes change as a result of injury and training, there is reason to consider using the H-reflex as a probe to detect otherwise asymptomatic brain trauma and injury.

## **1.6 Application of Balance and Dynamic Postural Challenge Assessment**

Postural instability is a telling sign of concussion immediately after a head impact, and is often one symptom that triggers a professional neurological evaluation. As balance impairments in certain populations are usually indicative of neurological challenges, it goes without question that practitioners need a reliable and accessible tool to objectively measure these changes. COP velocity is a reliable indicator of one's balance as it is a representation of the central anticipatory adjustments needed to maintain stability (Powers, Kalmar & Cinelli, 2014). COP path length and total area of ellipse is another way to measure postural instability, as seen in a study conducted at the University of Victoria, total COP in the eyes closed, single leg condition had significant

differences from pre-to-post season in concussed rugby players, more so than any other stance condition. This is likely attributed to challenges associated with sensory integration due to the reduced amount of available somatosensory information compared to double leg and tandem stance conditions (Cullen, 2017). It is likely that an objective balance test using these measures will serve to identify underlying sensory integration issues which would otherwise go undetected in individuals who have been subject to recurrent subconcussion. The Nintendo Wii Balance Board (WBB) (*Figure 1*) has with sampling rate of  $\sim 30\text{-}50$  Hz, can be used in place of a scientific-grade force plate to effectively measure COP changes in individuals. This tool has been validated to predict falling among elderly using a stillness test which integrates COP approximation data in both the medial-lateral (ML) and posterior-anterior (AP) planes (Jorgensen, Hansen, Perez & Spaich, 2014). Additionally, COP path length data measured using the WBB in healthy adults has been validated against force plate data in all 3 stance conditions of the BESS (Goble, Cone & Fling, 2014). A validated force detecting tool that can measure subtle changes to COP should be considered in future assessments for uncovering subtle neurological changes as a result of subconcussion.



*Figure 1. Top view of the commercially available (Nintendo® Wii Fit™) balance board (WBB): illustrating four force sensor locations: TL (Top Left), Top Right (TR), Bottom Left (BL), and Bottom Right (BR) (Cullen, 2017)*

### **1.6.1 Application of Spinal Cord Excitability Assessment**

Evoking the H-reflex is one way clinical researchers investigate spinal cord excitability and mechanisms of neural control. The H-reflex is a monosynaptic reflex that, through electrical stimulation, causes activation of motor units resulting in a muscular contraction (Misiaszek, 2003). The H-reflex is evoked by stimulating a mixed peripheral nerve, which has both sensory and motor axons (Zehr, 2002). As postural tasks become more challenging (ie. lying down to standing up), H-reflex amplitude is increasingly down regulated in neurologically intact individuals, this process may be associated with a motor-control shift from spinal to supraspinal centres (Kim et al., 2016). Investigating H-reflex variability is one way to determine the influence of synaptic inputs, such as supraspinal origins, onto motoneurons and resulting spinal cord pathways (Mezzarane, Nakajima & Zehr, 2017).

As previously documented by Katayama et al., (1985), there is a depression of sensory transmission after a concussive head injury, which is supraspinal in origin. It is for these reasons that monitoring the bilateral fluctuations in H-reflex in asymptomatic athletes after sustaining multiple subconcussion may present some characteristic change that would otherwise go unrecognized. As a generally accepted theory, fluctuations in H-reflex excitability occur as a result of both pre-and post-synaptic origins (Funase & Miles, 1999), and interact with coordinated bilateral muscle activation during movement. Given there is a relationship between synaptic inputs to the Ia-motoneuron circuits in the soleus muscles of both the legs, as documented by Mezzarane and Kohn (2002), there is a possibility that variability in the bi-lateral

reflex amplitudes that are not within an acceptable range are the result of supraspinal injury, such as subconcussion. Seeing as there is not an existing, objective measurement tool to assess subconcussion status, measuring bilateral H-reflex variability is one possible avenue that could indicate neurological changes that take place following recurrent subconcussive head injury.

### **1.6.2 Application of Subconcussion Video Review**

The utility of using visible signs (VS) of concussion in predicting the diagnosis in NHL players was examined in a study by Echmemendia et al. (2017). This was performed through close video review with at least two raters who were trained to detect and code specific visual signs during video review of regular season games. Of the 735 games that were reviewed, there were 861 identified concussive events. 47% of confirmed concussions had associated visual signs, and 53% had none. In a study looking at video review of multiple concussion signs in Rugby League, a single reviewer completed the coding of the likely concussive events using six identified signs including clutching head, slow to get up, unresponsive, unstable gait, possible seizure and vacant stare. A second video reviewer then confirmed or negated these previously identified instances (Gardner, Howell & Iverson, 2018). By combining video reviewing and coding protocols from the aforementioned studies, researchers can quantify the number of subconcussive head impacts individual players sustain over the course of the season. Additionally, by employing the same coding structure in identifying instances of subconcussion, researchers will be able to recognize if any subconcussive instances are accompanied by certain behaviors ie. clutching head. Although video review will be helpful in identifying a metric associated with the number of subconcussions sustained per season for individual players, the need for a more comprehensive tool for subconcussion recognition still exists.

## 1.7 Summary

With an increasing body of evidence supporting the neurological damage acquired after subconcussive head impacts, it is clear an objective test or measurement tool is required for clinicians and medical professionals to properly diagnose and treat individuals who have sustained subconcussion to prevent further injury. With evidence of neural changes (Bailes et al., 2017), (Baylock & Maroon, 2011), (Farkas, Lifshitz & Povlishock, 2006) following subconcussion, post-season cognitive deficits in non-concussed contact sport athletes (McAllister et al., 2012) as well as reduced postural control following a simulated football game (Clarke, Farthing, Lanovaz, & Krentz, 2015), there is reason to continue investigations towards finding sensitive measures to detect these aforementioned changes following subconcussion to raise awareness and prevent chronic sequelae.

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## **CHAPTER Two: A pilot study to establish prodromal manifestation of concussion**

### **2.1 Introduction**

As a form of so-called “mild traumatic brain injury”, the neurological and functional assessment of concussion and behavioural outcomes remains poorly understood. While explorations of “visible” concussive incidents are receiving increased attention, an area often undetected and neglected is that of subthreshold concussive effects that may accumulate with repeated exposure to physical impact (Montenigro et al., 2017), (Wong, Wong, & Bailes, 2014), (Bailes, Petraglia, Omalu, Nauman & Talavage, 2013). “Subconcussion” is a relatively new term, introduced to describe head trauma that are ‘thought to occur in association with repeated head-jarring episodes in contact sport, with the likelihood of cumulative effects’ (Rutherford, Stephens, & Potter, 2013). Subconcussions are caused in a similar manner to concussions, however involve smaller impact forces that operate below the threshold necessary to produce symptoms (Shuttleworth-Edwards, Smith, & Radloff, 2008). It has been proposed that cumulative brain trauma of this nature may result in neuropsychological vulnerability (Shuttleworth-Edwards, Smith & Radloff, 2008). The neuronal changes produced by repetitive subconcussion are subtle and not easily identified. However, neuropsychological and neurophysiological deficits may be evident when tested for specifically as evidenced in one study where contact sport athletes consistently demonstrated gait imbalances (slower gait, increased sway and increased sway velocity) in the absence of concussion and compared to non-athletes (Parker, Osternig, Van Donkelaar, & Chou, 2008). Similarly, after one season, collegiate level contact sport athletes scored significantly lower on post-season measures of new learning using the California Verbal Learning Test (CVLT) compared to non-contact sport athlete controls (McAllister et al., 2012).

There is currently no standard clinical method to detect altered neurological function in contact-sport athletes, who may have experienced subconcussion (from multiple direct or indirect head impacts) but who have not suffered from a medically diagnosed concussion. The existing concussion assessment tools are not sensitive or accurate enough to pick up on the subtle decrements in either the cognitive or physical domains that are often produced by subconcussive impacts (Bailes et al., 2013).

Decreased performance on cognitive assessments (e.g. Standardized Assessment of Concussion (SAC) as part of the greater Sport Concussion Assessment Tool (SCAT), or Immediate Post-Concussion Assessment and Cognitive Test (ImPACT)), is a so-called 'red flag' symptom in concussion diagnosis (Tjarks, Dorman, Valentine, Munce, Thompson, Kindt, & Bergeron, 2013). Although there is evidence to suggest through advanced imaging techniques (Davis, Iverson, Guskiewicz, Ptito, & Johnston, 2009), (Lin, Muehlmann, Koerte, Merugumala, Liao, Starr, & Stern, 2015) suggest that subconcussion results in cerebral dysfunction, no current clinical tool used to assess cognitive status is sensitive enough to uncover these prodromal neurological changes. Jennings et al., (2015) found no change in cognitive function as measured by the SAC after a season of subconcussive impacts to youth football athletes which is evidence for the development of a test which can identify subtle neurological decrements that accompany subconcussion.

It is possible the reason the clinical assessments do not show significant change after subconcussion is due to a lack of underlying neural damage. However, based on the results of previous studies which show evidence for vestibular dysfunction (Hwang, Ma, Kawata, Tierney, & Jeka 2017), axonal injury (Bailes et al., 2013) and changes to magnetic resonance

spectroscopy (MRS) markers of neuroinflammation (Lin, Muehlmann, Koerte, Merugumala, Liao, Starr, & Stern, 2015) following subconcussion, it is evident that neurological changes exist even if the measurement tools are insensitive for their identification.

Balance assessment, using various clinical tools such as the Balance Error Scoring System (BESS), has become a fundamental neurological probe for concussion diagnosis and recovery assessment. However, results using these tools in clinical assessments after subconcussion remain inconsistent, indicating a lack of sensitivity (Hwang et al., 2017). In addition, current balance testing protocols remain heavily subjective and have the potential to be affected by rater bias, as seen with the BESS which is limited by poor validity and interrater reliability (Chang, Levy, Seay & Goble, 2014).

More objective tests that have the ability to identify the neurophysiological deficits exhibited after repetitive subconcussion, are required as cognitive recovery differs temporally from motor function recovery. Parker, Osternig, van Donkelaar, & Chou, (2008) demonstrated that complex motor tasks such as walking requires a longer recovery time compared to cognitive measures, following concussion. A potential avenue to test objectively for changes in neurophysiological measures such as balance, would be to employ an instrument that removes rater bias and objectively quantifies changes to centre of pressure (COP) such as a force plate. In addition to static balance testing on a validated force detecting instrument, incorporating a challenging, dynamic postural task to balance assessment protocols is a good way to detect underlying balance deficits that may go undetected with current balance measurements due to task specificity and associated neuronal control.

Another potential approach to assess subtle decrements to neurological status after subconcussion could be through the measurement of spinal cord excitability. Changes to Hoffmann (H-) reflex amplitude are evident in individuals who have experienced damage to supraspinal centres following chronic stroke (Zehr, 2011). Understanding that interrupted and dysfunctional supraspinal regulation caused by neural damage affects H-reflex modulation, it is possible that increased variability in H-reflex amplitude would be experienced by individuals with subconcussion in addition to the bilateral asymmetries that exist in a healthy population as evidenced by Mezzarene & Kohn, (2002). Between sides, individual spinal excitability variability exists, and can be reduced through remote limb cycling (legs) as evidenced by Mezzarene, Nakajima & Zehr, (2017). Recognizing that supraspinal centres, afferents from moving limbs and spinal cord networks all influence the reflex variability (coefficient of variation (CV)) of each side of the spinal cord (Mezzarene et al., 2017), there is an opportunity to characterize typical bilateral reflex fluctuation ranges. Exploring atypical changes to bilateral fluctuations of spinal cord reflex variability remains a potential avenue for assessing neurological changes after subconcussion.

By utilizing the combined, objective assessments of balance and spinal cord excitability, it is possible that predictive prodromal features may be uncovered in individuals who have sustained multiple subconcussion. It is hypothesized that individuals will have decreased performance in postural assessments and will have significant bilateral fluctuations in measures of spinal cord excitability compared with pre-season. The identification of these prodromal features and possible risk factors will help to prevent future concussions from occurring, as well as help to identify athletes who may not be neurologically fit to participate in contact sport.

Additionally, investigating subconcussion more carefully may increase our understanding of the mechanisms of disruption underlying symptomatic experience of concussion.

The purpose of the current study was to provide a starting point for more objective assessment tools to detect subtle underlying neurological deficits that accompany subconcussive head injuries. It is proposed that the combined assessment of balance control and spinal cord excitability would provide both the sensitivity and objectivity necessary to uncover neurological changes associated with a season's worth of subconcussive head impacts in university level rugby athletes.

## **2.2 Methods**

### **2.2.1 Experimental Design**

A multiple baseline, time-series design with repeated measures was used in this research study. The multiple baseline design included three testing appointments within seven days prior to the start of the varsity season.

### **2.2.2 Baseline Control Procedures**

As in previous related experiments, a multiple baseline within-participant control design took the place of a separate control group (Klarner, Barss, Sun, Kaupp, Beattie, & Zehr, 2014), (Kaupp, Pearcey, Klarner, Sun, Cullen, Barss, & Zehr, 2018), (Sun, Ledwell, Boyd, & Zehr, 2018). This design, while time and labor intensive, has several benefits compared to a traditional control group design. The multiple baseline design has been used as a valid replacement to the design with a control group and given high internal consistency of measures (Butefisch et al., 1995). This design allows participants to create a reliable preintervention baseline and enables

them to act as their own preintervention control. Three *Pre-season* tests and one *Post-season* test were performed allowing a multiple baseline within-participant control design to be applied. To evaluate individual subject data, a 95% confidence interval (95% CI) of all measurements was calculated from the three baselines and those whose *Post-Season* values fell outside of this range were defined as a responder (Sun et al., 2018).

### 2.2.3 Participants

Initially, 14 competitive female rugby athletes without chronic disease, acute lower-limb injuries affecting balance or neurological impairments were recruited for study participation. 13 individuals competed for The University of Victoria Women's Rugby Team, while 2 individuals competed for either the Castaway Wanderer's Rugby Club or the Westshore Velox Rugby Club, two of British Columbia's women's recreational rugby teams. Due to one participant withdrawing from the study, a final sample size of 13 female participants (age =  $21 \pm 1.85$  years; height =  $167.64 \text{ cm} \pm 6.7 \text{ cm}$ ; weight =  $72.89 \text{ kg} \pm 6.17 \text{ kg}$ ) resulted due to a participant withdrawing from the research study. Participants had a mean of 6 years of rugby experience before study participation. Screening for disorders that could possibly affect test performance such as diagnosed colorblindness or Attention deficit hyperactive disorder (ADHD) took place using a demographic questionnaire. In addition, questions relating to current lower body injuries that could affect balance performance were also included. Participants provided written informed consent to study participation.

Of the 13 participants, 8 were identified as having a history of sustaining a minimum of one medically diagnosed concussion, where the mean recovery time was 10.32 days. The number of previous medically diagnosed concussions ranged from 0-3 with a mode of 1. Three participants were left foot dominant, and all but two participants were right hand dominant.

### **2.2.4 Study Procedure**

This study received approval by the University of Victoria Human Research Ethics Board (Appendix A, Protocol #15-193). All data collection took place in the Rehabilitation Neuroscience Laboratory at the University of Victoria. Consenting participants who met inclusion criteria attended four one-hour data collection appointments at two defined intervals during the varsity rugby season: 1) *Pre-season and*, 2) *Post-season*.

### **2.2.5 Instruments & Outcome Measures**

Six instruments were used for data collection in this study. Research assistants involved in data collection procedures were trained in instrument administration prior to data collection. All questionnaires were scored by a single researcher. Participants completed the demographic questionnaire (Appendix B) and SCAT-5 (Appendix C) as a part of study intake. Participants completed Soleus H-Reflex measurements, static balance assessment (Appendix E) and a dynamic postural challenge assessment (Appendix D) measures and at *Pre-season* and *Post-season*. Electromyography data were collected for all participants at all data collection appointments. A Video Analysis Frequency Chart (Appendix F) for all season games was also used as an instrument to quantify subconcussion for each participant. The order of test administration was consistent for all participants and all testing sessions.

### **2.5.1 Demographic Questionnaire**

During the first data collection appointment at *Pre-season*, participants completed a demographic questionnaire (Appendix B). This questionnaire gathered general physical measurements about each participant (e.g., age, height, weight, etc.) in addition to more detailed information regarding both medical and athletic history (e.g. concussion history, years of rugby participation, etc.). This questionnaire was helpful in confirming participants did not have any acute lower body injuries (i.e. ankle sprain, adductor strain, plantar fasciitis) or visual decrements (i.e., colourblindness) that may affect participant's ability to adequately perform in the static or dynamic balance assessments.

### **2.5.2 Standardized Concussion Evaluation Tool**

The SCAT-5 was administered by an accredited Athletic Therapist in accordance with the guidelines published within the 2016 Consensus Statement on Concussion in Sport (McCroory et al., 2017). This tool was employed to assess somatic symptoms, cognitive ability and overall balance control. Section one (Red Flags, Observable Signs, Maddocks Questions, Glasgow Coma Scale, Cervical Spine Assessment) was omitted for lack of clinical relevance to participants without concussion. All scores of the SCAT-5 were done per The Concussion in Sport Group (CISG) guidelines.

### **2.5.3 Quantified Balance Assessment**

An instrument previously used by Cullen, Sun, Christie & Zehr (2016) for quantified balance data collection, (Nintendo Wii Fit Balance Board (WBB)) was interfaced through Bluetooth with a laptop computer (Microsoft Windows 10 operating system) using custom

software (LabVIEW 2011 National Instruments, Austin, TX, USA) (Holmes, Jenkins, Johnson, Hunt, & Clark, 2012). Before each testing appointment, the WBB was calibrated using custom software (LabVIEW 2011 National Instruments, Austin, TX, USA). Data were sampled at 100 Hz. The WBB program integrated both static and dynamic balance components. The WBB is a validated force detecting instrument that is widely available and relatively inexpensive. This instrument has been validated against force plates, which are the gold standard tool for balance assessment and has extremely good validity ( $r=.099$ ) and test-retest reliability of ( $R=0.88$ ) respectively (Chang et al., 2014), although any validated force detecting tool would be acceptable to use for detecting subtle changes to COP after subconcussion.

During the static balance task, the BESS was administered to each participant while standing on the WBB, in accordance with the CISG guidelines (McCrory, Meeuwisse, Aubry, Cantu, Dvorák, et al., 2013) as to administer the assessment tool in the same way as it would be done in a clinical setting, regardless of how the outcome measures are being assessed. Each participant performed one 20-second trial of each BESS stance (i.e. *double, single, and tandem*) with eyes closed and hands placed on the hips at each testing appointment. The stances included: double leg (*double*), non-dominant leg (*single*), and tandem leg (*tandem*) where the non-dominant leg was placed at the back. All three stances were performed barefoot and were repeated using a medium density foam placed on top of the WBB (Airex Balance Pad Elite 81002, 50.08 cm x 40.64 cm x 6.35 cm). Participants were given appropriate time between trials to rest. For the purposes of this study, COP was defined as “the point location of the vertical ground reaction force vector [and] represents a weight average of all the pressure of the surface of area in contact with the ground” (Winter, 1995). WBB force data were used to calculate:

*Equation 1. Center of Pressure X (COP<sub>x</sub>):*

$$COP_x = \frac{F_{TR} + F_{BR}}{(TR + BR + TL + BL)}$$

*Equation 2. Center of Pressure Y (COP<sub>y</sub>):*

$$COP_y = \frac{F_{TL} + F_{TR}}{(TR + BR + TL + BL)}$$

**Equation 3. Center of Pressure medial-lateral path length (COP<sub>ML</sub>):**

$$COP_{ML} = | \sum COP_x (n + 1) - COP_x (n) |$$

**Equation 4. Center of Pressure anterior-posterior path length (COP<sub>AP</sub>):**

$$COP_{AP} = | \sum COP_y (n + 1) - COP_y (n) |$$

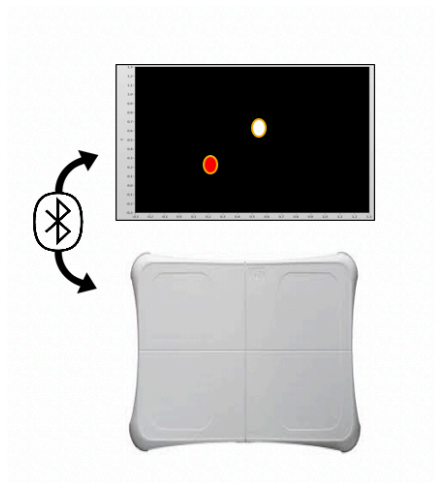
**Equation 5. Center of Pressure total path length (COP<sub>T</sub>):**

$$COP_T = \sum \sqrt{[COP_x (n) - COP_x (n + 1)]^2 + [COP_y (n) - COP_y (n + 1)]^2}$$

#### **2.5.4 Dynamic Postural Challenge Assessment**

The dynamic postural challenge assessment took place using the WBB paired with a LabVIEW program through Bluetooth technology. To begin, each participant stood barefoot on the WBB with their hands placed on hips. Directly in front of the participant there was a laptop screen at chest height which displayed COP. Upon the initiation of a trial, a target dot appeared on

the screen and moved in random sequence among eight cardinal and ordinal directions. Participants were instructed to shift their weight on the WBB so that the COP met the target on the screen as quickly and as accurately as possible.



**Figure 2.** Balance board (WBB) is pictured on the bottom, with a single trial of the program (LabVIEW) displayed on laptop monitor. The white dot is the participants COP while the red dot is the target in one of the 8 ordinal locations that appeared in each trial. These instruments were paired using Bluetooth technology as indicated by the arrow on the left.

Trial 1 was used as a practice trial, to familiarize participants with the instructions and procedure, and was not analyzed as part of the data set. Each participant completed  $n=6$  trials per appointment and were given appropriate rest time between each trial. Data from trials 2-6 was averaged. The outcome measure of interest was the recovery time from virtual perturbation for this dynamic WBB assessment. The time it took the participant to reach each target ( $t_{\text{Target}}$ ) and time to return to center from target ( $t_{\text{Centre}}$ ) were recorded. These times were summed to compute  $t_{\text{TOTAL}}$  (Equation 6) (Cullen, Sun, Christie, & Zehr, 2016), (Cullen, 2017). Appendix D contains the WBB & LabVIEW instructions given to participants.

**Equation 6.** Total recovery time ( $t_{TOTAL}$ )

$$t_{Total} = t_{Target} + t_{Centre}$$

**2.5.5 Assessment of Spinal Cord Excitability**

Bipolar surface electrodes (Thought Technology Ltd., Montreal, QC, Canada) were placed over the popliteal fossa on both legs. A square wave (1ms) electrical stimulus was applied to the tibial nerves using a Digitimer (Mendtel, NSW, Australia) constant current stimulator (model DS7A). Electrode position was adjusted to elicit the largest response in the soleus without a response in the tibialis anterior. A recruitment curve was recorded prior to the initiation of the experimental procedure, where the stimulus intensity was continuously increased from 45-70% of Hmax, to elicit a supramaximal M-wave ( $M_{Max}$ ). Bilateral H-reflexes were then evoked pseudorandomly (between 1 and 3 seconds) and the intensity of stimulation was adjusted to a level that caused evoked waveforms between 50% and 80% of Hmax recorded on the ascending limb of the stimulus response curve. In all cases, there was a measurable M-wave. 510 sweeps were collected on both legs simultaneously and the first 10 were discarded to remove the initial transient caused by homosynaptic depression (Mezzarane et al., 2017). A non-contact milliammeter (mA-200, Bell Technologies, Orlando, FL, USA) was used to measure the current delivered during each stimulus. Coefficient of Variation (CV) for the H-reflex was calculated to describe the bilateral variability of the reflex. The ratio between standard deviation and the mean of the remaining 500 responses (Mezzarane & Kohn, 2002) was then used to determine if there were significant differences bilaterally.

### **2.5.6 Electromyography**

While seated with both feet flat on the floor, the EMG from the Tibialis Anterior (TA), Vastus Lateralis (VL), and Soleus (SOL) muscles was collected bilaterally for each participant. Before collection, the skin was prepared for electrode placement by land marking each muscle, and cleansing the area using an alcohol swab. Bipolar surface electrodes were placed bilaterally on the TA, VL and SOL muscles while a single grounding electrode was placed over the right and left patella. EMG recordings were amplified (500 times for SOL and 5000 times for all other muscles) and filtered (10-1000 Hz for SOL and 100-300 Hz for all other muscles, P511 Grass Instruments, AstroMed Inc, West Warwick, RI, USA).

### **2.5.7 Video Analysis**

Game film for each match of the season was obtained from YouTube, a public use website used for video sharing. The film was accessed from the personal YouTube channel of Brittany Waters (<https://www.youtube.com/channel/UCa1hCL60CUGihWKC7PQws2Q/videos>), the Head Coach of the UVic Women's rugby team. Film was analyzed for each participant in the study by two former rugby athletes who were knowledgeable of the rules of the game. The two reviewers were trained to detect and record events which resulted in subconcussion using video examples, current literature and the latest operational definitions outlining the mechanism of subconcussion. As seen by Gardner, Howell, & Iverson (2018), in a video review study of multiple concussion signs in National Rugby League, a single reviewer completed the coding of possible subconcussive events. Times when collisions resulted in direct head impacts or indirect impacts where impulsive forces resulted in whip-lash type head movements were recorded.

These events were coded based on impact type (tackled from front, tackled from behind, ruck), impact location (head, upper body), signs of concussion (loss of consciousness, clutching head, gait unsteadiness, vacant stare, possible seizure) and lastly presence of head impact. In addition to the times recorded by the first reviewer, fictitious times in each game were included to the document which was then provided to the second reviewer. The second reviewer then evaluated the identified instances and coded them as either positive or negative for head impact, a method utilized in a study conducted by Echmemendia et al. (2017) which reviewed visible signs as predictors for concussion diagnosis in the National Hockey League. YouTube, the media platform by which all game film was watched and analyzed, had the capacity for slow motion and rewind functions, and there was no limit placed on how many times a particular event was reviewed. Two independent coders reviewed each regular season and playoff game, for a total of 8 games in the 2017 season. The average amount of exposures per player over the course of the season was comparable to studies which looked to identify if balance deficits were discernable following a bout of soccer ball heading exposures (Mangus, Wallmann, & Ledford, 2007), (Hwang et al., 2017).

### **2.2.6 Statistical Analysis**

Data were entered and organized into Microsoft Excel Version 15.3 for Mac. All statistical analysis was performed using Statistical Package for the Social Sciences (IBM SPSS Statistics for Macintosh, Version 24.0. Armonk, NY: IBM Corp) with the level of significance set at  $p < .05$ . Two forms of analysis were performed: single participant and group analyses. For individual comparisons, a 95% confidence interval (CI) was established from the three *Pre-season* values. *Post-season* values were then compared to the 95% CI, and were considered

statistically significant if they fell outside the CI (Cummings, 2013). The total number of participants who showed significant changes over the season is reported in Table 11.

For group comparisons, a Repeated Measures Analysis of Variance (RM-ANOVA) was run to compare differences across the three *Pre-season* testing sessions. If no significant differences were found, an average *Pre-season* value was formed by pooling the data together for each measure. RM-ANOVAs were performed to assess the main effect of time for *Pre-season* and *Post-season*. Data were assessed to confirm the assumptions of parametric analyses were met, and in instances where the assumption of sphericity was violated, the Greenhouse-Geisser correction was applied and degrees of freedom were adjusted. Cohen's *d* effect size comparisons between *Pre-season* *Post-season* time points were then calculated to provide magnitude of change, with  $0.2 \leq d < 0.5$ ,  $0.5 \leq d < 0.8$  and  $d \leq 0.8$  representing small, medium and large effects, respectively (Cohen, 1988).

## 2.3 Results

### 2.3.1 Participant Characteristics

**Table 1:** *Pre-season participant characteristics*

	M ± SD
Age (years)	21 ± 1.84
Height (cm)	167.64 ± 0.07
Weight (kg)	72.88 ± 6.19
BMI (kg/m <sup>2</sup> )	26.48 ± 2.49
Right Hand Dominant	83%
Right Foot Dominant	75%

History of Diagnosed Concussion	50%
Number of Previous Concussions	1.5 ± 1.07
Days Needed to Recover from Last Concussion	10 ± 6.32
Number of Years Playing Rugby	6 ± 2.7

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*Note:* M= Mean; SD = Standard Deviation; BMI = Body Mass Index

### 2.3.1.1 Quantified Balance & Postural Challenge Assessment

*Static balance on stable floor surface:* In the *double* stance condition for COP<sub>ML</sub> there was no change between *Pre-season* and *Post-season* ((27% increase ( $F_{1,12} = 3.867$ ,  $d=0.8$ ,  $p=.073$ )). Between *Pre-season* and *Post-season* COP<sub>AP</sub> worsened by 31% ( $F_{1,12} = 6.557$ ,  $d=0.9$ ,  $p=.025$ ). Additionally, mean COP<sub>T</sub> worsened by 26% ( $F_{1,12} = 5.454$ ,  $d=0.9$ ,  $p=.038$ ) between *Pre-season* and *Post-season*. No statistically significant differences were observed between time points for any outcome measures in *single* stance: COP<sub>ML</sub> ( $F_{1,10} = 2.341$ ,  $d=0.6$ ,  $p=.157$ ), COP<sub>AP</sub> ( $F_{1,10}=1.440$ ,  $d=0.5$ ,  $p=.258$ ) or COP<sub>T</sub> ( $F_{1,10} = 1.646$ ,  $d= 0.5$ ,  $p=.228$ ) or *tandem* stance: COP<sub>ML</sub> ( $F_{1,12} = 1.164$ ,  $d=0.4$ ,  $p=.302$ ), COP<sub>AP</sub> ( $F_{1,12} = 1.078$ ,  $d=0.4$ ,  $p=.320$ ), COP<sub>T</sub> ( $F_{1,12} = 0.148$ ,  $d=0.006$ ,  $p=.707$ ). These results are outlined in Table 2. Focusing specifically on the *double* stance condition, COP<sub>AP</sub> worsened by 31% ( $F_{1,12} = 6.557$ ,  $d=0.9$ ,  $p=.025$ ) and COP<sub>T</sub> worsened by 26% ( $F_{1,12} = 5.454$ ,  $d=0.9$ ,  $p=.038$ ) between *Pre-season* and *Post-season*.

**Table 2:** Static postural balance outcome measures (Centre of Pressure<sub>Medio-Lateral</sub>, Centre of Pressure<sub>Anterior-Posterior</sub> and Centre of Pressure<sub>Total</sub>) for double, single, and tandem stances on stable floor surface from whole group analysis.

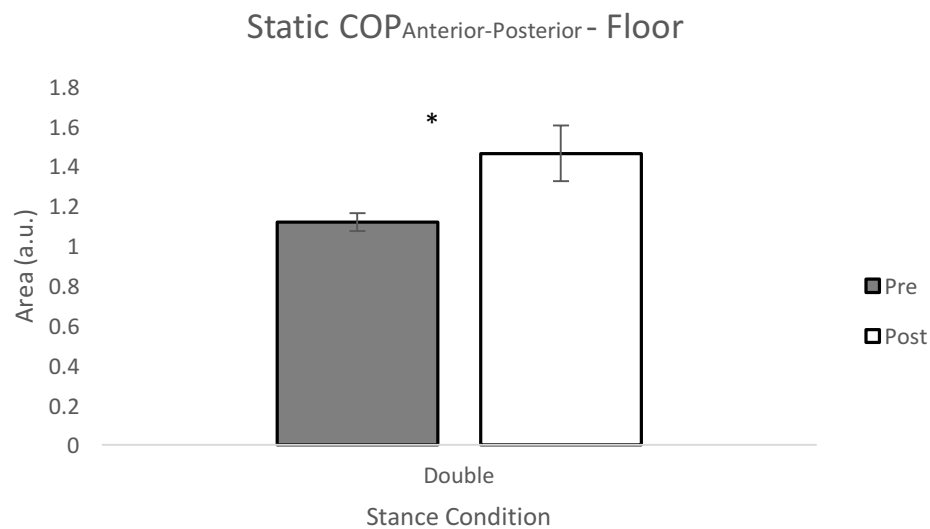
	<i>Pre-season</i>	<i>Post-season</i>	<i>Effect Size</i>	<i>p</i>	<i>% Δ</i>
<b>COP<sub>ML</sub></b>					
<i>double</i>	0.674 ± 0.03	0.858 ± 0.09	0.8	.073	27%
<i>single</i>	2.846 ± 0.12	5.106 ± 1.51	0.6	.157	79%
<i>tandem</i>	5.639 ± 2.45	2.880 ± 0.26	0.4	.302	-50%
<b>COP<sub>AP</sub></b>					
<i>double</i>	1.118 ± 0.05	1.463 ± 0.14	0.9	<b>.025</b>	<b>31%</b>
<i>single</i>	4.973 ± 0.30	8.425 ± 2.84	0.5	.258	71%
<i>tandem</i>	8.216 ± 3.88	4.076 ± 0.24	0.4	.320	-50%
<b>COP<sub>T</sub></b>					
<i>double</i>	1.539 ± 0.06	1.939 ± 0.16	0.9	<b>.038</b>	<b>26%</b>
<i>single</i>	6.474 ± 0.35	10.97 ± 3.60	0.5	.228	69%
<i>tandem</i>	20.83 ± 14.4	20.53 ± 14.3	0.0	.707	-1.4%

*Note:* Cohen's *d* effect size comparing *Pre-season* to *Post-season*. '*p*' represents the results of a *RM-ANOVA* between *Pre-and Post-season*. **Bold** indicates significant change ( $p < .05$ ).

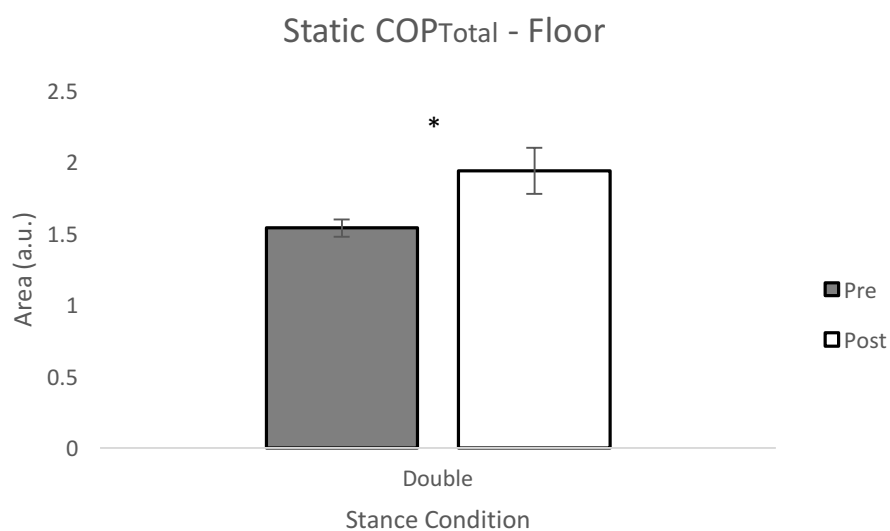
**Table 3:** Single subject analysis for static postural balance measures (Centre of Pressure<sub>Medio-Lateral</sub>, Centre of Pressure<sub>Anterior-Posterior</sub> and Centre of Pressure<sub>Total</sub>) on the stable floor condition. Numbers indicate participants (from total n) who had significant changes (improved, worsened or remained unchanged) in pre-post comparisons.

	<i># of decreased performance</i>	<i># of maintained performances</i>	<i># of improved performances</i>	<i>% Δ</i>
<b>COP<sub>ML</sub></b>				
<i>double</i>	6/13	7/13	0/13	27%
<i>single</i>	5/13	4/13	2/13	79%
<i>tandem</i>	5/13	8/13	0/13	-50%
<b>Total</b>	<u>16</u>	<u>19</u>	<u>2</u>	
<b>COP<sub>AP</sub></b>				
<i>double</i>	8/13	5/13	0/13	<b>31%</b>
<i>single</i>	2/13	11/13	0/13	71%
<i>tandem</i>	4/13	8/13	1/13	-50%
<b>Total</b>	<u>14</u>	<u>24</u>	<u>1</u>	
<b>COP<sub>T</sub></b>				
<i>double</i>	7/13	4/13	2/13	<b>26%</b>
<i>single</i>	4/13	7/13	0/13	69%
<i>tandem</i>	5/13	6/13	2/13	-1.4%
<b>Total</b>	<u>16</u>	<u>17</u>	<u>4</u>	

*Note:* Cohen's *d* effect size comparing *Pre-season* to *Post-season*. '*p*' represents the results of a *RM-ANOVA* between *Pre-and Post-season*. **Bold** indicates significant change ( $p < .05$ ).



**Figure 3.** Static Postural Balance Assessment on Floor in the Anterior-Posterior direction. \* denotes RM-ANOVA significance at  $p < .05$  from Pre-to-Post Season. There was a significant increase in  $COP_{Anterior-Posterior}$  in the double stance condition from Pre-to Post-Season.



**Figure 4.** Static Postural Balance Assessment on Floor for the Total Area. \*denotes RM-ANOVA significance at  $p < .05$  from Pre-to-Post Season.

*Static balance on foam surface:* No statistically significant differences were observed between time points for any outcome measures in *double* stance: COP<sub>ML</sub> ( $F_{1,12} = 0.061, p=.483$ ), COP<sub>AP</sub> ( $F_{1,12} = 0.456, p=.265$ ) or COP<sub>T</sub> ( $F_{1,11} = 122, p=.733$ ). In the *single* stance condition, COP<sub>ML</sub> did not change between *Pre-season* and *Post-season* (worsened by 25% ( $F_{1,10} = 2.477, d=0.6, p=0.147$ )). There was no change between *Pre-season* and *Post-season* in COP<sub>AP</sub> (13% improvement ( $F_{1,10} = 0.703, d=0.3, p=.421$ )). COP<sub>T</sub> did not change between *Pre-season* and *Post-season* (improved by 4% ( $F_{1,11} = 0.109, d=0.06, p=0.747$ )). In the *tandem* stance condition, COP<sub>ML</sub> worsened between *Pre-season* and *Post-season* by 180% ( $F_{1,12} = 8.219, d=1.0, p=.014$ ). COP<sub>AP</sub> worsened by 176% ( $F_{1,12} = 6.519, d=0.9, p=.025$ ) between *Pre-season* and *Post-season*. COP<sub>T</sub> worsened *Pre-season* and *Post-season* by 141% ( $F_{1,12} = 11.903, d=1.3, p=.005$ ). These results are outlined in Table 3. Focusing specifically on the *tandem* stance condition, COP<sub>ML</sub> worsened by 180% ( $F_{1,12} = 8.219, d=1.0, p=.014$ ), and COP<sub>AP</sub> worsened by 176% ( $F_{1,12} = 6.519, d=0.9, p=.025$ ) and COP<sub>T</sub> worsened by 141% ( $F_{1,12} = 11.903, d=1.3, p=.005$ ). between *Pre-season* and *Post-season*.

**Table 4:** Static postural balance outcome measures (Centre of Pressure<sub>Medio-Lateral</sub>, Centre of Pressure<sub>Anterior-Posterior</sub> and Centre of Pressure<sub>Total</sub>) for double, single, and tandem stances on foam surface from whole group analysis.

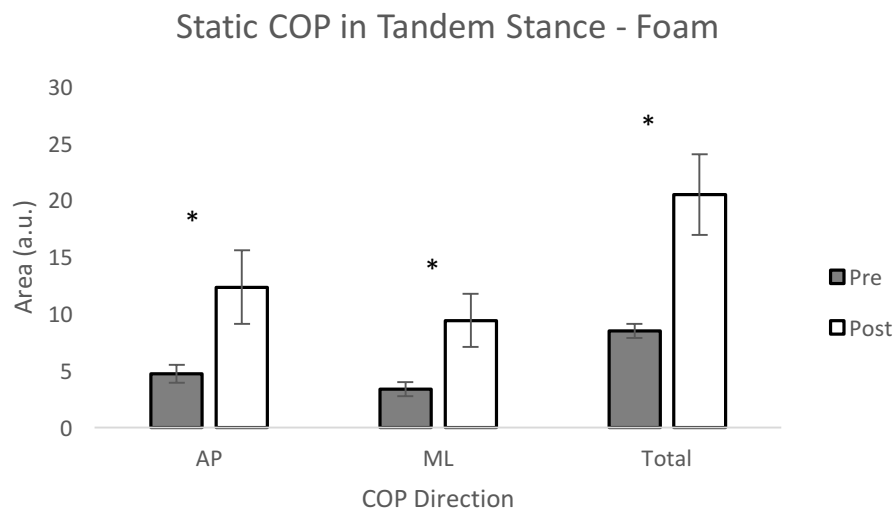
	<i>Pre-season</i>	<i>Post-season</i>	<i>Effect Size</i>	<i>p</i>	<i>% Δ</i>
<b>COP<sub>ML</sub></b>					
<i>double</i>	1.225 ± 0.07	1.433 ± 0.08	0.8	.483	17%
<i>single</i>	4.455 ± 0.55	5.577 ± 0.65	0.6	.147	25%
<i>tandem</i>	3.369 ± 0.61	9.419 ± 2.34	1.0	<b>.014</b>	<b>180%</b>
<b>COP<sub>AP</sub></b>					
<i>double</i>	3.012 ± 0.21	2.976 ± 0.14	0.1	.265	1%
<i>single</i>	8.027 ± 0.92	9.089 ± 1.10	0.3	.421	13%
<i>tandem</i>	4.475 ± 0.79	12.342 ± 3.21	0.9	<b>.025</b>	<b>176%</b>
<b>COP<sub>T</sub></b>					
<i>double</i>	3.614 ± 0.22	3.764 ± 0.18	0.2	.733	4%
<i>single</i>	16.683 ± 5.72	16.096 ± 2.44	0.1	.747	4%
<i>tandem</i>	8.485 ± 0.62	20.484 ± 3.53	1.3	<b>.005</b>	<b>141%</b>

*Note:* Cohen's *d* effect size comparing *Pre-season* to *Post-season*. '*p*' represents the results of a RM-ANOVA between *Pre-and Post-season*. Bold indicates significant change ( $p < .05$ ).

**Table 5:** Single subject analysis for static postural balance measures (Centre of Pressure<sub>Medio-Lateral</sub>, Centre of Pressure<sub>Anterior-Posterior</sub> and Centre of Pressure<sub>Total</sub>) on the unstable foam condition. Numbers indicate participants (from total n) who had significant changes (improved, worsened or remained unchanged) in pre-post comparisons.

	<i># of decreased performances</i>	<i># of maintained performances</i>	<i># of improved performances</i>	<i>% Δ</i>
<b>COP<sub>ML</sub></b>				
<i>double</i>	4/13	9/31	0/13	17%
<i>single</i>	8/13	3/13	0/13	25%
<i>tandem</i>	10/13	3/13	0/13	<b>180%</b>
<b>Total</b>	<u>22</u>	<u>15</u>	<u>0</u>	
<b>COP<sub>AP</sub></b>				
<i>double</i>	2/13	6/13	4/13	1%
<i>single</i>	5/13	5/13	1/13	13%
<i>tandem</i>	8/13	4/13	1/13	<b>176%</b>
<b>Total</b>	<u>15</u>	<u>15</u>	<u>6</u>	
<b>COP<sub>T</sub></b>				
<i>double</i>	4/13	4/13	4/13	4%
<i>single</i>	7/13	3/13	2/13	4%
<i>tandem</i>	10/13	2/13	1/13	<b>141%</b>
<b>Total</b>	<u>21</u>	<u>9</u>	<u>1</u>	

*Note:* Cohen's *d* effect size comparing *Pre-season* to *Post-season*. '*p*' represents the results of a *RM-ANOVA* between *Pre-and Post-season*. **Bold** indicates significant change ( $p < .05$ ).



**Figure 5.** Static Postural Balance Assessment on Foam surface, presenting Centre of Pressure (COP) deviations in the Anterior-Posterior (AP), Medio-Lateral (ML) directions and combined deviations (Total). \* denotes RM-ANOVA significance at  $p < .05$  from Pre-to-Post Season. There was a significant increase in  $COP_{ML}$ ,  $COP_{AP}$  and  $COP_T$  in the tandem stance condition from Pre-to Post-Season.

*Dynamic Postural Challenge Assessment:*

*Dynamic Postural Challenge:* No statistical differences were observed in tTarget between Pre-season and Post-season ( $F_{2,24} = 4.048$ ,  $d=0.5$ ,  $p=.069$ ). For tCentre there was a 24% improvement ( $F_{2,22} = 10.012$ ,  $d=1.2$ ,  $p=.004$ ) from Pre-season to Post-season. tTotal improved by 14% ( $F_{2,24} = 2.222$ ,  $d=1.2$ ,  $p=.001$ ) between Pre-season and Post-season.

**Table 6:** Dynamic postural challenge outcome measures (Time to Target, Time to Centre, and Time Total) from whole group analysis.

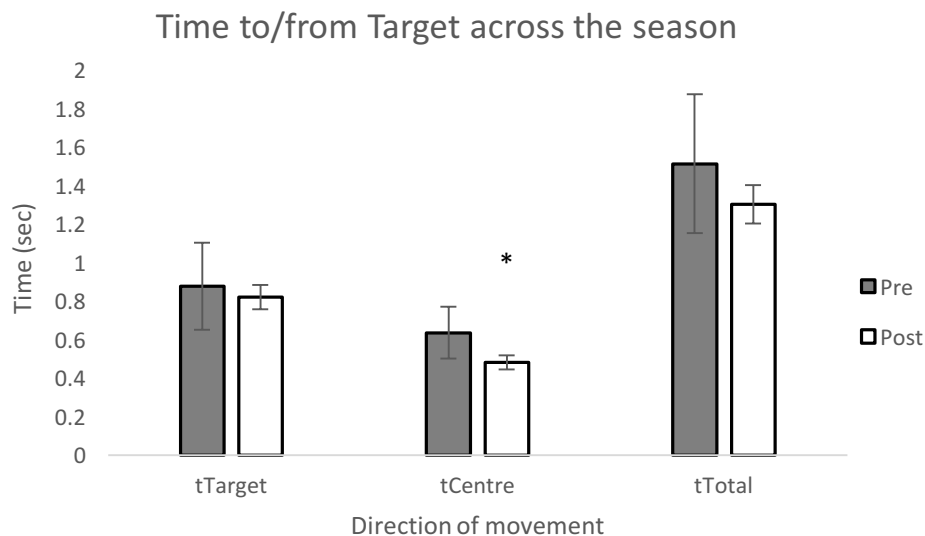
	<i>Pre-season</i>	<i>Post-season</i>	<i>Effect Size</i>	<i>p</i>
<b>tTarget</b>	0.877 ± 0.03	0.820 ± 0.03	0.5	.052
<b>tCentre</b>	0.636 ± 0.04	0.482 ± 0.02	1.2	<b>.002</b>
<b>tTotal</b>	1.512 ± 0.05	1.302 ± 0.05	1.2	<b>.001</b>

*Note:* Cohen's *d* effect size comparing *Pre-season* to *Post-season*. '*p*' represents the results of a *RM-ANOVA* between *Pre-and Post-season*. **Bold** indicates significant change ( $p < .05$ ).

**Table 7:** Single subject analysis for dynamic postural challenge outcome measures (Time to Target, Time to Centre, and Time Total). Numbers indicate participants (from total *n*) who had significant changes (improved, worsened or remained unchanged) in pre-post comparisons.

	<i># of decreased performance</i>	<i># of maintained performances</i>	<i># of improved performances</i>	<i>Effect Size</i>	<i>p</i>
<b>tTarget</b>	3/13	6/13	4/13	0.5	.052
<b>tCentre</b>	0/13	6/13	7/13	1.2	<b>.002</b>
<b>tTotal</b>	0/13	6/13	7/13	1.2	<b>.001</b>
<b>Total</b>	<u>3</u>	<u>18</u>	<u>14</u>		

*Note:* Cohen's *d* effect size comparing *Pre-season* to *Post-season*. '*p*' represents the results of a *RM-ANOVA* between *Pre-and Post-season*. **Bold** indicates significant change ( $p < .05$ ).



**Figure 6.** *Dynamic Postural Challenge Task Completion and Recovery Time*  
 \* denotes post-hoc significance at  $p < .05$  from Pre-to-Post Season. There was a significant decrease in the time it took for participants to return to centre from target ( $t_{Centre}$ ) and total time from centre to target + time from target back to centre ( $t_{Total}$ ) in the assessment from Pre- to Post-Season. Interestingly, unlike the other two components of the dynamic assessment, there was no significant improvement in the time it took participants to reach the target ( $t_{Target}$ ).

**Table 8:** 95% CI ellipse data of static balance outcome measures for stance (*double, single, and tandem*) for the *floor* and *foam* conditions from whole group analysis.

		<i>DF</i>	<i>F</i>	<i>p</i>
<b>Floor</b>	<i>Double</i>	2	1.012	.298
	<i>Single</i>	2	0.383	.180
	<i>Tandem</i>	2	1.216	.342
<b>Foam</b>	<i>Double</i>	2	1.165	.061
	<i>Single</i>	2	2.051	.623
	<i>Tandem</i>	2	1.138	.112

Note: '*p*' represents results of a RM-ANOVA between Pre-and Post-season with significance set at ( $p < .05$ ). There were no significant changes in AoE from Pre- to Post-Season.

### 2.3.1.2 Quantified Video Analysis and Balance Assessment

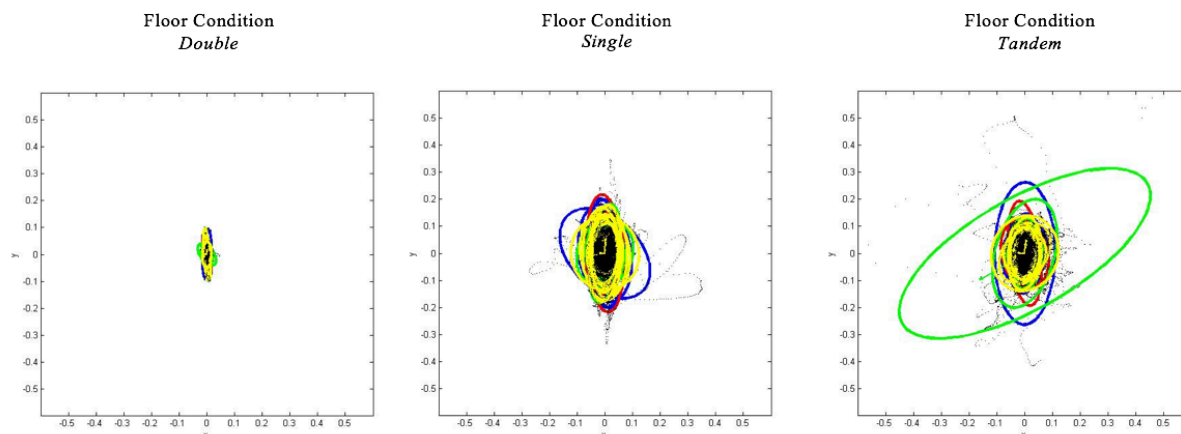
*Correlation between Area of Ellipse and Quantified Subconcussive impacts:*

Linear regression was used to determine if there was significant relationship between number of in-game subconcussive impacts, as determined by video analysis, and % change of area of ellipse (AoE) during static balance trials between time points. There was a significant ( $p=0.04$ ) correlation ( $r=0.760$ ) for AoE during *double* stance for the *floor* surface, to decrease with an increased number of subconcussive impacts from *Pre-season* to *Post-season*.

**Table 9:** Correlation statistics between Area of Ellipse (quantified value of COP deviations) from static balance outcome measures for all three stance conditions (double, single, and tandem) with number of subconcussive impacts sustained between *Pre*-and *Post-Season*, which were quantified from video analysis by two independent raters.

	Pre-to Post	
	<i>p</i>	R
<b>Floor</b>		
<i>Double</i>	<b>.040</b>	<b>.760</b>
<i>Single</i>	.478	-.030
<i>Tandem</i>	.247	-.352
<b>Foam</b>		
<i>Double</i>	.300	.274
<i>Single</i>	.371	-.174
<i>Tandem</i>	.163	.488

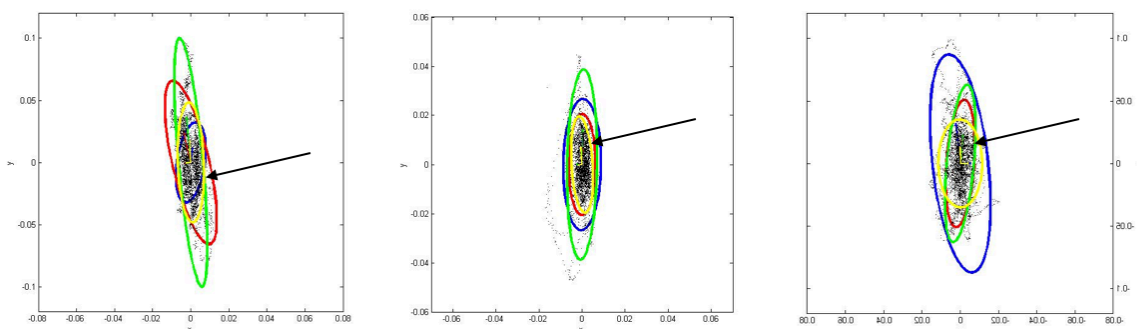
*Note:* Bold indicates correlation ( $0.7 \leq r \leq 1.0$ ). '*p*' represents the results of the correlation analysis with significance set at ( $p < .05$ ). Interestingly, results indicate a strong negative correlation between AoE and increasing # of subconcussive impacts sustained between *Pre*-to *Post-Season* in *Double* stance on the most stable of the two surface conditions.



**Figure 7:** Group average 95% CI Area of Ellipses in Floor Condition at each time point

Note: Blue = Pre-1, Red = Pre-2, Green = Pre-3, Yellow = Post-Season

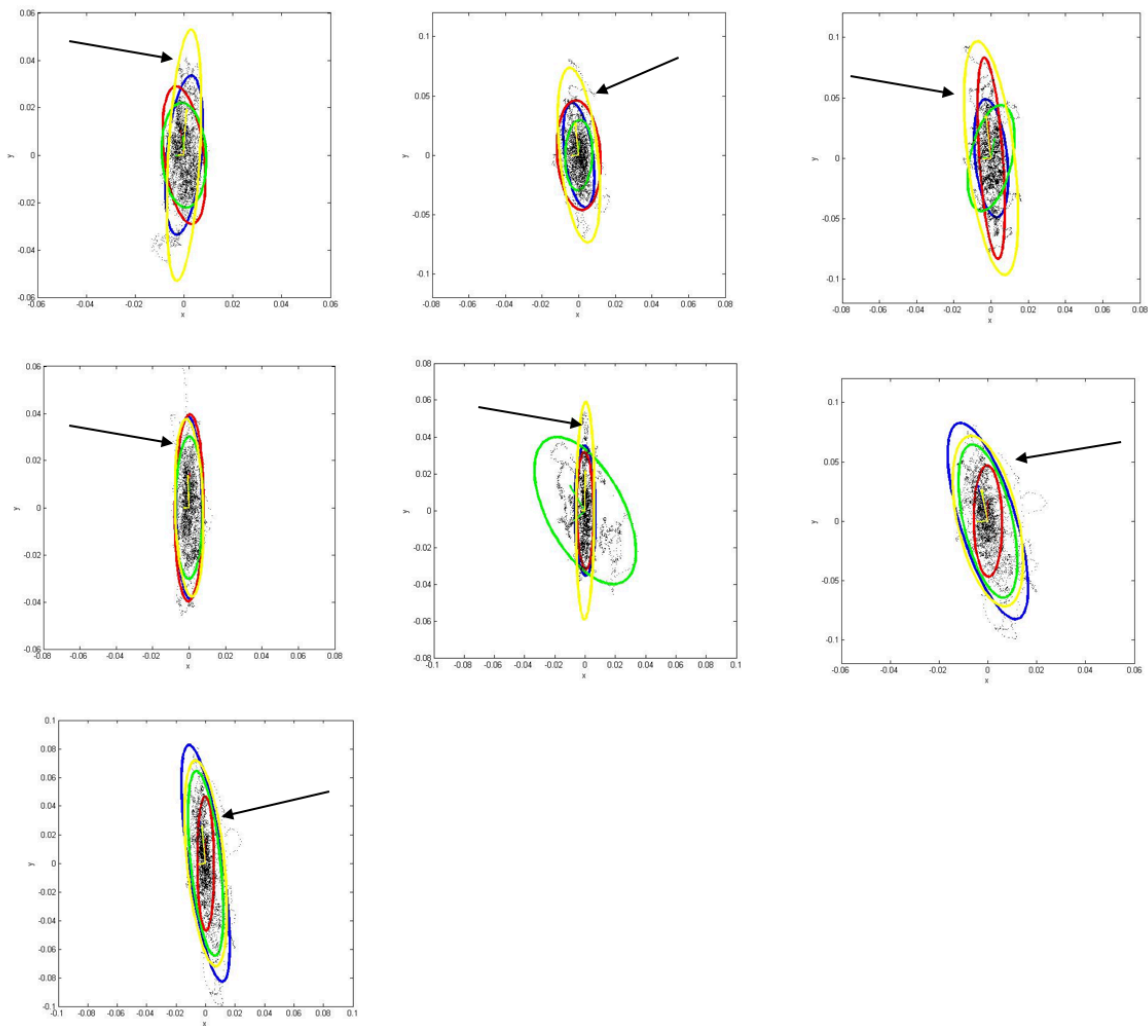
This figure highlights the variability of each stance condition, where a tighter ellipse is representative of a more stable stance condition. For instance, double stance is the least variable (and most stable) condition, evidenced by the consistently tight ellipses across time. Conversely, single stance had greater variability (less stability) as evidenced by a greater diameter of area of ellipse representations. The most variable and least stable condition was tandem stance, which has the greatest diameter of area of ellipse of the three conditions.



**Figure 8:** Single Subject Analysis of Area of Ellipses traces in Double stance who improved over time.

Note: Blue = Pre-1, Red = Pre-2, Green = Pre-3, Yellow = Post-Season

This figure is the individual data for three participants who's AoE improved across the season. In all three individuals, the three Pre-season traces (Blue, Red, Green) have greater diameters and cover a larger area compared to the Post-season trace (yellow), which has the smallest diameter of all testing appointments, as indicated by arrow. This result display that the AoE in double stance was reduced in these individuals over time, indicating task improvement from Pre- to Post-season, which would be expected after task familiarization and practise.



**Figure 9:** Single Subject analysis of Area of Ellipses traces on floor in Double stance whose performance worsened over time.

Note: Blue = Pre-1, Red = Pre-2, Green = Pre-3, Yellow = Post-Season. This figure is the individual data for all participants who's AoE in double stance increased in diameter across the season, which is indicative of poorer task performance over time. Deteriorating individual performance is evidenced by the majority of Pre-season traces (blue, red, green) lying within the area of the Post-season (yellow) trace. With increased exposure to a specific task, it is expected for task performance to improve over time (i.e. smaller diameter of yellow trace than all other colours). These results suggest that in these individuals, some mechanism of balance execution and performance interfered with the ability to decrease variability of centre of pressure deviation from Pre-to Post-season, even after task familiarization and practise as seen by the yellow trace (indicated by arrow) lying outside of all other traces.

### 2.3.1.3 Spinal Cord Excitability Assessment

Across study time points reflex amplitudes (normalized to supramaximal M-wave amplitudes) were not significantly different. Pre-season left and right Hmax/Mmax ratios were 54% and 63% respectively. Post-season left and right Hmax/Mmax ratios were 42% and 45% respectively. *Pre-season* right and left H-reflex amplitudes were  $48.9\% \pm 13\%$  and  $46.0\% \pm 11.6\%$  of Hmax ( $26.4\% \pm 18.9\%$  and  $32.4\% \pm 21.7\%$  of Mmax respectively). *Post-season* right and left H-reflex amplitudes were  $65.6 \pm 14\%$  and  $65 \pm 14\%$  of Hmax ( $27.3\% \pm 15.1\%$  and  $31.6\% \pm 14.7\%$  of Mmax respectively). *Pre-season* M-wave amplitudes on the right and left sides were  $6.2\% \pm 9.4\%$  and  $6.2\% \pm 7\%$  of Mmax. *Post-season* M-wave amplitudes on the right and left sides were  $8.3\% \pm 7\%$  and  $6.9\% \pm 10.2\%$  of Mmax respectively. A paired t-test confirmed that there were no statistically significant changes in H-reflex amplitude for right or left legs ( $p=.290$ ), ( $p=.672$ ), respectively). Each H-reflex sequence which contained 510 responses per leg had the first 10 responses discarded to ensure the results were not affected by initial homosynaptic depression (Mezzarane & Kohn, 2002).

As confirmed by a paired t-test, the Coefficient of Variation for the right (CVR) and left (CVL) legs did not show significant differences ( $p=0.299$ ), ( $p=0.218$ ) over time, which is outlined in Table 7.

**Table 7:** Coefficients of Variation for Right (CVR) and Left (CVL) legs and Zero-Lag Cross-Covariance (CCV) outcome measures between *Pre*-and *Post-Season* from whole group analysis.

	<i>Pre-Season</i>	<i>Post-Season</i>	<i>p</i>
<b>CVR</b>	0.40114	0.32545	0.2997
<b>CVL</b>	0.44738	0.30901	0.281
<b>Zero-Lag CCV</b>	0.51385	0.53352	0.530

*Note: 'p' represents results of paired t-tests. There were no significant changes in CVR, CVL or Zero-Lag CCV between Pre-and Post-season.*

**Table 11:** Single subject analysis for average peak values at the Cross-Covariance (CCV) sequence (at the zero-lag) between right and left soleus muscles

<b>Subject</b>	<i>Pre</i>	<i>Post</i>
S1	0.641647472	0.649968138
S2	0.355784506	0.395374992
S3	0.29577806	0.159988312
S4	0.426398329	0.595555204
S5	0.603113997	0.668668514
S6	0.54399334	0.578087284
S7	0.680061773	0.701722841 *
S8	0.680061773	0.616485245
S9	0.710209473	0.323127027 **
S10	0.377596341	0.632248245 *
S11	0.500520418	0.453376053
S12	0.384164057	0.499680391 *
S13	0.547938014	0.683901626

Three individual's CCV data fell above the established 95% CI indicating a significant peak ( $p < 0.05$ ), this is signified by a single asterisk (\*), from *Pre-to Post-season*. One individual's CCV data fell below the established 95% CI, which is indicated by two asterisks (\*\*), from *Pre-*

to *Post-season*. The percentage of occurrences for significant peak proportion across participants in *Post-season* was 30.7%.

## 2.4 Discussion

The goal of this prospective study was to assess objectivity and sensitivity of challenging, quantifiable balance assessments and spinal cord excitability measures to detect altered postural control after accumulated subconcussion in contact sport athletes. Four main findings emerged after data analysis: 1) double stance on a stable surface and tandem stance on an unstable surface were the most sensitive to balance decrements over the course of the season; 2) there was a significant negative correlation between Area of Ellipse and quantified subconcussive head impacts from *Pre-to Post-season*; 3) there was significant increase in the time needed to recover from postural perturbation from *Pre-to Post-season*; and 4) the presence of abnormally high *Pre-season* spinal cord excitability measures of CVR, CVL and CCV values suggest prior neurological damage. These findings are indicative of assessment tools that are capable of discriminating balance control decrements after accumulated subconcussive head impacts and provides direction for future research.

### 2.4.1 Double and Tandem Stances Show Greatest Change Across Season

Of the three static balance conditions in the current study, *double* stance on the stable floor condition is the least challenging, in that previous studies have not found significant differences among subjects (Hunt et al., 2009). This is likely because *double* stance is an fundamental stance position for human locomotion development (Adolph, 2006), and inherently has the largest base of support of the three conditions (*double, single, tandem*). In the current study, *double* stance on a stable floor surface worsened by 31% in COP<sub>AP</sub> (8/13 participants had decreased performance)

and  $COP_T$  worsened by 26% (7/13 participants had decreased performance) from *Pre-to Post-season*. As a fundamental posture with characteristically low variability (Hunt, Ferrara, & Bornstein, 2009), the significant reductions to *double* stance performance over the course of the season is noteworthy.

Practise effects are improvements to a certain task seen between concurrent testing sessions based on previous exposure and familiarity, while learning effects relate more to retention of this improvement over time (McLeod, Perrin, & Gansneder, 2004). Both practise and learning effects, which often proceed the acquisition of a novel task and result in increased variability, can reduce or inhibit an experimental outcome from being detected thereby confounding interpretation of test scores (McLeod, Perrin, & Gansneder, 2004). For this reason, it is possible that in the static, stable floor balance assessment of our study, participants likely experienced a learning effect in *single* and *tandem* stance, evidenced by the high variability in these conditions. This is consistent with previous findings where the serial administration of the BESS test produced a learning effect in the *tandem* stance condition in young athletes (McLeod et al., 2004), and in the *single* stance condition in high school athletes (Valovich, Perrin, & Gansneder, 2003). Barring this knowledge, learning effects may provide a reasonable explanation as to why *single* and *tandem* stance conditions did not have significant performance decrements with increasing number of subconcussive impacts over the season. Although results are not statistically significant, in both the *single* and *tandem* stance conditions for  $COP_{ML}$ ,  $COP_{AP}$  and  $COP_T$ , only two participants improved performance from *Pre-to Post-season* in each respective stable floor condition.

Our data suggest that *tandem* stance on an unstable surface is the most sensitive static balance measure for subtle postural decrements. This finding was indicated by statistically

significant increases in COP displacement from *Pre-Season* to *Post-Season* where  $COP_{ML}$ ,  $COP_{AP}$  and  $COP_T$  worsened by 180% (10/13 participants had decreased performance), 176% (8/13 participants had decreased performance) and 141% (10/13 participants had decreased performance) respectively, between *Pre-and Post-season*. These results suggest that objectively measuring changes to a challenging postural task can uncover subtle decrements to balance in asymptomatic individuals who have sustained subconcussive head impacts, that may not be detected using subjective measurement tools like the current standard mBESS. In addition to recognizing balance decrements in challenging postural tasks, the absence of improvement in a repeatedly practised assessment may be indicative of subtle neurological damage, as serial exposure and familiarization is associated with improved performance (McLeod, Perrin, & Gansneder, 2004). For this reason, it is interesting that out of 13 participants in *tandem* stance, three individuals had no change in performance in  $COP_{ML}$ , four had no change in  $COP_{AP}$ , and two experienced no change in  $COP_T$  from *Pre-to Post-season*. Only one individual showed significant improvement in *tandem*  $COP_{AP}$  and  $COP_T$ .

Other studies which have used the mBESS to investigate the effect of subconcussion on postural balance have found no significant difference between control and experimental groups (Hwang et al., 2017). One conclusion from this is the force of impact, such as soccer ball heading, is too small to result in disruption in central nervous system function and ultimately impaired balance control among other symptoms. However, one key gap in the current body of literature is a lack of discrimination between scores for increasingly difficult balance postures (*double, single, tandem*). Instead, analysis relied on total mBESS score either indicating successful or unsuccessful task completion. Without score differentiation between postural tasks which range in difficulty, it is possible that successful performance of less challenging postures, or learning effects in serial

administration of balance assessments may mask the subtle changes to balance that were observed in this study.

Our findings suggest that significant changes to balance are not revealed due to test sensitivity, not because the subconcussive impacts are too small to cause brain injury.

Assessing postural control is an indirect way of uncovering neurophysiological damage to supraspinal centres after suspected concussion (Cavanaugh, 2005). In instances of subconcussion where no overt symptoms are present, implementing a challenging and objective balance measure as a clinical assessment may uncover subtle balance decrements as a result of neural damage sustained from repetitive subthreshold trauma. Having an assessment tool that can objectively discriminate changes to an individual's postural or dynamic balance is valuable to prevent further neural damage or even concussion.

#### **2.4.2 Subconcussion Negatively Associates with Area of Ellipse in Familiar Static Postural Task**

In addition to investigating changes to COP, the Area of Ellipse (AoE) was calculated to describe changes in balance or postural adjustments that may go undetected when using COP calculations in isolation. AoE calculations show the amount of movement associated with COP and the predominant direction of that movement (Rose, 2016). Results revealed a significant negative correlation between the % change of AoE over the time and number of subconcussive head impacts, derived from video analysis, in the *double* stance condition on a firm surface from *Pre- to Post-season*. Unlike COP, which is an average calculation of each balance trial, AoE measurement provides information about COP movement over the course of each trial. Detecting significant negative correlations between % change in AoE and subconcussive impacts in only

one condition, which is also the least challenging, may not be indicative of the influence of subconcussion on more strenuous postural tasks.

The negative correlation observed between percent change in AoE during *double* stance and number of subconcussive impacts (and was not observed for the increasingly challenging conditions (*single, tandem*)) highlights decrements associated with balance postures of increasing complexity that often get overlooked by assessments that lack sensitivity or specificity. For instance, assessments such as the BESS lack sensitivity in where subtle decrements to the highly controlled *double* stance would be overlooked due to the subjective nature of the assessment scoring. Conversely, current balance assessments which use challenging, novel postural tests, such as ‘*single* stance with eyes closed on a foam surface’ inherently increase the variability of the results. Unlike in *double* stance, the outcome of novel tests may be masked and diluted by learning and practise effects as well as the overall variability of the assessment. For reasons relating to the lack of sensitivity and subjectivity of current balance assessments as well as the high variability of novel postures included in these assessments, there is reason to work towards developing an assessment protocol that can discriminate subtle, underlying balance deficits exhibited after subconcussion.

### **2.4.3 Despite Accumulated Subconcussion, Postural Perturbation Recovery Time Improves in Athletic Population**

In contrast to balance impairments observed in the static balance assessments between study time points, there was a 20% decrease (7/13 participants performance improved) in the time it took for participants to return to the centre (tCentre) and a 14% decrease (7/13 participants performance improved) in the total time (time to and from target (tTotal)) after a

postural perturbation from *Pre-to-Post season*. The negative influence of time on the tCentre and tTotal measurements in this study are also indicative of practise and learning effects. Both tCentre and tTotal outcome measures decreased at *Post-season*, which indicated skill improvement, although there was no significant change in the time it took participants to reach the target (tTarget) which is noteworthy, as this was the only condition that where three individuals exhibited decreased performance.

It was expected that in dynamic balance tasks where attention must be divided between cognitive and motor functions, individuals who have acquired a season's worth of subconcussions would present task incompetencies due to the competition for attention resources between simultaneous tasks (Register-mihalik, Littleton, & Guskiewicz, 2013). This competition between motor and cognitive resources has been shown to persist up to one month following concussion (Parker et al., 2008). However, considering that participants were all university level athletes who were likely skilled at performing multiple object tracking (Zhang, Yan, & Yangang, 2009), it is possible that the dynamic postural assessment used in our study did not sufficiently challenge these individuals. Further, given the competitive nature of most athletes, it is possible that improvements seen in the dynamic postural challenge could be attributed in part to task motivation, where it is possible that individuals were motivated to try harder at the *Post-season* assessment to show personal improvement of the task. Task motivation is a potential confounding factor in other athlete studies, as seen in (Mcallister et al., 2012), (Chin, Nelson, Barr, McCrory, & McCrea, 2016). Despite any observable task ineptitude from *Pre-to-Post season*, computerized dynamic balance assessment remains a potential area for clinicians to explore in order to develop an objective test for assessing neurophysiological decline with accumulated subconcussion.

#### **2.4.4 Spinal Cord Excitability Cross Covariance Suggests Prior Neurological Damage in Contact Sport Athletes Compared with Healthy Population**

Using the Cross Covariance (CCV) technique at the zero-lag enables the detection of bilateral fluctuations in H-reflex excitability and exposes temporal linkages between right and left legs (Mezzarane, Nakajima, & Zehr, 2017). CCV values did not change significantly (3/13 participants exhibited significant peak proportions) from *Pre-to Post-season* despite a season's worth of accumulated head impacts. However, when comparing both *Pre-and Post-season* CVR and CVL results of the current study to those of Mezzarane & Kohn, (2002), the study from which our bilateral H-reflex methods were adapted from, our results are higher on average by 1.5 times compared to their neurologically intact control population. In addition, in the 'Static' condition in the study by Mezzarane & Kohn (2002), which is the most comparable condition to that of the present study, the average CCV at the zero-lag between right and left soleus muscles was 0.174, while our average *Pre-season* CCV value was 0.514, which is almost 3-fold higher. Although the results do not indicate any abnormal change in bilateral H-reflex amplitude fluctuation as a result of subconcussive head impacts over a season, the elevated CVR (0.40 compared to 0.27 (Mezzarane & Kohn, (2002))) and CVL (0.44 compared to 0.24 (Mezzarane & Kohn, (2002))) values, in addition to comparably high *Pre-season* CCV values in rugby athletes in this study, compared to a healthy population, is suggestive that there may already be neurological damage from years of accumulated head impacts. Full exploration of this was beyond the scope of this project but warrants future consideration.

It is possible that there are H-reflex changes that occur after subconcussion, that went undetected during this study based on the decision to measure changes to bilateral reflex

fluctuation. Alternatively, perhaps this measure may only be suitable for symptomatic athletes as there is likely greater damage to supraspinal control centres.

#### **2.4.5 Conclusion and Recommendations**

Subconcussion, unlike concussion, is best defined and identified by a lack of observable symptoms after minor head impacts. Over time, accumulation of these impacts can result in long term neurological damage in individuals who are asymptomatic in areas of motor and/or cognitive impairment that is known to accompany neurotrauma. Even with known physiological damage as a result of subconcussion, there is currently no standardized assessment tool sensitive enough to detect subtle motor impairments resulting from neurological changes associated with an injury of this nature. For these reasons, a more sensitive and objective assessment tool is required to assess and recognize impairments in at risk athletes and populations. The current study identified significant changes to static balance using objective postural assessment of COP and Area of Ellipse calculations using a low-cost balance board and basic software interface. Our results indicate that these outcome measures are sensitive and can discriminate subconcussive impacts. Hopefully these measures may provide possible assessment tools to prevent further neurological damage. Further, our results suggest neurological damage resulting from subconcussive impacts can be identified through objectively measuring changes to challenging balance tasks. Future work should explore changes to cognition that are also likely affected by subconcussion to provide a greater framework and understanding of the underlying central damage that occurs after repeated head injury. Although the current study provides a platform for future research investigating bilateral fluctuation in spinal cord excitability and objective balance assessments for subconcussion, there is potential for selection bias, population demographics and small sample

size which limit the power and generalizability of the aforementioned results. Future studies should take these limitations into consideration.

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## Appendix A: Certificate of Ethics Approval for Modification of an Approved Protocol



Office of Research Services | Human Research Ethics Board  
 Michael Williams Building Box 8200 PO Box 1700 STN CSC Victoria BC V8W 2Y2 Canada  
 T 250-472-4545 | F 250-721-8960 | ethic@uvic.ca | uvic.ca/research |

### Modification of an Approved Protocol

PRINCIPAL INVESTIGATOR:	E. Paul Zehr	ETHICS PROTOCOL NUMBER:	15-193
UVic STATUS:	Faculty	<small>Minors/Full Review - Board members</small>	
UVic DEPARTMENT:	EPHE	ORIGINAL APPROVAL DATE:	28-Jul-15
		MODIFIED ON:	19-Jun-17
		APPROVAL EXPIRY DATE:	27-Jul-17
PROJECT TITLE: <b>Assessing accumulation of sub-concussive impacts on postural balance in contact-sport athletes using alternative assessment tools</b>			
RESEARCH TEAM MEMBER	Research Assistant(UVic): Yao Sun, Steven Noble, Greg Poinroy, Mary Curran, Lauren Smith; Student/Research Assistant: Stephanie Black.		
DECLARED PROJECT FUNDING:	Canada Foundation for Innovation (under Dr. Christie); CHR (under Dr. Christie)		
ADDITIONAL COMMENTS:	Previous Title: 'Analysis of alternative assessment tools for post-concussion cognitive and balance deficit'		
<b>CONDITIONS OF APPROVAL</b>			
This Certificate of Approval is valid for the above term provided there is no change in the protocol.			
<b>Modifications</b>			
To make any changes to the approved research procedures in your study, please submit a "Request for Modification" form. You must receive ethics approval before proceeding with your modified protocol.			
<b>Renewals</b>			
Your ethics approval must be current for the period during which you are recruiting participants or collecting data. To renew your protocol, please submit a "Request for Renewal" form before the expiry date on your certificate. You will be sent an emailed reminder prompting you to renew your protocol about six weeks before your expiry date.			
<b>Project Closure</b>			
When you have completed all data collection activities and will have no further contact with participants, please notify the Human Research Ethics Board by submitting a "Notice of Project Completion" form.			
<b>Certification</b>			
This certifies that the UVic Human Research Ethics Board has examined this research protocol and concluded that, in all respects, the proposed research meets the appropriate standards of ethics as outlined by the University of Victoria Research Regulations involving Human Participants.			
 Dr. Rachael Scarth Associate Vice-President Research Operations			

Certificate Issued On: 15-Jun-17



## Appendix B: Demographics Questionnaire

### Demographics Questionnaire

PARTICIPANT CONTACT INFORMATION			
First Name		Last Name	
Phone		Email	

EMERGENCY CONTACT INFORMATION			
First Name		Last Name	
Phone		Email	

GENERAL PARTICIPANT INFORMATION			
Height (ft)		Weight (lbs)	
Age		DOB (mm/dd/yyyy)	
Gender			

MEDICAL INFORMATION			
Have you been diagnosed with ADHD		Have you been diagnosed with dyslexia?	
Have you been diagnosed with ADD		Are you colourblind?	
List any medications you are currently taking		Do you have a current lower body injury?	
Have you ever been hospitalized for a head injury?		Have you ever been diagnosed with headache disorder or migraines?	
How many diagnosed concussions have you had in the past?		When was the most recent concussion?	

## Appendix C: Sport Concussion Assessment Tool – 5<sup>th</sup> Edition

Downloaded from <http://bjsm.bmj.com/> on June 8, 2017 - Published by [group.bmj.com](http://group.bmj.com)  
**BJSM Online First, published on April 26, 2017 as 10.1136/bjsports-2017-097506SCAT5**  
 To download a clean version of the SCAT tools please visit the journal online (<http://dx.doi.org/10.1136/bjsports-2017-097506SCAT5>)

**SCAT5<sup>®</sup>** **SPORT CONCUSSION ASSESSMENT TOOL – 5<sup>TH</sup> EDITION**  
 DEVELOPED BY THE CONCUSSION IN SPORT GROUP  
 FOR USE BY MEDICAL PROFESSIONALS ONLY

supported by







**Patient details**

Name: \_\_\_\_\_

DOB: \_\_\_\_\_

Address: \_\_\_\_\_

ID number: \_\_\_\_\_

Examiner: \_\_\_\_\_

Date of Injury: \_\_\_\_\_ Time: \_\_\_\_\_

### WHAT IS THE SCAT5?

The SCAT5 is a standardized tool for evaluating concussions designed for use by physicians and licensed healthcare professionals<sup>1</sup>. The SCAT5 cannot be performed correctly in less than 10 minutes.

If you are not a physician or licensed healthcare professional, please use the Concussion Recognition Tool 5 (CRT5). The SCAT5 is to be used for evaluating athletes aged 13 years and older. For children aged 12 years or younger, please use the Child SCAT5.

Preseason SCAT5 baseline testing can be useful for interpreting post-injury test scores, but is not required for that purpose. Detailed instructions for use of the SCAT5 are provided on page 7. Please read through these instructions carefully before testing the athlete. Brief verbal instructions for each test are given in italics. The only equipment required for the tester is a watch or timer.

**This tool may be freely copied in its current form for distribution to individuals, teams, groups and organizations. It should not be altered in any way, re-branded or sold for commercial gain. Any revision, translation or reproduction in a digital form requires specific approval by the Concussion in Sport Group.**

### Recognise and Remove

A head impact by either a direct blow or indirect transmission of force can be associated with a serious and potentially fatal brain injury. If there are significant concerns, including any of the red flags listed in Box 1, then activation of emergency procedures and urgent transport to the nearest hospital should be arranged.

### Key points

- Any athlete with suspected concussion should be REMOVED FROM PLAY, medically assessed and monitored for deterioration. No athlete diagnosed with concussion should be returned to play on the day of injury.
- If an athlete is suspected of having a concussion and medical personnel are not immediately available, the athlete should be referred to a medical facility for urgent assessment.
- Athletes with suspected concussion should not drink alcohol, use recreational drugs and should not drive a motor vehicle until cleared to do so by a medical professional.
- Concussion signs and symptoms evolve over time and it is important to consider repeat evaluation in the assessment of concussion.
- The diagnosis of a concussion is a clinical judgment, made by a medical professional. The SCAT5 should NOT be used by itself to make, or exclude, the diagnosis of concussion. An athlete may have a concussion even if their SCAT5 is "normal".

### Remember:

- The basic principles of first aid (danger, response, airway, breathing, circulation) should be followed.
- Do not attempt to move the athlete (other than that required for airway management) unless trained to do so.
- Assessment for a spinal cord injury is a critical part of the initial on-field assessment.
- Do not remove a helmet or any other equipment unless trained to do so safely.

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### IMMEDIATE OR ON-FIELD ASSESSMENT

The following elements should be assessed for all athletes who are suspected of having a concussion prior to proceeding to the neurocognitive assessment and ideally should be done on-field after the first first aid / emergency care priorities are completed.

If any of the "Red Flags" or observable signs are noted after a direct or indirect blow to the head, the athlete should be immediately and safely removed from participation and evaluated by a physician or licensed healthcare professional.

Consideration of transportation to a medical facility should be at the discretion of the physician or licensed healthcare professional.

The GCS is important as a standard measure for all patients and can be done serially if necessary in the event of deterioration in conscious state. The Maddocks questions and cervical spine exam are critical steps of the immediate assessment; however, these do not need to be done serially.

### STEP 1: RED FLAGS

#### RED FLAGS:

- Neck pain or tenderness
- Double vision
- Weakness or tingling/burning in arms or legs
- Severe or increasing headache
- Seizure or convulsion
- Loss of consciousness
- Deteriorating conscious state
- Vomiting
- Increasingly restless, agitated or combative

### STEP 2: OBSERVABLE SIGNS

Witnessed  Observed on Video

	Y	N
Lying motionless on the playing surface		
Balance / gait difficulties / motor incoordination: stumbling, slow / laboured movements		
Disorientation or confusion, or an inability to respond appropriately to questions		
Blank or vacant look		
Facial injury after head trauma		

### STEP 3: MEMORY ASSESSMENT MADDOKS QUESTIONS<sup>2</sup>

*"I am going to ask you a few questions, please listen carefully and give your best effort. First, tell me what happened?"*

Mark Y for correct answer / N for incorrect

	Y	N
What venue are we at today?		
Which half is it now?		
Who scored last in this match?		
What team did you play last week / game?		
Did your team win the last game?		

Note: Appropriate sport-specific questions may be substituted.

Name: \_\_\_\_\_  
 DOB: \_\_\_\_\_  
 Address: \_\_\_\_\_  
 ID number: \_\_\_\_\_  
 Examiner: \_\_\_\_\_  
 Date: \_\_\_\_\_

### STEP 4: EXAMINATION GLASGOW COMA SCALE (GCS)<sup>3</sup>

Time of assessment			
Date of assessment			

#### Best eye response (E)

	1	2	3
No eye opening			
Eye opening in response to pain			
Eye opening to speech			
Eyes opening spontaneously			

#### Best verbal response (V)

	1	2	3
No verbal response			
Incomprehensible sounds			
Inappropriate words			
Confused			
Oriented			

#### Best motor response (M)

	1	2	3
No motor response			
Extension to pain			
Abnormal flexion to pain			
Flexion / Withdrawal to pain			
Localizes to pain			
Obeys commands			
<b>Glasgow Coma score (E + V + M)</b>			

### CERVICAL SPINE ASSESSMENT

Does the athlete report that their neck is pain free at rest?	Y	N
If there is <b>NO neck pain at rest</b> , does the athlete have a full range of ACTIVE pain free movement?	Y	N
Is the limb strength and sensation normal?	Y	N

**In a patient who is not lucid or fully conscious, a cervical spine injury should be assumed until proven otherwise.**

### OFFICE OR OFF-FIELD ASSESSMENT

Please note that the neurocognitive assessment should be done in a distraction-free environment with the athlete in a resting state.

#### STEP 1: ATHLETE BACKGROUND

Sport / team / school: \_\_\_\_\_

Date / time of injury: \_\_\_\_\_

Years of education completed: \_\_\_\_\_

Age: \_\_\_\_\_

Gender: M / F / Other

Dominant hand: left / neither / right

How many diagnosed concussions has the athlete had in the past?: \_\_\_\_\_

When was the most recent concussion?: \_\_\_\_\_

How long was the recovery (time to being cleared to play) from the most recent concussion?: \_\_\_\_\_ (days)

#### Has the athlete ever been:

	Yes	No
Hospitalized for a head injury?		
Diagnosed / treated for headache disorder or migraines?		
Diagnosed with a learning disability / dyslexia?		
Diagnosed with ADD / ADHD?		
Diagnosed with depression, anxiety or other psychiatric disorder?		

Current medications? If yes, please list:

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

Name: \_\_\_\_\_

DOB: \_\_\_\_\_

Address: \_\_\_\_\_

ID number: \_\_\_\_\_

Examiner: \_\_\_\_\_

Date: \_\_\_\_\_

2

#### STEP 2: SYMPTOM EVALUATION

The athlete should be given the symptom form and asked to read this instruction paragraph out loud then complete the symptom scale. For the baseline assessment, the athlete should rate his/her symptoms based on how he/she typically feels and for the post injury assessment the athlete should rate their symptoms at this point in time.

Please Check:  Baseline  Post-Injury

Please hand the form to the athlete

	none	mild	moderate	severe			
Headache	0	1	2	3	4	5	6
"Pressure in head"	0	1	2	3	4	5	6
Neck Pain	0	1	2	3	4	5	6
Nausea or vomiting	0	1	2	3	4	5	6
Dizziness	0	1	2	3	4	5	6
Blurred vision	0	1	2	3	4	5	6
Balance problems	0	1	2	3	4	5	6
Sensitivity to light	0	1	2	3	4	5	6
Sensitivity to noise	0	1	2	3	4	5	6
Feeling slowed down	0	1	2	3	4	5	6
Feeling like "in a fog"	0	1	2	3	4	5	6
"Don't feel right"	0	1	2	3	4	5	6
Difficulty concentrating	0	1	2	3	4	5	6
Difficulty remembering	0	1	2	3	4	5	6
Fatigue or low energy	0	1	2	3	4	5	6
Confusion	0	1	2	3	4	5	6
Drowsiness	0	1	2	3	4	5	6
More emotional	0	1	2	3	4	5	6
Irritability	0	1	2	3	4	5	6
Sadness	0	1	2	3	4	5	6
Nervous or Anxious	0	1	2	3	4	5	6
Trouble falling asleep (if applicable)	0	1	2	3	4	5	6

Total number of symptoms: \_\_\_\_\_ of 22

Symptom severity score: \_\_\_\_\_ of 132

Do your symptoms get worse with physical activity?  Y  N

Do your symptoms get worse with mental activity?  Y  N

If 100% is feeling perfectly normal, what percent of normal do you feel?

If not 100%, why?

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

Please hand form back to examiner

3

### STEP 3: COGNITIVE SCREENING

Standardised Assessment of Concussion (SAC)<sup>4</sup>

#### ORIENTATION

What month is it?	0	1
What is the date today?	0	1
What is the day of the week?	0	1
What year is it?	0	1
What time is it right now? (within 1 hour)	0	1
<b>Orientation score</b>	<b>of 5</b>	

#### IMMEDIATE MEMORY

The Immediate Memory component can be completed using the traditional 5-word per trial list or optionally using 10-words per trial to minimise any ceiling effect. All 3 trials must be administered irrespective of the number correct on the first trial. Administer at the rate of one word per second.

Please choose EITHER the 5 or 10 word list groups and circle the specific word list chosen for this test.

I am going to test your memory. I will read you a list of words and when I am done, repeat back as many words as you can remember, in any order. For Trials 2 & 3, I am going to repeat the same list again. Repeat back as many words as you can remember in any order, even if you said the word before.

List	Alternate 5 word lists					Score (of 5)		
						Trial 1	Trial 2	Trial 3
A	Finger	Penny	Blanket	Lemon	Insect			
B	Candle	Paper	Sugar	Sandwich	Wagon			
C	Baby	Monkey	Perfume	Sunset	Iron			
D	Elbow	Apple	Carpet	Saddle	Bubble			
E	Jacket	Arrow	Pepper	Cotton	Movie			
F	Dollar	Honey	Mirror	Saddle	Anchor			
<b>Immediate Memory Score</b>						<b>of 15</b>		
<b>Time that last trial was completed</b>								

List	Alternate 10 word lists					Score (of 10)		
						Trial 1	Trial 2	Trial 3
G	Finger	Penny	Blanket	Lemon	Insect			
	Candle	Paper	Sugar	Sandwich	Wagon			
H	Baby	Monkey	Perfume	Sunset	Iron			
	Elbow	Apple	Carpet	Saddle	Bubble			
I	Jacket	Arrow	Pepper	Cotton	Movie			
	Dollar	Honey	Mirror	Saddle	Anchor			
<b>Immediate Memory Score</b>						<b>of 30</b>		
<b>Time that last trial was completed</b>								

Name: \_\_\_\_\_  
 DOB: \_\_\_\_\_  
 Address: \_\_\_\_\_  
 ID number: \_\_\_\_\_  
 Examiner: \_\_\_\_\_  
 Date: \_\_\_\_\_

#### CONCENTRATION

#### DIGITS BACKWARDS

Please circle the Digit list chosen (A, B, C, D, E, F). Administer at the rate of one digit per second reading DOWN the selected column.

I am going to read a string of numbers and when I am done, you repeat them back to me in reverse order of how I read them to you. For example, if I say 7-1-9, you would say 9-1-7.

Concentration Number Lists (circle one)					
List A	List B	List C			
4-9-3	5-2-6	1-4-2	Y	N	0
6-2-9	4-1-5	6-5-8	Y	N	1
3-8-1-4	1-7-9-5	6-8-3-1	Y	N	0
3-2-7-9	4-9-6-8	3-4-8-1	Y	N	1
6-2-9-7-1	4-8-5-2-7	4-9-1-5-3	Y	N	0
1-5-2-8-6	6-1-8-4-3	6-8-2-5-1	Y	N	1
7-1-8-4-6-2	8-3-1-9-6-4	3-7-6-5-1-9	Y	N	0
5-3-9-1-4-8	7-2-4-8-5-6	9-2-6-5-1-4	Y	N	1
List D	List E	List F			
7-8-2	3-8-2	2-7-1	Y	N	0
9-2-6	5-1-8	4-7-9	Y	N	1
4-1-8-3	2-7-9-3	1-6-8-3	Y	N	0
9-7-2-3	2-1-6-9	3-9-2-4	Y	N	1
1-7-9-2-6	4-1-8-6-9	2-4-7-5-8	Y	N	0
4-1-7-5-2	9-4-1-7-5	8-3-9-6-4	Y	N	1
2-6-4-8-1-7	6-9-7-3-8-2	5-8-6-2-4-9	Y	N	0
8-4-1-9-3-5	4-2-7-9-3-8	3-1-7-8-2-6	Y	N	1
<b>Digits Score:</b>					<b>of 4</b>

#### MONTHS IN REVERSE ORDER

Now tell me the months of the year in reverse order. Start with the last month and go backward. So you'll say December, November. Go ahead.

Dec - Nov - Oct - Sept - Aug - Jul - Jun - May - Apr - Mar - Feb - Jan	0	1
<b>Months Score</b>	<b>of 1</b>	
<b>Concentration Total Score (Digits + Months)</b>	<b>of 5</b>	

4

### STEP 4: NEUROLOGICAL SCREEN

See the instruction sheet (page 7) for details of test administration and scoring of the tests.

Can the patient read aloud (e.g. symptom checklist) and follow instructions without difficulty?	Y	N
Does the patient have a full range of pain-free PASSIVE cervical spine movement?	Y	N
Without moving their head or neck, can the patient look side-to-side and up-and-down without double vision?	Y	N
Can the patient perform the finger nose coordination test normally?	Y	N
Can the patient perform tandem gait normally?	Y	N

### BALANCE EXAMINATION

#### Modified Balance Error Scoring System (mBESS) testing<sup>5</sup>

Which foot was tested (i.e. which is the non-dominant foot)  Left  Right

Testing surface (hard floor, field, etc.) \_\_\_\_\_

Footwear (shoes, barefoot, braces, tape, etc.) \_\_\_\_\_

Condition	Errors
<b>Double leg stance</b>	_____ of 10
<b>Single leg stance (non-dominant foot)</b>	_____ of 10
<b>Tandem stance (non-dominant foot at the back)</b>	_____ of 10
<b>Total Errors</b>	_____ of 30

Name: \_\_\_\_\_

DOB: \_\_\_\_\_

Address: \_\_\_\_\_

ID number: \_\_\_\_\_

Examiner: \_\_\_\_\_

Date: \_\_\_\_\_

5

### STEP 5: DELAYED RECALL:

The delayed recall should be performed after 5 minutes have elapsed since the end of the Immediate Recall section. Score 1 pt. for each correct response.

*Do you remember that list of words I read a few times earlier? Tell me as many words from the list as you can remember in any order.*

**Time Started** \_\_\_\_\_

Please record each word correctly recalled. Total score equals number of words recalled.

\_\_\_\_\_

\_\_\_\_\_

\_\_\_\_\_

**Total number of words recalled accurately:** \_\_\_\_\_ of 5 or \_\_\_\_\_ of 10

6

### STEP 6: DECISION

Domain	Date & time of assessment:		
Symptom number (of 22)			
Symptom severity score (of 132)			
Orientation (of 5)			
Immediate memory	_____ of 15 _____ of 30	_____ of 15 _____ of 30	_____ of 15 _____ of 30
Concentration (of 5)			
Neuro exam	Normal Abnormal	Normal Abnormal	Normal Abnormal
Balance errors (of 30)			
Delayed Recall	_____ of 5 _____ of 10	_____ of 5 _____ of 10	_____ of 5 _____ of 10

Date and time of injury: \_\_\_\_\_

If the athlete is known to you prior to their injury, are they different from their usual self?  
 Yes  No  Unsure  Not Applicable  
 (If different, describe why in the clinical notes section)

Concussion Diagnosed?  
 Yes  No  Unsure  Not Applicable

If re-testing, has the athlete improved?  
 Yes  No  Unsure  Not Applicable

**I am a physician or licensed healthcare professional and I have personally administered or supervised the administration of this SCAT5.**

Signature: \_\_\_\_\_

Name: \_\_\_\_\_

Title: \_\_\_\_\_

Registration number (if applicable): \_\_\_\_\_

Date: \_\_\_\_\_

**SCORING ON THE SCAT5 SHOULD NOT BE USED AS A STAND-ALONE METHOD TO DIAGNOSE CONCUSSION, MEASURE RECOVERY OR MAKE DECISIONS ABOUT AN ATHLETE'S READINESS TO RETURN TO COMPETITION AFTER CONCUSSION.**

## INSTRUCTIONS

Words in *Italics* throughout the SCAT5 are the instructions given to the athlete by the clinician

### Symptom Scale

The time frame for symptoms should be based on the type of test being administered. At baseline it is advantageous to assess how an athlete "typically" feels whereas during the acute/post-acute stage it is best to ask how the athlete feels at the time of testing.

The symptom scale should be completed by the athlete, not by the examiner. In situations where the symptom scale is being completed after exercise, it should be done in a resting state, generally by approximating his/her resting heart rate.

For total number of symptoms, maximum possible is 22 except immediately post injury, if sleep item is omitted, which then creates a maximum of 21.

For Symptom severity score, add all scores in table, maximum possible is 22 x 6 = 132, except immediately post injury if sleep item is omitted, which then creates a maximum of 21x6=126.

### Immediate Memory

The Immediate Memory component can be completed using the traditional 5-word per trial list or, optionally, using 10-words per trial. The literature suggests that the Immediate Memory has a notable ceiling effect when a 5-word list is used. In settings where this ceiling is prominent, the examiner may wish to make the task more difficult by incorporating two 5-word groups for a total of 10 words per trial. In this case, the maximum score per trial is 10 with a total trial maximum of 30.

Choose one of the word lists (either 5 or 10). Then perform 3 trials of immediate memory using this list.

Complete all 3 trials regardless of score on previous trials.

*"I am going to test your memory. I will read you a list of words and when I am done, repeat back as many words as you can remember, in any order."* The words must be read at a rate of one word per second.

Trials 2 & 3 MUST be completed regardless of score on trial 1 & 2.

Trials 2 & 3:

*"I am going to repeat the same list again. Repeat back as many words as you can remember in any order, even if you said the word before."*

Score 1 pt. for each correct response. Total score equals sum across all 3 trials. Do NOT inform the athlete that delayed recall will be tested.

### Concentration

#### Digits backward

Choose one column of digits from lists A, B, C, D, E or F and administer those digits as follows:

*Say: "I am going to read a string of numbers and when I am done, you repeat them back to me in reverse order of how I read them to you. For example, if I say 7-1-9, you would say 9-1-7."*

Begin with first 3 digit string.

If correct, circle "Y" for correct and go to next string length. If incorrect, circle "N" for the first string length and read trial 2 in the same string length. One point possible for each string length. Stop after incorrect on both trials (2 N's) in a string length. The digits should be read at the rate of one per second.

#### Months in reverse order

*"Now tell me the months of the year in reverse order. Start with the last month and go backward. So you'll say December, November ... Go ahead"*

1 pt. for entire sequence correct

#### Delayed Recall

The delayed recall should be performed after 5 minutes have elapsed since the end of the Immediate Recall section.

*"Do you remember that list of words I read a few times earlier? Tell me as many words from the list as you can remember in any order."*

Score 1 pt. for each correct response

### Modified Balance Error Scoring System (mBESS)<sup>5</sup> testing

This balance testing is based on a modified version of the Balance Error Scoring System (BESS)<sup>5</sup>. A timing device is required for this testing.

Each of 20-second trial/stance is scored by counting the number of errors. The examiner will begin counting errors only after the athlete has assumed the proper start position. The modified BESS is calculated by adding one error point for each error during the three 20-second tests. The maximum number of errors for any single condition is 10. If the athlete commits multiple errors simultaneously, only

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one error is recorded but the athlete should quickly return to the testing position, and counting should resume once the athlete is set. Athletes that are unable to maintain the testing procedure for a minimum of five seconds at the start are assigned the highest possible score, ten, for that testing condition.

OPTION: For further assessment, the same 3 stances can be performed on a surface of medium density foam (e.g., approximately 50cm x 40cm x 6cm).

### Balance testing – types of errors

- |                                 |   |   |
|---------------------------------|---|---|
| 1. Hands lifted off iliac crest | 3. Step, stumble, or fall                 | 5. Lifting forefoot or heel               |
| 2. Opening eyes                 | 4. Moving hip into > 30 degrees abduction | 6. Remaining out of test position > 5 sec |

*"I am now going to test your balance. Please take your shoes off (if applicable), roll up your pant legs above ankle (if applicable), and remove any ankle taping (if applicable). This test will consist of three twenty second tests with different stances."*

(a) Double leg stance:

*"The first stance is standing with your feet together with your hands on your hips and with your eyes closed. You should try to maintain stability in that position for 20 seconds. I will be counting the number of times you move out of this position. I will start timing when you are set and have closed your eyes."*

(b) Single leg stance:

*"If you were to kick a ball, which foot would you use? [This will be the dominant foot] Now stand on your non-dominant foot. The dominant leg should be held in approximately 30 degrees of hip flexion and 45 degrees of knee flexion. Again, you should try to maintain stability for 20 seconds with your hands on your hips and your eyes closed. I will be counting the number of times you move out of this position. If you stumble out of this position, open your eyes and return to the start position and continue balancing. I will start timing when you are set and have closed your eyes."*

(c) Tandem stance:

*"Now stand heel-to-toe with your non-dominant foot in back. Your weight should be evenly distributed across both feet. Again, you should try to maintain stability for 20 seconds with your hands on your hips and your eyes closed. I will be counting the number of times you move out of this position. If you stumble out of this position, open your eyes and return to the start position and continue balancing. I will start timing when you are set and have closed your eyes."*

### Tandem Gait

Participants are instructed to stand with their feet together behind a starting line (the test is best done with footwear removed). Then, they walk in a forward direction as quickly and as accurately as possible along a 38mm wide (sports tape), 3 metre line with an alternate foot heel-to-toe gait ensuring that they approximate their heel and toe on each step. Once they cross the end of the 3m line, they turn 180 degrees and return to the starting point using the same gait. Athletes fail the test if they step off the line, have a separation between their heel and toe, or if they touch or grab the examiner or an object.

### Finger to Nose

*"I am going to test your coordination now. Please sit comfortably on the chair with your eyes open and your arm (either right or left) outstretched (shoulder flexed to 90 degrees and elbow and fingers extended), pointing in front of you. When I give a start signal, I would like you to perform five successive finger to nose repetitions using your index finger to touch the tip of the nose, and then return to the starting position, as quickly and as accurately as possible."*

### References

1. McCrory et al. Consensus Statement On Concussion In Sport – The 5th International Conference On Concussion In Sport Held In Berlin, October 2016. British Journal of Sports Medicine 2017 (available at [www.bjsm.bmj.com](http://www.bjsm.bmj.com))
2. Maddocks, DL; Dicker, GD; Saling, MM. The assessment of orientation following concussion in athletes. Clinical Journal of Sport Medicine 1995; 5: 32-33
3. Jennett, B., Bond, M. Assessment of outcome after severe brain damage: a practical scale. Lancet 1975; i: 480-484
4. McCreary M. Standardized mental status testing of acute concussion. Clinical Journal of Sport Medicine. 2001; 11: 176-181
5. Guskiewicz KM. Assessment of postural stability following sport-related concussion. Current Sports Medicine Reports. 2003; 2: 24-30

## CONCUSSION INFORMATION

**Any athlete suspected of having a concussion should be removed from play and seek medical evaluation.**

### Signs to watch for

Problems could arise over the first 24-48 hours. The athlete should not be left alone and must go to a hospital at once if they experience:

- Worsening headache
- Drowsiness or inability to be awakened
- Inability to recognize people or places
- Repeated vomiting
- Unusual behaviour or confusion or irritable
- Seizures (arms and legs jerk uncontrollably)
- Weakness or numbness in arms or legs
- Unsteadiness on their feet.
- Slurred speech

**Consult your physician or licensed healthcare professional after a suspected concussion. Remember, it is better to be safe.**

### Rest & Rehabilitation

After a concussion, the athlete should have physical rest and relative cognitive rest for a few days to allow their symptoms to improve. In most cases, after no more than a few days of rest, the athlete should gradually increase their daily activity level as long as their symptoms do not worsen. Once the athlete is able to complete their usual daily activities without concussion-related symptoms, the second step of the return to play/sport progression can be started. The athlete should not return to play/sport until their concussion-related symptoms have resolved and the athlete has successfully returned to full school/learning activities.

When returning to play/sport, the athlete should follow a stepwise, **medically managed exercise progression, with increasing amounts of exercise.** For example:

### Graduated Return to Sport Strategy

Exercise step	Functional exercise at each step	Goal of each step
1. Symptom-limited activity	Daily activities that do not provoke symptoms.	Gradual reintroduction of work/school activities.
2. Light aerobic exercise	Walking or stationary cycling at slow to medium pace. No resistance training.	Increase heart rate.
3. Sport-specific exercise	Running or skating drills. No head impact activities.	Add movement.
4. Non-contact training drills	Harder training drills, e.g., passing drills. May start progressive resistance training.	Exercise, coordination, and increased thinking.
5. Full contact practice	Following medical clearance, participate in normal training activities.	Restore confidence and assess functional skills by coaching staff.
6. Return to play/sport	Normal game play.	

In this example, it would be typical to have 24 hours (or longer) for each step of the progression. If any symptoms worsen while exercising, the athlete should go back to the previous step. Resistance training should be added only in the later stages (Stage 3 or 4 at the earliest).

**Written clearance should be provided by a healthcare professional before return to play/sport as directed by local laws and regulations.**

### Graduated Return to School Strategy

Concussion may affect the ability to learn at school. The athlete may need to miss a few days of school after a concussion. When going back to school, some athletes may need to go back gradually and may need to have some changes made to their schedule so that concussion symptoms do not get worse. If a particular activity makes symptoms worse, then the athlete should stop that activity and rest until symptoms get better. To make sure that the athlete can get back to school without problems, it is important that the healthcare provider, parents, caregivers and teachers talk to each other so that everyone knows what the plan is for the athlete to go back to school.

**Note: If mental activity does not cause any symptoms, the athlete may be able to skip step 2 and return to school part-time before doing school activities at home first.**

Mental Activity	Activity at each step	Goal of each step
1. Daily activities that do not give the athlete symptoms	Typical activities that the athlete does during the day as long as they do not increase symptoms (e.g. reading, texting, screen time). Start with 5-15 minutes at a time and gradually build up.	Gradual return to typical activities.
2. School activities	Homework, reading or other cognitive activities outside of the classroom.	Increase tolerance to cognitive work.
3. Return to school part-time	Gradual introduction of school-work. May need to start with a partial school day or with increased breaks during the day.	Increase academic activities.
4. Return to school full-time	Gradually progress school activities until a full day can be tolerated.	Return to full academic activities and catch up on missed work.

If the athlete continues to have symptoms with mental activity, some other accommodations that can help with return to school may include:

- Starting school later, only going for half days, or going only to certain classes
- More time to finish assignments/tests
- Quiet room to finish assignments/tests
- Not going to noisy areas like the cafeteria, assembly halls, sporting events, music class, shop class, etc.
- Taking lots of breaks during class, homework, tests
- No more than one exam/day
- Shorter assignments
- Repetition/memory cues
- Use of a student helper/tutor
- Reassurance from teachers that the child will be supported while getting better

**The athlete should not go back to sports until they are back to school/learning, without symptoms getting significantly worse and no longer needing any changes to their schedule.**

### **Appendix D. Wii Balance Board & LabVIEW Instructions**

1. You will stand on the WBB with your feet hip width apart. You will face the laptop screen.
2. A white dot will appear on the screen. This represents your Centre of Gravity (COG).
3. A red dot will appear on the screen. This is your target dot.
4. The red dot will appear on the screen. This white dot represents you.
5. The red dot will move in eight different directions, in random order. Your job is to manipulate the white COG dot in order to “catch” the red target dot. You can move the white COG dot on the screen by moving your body on the WBB to change your COG.
6. The red target dot will move in random sequences in the eight cardinal and ordinal directions of the screen. These eight trials represent one complete session.

You will complete three sessions today. Each session will take approximately two minutes to complete. You will be given a short break in between sessions.

## Appendix E: Balance Error Scoring System

### The Balance Error Scoring System (BESS)

*Obtain Preseason Baseline Score; Compare with Post-Concussion Score<sup>33-34</sup>*

The Balance Error Scoring System<sup>33-34</sup> provides a portable, cost-effective and objective method of assessing static **postural stability**. The BESS can be used to assess the effects of mild head injury on static postural stability. Information obtained from this clinical balance tool can be used to assist clinicians in making return to play decisions following mild head injury. The BESS can be performed in nearly any environment and takes approximately 10 minutes to conduct.

The balance-testing regime consists three stances on two different surfaces. The three stances are **double leg stance**, **single leg stance** and **tandem stance**. The two different surfaces include both a **firm** (ground) and **foam** surface. **Athletes' stance should consist of the hands on the iliac crests, eyes closed and a consistent foot position depending on the stance.** Shoes should not be worn.

In the **double leg stance**, the feet are flat on the testing surface approximately pelvic width apart.

In the **single leg stance** position, the athlete is to stand on the non-dominant leg with the contralateral limb held in approximately 20° of hip flexion, 45° of knee flexion and neutral position in the frontal plane.

In the **tandem stance** testing position, one foot is placed in front of the other with heel of the anterior foot touching the toe of the posterior foot. The athlete's non-dominant leg is in the posterior position. Leg dominance should be determined by the athlete's kicking preference.

**Administering the BESS:** Establish baseline score prior to the start of the athletic season. After a concussive injury, re-assess the athlete and compare to baseline score. Only consider return to activity if scores are comparable to baseline score. Use with Standardized Symptom Scale Checklist.

**Scoring the BESS:** Each of the trials is **20 seconds**. Count the number of errors (deviations) from the proper stance. The examiner should begin counting errors only after the individual has assumed the proper testing position.



Double Leg Stance  
Firm Surface



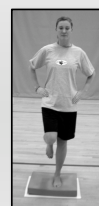
Single Leg Stance  
Firm Surface



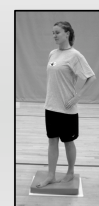
Tandem Stance  
Firm Surface



Double Leg Stance  
Foam Surface



Single Leg Stance  
Foam Surface



Tandem Stance  
Foam Surface

#### Errors:

- Moving the hands off the hips
- Opening the eyes
- Step, stumble or fall
- Abduction or flexion of the hip beyond 30°
- Lifting the forefoot or heel off of the testing surface
- Remaining out of the proper testing position for greater than 5 seconds

*The maximum total number of errors for any single condition is 10.*

*If a subject commits multiple errors simultaneously, only one error is recorded.*

#### B.E.S.S. SCORECARD

Count Number of Errors max of 10 each stance/surface	FIRM Surface	FOAM Surface
<b>Double Leg Stance</b> (feet together)		
<b>Single Leg Stance</b> (non-dominant foot)		
<b>Tandem Stance</b> (non-dominant foot in back)		
<b>TOTAL SCORES:</b> total each column		
<b>B.E.S.S. TOTAL:</b> (Firm+Foam total)		

Airex™ Foam Balance Pads available at [www.power-systems.com](http://www.power-systems.com) or through most sporting goods stores.

### Appendix F: Video Analysis Impact Frequency Chart

		7	14	2	5	13	11	1	3	22	15	23	00
Impact Source	Tackled (F)												
	Tackled (B)												
	Tackler												
	Ruck												
Impact Location	Head												
	Upper Body												
	LOC												
Signs of Concussion	Clutching Head												
	Gait Unsteadiness												
	Vacant Stare												
	Possible Seizure												

NOTES: