The evaluation of between-limb synchrony and reactive balance control measures as diagnostic tools for concussion in young ice hockey players

By

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Abstract

Problem

This work explored the potential to detect changes in interlimb coordination following sport-related concussion (SRC) among young male hockey players. We hypothesized athletes who have sustained SRC over the season would show a reduced magnitude of between-limb CoP spatial symmetry and temporal synchrony, which will suggest greater instability post-concussion.

Methods

A convenience sample of 104, 13–18-year-old top-level competitive male ice hockey players with 146.63±12.75 days between tests was used. Participants were grouped based on whether they sustained a SRC between the pre- and post-season data collection time points, with 12 sustaining a SRC. Participants performed one 60 second trial of quiet standing with eyes open on force platforms. Participants who sustained a SRC participated in post-season balance testing 77.25±27.94 days after time of injury. Participants were placed in the fatigued group if they had completed performance testing prior to the balance test. The ratio of left and right limb root-mean-square CoP displacements were calculated from the anteroposterior (AP) and mediolateral (ML) CoP time series, to assess spatial symmetry. The cross-correlation of right and left limb CoP time series was used to obtain between-limb temporal synchrony of CoP displacements in AP and ML directions. Frequency decomposition of the data was completed to parse out the proactive and reactive components of balance control. Separate analysis of covariance ($p < 0.05$) on post-season temporal synchrony and spatial symmetry measures were conducted where SRC, fatigue status, and age were the dependent variables, and pre-season measures were the covariate.

Results

There were no statistically significant differences in post-season ML and AP temporal synchrony and spatial symmetry scores between the SRC, fatigue, or age groups. The same can be said for all analysis with the frequency decomposed measures.

Conclusions

Deficits in temporal and spatial between-limb synchrony and symmetry was not detected long-term in young male ice hockey players who have sustained a SRC. As well, fatigue has little effect on these measures which has clinical relevance in when this test may be conducted. Further research is required to clarify whether deficits exist closer to time of injury, and when those deficits resolve.

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Dedication

I would like to dedicate this to my wonder wife, Haley, and son, Theo. Thank you for allowing me to pursue my ambitions. Thank you for the support and love you have given me throughout my degree. Without it I do not believe I would have made it this far.

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Chapter 1 : Introduction

According to Statistics Canada, from 2009-2010, there were over 94,000 concussions/other brain injuries, with 29,000 being reported within individuals 12-19 years of age, and 60,000 within individuals 20-60 years of age (Billette & Janz, 2011). Over 30% of concussions/other brain injuries are occurring to individuals 12-19 years of age, a population that makes up approximately 10.8% of the Canadian population (Public Health Agency of Canada, 2017). A breakdown of concussions/other brain injuries by sports and recreation activities shows that ice hockey accounts for approximately 1/3 and 1/10 of injuries in males and females 10-19 years old, respectively (Public Health Agency of Canada, 2017). However, these estimates may be low as the underreporting of concussions in the United States has been suggested to be anywhere from 50-80% (Buckley et al., 2016; Ferdinand Pennock et al., 2020; Guskiewicz, 2011).

Popularity of concussion research, in North America especially, has exploded due to our understanding of the complex and long-term impacts of concussions, and recent lawsuits occurring in major sporting associations (Almasy & Martin, 2015; Associated Press, 2016; Burnside, 2016). All the lawsuits are citing poor diagnosis, management, and treatment of concussions as the main motives for legal action (Almasy & Martin, 2015; Associated Press, 2016; Burnside, 2016). This has led to major changes in concussion diagnosis, management, and treatment in many major sporting organizations (NHL Public Relations, 2016; Stites, 2016; Ubelacker, 2015).

Diagnosis and management of concussions can be linked closely with one another, as management involves continued monitoring of patients via diagnostic techniques. Due to pathophysiological changes post-concussion and the effects these changes have on the brain, balance and stability have been associated with concussion (Guskiewicz, 2011; McCrory et al., 2017). Recently, research has found that deficits in balance and stability are lasting much longer than originally thought, with balance deficiencies being one of the most common symptoms; the study of postural control and balance can assist in the understanding of sport-related concussion (Murray et al., 2014; Pan et al., 2015; Quatman-Yates et al., 2013). It has been found that sport-related concussion (SRC) slows processing speed and motor control, especially higher cognitive processes, and effects multi-limb control and coordination (Vartiainen et al., 2016). Newer balance measures, such as inter-limb symmetry and synchronization of centre of pressure displacements, can provide a measurable outcome of inter-limb control/coordination, while assessing postural control.

The purpose of the proposed research will be to establish a link between these newly developed indices of balance control and SRC to determine if such measures could be used to assist in diagnosis. These measures have been purported to have the potential to disentangle the reactive balance control components (i.e. recovering from unexpected perturbation), which may be largely influenced by concussion, from the proactive control elements (i.e. anticipatory), which may be less affected by other neurological conditions, such as stroke (Singer & Mochizuki, 2015). This study will be the first of its kind to employ such measures of postural control to individuals who have suffered a SRC, to understand if similar balance control challenges occur following concussion. As well, the study will be one of a few to use intra-individual comparison when taking measures post-concussion via pre-post-season measures.

Chapter 2 : Review of Literature

What is a concussion?

It is important to establish a clear definition of sport-related concussion, as there are varying definitions within literature, and by the general public (Robbins et al., 2014). Without a clear definition, it creates an uncertainty in the diagnosis of a concussion, as knowledge and understanding of current information may not be had by the athlete or medical personnel. Within the scope of this research, an effort will be made to ensure a standardized definition of a concussion is used, in respect to the one provided by the Concussion in Sport Group, as they are the leading authority on concussion diagnosis, management, and return-to-play in sport (P. McCrory et al., 2017).

The study of head injuries began nearly 3000 years ago, but not until first being defined by Rhazes in the 10th century, did a distinction between a concussion and head injury finally exist (McCrory & Berkovic, 2001). Rhazes defined a concussion as "Abnormal transient physiologic state without gross brain lesions." (McCrory & Berkovic, 2001, p. 2285). The definition of a SRC has become more elaborate in recent years, as the breadth of knowledge increases. The most recent definition developed by the Concussion in Sport Group in 2017 through a thorough review of literature states that a,

> Sport related concussion is a traumatic brain injury induced by biomechanical forces. Several common features that may be utilised in clinically defining the nature of a concussive head injury include:
>
> - SRC may be caused either by a direct blow to the head, face, neck or elsewhere on the body with an impulsive force transmitted to the head.
> - SRC typically results in the rapid onset of short-lived impairment of neurological function that resolves spontaneously. However, in some cases, signs and symptoms evolve over a number of minutes to hours.
> - SRC may result in neuropathological changes, but the acute clinical signs and symptoms largely reflect a functional disturbance rather than a structural injury and, as such, no abnormality is seen on standard structural neuroimaging studies.

> - SRC results in a range of clinical signs and symptoms that may or may not involve loss of consciousness. Resolution of the clinical and cognitive features typically follows a sequential course. However, in some cases symptoms may be prolonged.
>
> The clinical signs and symptoms cannot be explained by drug, alcohol, or medication use, other injuries (such as cervical injuries, peripheral vestibular dysfunction, etc.) or other comorbidities (eg. psychological factors or coexisting medical conditions). (McCrory et al., 2017, p. 2)

Further to the definition provided by the Concussion in Sport Group, no SRC presents the same, as symptomatology varies from case to case (Brukner et al., 2012). The immense number of possible signs and symptoms of a SRC can be classified into three domains, physical, cognitive, and emotional characteristics (Junn et al., 2015). Examples of physical signs and symptoms include headache, nausea, and vomiting. Cognitive signs and symptoms include difficulty concentrating/remembering or feeling slowed down. Emotional signs and symptoms include irritability, sadness, and nervousness. Signs and symptoms may include, but are not limited to, any of those listed in the Sport Concussion Assessment Tool, 5th Edition (Concussion in Sport Group, 2017) or the Child Sport Concussion Assessment Tool, 5th Edition (Concussion in Sport Group, 2017). Examples of signs and symptoms include headache, nausea, sensitivity to light/sound, and confusion (Concussion in Sport Group, 2017). In the long term, conditions and comorbidities related to SRC are second impact syndrome, concussive convulsions, chronic traumatic encephalopathy, post-concussion syndrome, and mental health issues (Brukner et al., 2012).

Mechanism of injury for a sport-related concussion

The causes of concussions have been debated in the literature in the past, however, over the recent years, researchers have been able to agree on several causes. At the 5th International

Conference on Concussion in Sport, it was determined that a “concussion may be caused either by a direct blow to the head, face, neck or elsewhere on the body with an ‘impulsive’ force transmitted to the head.” (McCrory et al., 2017, p. 2). The forces that cause concussions can be “an acceleration/deceleration injury resulting from biomechanical forces transmitted to the cerebral tissues from impacts to the head or torso.” (Broglio et al., 2010, p. 2). Impacts can be person-to-person, or with inanimate objects such as the ground. These forces cause linear and/or rotational head accelerations, which are thought to be the primary mechanisms for concussions (Guskiewicz & Mihalik, 2011). The forces that cause these accelerations can be direct or inertial loading of the head (Guskiewicz & Mihalik, 2011). Concussions caused by impacts not to the head and therefore by inertial loading, can create an acceleration-deceleration injury or whiplash type effect, which creates accelerations needed to sustain a concussion, and this is no different than one sustained through a direct blow to the head (Barth et al., 2001). Finally, Rowson et al. (2014) could conclude that head accelerations are correlated with the risk of concussion.

Causes of concussions can vary between individuals, and risk factors do exist. Possible risk factors for concussions include prior history of concussions, individual characteristics, body mass index, and type of protective equipment worn by the player (McGuine et al., 2014). It has been found that a prior history of concussions increases your risk with a high level of certainty (Abrahams et al., 2014; Van Pelt et al., 2019). When assessing how individual characteristics, it has been found that females appear to be at a greater risk then males, age plays a minor role, genetic risk has a low level of certainty, and overall behavior of the individual and sport have a low level of certainty on SRC risk (Abrahams et al., 2014). Protective equipment has a low level of certainty (Abrahams et al., 2014).

Pathophysiology of SRC

When a SRC is sustained, research shows that pathophysiological changes occur in the brain (Ellis et al., 2015). Studies have found that neurometabolic dysfunction occurs in the brain from forces stretching the axons causing a disruption to their membrane. This can be brought about by transitional, rotational, angular, and/or shearing forces. SRC is commonly referred to as a functional injury, due to no physical damage being present on imaging of the brain (Buckley et al., 2016). The term used to describe the effect SRCs have on the brain is spreading depression on the neuron, as multiple areas of the brain can be affected (Buckley et al., 2016). A part of the neurometabolic dysfunction is a process called the neurometabolic cascade. The neurometabolic cascade creates a need for energy within the cell, but due to decreased cerebral blood flow, the demand for energy cannot be met (MacFarlane & Glenn, 2015).

The neurometabolic cascade begins with the release of neurotransmitters, primarily glutamate, into the synapse causing an efflux of potassium, and influx of sodium and calcium (MacFarlane & Glenn, 2015). To restore homeostasis, the transportation of the ions in reverse order involves hyperglycolysis. Hyperglycolysis and increased calcium levels in the cell which impair mitochondrial functioning, coupled with decreased cerebral blood flow creates an energy crisis as ATP production is decreased (Ellis et al., 2015; MacFarlane & Glenn, 2015). Calcium and cerebral blood flow changes can last 3-4 days and 7-10 days, respectively (MacFarlane & Glenn, 2015). It should be noted that metabolic changes can last longer than 10 days, with cerebral glucose metabolism being decreased 2-4 weeks post-SRC, and N-acetylaspartate levels being reduced from 1 month to 1-year post-SRC (MacFarlane & Glenn, 2015). This along with other changes may explain why signs and symptoms may persist longer then 10 days. According to Giza & Hovda (2014), the ionic influx is associated with migraine headache, photophobia, and phonophobia. As well, the axonal injury and impaired neurotransmission is associated with Impaired cognition, slowed processing, and slowed reaction time (Giza & Hovda, 2014).

Incidence of SRC in youth ice hockey

Incidence of concussions in sports are being expressed through the number of athlete exposures (AE), by player game hours (PGH), or player participation hours (PPH). When looking at incidence of SRC with either AE, PGH, or PPH, rates are represented by x/1000. All previous ways mentioned only include concussions sustained in games and not practices, as past research has shown the injury rate at practices to have a negligible effect on overall injury rate (Williamson & Goodman, 2006). An AE can be defined as participation in a game, whereas PGH can be defined as the number of hours within each game a player is at risk for injury (Williamson & Goodman, 2006). With hockey, it can be estimated that each player is at risk for 0.25 hours/game, therefore, to find out the total PGH, you take AE x 0.25 hours/player/game. PPH can be defined as participation in a game or practice, either a full PPH (>75%), partial PPH (<75%), or no PPH can be awarded for a session (Emery & Meeuwisse, 2006). Table 2.1 summarizes the findings from previous studies looking at the incidence of concussions in the target population in Canada. Much of the discrepancy in concussion incidence rate has been connected to the under reporting of SRC (Williamson & Goodman, 2006). When examining the table below, 0.06 AE can be interpreted as 0.06 SRCs will occur per AE, 0.25 PGH can be understood as 0.25 SRCs will occur for every 1000 hours of game play, and 1.47 PPH means the incidence of a SRC is 1.47 per PPH.

Table 2.1. SRC incidence in youth male ice hockey athletes.

Article	Population	Concussion definition	Incidence in AE	Incidence in PGH	Incidence in PPH
Emery et al. (2010)	Peewee (11-12 years old)	McCrory et al. (2005)			1.47 (Alberta) 0.39 (Quebec)
Emery & Meeuwisse (2006)	Atom (9-10 years old)	Did not specify			0.24
	Peewee (11-12 years old)	Did not specify			0.81
	Bantam (13-14 years old)	Did not specify			0.97
	Midget (15-16 years old)	Did not specify			0.82
Schneider et al. (2021)	Bantam (13-14 years old)	McCrory et al. (2008)			1.33
	Midget (15-17 years old)	McCrory et al. (2008)			1.32
Williamson & Goodman (2006)	Official Injury Reports	Did not specify	0.06-0.15	0.25-0.61	
	Volunteers	"A physician diagnosed concussion or an episode considered seriously indicative of a concussion based on observed signs or symptoms" (Williamson & Goodman, 2006, p.129)	1.11-1.98	4.44-7.94	
	R. Survey w/ Elite	"Participants were asked to report if they had ever suffered a significant hockey induced hit to the head that presented signs and symptoms of concussion" (Williamson & Goodman, 2006, p.129)	1.66-2.08	6.65-8.32	
	R. Survey w/ Non-elite		2.43-6.07	9.72-24.30	

Concussion assessment

The assessment of SRC usually involves a multidimensional approach, due to the high sensitivity (0.89-0.96) of such assessment in the acute setting (Buckley et al., 2016; Guskiewicz, 2011). These assessments include a history followed by neurocognitive evaluations, which may contain a symptom, cognitive, balance, and coordination examination (Guskiewicz, 2011; McCrory et al., 2017). However, post-concussion, these multidimensional approaches drop in sensitivity after a week due to changes in proactive control (i.e. learning effect) (Buckley et al., 2016). Therefore, the frequency-based analysis that was done for my research may be beneficial as reactive components of balance and postural control can be parsed out and evaluated. These multidimensional approaches do not replace a comprehensive neurological examination by a professional in the diagnosis and management of a SRC (McCrory et al., 2017). A clinical assessment of SRC by a physician may include an assessment of vital signs, mental status, the head for trauma, cranial nerve testing, cervical spine assessment, vestibulocular exam, balance assessment, and/or neurological exam, however no standardized examination for concussions exists (Matuszak et al., 2016).

It has been noted that signs and symptoms of concussions recover independent of one another, with the three most common symptoms being headaches, dizziness, and balance problems (Buckley et al., 2016; Murray et al., 2014). Of these three symptoms, dizziness and balance problems are closely related, as the body systems for these symptoms work together (Murray et al., 2014). If balance assessment tools for the examination and monitoring of recovery for concussions can be validated, there is a possibility that these tools may be able to provide quantitative, reliable measures (Guskiewicz, 2011; Murray et al., 2014).

Balance, stability, and postural control

In mechanics, balance or equilibrium refers to “the state of an object when the resultant load actions (forces or moments) acting upon it are zero (Newton’s First Law).” (Pollock et al., 2000, p. 402). An object will be able to balance, in a static situation, if the line of gravity stays within the base of support of the object (Pollock et al., 2000). However, if the line of gravity moves outside the base of support, the object will fall (Pollock et al., 2000). Stability can be viewed as the ability for an object to withstand internal or external perturbing forces and return to its initial state (e.g. position, velocity, acceleration) (Pollock et al., 2000).

In humans, postural control is the maintenance of a certain body configuration (e.g. upright in quiet standing), and the ability to balance is known as equilibrium control (Pollock et al., 2000). Many individuals have proposed that these two processes (postural control and equilibrium control) together contribute to balance control. All previously mentioned relationships discussed for balance in objects can be applied to humans. However, a human, or animal, can detect threats to stability, and generate and apply forces to the environment to prevent a fall (Pollock et al., 2000). Postural control has implications in human movement. Postural control assists in three classes of human activity (stability, instability, and increased stability), which maintain and restore the line of gravity within the base of support. According to Pollock et al. (2000), “Human stability can be defined as the ‘inherent ability’ of a person to maintain, achieve or restore a state of balance, but in this case the ‘inherent ability’ encompasses the sensory and motor systems.” (p. 404). It was previously thought that reflex (reactive) responses were automatically controlled by the sensory system, however now it is known that postural control responses are done by the central nervous system through the assessment and control of many variables (Pollock et al., 2000). The sensory and motor systems must work together to detect threats to stability, via the sensory system, and produce movements to maintain stability, via the motor system (Pollock et al., 2000).

Postural control can be reactive and/or predictive in nature. Predictive movements involve the initiation of postural control strategies prior to a disturbance (Pollock et al., 2000). Reactive postural control occurs after a disturbance has been detected (Pollock et al., 2000). Both postural control strategies (reactive and predictive) can use either fixed-support or change-in-support strategies depending on the body's position and movement through space (Pollock et al., 2000). Fixed-support strategies utilize hip and ankle strategies to maintain postural control, while change-in-support strategies utilize stepping or grasping responses to maintain postural control, with the goal being to increase the base of support and the potential for larger external restabilizing moments to be applied about the centre of mass. An example of a fixed-support strategy is balancing on a narrow beam, such as the high beam in gymnastics – with an inability to produce ankle moments of force (because of the narrow base of support) the hip strategy would be used to regulate the relationship between the centre of mass and base of support. Predominantly, hip strategies will also be used to keep the person from falling laterally off the beam, which involves the use of hip ab/adductor musculature to differentially load and unload the limbs, thereby moving the centre of mass laterally. A change-in-support strategy would result from being pushed from behind by someone and having to step forward with one foot to prevent yourself from falling forward.

Centre of pressure

The study of centre of pressure (CoP) displacements can be used to help understand the balance control system. CoP is the location of the point of application of the ground reaction forces under the feet (Winter et al., 1996). CoP can be one point on the ground, as a sum of all forces being applied, also known as the net centre of pressure (CoP_{net}), or as individual CoP displacements underneath each foot (Winter et al., 1996). Displacements of the CoP serve to control the centre of mass (CoM), through the generation of an external moment causing both linear and angular accelerations (an consequent displacements) (Winter et al., 1996). CoP can be broken down into anteroposterior (AP) and mediolateral (ML) components and corresponding stability strategies. Anteroposterior corresponds with the sagittal anatomic plane, and mediolateral corresponds with the frontal anatomic plane. AP strategies are ankle dominant and involve plantarflexion and dorsiflexion of the ankle joint to control the CoP location (Winter et al., 1996). ML strategies are hip dominant, which involve activation of abductor and adductor musculature to control the CoP_{net} location, with slight adjustments under each foot made possible with the ankle invertor/evertor musculature (Winter et al., 1996). The individual limb and CoP_{net} displacements are believed to be a measure of neuromuscular control of stability, as they reflect the combined control of the left and right stability strategies (Winter et al., 1996). According to (Winter et al., 1996), "the CoP is the net neuromuscular response to the control of the passive CoG [centre of gravity]." (pg. 2335). The CoG is "the vertical projection of the CoM onto the ground." (Winter, 1995, p. 194). However, while the CoP controls the displacements of the CoM, measures of the CoM and CoP are independent of one another (i.e., the CoP and CoM are independent quantities). The ability to control the body's CoM via the CoP is believed to be a good true indicator of balance and posture control, as standard measures of CoP displacement are correlated with overall movement of the CoM (Winter et al., 1996).

Postural control, balance, and concussions

The length that postural control deficits last post-concussion has been disputed in the literature. On average, it is reported that deficits in balance and posture control last anywhere from as little as 3 days to 10 days (Guskiewicz, 2011; Murray et al., 2014; Powers et al., 2014). Factors thought to contribute to these deficits beyond impairments to the sensory systems are concentration and attention impairments. However, newer research has started to suggest that balance and postural deficits may last months to years (Pan et al., 2015; Quatman-Yates et al., 2013).

Indeed, complex, objective measures of balance and postural control can assist in the accurate evaluation of a concussion (Guskiewicz, 2011; Murray et al., 2014). The most common clinical postural control and balance concussion assessments are the Romberg Test, the Balance Error Scoring System (BESS), and the Sensory Organization Test (SOT) (Murray et al., 2014). Of these assessments the Romberg Test and BESS are subjective and offer less objectivity then the SOT (Murray et al., 2014). However, there is no validity or reliability data that exists to support any of these tools in the examination of balance and postural impairment in individuals with a concussion (Murray et al., 2014). This is a concern as these tools help guide the decision-making process with respect to SRC diagnosis, management, and return-to-play (RTP).

Romberg test

The Romberg Test is a static, quiet balance test upon which an examiner subjectively assesses an individual’s balance and postural control. Many variations and descriptions of the test exists; however, all tests ask the participant to stand still, with feet together in various positions (Rogers, 1980). They then complete two trials for each foot-configuration, one with eyes open, and one with eyes closed (Rogers, 1980). Postural control normally decreases in the eyes closed position, as seen through a step taken, increased sway, or a fall (Rogers, 1980). It has been found that the subjectivity of the test leads to poor validity regarding its use with concussion, as well as its use as a screening tool for pathologies or diseases involving vestibular impairment (Buckley et al., 2016; Longridge & Mallinson, 2010; Matuszak et al., 2016). The test has been shown to have poor reliability as well (Longridge & Mallinson, 2010). This is due to the varying testing protocols available with not one testing protocol always being used. Due to the Romberg Test's ease of use, research has been done to assess the use of such testing, albeit with longer trial lengths, on force plates to objectify the test, and overcome the challenges with using this test (Riemann & Guskiewicz, 2000). Research has been done using the Romberg Test's protocols with linear measures and approximate entropy methods. Results have shown impairments in balance and postural control after clinical recovery of a concussion when using approximate entropy methods only (Buckley et al., 2016). This shows the tests ability to be used when assessing postural control and balance, but only when force plates and advanced data processing are utilized. The research has led to the use of the Romberg Test as a basis for the developing novel testing procedures. The use of quiet standing with feet together with the individual's eyes open and eyes closed is the method used to develop new balance outcome measures.

Balance Error Scoring System (BESS)

The BESS has become the most used balance assessment for a concussion (Buckley et al., 2016). According to Bell et al. (2011),

> The Balance Error Scoring System (BESS) consists of 3 stances: double-leg stance (hands on the hips and feet together), single-leg stance (standing on the nondominant leg with hands on hips), and a tandem stance (nondominant foot behind the dominant foot) in a heel-to-toe fashion. The stances are performed on a firm surface and on a foam surface with the eyes closed, with errors counted during each 20-second trial. An error is defined as opening eyes, lifting hands off hips, stepping, stumbling or falling out of position, lifting forefoot or heel, abducting the hip by more than 30°, or failing to return to the test position in more than 5 seconds. (p. 287).

Figure 2.1 shows the 6 different stances used in the BESS. The Sport Concussion Assessment Tool 5 (SCAT5), developed by experts in the field at the 5th International Conference on

Concussion in Sport, uses a modified BESS within the assessment as the balance evaluation, due to it being the only validated and reliable assessment of balance post-concussion (McCrory et al., 2017; Murray et al., 2014). The BESS has become a popular assessment tool due to its ease and time of administration, and validation against the SOT (Matuszak et al., 2016; Quatman-Yates et al., 2013). The BESS has shown concussion balance deficits to last 3-5 days post-concussion (Matuszak et al., 2016). However, research has shown that the BESS has low to moderate inter-tester reliability measure, low sensitivity, a high false positive rate, and greatly affected by the learner's effect (Buckley et al., 2016; Matuszak et al., 2016; Quatman-Yates et al., 2013). Factors that influence these findings are environmental distractions, fatigue, age, functional ankle instability, and dehydration (Buckley et al., 2016; Quatman-Yates et al., 2013). This demonstrates the need for assessment tools with greater objectivity, and specificity.

Figure 2.1. Stances used in BESS. A: double-leg stance; B: single-leg stance; C: tandem stance; D: double-leg stance on foam; E: single-leg stance on foam; F: tandem stance on foam. Retrieved from Bell et al. (2011).

Sensory Organization Test (SOT)

The SOT uses force plate measured centre of pressure (CoP) displacements to assess postural control and balance in individuals (Murray et al., 2014). The SOT uses 6 conditions to assess balance and posture control (Figure 2.2), which consist of a combination of three visual conditions (eyes open, eyes closed, and sway referenced), and 2 surface conditions (stable, and sway referenced) (Guskiewicz, 2011). The SOT assists researchers/clinicians to differentiate which sensory system (i.e., visual, vestibular, and somatosensory) is affected (Guskiewicz, 2011). It has been found that sensory integration and balance deficits last 3-5 days post-SRC when a standard linear analysis is used, which will be discussed in the next section (Cavanaugh, Guskiewicz, Giuliani, et al., 2005; Cavanaugh, Guskiewicz, & Stergiou, 2005). The outcome measures looked at were postural steadiness, a measure of the amplitude of COP displacements (Cavanaugh, Guskiewicz, Giuliani, et al., 2005). However, when an approximate entropy analysis is used deficits last longer (depression in the mediolateral CoP time series), and deficits are evident in those who were previously thought to have no postural control issues (Cavanaugh, Guskiewicz, Giuliani, et al., 2005; Cavanaugh, Guskiewicz, & Stergiou, 2005). The length of these deficits is unknown as the approximate entropy methods were applied to previously collected data that went up to 96 hours post injury. This is due to approximate entropy measuring randomness in the COP time series and does not rely on amplitude of the signal alone (Cavanaugh, Guskiewicz, Giuliani, et al., 2005; Cavanaugh, Guskiewicz, & Stergiou, 2005). Approximate entropy will be discussed more in a later section.

Due to the SOT needing expensive apparatus to administer, it is a very unrealistic tool for clinicians to use (Murray et al., 2014). According to the Shirley Ryan Ability Lab (2013), the system needed to conduct the SOT, either the NeuroCom EquiTest, Balance Master, or Clinical Research System, costs $80,000-$180,000 USD. The SOT has shown recovery of balance deficits to occur in timing similar to the BESS, therefore the BESS has been used due to its positives as compared to the expensive SOT (Buckley et al., 2016; Guskiewicz, 2011). The SOT has been shown to have moderate reliability in healthy younger and older adults, however its reliability in injured populations is not well known (Murray et al., 2014).

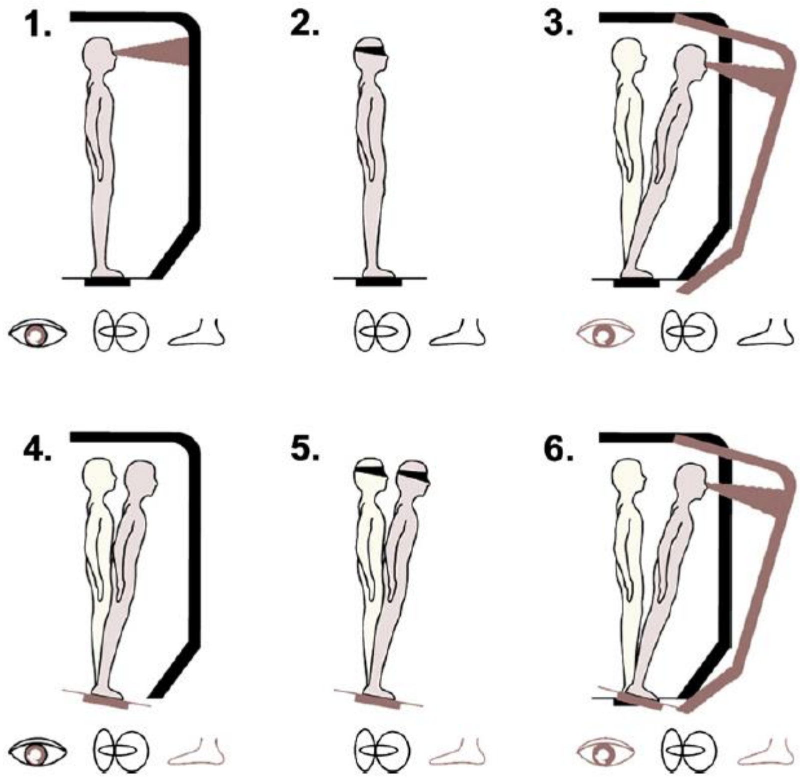


Figure 2.2. *Six testing conditions (1–6) for the Sensory Organization Test. Condition 1 has normal vision with a fixed support. Condition 2 has absent vision with a fixed support. Condition 3 sway-referenced vision with a fixed support. Condition 4 has normal vision with sway-referenced support. Condition 5 has absent vision with sway-referenced support. Condition 6 has sway-referenced vision with sway-referenced support. Retrieved from Guskiewicz (2011).*

Linear measures of centre of pressure

The use of force plate measures of balance has been recently increasing due to their ability to provide greater objectivity over the current gold standard of posture and balance assessment in concussion evaluations, the BESS (Buckley et al., 2016; Guskiewicz, 2011). Linear measures of balance and postural control (i.e., position, displacement, velocity, and acceleration) assume larger variations of CoP displacements measures as impaired control (Buckley et al., 2016). This is based off the stimulus-response paradigm (Buckley et al., 2016). The stimulus-response paradigm suggests that “postural steadiness is measured by variations in the center of pressure (CoP) as a function of time whereas an increase in the area of CoP measures is associated with greater impairment in postural stability.” (Buckley et al., 2016, p.

62). Many linear measures of CoP displacements have identified postural control deficiencies past the previously believed maximum of five days, with deficits lasting up to 30 days post-concussion, and some research not noting recovery for 6 months (Buckley et al., 2016; Matuszak et al., 2016). It was found that BESS scores typically return to baseline 2-5 days post injury, SOT scores return to baseline 3-5 days post injury (Buckley et al., 2016). Powers et al. (2014) looked at linear CoP displacements of university football athletes and found postural control deficits past the 5-day mark, and even continuing past the time that they were able to return-to-play. Although promising results have been shown through linear, amplitude-based measures for assessment of postural control and balance following SRC, nonlinear measures of balance may be more informative, as they have greater sensitivity to change in postural control patterns (Buckley et al., 2016). In a study by Quatman-Yates et al. (2015), they found that linear assessment of quiet stance with eyes open post-SRC revealed the only statistically significant finding to be path length statistics, however non-linear measures of CoP had more significant findings such as Sample and Renyi Entropies were more regular. These analysis were performed on the same raw force platform data. These findings show the need to assess postural control and balance following a SRC using methods with greater sensitivity and specificity.

Nonlinear measures of centre of pressure

Nonlinear measures of CoP, like linear measures, use quiet stance on force plates to look at CoP displacements under the feet. Nonlinear measures, however, are concerned with variability in movement patterns, where greater variability indicates impaired postural control (Buckley et al., 2016). We are never in perfect equilibrium with our external environment, and the human body uses fluctuations in movement to provide the body with constant feedback

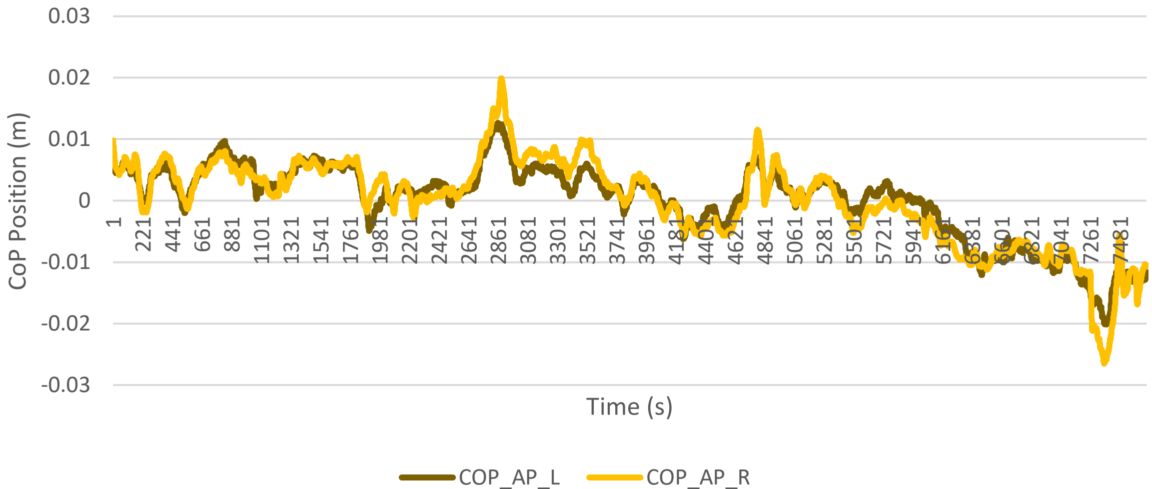
(Buckley et al., 2016). One of these dynamic measures of balance and postural control is approximate entropy (ApEn), which looks at the regularity of CoP patterns. Application of ApEn to SOT data has only been used up to 4 days post-concussion, therefore it is not possible at the current time to tell how long these deficits last (Buckley et al., 2016). However, ApEn methods have been applied to data of athletes who suffered at least 1 SRC within the past 9 months, and it was found that ApEn values and CoP displacement randomness were lower than those who had not sustained a concussion (De Beaumont et al., 2011). Shannon entropy measures were used to assess postural control and balance 1-day post-SRC and 12-days post-SRC (Gao et al., 2011). Findings suggest impairments that improved over the 12 days, but only in trials lasting longer than 20 seconds (trial length was 120 seconds). The data processing method used (i.e., Shannon entropy) to assess for balance deficits required longer trial times to find significant findings, which were balance deficits beyond 10 days, and an exponential increase in the area of the CoP (Gao et al., 2011). The authors suggested that this also has direct impact on the validity of the 20 second trial in the BESS, suggesting the BESS would need a longer trial time as the period of time since the injury increases (Gao et al., 2011). Other measures of dynamic balance have been used to look at balance post-concussion as described by Buckley et al. (2016) (see Table 2.2). With all entropy measures, conditions 1 (eyes open, fixed surface) and 2 (eyes closed, fixed surface) of the SOT showed the greatest promise for monitoring postural control post-concussion (see Figure 2.2), therefore if nonlinear measures are used, these would be the only conditions necessary to be tested (Buckley et al., 2016). It has been found that non-linear assessment of CoP does provide valuable insight into postural control capabilities post-concussion, however, with a multitude of entropy measures, there has not been consensus on the one to use (Quatman-Yates et al., 2015).

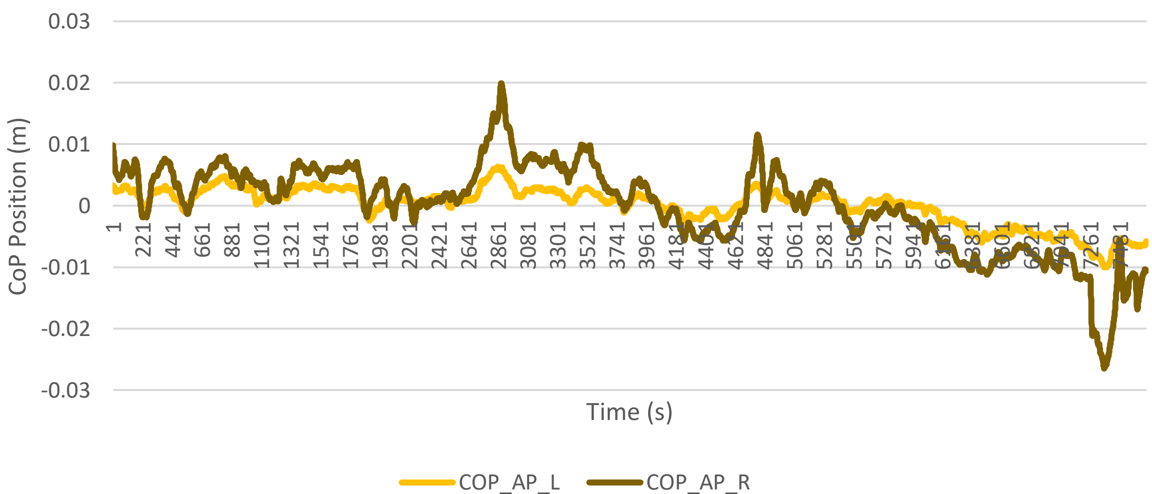
Table 2.2. Entropy measures used in concussion populations and their limitations

Entropy measure	Description	Limitation
Approximate entropy	Calculated by determining the probability that if two series data points are similar for a length of m points, then they will remain similar at the next point	Biased toward regularity in that it includes self-matches and lacks relative consistency in that it is more sensitive to changes in input parameters, m and r
Sample entropy	A modification of approximate entropy that does not include self-matches and is independent of data length	Does not discriminate between groups with a shorter data as well as approximate entropy
Shannon entropy	Calculated by mapping a CoP trace onto a grid and then determining the probability of the CoP occupying a given box during the CoP trace	Substantial influence of samples on Shannon entropy
Renyi entropy	A mathematical generalization of Shannon entropy, which does not assume the additivity of independent events	Substantial influence of samples on Renyi entropy

Measurement of individual limb centre of pressure

All work previously mentioned has used a single force plate to observe CoP_{net}, which combines the stability contributions from both limbs. Having a force plate under each foot allows for evaluation of weight-bearing symmetry, contribution of each limb to maintenance of stable posture, and synchronization between limbs (Mansfield et al., 2011). For synchronization of limbs in time to occur, the CoP under each foot moves in the same direction at the same time (Mansfield et al., 2012). Individual limb CoP measures can be compared to assess synchronization of limbs both temporally and spatially (Mochizuki et al., 2005; Winter et al., 1996). Spatial symmetry is taking a comparative look at the CoP trajectories under each foot and assessing how similar the root-mean-square amplitudes are (Winter et al., 1996). The use of individual limb CoP measures would allow for linear, nonlinear, and comparative measures to be used between the left and right lower limbs CoP.





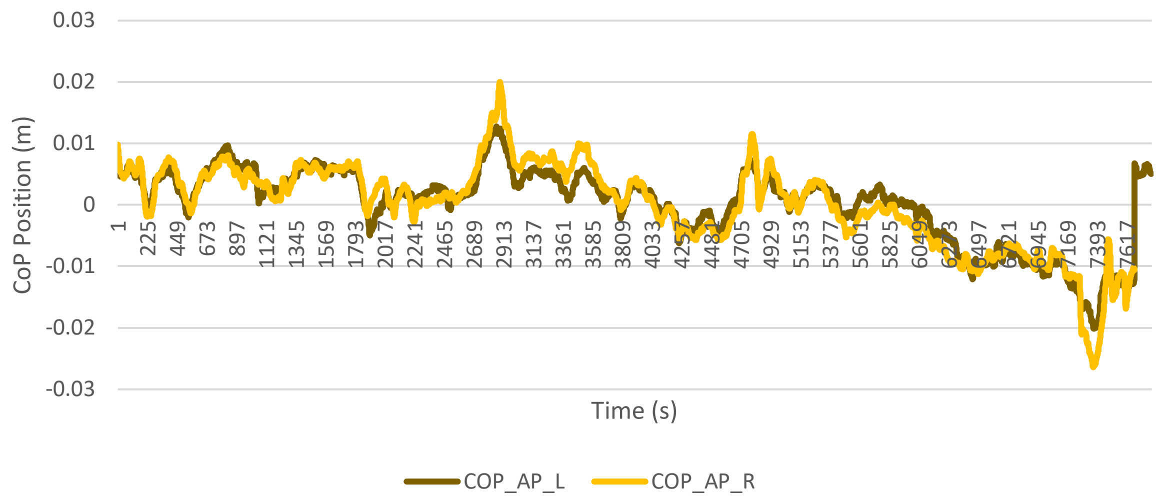


Figure 2.3. The top graph has R and L limb CoP displacements that have similar amplitude and phase; on the bottom the R and L limb CoP displacements have different amplitude (but similar phase). The top graph has high symmetry and synchrony. The bottom graph has high synchrony but low symmetry. The middle graph has poor synchrony and good symmetry. The graphs are made with fictitious data and are used to demonstrate the information content in the outcome variables being used.

Literature shows that inter-limb symmetry measures among healthy individuals (27±5 years) with no neurological or musculoskeletal conditions are highly positively correlated in the anteroposterior direction, and moderately negatively correlated in the mediolateral direction (Mansfield et al., 2011). A positive correlation in the AP direction is expected as when an individual is trying to correct AP CoG movements, they will use their feet in unison to correct for that movement. For example, if their CoG is moving anterior, they will move he CoP anteriorly under the foot (i.e., bilaterally plantarflex) to counteract the movement of the CoG. In comparison, a negative correlation is expected in the ML direction as a lateral movement of the GoG will elicit a CoP response in the same direction. This however would mean inversion of the contralateral ankle and eversion of the ipsilateral ankle. Previous work has shown a reduction in between-limb temporal synchronization in a post-stroke population, specifically they have increased postural sway in the ML direction and an increased weight-bearing asymmetry (Mansfield et al., 2011; Singer et al., 2013, 2016; Singer & Mochizuki, 2015). Although SRC and stroke are different neurologic disorders, with their own unique pathophysiology, the viability of these measures in the stroke population may be found in the SRC population too.

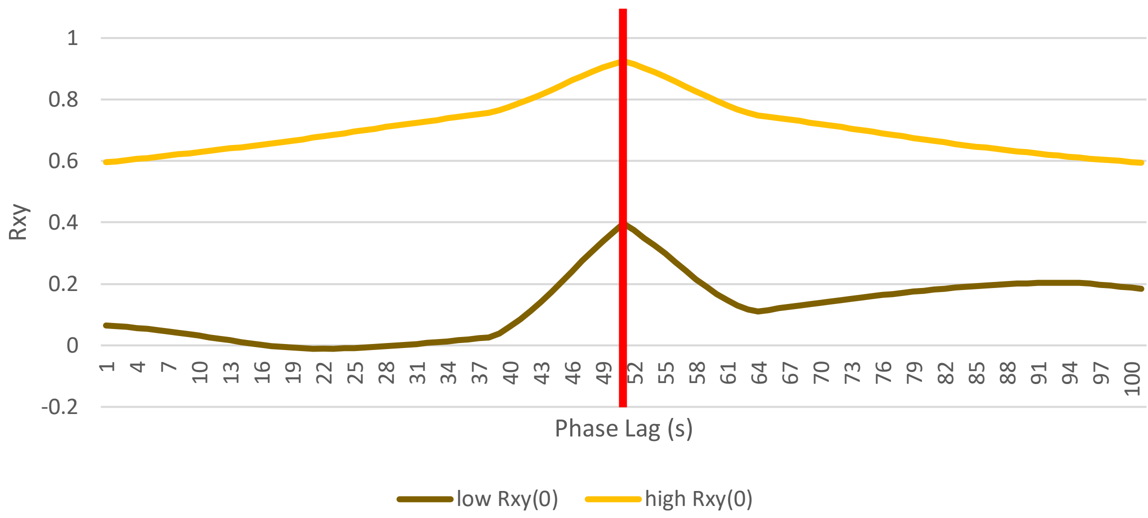


Figure 2.4. The above graph is two sample Rxy functions from the pre-season data. The top (yellow) line has high Rxy and bottom (brown) line has low Rxy.

Frequency decomposition of individual limb centre or pressure trajectories

The possibility of using such measures in the concussion population may elicit promising results, due to their potential to parse the proactive and reactive control elements. According to Stuphorn & Emeric (2012), proactive control is a “form of early selection in which goal-relevant information is actively maintained in a sustained manner, before the occurrence of cognitively demanding events, to optimally bias attention, perception, and action systems in a goal-driven manner.” (p. 1). Reactive control is utilized only when needed, such as after a high interference event, and a late correction mechanism (Stuphorn & Emeric, 2012). A wavelet-based frequency decomposition of the data allows for CoP signals to be broken down into their frequency components, while maintaining the temporal aspects of the signal. Different from Fourier decompositions, where the temporal information is lost, wavelet-based decomposition can be used to compare both temporal and spatial aspects of the CoP trajectories from left and right limbs, within certain frequency bandwidths stemming from the wavelet decomposition. The threshold for determining high (reactive) and low (proactive) frequencies within the signal was 0.4Hz (Singer & Mochizuki, 2015). Due to the findings with other brain pathologies, it is thought that only certain frequency components (i.e., reactive, or proactive control) may be affected by SRC. Current research is being done to link these measures with the ability to control the body's centre of mass, a true measure of instability and postural control, in young and older adults (McLennan & Singer, in preparation). The research will explore the mechanical relationship between symmetry and synchrony of the individual limb CoP and CoM control. The aim is to better describe the mechanical and theoretical basis as to why between-limb measures of stability control may be less prone to confounds, such as age and fatigue (discussed later), and better able to quantify the influence of pathology. With the potential for a differential recovery of proactive and reactive balance elements following concussion, such newer indices of balance control may have the potential to improve understanding of the temporal evolution of recovery.

Concussion and between-limb measures of balance control

Concussions can produce observable changes within the brain. Evidence of both white and grey matter damage has been observed (Dean et al., 2015; Sussman et al., 2017). Specifically, "reductions in white matter volume, mean cortical thickness and total cortical volume following a single concussion that were independent of age or intelligence" (Sussman et al., 2017, p. 55) were observed in patients who had a concussion in the past 3 months. Cortical thinning was observed in the left superior frontal gyrus, postcentral gyrus, and the right parahippocampal gyrus, meanwhile cortical thickening occurred in the right superior temporal gyrus (Sussman et al., 2017). However, no significant differences in any subcortical structures or lobules of the cerebellum occurred post-concussion (Sussman et al., 2017). These structural changes increase with increased post-concussion symptom score (Dean et al., 2015). Grey matter content has been associated with bimanual coordination through a bimanual tracking task developed by Sisti et al. (2011). Therefore, the damage observed could affect coordination which would be assessed through the between-limb measures of balance control being used in this research (van Ruitenbeek et al., 2017). Deficits in bimanual coordination from grey matter damage/atrophy are thought to be due to impaired predictive control, movement prediction, and movement preparation (Gooijers et al., 2016). This leads to the prediction that bilateral control may be affected post-SRC, specifically lower (anticipatory/predictive) frequency contributions.

Between-limb measures of balance control have the ability to differentiate between reactive and proactive control mechanisms, as mentioned previously. According to Singer & Mochizuki (2015), lower frequency components may represent an anticipatory control mechanism, indicative of CoM dynamics, exploratory CoP migrations, or errors in state estimation. Higher frequency components may be representative of reactive control, specifically balance corrections executed in response to transient instability. The threshold for determining high and low frequencies within the signal was 0.4Hz, which is task dependent (Singer & Mochizuki, 2015). It was found that individuals post-stroke exhibited a reduced temporal synchronization of high-frequency (reactive) components (Singer & Mochizuki, 2015). Moreover, individuals with a decreased ability to recover their balance have been found to exhibit higher RMS value for high frequency components, suggesting specific challenges modulating reactive balance corrections post-stroke (Schinkel-Ivy et al., 2016). Wavelet decomposition allows you to examine the components of a signal with greater lower frequency resolution then a Fourier transform, while preserving the temporal aspects of the signal

(Schinkel-Ivy et al., 2016). Deficits in reactive abilities post-concussion have been found via simple reaction time tasks, and functional reaction time tasks, which were sport-specific movements assessed using high-speed video analysis (Del Rossi, 2017; Lynall et al., 2017). Therefore, if reaction time is affected, it is possible that we may see reduced temporal synchronization and spatial symmetry between limbs within the higher frequency CoP components, as these are subconscious reactions to stabilize the CoM.

Effects of confounding variables on balance

Balance and postural control can be affected by confounding variables, which can produce similar deficits as would be seen by a SRC. The current clinical standard of the mBESS to assess postural control post-concussion is influenced by injuries of the ankle, sport played, and fatigue (Buckley et al., 2016; Guskiewicz, 2011). Verschueren et al. (2021) explain that "acute physical fatigue is defined as an exercise induced decline of performance and is known to impair single muscle performance, proprioception, balance and postural control, and to alter movement patterns." (p. 188). It has been found that static and dynamic balance are affected by exercise, however those effects disappear after 15 minutes rest (Clifton et al., 2013; Schneiders et al., 2012). The effect of fatigue on measures on inter-limb symmetry has not been tested. The current thesis will help to determine if the measures are robust to fatigue, or if a period of rest needs to be used before measures can be taken like with other tests.

Population-specific changes in balance control

Research has been done looking at other metrics in this same population. In a study looking at how players changed over a 3 year period they found that many physical and physiological changes occur between the ages of 13 and 15 years (Cordingley et al., 2019). The changes observed were anthropometric measurements, muscular, anaerobic, and aerobic fitness (Cordingley et al., 2019). Cordingley et al. (2019) noted that height and body mass each increased with age but there was no change in body fat. With no observed differences in body fat as players increased age, it could indicate that there is an optimal strength/fat-free mass ratio that the athletes naturally maintain for performance purposes. Compared to sex- and age-matched 20-m shuttle run data, the athletes scored in the 95th, 95th, and 90th percentiles at ages 13, 14, and 15 years, respectively. This would suggest that when interpreting fitness testing results for athletes, it is important to compare to sport-, age-, and competition-level-matched data for accurate indication of how athletes compare. Aerobic fitness decreased from the age of 14 years to the age of 15 years. The absolute peak and average power improvement observed from 14 to 15 years of age would not be reflected in the relative power output values because of the increase in body mass observed. There was no change in the fatigue index observed between any age group (Cordingley et al., 2019). These results suggest that sport, age, and competition level may need to be taken into consideration when looking at postural control and balance data in this population.

Age-specific postural control, balance, stability, and concussion

Measures of between limb balance control have never been used in this population before, therefore it is important to discuss findings from other methods of assessing balance and postural control. A study by Avery et al. (2018), evaluating changes in functional fitness and concussion status over the course of a competitive season in youth ice-hockey found that players reach distance scores for the Y Balance Test (YBT) decreased over the season. These findings show there is a reduced ability to perform a dynamic balance task, with a mean decrease in the YBT-LQ composite score of 2.8 cm (Avery et al., 2018). However, when injured and uninjured athletes were compared, no differences in scores were observed (Avery et al., 2018). A study by Schneider et al. (2021), looking at 13–17-year-old ice hockey players, both male and female, found that the Balance Examination Score (BES) was not a risk factor for a concussion. Another study found in a similar group that tandem stance scores from the modified Balance Error Scoring System (mBESS) that were greater than or equal to 4 was a significant predictor of longer clinical recovery (Emery et al., 2021). A study by Mitchell & Cinelli (2019), looked at a lower limb visuomotor task, and whether it could identify balance control differences between youth athletes with and without previous SRC (M = 14.7 years of age). Their findings suggested that concussed young ice hockey players consistently performed the task more conservatively, and that a lower limb Go/No-Go task may identify differences between youth athletes with and without previous SRC (Mitchell & Cinelli, 2019). Schneider et al (2018) found dynamic balance scores were not significantly different from baseline measures when assessed using a dynamic balance test (Functional Gait Assessment) in young ice hockey players closely following a concussion (median = 4 days). All these findings mentioned show the lack of a definitive conclusion around how a SRC effects balance and postural control in young ice hockey players.

Normative values of between limb measures of balance control

Currently, there have been no studies looking at these measures in this population or in a youth population. Singer et al. (2013) looked at these measures in an adult population with a mean age of 65 years old. They found in healthy controls had spatial symmetry of 0.75 in the AP direction and 1.04 in the ML direction. Cross correlation of individual limb CoP timeseries was performed. In the AP direction, values at 1 indicate perfect temporal synchrony; in the ML direction values of -1 indicate perfect temporal synchrony. For spatial symmetry, the ration of right and left RMS displacements was used. A value of 1.00 would indicate perfect spatial between-limb symmetry; As we had no hypothesis concerning footedness, the smaller RMS displacement was always taken as the numerator – as such, values less than 1 suggest a reduction in spatial symmetry, irrespective of the limb. Healthy participants anteroposterior (AP) temporal synchronization was 0.85 and mediolateral (ML) temporal synchronization of –0.55 (Singer et al., 2013). Peak values for AP and ML temporal synchronization were 0.86 and –0.58, respectively (Singer et al., 2013), which suggests that, for healthy participants, the peak synchronization between limbs occurs at zero phase lag (i.e. there is no lag between limbs). Using these values, we can set expectations as to what we should find in our healthy (non-concussed) population in terms of mean values and range. However, due to the differences between young ice hockey players and those in the previous mentioned studies, we can only use this as a guideline or reference for what we may expect. Completely different statistics in the healthy (non-concussed) population of my research may be found.

Chapter 3 : Objectives and Hypothesis

Objectives

The main objective of the research was to determine if newly developed indices of balance control (i.e., interlimb temporal and spatial synchronization of CoP displacements) are capable of detecting changes in balance control that may be brought about by concussion. The ultimate goal of this line of work was to implement such measures to assist in SRC diagnosis and RTP. The main outcome measures were inter-limb CoP symmetry and synchrony measures. Secondary outcome measures will examine whether time-frequency-based measures of stability control, extracted from individual-limb CoP timeseries, are capable of providing further context into stability control by examining proactive and reactive control of standing balance. This investigation had five aims:

1. Determine if inter-limb CoP symmetry, synchrony, and time-frequency-based measures of postural control are sensitive to changes in stability control brought about by SRC.
2. Establish if intra-individual (compare to pre-concussed self) or inter-group comparison (compared to group mean values to determine if they fall outside cut-off value) needs to be used to assess for the effects of SRC on the measures of posture control.
3. Provide baseline measures documenting the natural within-subject variation in these indices in the healthy controls for future work.
4. Explore if these measures are affected by confounding variables such as fatigue, and age.
5. Ultimately, evaluate whether these measures have the potential for the use in the assessment, management, and return to play decisions associated with SRC in adolescents.

Hypothesis

The author hypothesized that athletes who have sustained a concussion over the season will show a reduced magnitude of between-limb CoP symmetry and synchrony, which will suggest greater instability than prior to the concussion. Athletes who sustain a SRC will have decreased between-limb synchrony in their higher- and lower-frequency components of the CoP signal, indicating impaired control of reactive balance corrections. This has been found in the past with simple reaction time tests post-concussion, however has never been found in tasks not requiring conscious control, such as quiet stance (Del Rossi, 2017; Lynall et al., 2017). The author hypothesizes that intra-individual and inter-individual comparisons will be able to be used to assess impairment of postural control (i.e., not only will we be able to detect changes at the group level, but individual difference also pre-post-concussion will be apparent). With 249 subjects, the author believes great enough power will be attained to document natural within-subject variability in these measures. As noted previously, confounding variables, such as fatigue, that are associated with sport participation, may influence the testing outcomes as seen with other assessments of balance and postural control post-SRC. However, age will have minimal effect on the measures in the samples of participants obtained, as the range in this study is 13-18 years old.

Chapter 4 : Methods

Participants

Participants were taken from a group of 249 young (13-18 years old) male top-level competitive ice hockey players. Of those, 19 participants did not complete both pre- and post-season physiological testing. A further 83 participants did not consent to having their results used for research purposes. A total of 147 players consented and completed both pre- and post-season testing. Participants were chosen through a convenience sampling method, as the principal investigator had access to the sample population through physiological testing done pre- and post-season. The testing was done as part of the pre-season and post-season physiological testing. Inclusion and exclusion criteria were very minimal, as the testing was being done on a very specific demographic. Inclusion/exclusion criteria includes:

- Invited to participate in the 2017/2018 AAA Hockey physiological testing at the BellMTS IcePlex (Winnipeg, MB, Canada)
- Parent/guardian provided informed consent for their testing results to be used in research
- No prior injury or underlying health issues, resulting in the inability to complete the testing due to not being able to bear weight on both lower limbs

Based off SRC incidence rates ranging from 1.66-2.08/1000 AE in top-level competitive male ice hockey players through a retrospective survey, the expected number of SRCs over the season within the chosen sample size ranges from 13 to 16 (based off a 50-game season) (Emery et al., 2010; Emery & Meeuwisse, 2006; Williamson & Goodman, 2006). Calculations for the incidence rates are as follows, where x is the number of SRCs:

$$incidence\ rate\ (AE) = \frac{x}{\#\ of\ AE}$$

$$\frac{1.66}{1000} = \frac{x}{147\ players\ \times\ 50\ games}$$

$$x = 12.201 = 12$$

Below is a sample size calculation for this study based off a sample size calculation from Charan & Biswas (2013):

$$Sample\ Size = \frac{{Z_{1-\alpha/2}}^2 p(1-p)}{d^2}$$

Where, $Z_{1-\alpha/2}$ is the standard normal variate, $Z_{1-\beta}$, p is the expected proportion in the population based on previous research, and d is the absolute error. The standard normal variate will be set at $P < 0.05$, $p = \frac{minimum\ \#\ of\ expected\ SRCs}{Total\#\ of\ participants}$, and the absolute error will be set at 5%. Therefore, the sample size calculation is:

$$Sample\ Size = \frac{{Z_{1-\alpha/2}}^2 p(1-p)}{d^2}$$

$$Sample\ Size = \frac{(1.96)^2(\frac{13}{147})\left(1-(\frac{16}{151})\right)}{(0.05)^2}$$

$$Sample\ Size = 145.57$$

$$Sample\ Size = 146$$

Based off this calculation a total required sample size of 146 participants is needed to achieve a P value below 0.05 and with an expected error of 5%.

Instruments

Preseason data collection was done using two Kistler Type 9260AA6 force plates (Kistler Group, Winterthur, Switzerland), located within Pan Am Clinic Foundation Research Centre at the BellMTS IcePlex. The two force plates were placed side-by-side to allow for one foot to be placed on each force plate (Y-axis is along AP axis, with positive Y-axis anterior to individual; X-axis is in the ML direction, positive to the right of the individual; Z-axis is oriented upward (Figure 4.1)). Force plates captured data at a rate of 128 Hz. The chosen frequency was based off the Nyquist Sampling Theorem of sampling. According to (Hasan et al., 1996), the max frequency of the CoP signal in double leg stance with eyes open is 8Hz. Therefore, using this number in the Nyquist formula then multiplying the answer by 10 to ensure the data is accurately represented in the time domain, gives us a minimum sampling frequency (F_S) of 80Hz. 128 Hz was chosen as the next power of two, to ensure data could be subjected to frequency decomposition without interpolation. The Nyquist sampling formula is:

$$F_s = 2(N) + 1$$

Where N is the frequency of the sample. The data was collected using proprietary BioWare software (Kistler Group, Winterthur, Switzerland).

Postseason data collection was done using two AMTI ORS6-6-1000 force plates and AMTI MSA-6 amplifiers (Advanced Mechanical Technology, Inc., Watertown, MA) located within Pan Am Clinic Foundation Research Centre at the BellMTS IcePlex (Winnipeg, MB, Canada). Different force plates were used for postseason data collection due to the Kistler force plates being used for other data collection and being embedded in a walkway at the University of Manitoba Fort Garry campus. The two force plates were placed side-by-side (positive Y-axis

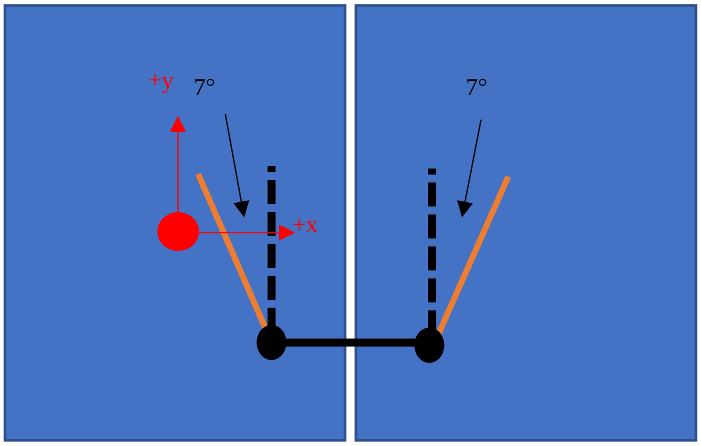


Figure 4.1. *Force plate orientation and positioning of participants on force plates.*

along AP axis, anterior to individual (Figure 4.1)) to allow for one foot to be placed on each force plate. Force plates captured data at a rate of 200 Hz. The difference in sampling rate exists due to restrictions within the force plate data collection software. The differences in sampling rate will not affect the outcome data – data were resampled at 128 Hz using spline interpolation, consistent with pre-season data. Modifications to the processing of the data using custom code in MATLAB were made depending on the sampling rate, as the rate is included within the data analysis script in the software. The data was collected using the NetForce software (Advanced Mechanical Technology, Inc., Watertown, MA) sold with the force plates.

Study design

A quasi-experimental design was used for the study, as a true experimental design was not feasible. Due to the nature of the intervention (i.e., sustaining a SRC), using an experimental design would be unethical. Data were collected at two time-points; therefore, a modified nonequivalent pretest-posttest control group design was used. Participants all began in the same experimental group, underwent the same pretest, then depending on whether they experienced a SRC or not between the pretest and posttest determined if they were part of the experimental group or control group. Both groups then underwent the same posttest. Figure 4.2 visually represents this study design.

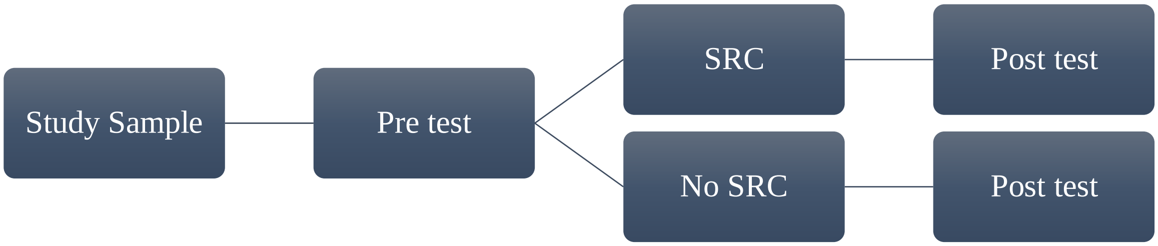


Figure 4.2. Study design.

Procedures

As mentioned above, data was collected at two time-points. Once in September/October 2017, prior to the commencement of the hockey season, and once in February/March 2018, after the hockey season has finished. The time between pre- and post-season testing was 146.63±12.75 days. Data was collected during physiological testing sessions attended by the teams over a two-week period. Other testing done at these sessions included a Wingate anaerobic test, body fat measurement, height, weight, grip strength, beep test, push up test, plank test, and the 5-10-5 shuttle run test. Athletes were split into two groups each session with one group completing the beep, 5-10-5, push, and plank tests, while the other group completed the rest of the tests. Athletes were allowed to complete the tests in any order, which did not allow for true randomization, but allows for some testing of the effects of confounding variables. The researcher recorded if the athletes were in the first or second (after beep, 5-10-5, push, and plank tests) group, and if they had recently completed the Wingate Anaerobic Test, which was assessed by the athlete showing signs of fatigue, and by asking the athlete how long it had been since they performed the test. These signs included breathlessness, sweating, and/or flush skin colour. Athletes were not timing themselves between completion of the Wingate and start of the force plate balance test, therefore times between these tests and the balance test were not exact. The best estimate of the time between tests is 5-10 minutes. Athlete fatigue status was recorded at both the pre- and post-season testing timepoints. Based on this, the athletes were placed into one of four fatigue groups. The first group was not fatigued at either timepoint, and was labelled ‘None’. The second group was not fatigued in the pre-season but was during post-season testing. This group was labelled ‘Post’. The third group was opposite to the second, and was fatigued during pre-season testing, but not during post-season. The third group was labelled ‘Pre’. The fourth group was fatigued at both timepoints, and accordingly labeled ‘Both’.

The data acquisition procedures used in the study will be like those of McLennan and Singer (in preparation). To ensure participants could be moved quickly through the standing balance tests and not interfere with the scheduled physiological testing, participants completed one trial of quiet standing with eyes open lasting 60 seconds each (Singer & Mochizuki, 2015). During this time, they were asked to try and stand as still as possible, with a standardized foot position, as per McIlroy & Maki (1997), of 17 cm between heels and external rotation of each foot by 7 degrees relative to the midline or 14 degrees relative to the contralateral foot (Figure 4.3). Participants were in bare feet or socks. The participant was asked to stand in a comfortable upright position with arms and hands by their sides. All data was collected with the principal investigator present. Ethics approval for the September 2017 data collection period was obtained by the Pan Am Clinic

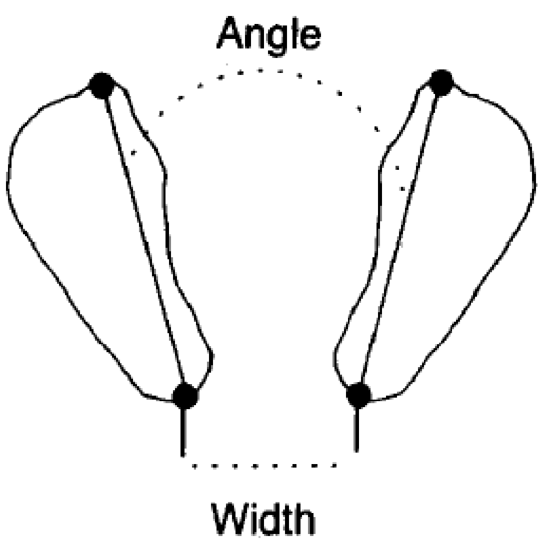


Figure 4.3. Stance width and angle. Retrieved from McIlroy and Maki (1997).

Research Foundation through the BREB at the University of Manitoba. Ethics approval for the February/April 2018 data collection period was done in the same manner. Information on SRC injuries was collected by Winnipeg AAA Hockey using an self-reported injury questionnaire that was completed by the athletes in the February/March 2018 physiological testing period. Use of this data was completed by applying for use of secondary data through the ethics review board (R1-2021:047 (HS24791)) and Shared Health Research and Innovation (SH2021:054). Data sharing agreements were completed with the Pan Am Clinic Foundation and AAA Hockey Winnipeg.

Data analysis

Raw data was processed like in McLennan and Singer (in preparation), which will allow for access to between-limb CoP synchronization measures. The data was filtered using a low-pass, zero-lag, fourth order, Butterworth filter, with a cutoff frequency of 10 Hz. A cutoff frequency of 10 Hz was used, as the frequency of kinetic measures of quiet standing do not exceed 10 Hz and will attenuate any noise present above the frequency (Hasan et al., 1996). A frequency analysis of the initial data found noise in the signal at a frequency of 19.5 Hz – following low-pass filtering, this frequency component contributed to less than 0.1% of total signal power. This noise was due to the facility’s mechanical room being situated beside the space where data collection took place. Following filtering, the ratio of left and right limb root mean square CoP displacements were calculated from the anteroposterior and mediolateral CoP time series, to assess interlimb spatial symmetry of CoP displacements. As we had no hypothesis concerning footedness, the RMS ration was expressed as the quotient of the individual limb RMS displacements – the smaller RMS value (regardless of limb) was always taken as the numerator, such that perfect spatial symmetry would be indicated by a ratio of 1.00, with reduced symmetry indicated by values less than 1.00.

Further, the cross-correlation of right and left limb CoP time series were used to obtain between-limb temporal synchrony of CoP displacements in anteroposterior and mediolateral directions. Cross-correlation coefficients are calculated by iteratively correlating two signals and looking at the linear combinations of neighboring data points at a certain time lag, consistent with the sampling interval (i.e., the interval between samples). In the anteroposterior direction a cross correlation coefficient at zero phase lag of +1.00 would indicate perfect temporal synchronization between individual limb centre of pressure displacements. In the mediolateral direction a cross correlation coefficient at zero phase lag of -1.00 would indicate perfect temporal synchronization between individual limb centre of pressure displacements (see Figure 4.4). The inverse relationship in the mediolateral direction stems from the fact that the positive mediolateral axes of the force platform are both oriented rightward. As such, activation of homologous muscle groups, resulting in either medial or lateral CoP displacements would be in opposite directions relative to the force platform axis system. The time lag is given by the sampling interval which was 1/25 seconds for the down sampled data. A cross-correlation coefficient will be calculated at zero phase lag, as temporal measures of between-limb synchronization of CoP are of interest, without specific focus on the extent of temporal offset between limbs. In previous work examining stroke survivors (Singer and Mochizuki, 2014), focus was placed on the peak of the cross-correlation function and the associated time-lag, as neuromuscular challenges could have led to a temporal offset between the individual limb CoP displacements, which is detectable using the cross-correlation function. In the present work, we had no evidence to suspect the potential of a temporal offset between individual limb CoP displacements.

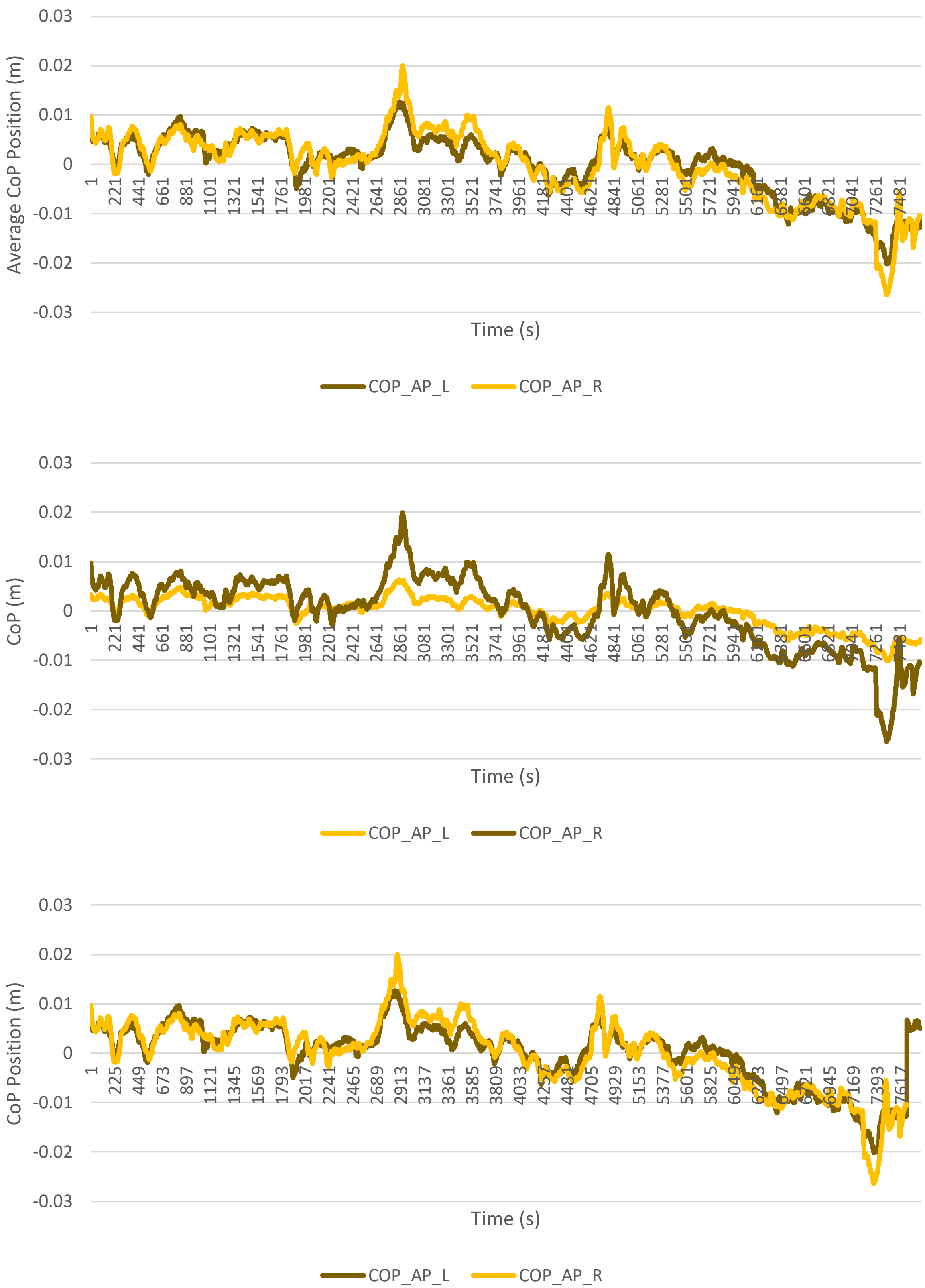


Figure 4.4. *The top graph has R and L limb CoP displacements that have similar amplitude and phase; on the bottom the R and L limb CoP displacements have different amplitude (but similar phase). The top graph has high symmetry and synchrony. The bottom graph has high synchrony but low symmetry. The middle graph has poor synchrony and good symmetry. The graphs are made with fictitious data and are used to demonstrate the information content in the outcome variables being used.*

Frequency decomposition of the data was completed by using cross-correlation coefficients at each frequency bandwidth extracted using a discrete wavelet decomposition. A discrete wavelet decomposition is similar to a Fourier transform in the sense that it breaks down the original signal into its frequency components, but it is also capable of retaining time information as well, which is lost with the Fourier Transform. See Figure 4.5 below for a visual representation of the transform. The maximum detectible frequency using the discrete wavelet decomposition is one half of the sampling (i.e., 64 Hz on the pre-season data and resampled post-season data. Given a high-frequency limit of 10 Hz on CoP data during standing balance, data was down-sampled to 25 Hz, yielding a high frequency limit of 12.5 Hz on the first decomposition level bandwidth (Hasan et al., 1996). There are 9 bandwidths of 0-0.4 Hz (Low frequency, anticipatory) and 0.5 Hz-10Hz (High frequency, reactive).

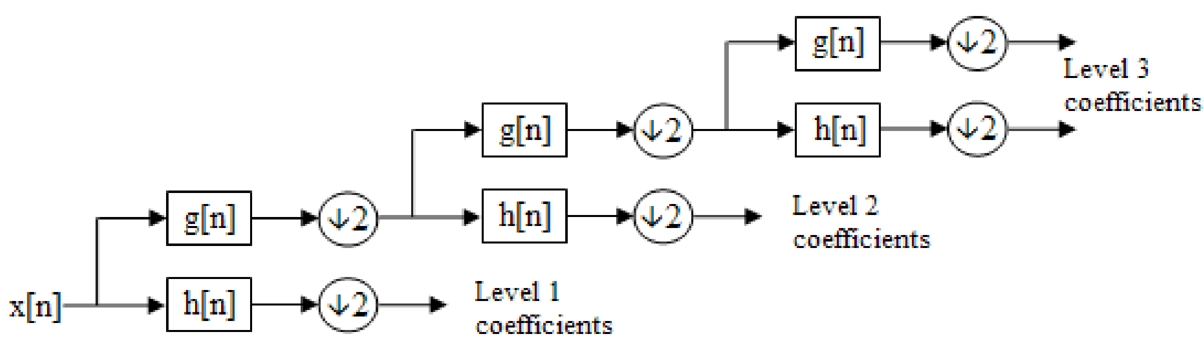


Figure 4.5. *Wavelet decomposition tree. At each level the signal is iteratively decomposed into low (g(n)) and high (h(n)) frequency bandwidths. Due to the decomposition process the input signal must be a multiple of 2^n where n is the number of levels. Retrieved from https://upload.wikimedia.org/wikipedia/commons/2/22/Wavelets_-_Filter_Bank.png*

Statistical analysis

To determine if inter-limb CoP symmetry, synchrony, and time-frequency-based measures of postural control (i.e., higher (>0.4 Hz) and lower (<0.4 Hz) frequency interlimb temporal synchrony) are sensitive to changes in stability control brought about by SRC, each outcome variable was separately assessed using a one-way analysis of covariance (ANCOVA) (p

< 0.05). A one-way ANCOVA was chosen over a repeated-measures ANOVA as there is belief that post-season scores may depend on the pre-season scores. Pre-season scores were used as the covariate in all analysis completed. Confounding variables (i.e., concussion status, fatigue status, and age) were included as independent variables. To use a one-way ANCOVA there are 10 assumptions that must be considered before running the test. These assumptions are listed below:

1. The dependent variable is measured at the continuous level. As the dependent variable in this case is interlimb temporal synchrony and symmetry measures, this holds true.
2. There is one independent variable that consists of two or more categorical, independent groups. Within the analysis for this study there will be three ANCOVA's run, where concussion status, fatigue status, and age are the independent variables, respectively, and this holds true.
3. The covariate must be measured at a continuous level. This holds true as pre-season interlimb temporal synchrony and symmetry will be used.
4. There should be independence of observations. With both independent variables, there is independence as a participant can only be in one group.

Assumptions five to ten will be mentioned below but cannot be tested until the statistical analysis has been ran and will be covered in the results section.

5. There should be a linear relationship between the dependent and covariate at each level/group of the independent variable. This will be assessed through visual inspection of the scatterplots with pre-season measures plotted against post-season measures.
6. Homogeneity of regression slopes should exist between the covariate and independent variable. This will be assessed by determining if there is a significant interaction between the covariate and the independent variable ($p > 0.05$).

7. The dependent variable should be approximately normally distributed for each group of the independent variable. This will be assessed on the standardized residuals following the ANCOVA test using Shapiro-Wilk's test ($p < 0.05$).
8. Homoscedasticity should exist in the error variances within each group. This will be assessed through visual inspection of the standardized residuals plotted against the predicted values.
9. Homogeneity of variances for the residuals should exist. This will be assessed by Levene's test of equality of variances ($p > 0.05$).
10. There should be no significant outliers in any of the independent variable groups for your dependent variable. Outliers will be identified in by assessing the standardized residuals for values greater than ±3 standard deviations.

For all follow up analyses Tukey's Honestly Significant Difference (HSD) tests $(\alpha = 0.05)$ will be used to localize main effects and interactions. Data will also be assessed using this method to answer a secondary study aim looking at the effect of fatigue or age on measures.

Chapter 5 : Results

As discussed in the methods section, a group of 249 young (13-18 years old) male top-level competitive ice hockey players completed testing for the 2017/18 season. Of those, a total of 147 players consented and completed both pre- and post-season testing. A further 43 participants were excluded following analysis of their pre- and post-season, which showed quiet stance for the entire trial length was not achieved. Analysis was accomplished by removing participants whose transient ML weight shifts or ML loading asymmetries exceeded 20% of the participant's body weight. Birnbaum et al. (2021) detailed the range of weight bearing asymmetries observed in a healthy sample of adults. Observing a 20% BW shift would be more than 2x the interquartile range, and make the trial considered an outlier (Birnbaum et al., 2021), as differential limb loading may alter interlimb CoP control independent of our independent variables. There are no data on the range, or effect, of ML weight asymmetries in healthy younger adults. See Table 5.10 for summary statistics on excluded participants. This left a total of 104 participants. See Table 5.1, 5.2, and 5.3 for a breakdown of the descriptive statistics.

Table 5.1. Days from SRC diagnosis to post-season testing

Days from SRC Diagnosis to Post-season testing				
Age (years)	0-29 days	30-59 days	60-89 days	90-119 days
13 (N)	0	3	0	1
14 (N)	0	0	1	2
15 (N)	0	2	0	0
16 (N)	0	0	2	1
17 (N)	0	0	0	0
18 (N)	0	0	0	0

Table 5.2. Participant Characteristics

Concussion Status	Concussion	No Concussion
Age (years)		
13 (N)	4	22
14 (N)	3	27
15 (N)	2	22
16 (N)	3	17
17 (N)	0	3
18 (N)	0	1
Pre-season ML Inter-limb Spatial Symmetry	0.808 (0.119)	0.719 (0.174)
Post-season ML Inter-limb Spatial Symmetry	0.739 (0.243)	0.725 (0.192)
Pre-season AP Inter-limb Spatial Symmetry	0.694 (0.155)	0.748 (0.143)
Post-season AP Inter-limb Spatial Symmetry	0.744 (0.222)	0.751 (0.158)
Pre-season ML Inter-limb Temporal Synchrony	-0.938 (0.034)	-0.926 (0.051)
Post-season ML Inter-limb Temporal Synchrony	-0.587 (0.256)	-0.588 (0.232)
Pre-season AP Inter-limb Temporal Synchrony	0.672 (0.137)	0.722 (0.167)
Post-season AP Inter-limb Temporal Synchrony	0.674 (0.199)	0.714 (0.174)

Table 5.3. Balance outcome variables

Fatigue Status	None	Post	Pre	Both	Missing Data
Age (years)					
13 (N)	6	2	2	3	13
14 (N)	7	9	5	5	4
15 (N)	5	6	3	10	0
16 (N)	6	4	5	5	0
17 (N)	2	0	0	1	0
18 (N)	0	0	1	0	0
Pre-season ML Inter-limb Spatial Symmetry	0.767 (0.147)	0.742 (0.148)	0.681 (0.210)	0.692 (0.189)	
Post-season ML Inter-limb Spatial Symmetry	0.764 (0.169)	0.738 (0.180)	0.689 (0.178)	0.704 (0.246)	
Pre-season AP Inter-limb Spatial Symmetry	0.765 (0.122)	0.754 (0.154)	0.701 (0.155)	0.737 (0.151)	
Post-season AP Inter-limb Spatial Symmetry	0.743 (0.162)	0.760 (0.147)	0.759 (0.166)	0.735 (0.174)	
Pre-season ML Inter-limb Temporal Synchrony	-0.911 (0.012)	-0.928 (0.009)	-0.913 (0.012)	-0.928 (0.009)	
Post-season ML Inter-limb Temporal Synchrony	-0.579 (0.231)	-0.618 (0.262)	-0.579 (0.186)	-0.637 (0.195)	
Pre-season AP Inter-limb Temporal Synchrony	0.677 (0.038)	0.717 (0.028)	0.697 (0.034)	0.733 (0.035)	
Post-season AP Inter-limb Temporal Synchrony	0.732 (0.028)	0.749 (0.033)	0.704 (0.038)	0.687 (0.037)	

Age (Years)	13	14	15	16	17	18
N	26	30	24	20	3	1
Pre-season ML Inter-limb Spatial Symmetry	-0.744 (0.144)	0.708 (0.161)	0.716 (0.170)	0.731 (0.178)	0.684 (0.157)	0.963
Post-season ML Inter-limb Spatial Symmetry	-0.685 (0.221)	0.776 (0.166)	0.725 (0.192)	0.679 (0.198)	0.774 (0.258)	0.987

Pre-season AP Inter-limb Spatial Symmetry	0.769 (0.157)	0.709 (0.136)	0.762 (0.158)	0.752 (0.132)	0.832 (0.175)	0.958
Post-season AP Inter-limb Spatial Symmetry	0.731 (0.191)	0.797 (0.132)	0.729 (0.151)	0.679 (0.163)	0.913 (0.066)	0.969
Pre-season ML Inter-limb Temporal Synchrony	-0.937 (0.029)	-0.923 (0.060)	-0.934 (0.035)	-0.911 (0.065)	-0.930 (0.052)	-0.946
Post-season ML Inter-limb Temporal Synchrony	-0.522 (0.262)	-0.578 (0.242)	-0.600 (0.202)	-0.648 (0.183)	-0.644 (0.419)	-0.873
Pre-season AP Inter-limb Temporal Synchrony	0.672 (0.180)	0.747 (0.156)	0.753 (0.140)	0.962 (0.165)	0.733 (0.238)	0.481
Post-season AP Inter-limb Temporal Synchrony	0.685 (0.205)	0.707 (0.173)	0.736 (0.149)	0.706 (0.139)	0.700 (0.411)	0.875
RMS CoP Displacements (mm)	M (SD)					
AP RMS CoP Displacement	5.08 (1.51)					
ML RMS CoP Displacement	3.53 (1.45)					
RMS CoP Velocity (mm/s)	M (SD)					
AP RMP CoP Velocity	13.96 (4.06)					
ML RMS CoP Velocity	11.35 (4.34)					

N = number of participants, Variables are presented as mean (standard deviation). Interlimb temporal synchrony and spatial symmetry measures a correlation value between -1 and 1, and therefore does not have a unit of measurement.

Effect of sport-related concussion on inter-limb synchrony and symmetry

An ANCOVA was run to determine the effect of a experiencing a SRC on post-season inter-limb temporal synchrony and spatial symmetry balance scores after controlling for pre-season interlimb balance scores. There was a poor linear relationship between pre- and post-season ML and AP inter-limb temporal synchrony and spatial symmetry for each group (concussion and no concussion), as assessed by visual inspection of a scatterplot. There was homogeneity of regression slopes as the interaction term was not statistically significant in the

ML, $F(1, 100) = 1.535$, $p = .218$, and AP direction, $F(1, 100) = 0.489$, $p = .486$ for temporal synchrony scores, or for spatial symmetry scores (ML: $F(1, 92) = 0.078$, $p = 0.780$, AP: $F(1, 92) = 1.689$, $p = 0.197$) . Standardized residuals for temporal synchrony in the ML and AP direction for the group that did sustain a concussion were normally distributed ($p > .05$), however the scores of the non-concussion groups were not normally distributed, as assessed by Shapiro-Wilk's test ($p < .05$). For spatial symmetry, the ML and AP groups that did not sustain a concussion and the AP concussion group were not normally distributed ($p < .05$). The ML concussion group was normally distributed ($p > .05$). As the ANCOVA is fairly robust to deviations from normal, and this does not have a large effect on Type I error rate, the tests will continue. There was homoscedasticity and homogeneity of variances, as assessed by visual inspection of a scatterplot and Levene's test of homogeneity of variance in the ML ($p = .726$) and AP direction ($p = 0.363$) for temporal scores, and in the ML ($p = 0.826$) and AP direction ($p = 0.254$) for spatial scores. There were no outliers in the data for both ML and AP inter-limb temporal and spatial symmetry, as assessed by no cases with standardized residuals greater than ±3 standard deviations. After adjustment for pre-season interlimb synchrony scores, there was no statistically significant difference in post-season ML ($F(1, 101) = 0.004$, $p = 0.949$) and AP inter-limb temporal synchrony ($F(1, 101) = 0.330$, $p = 0.567$) between the concussion groups. The same can be said for post-season ML ($F(1, 93) = 0.054$, $p = 0.817$) and AP inter-limb spatial symmetry scores ($F(1, 93) = 0.015$, $p = 0.904$) between concussion groups. A Post hoc analysis was not performed due to the non-significant findings from the ANCOVA. See Table 5.4 for unadjusted and adjusted means. See Figure 5.1 for a visual representation.

Effect of fatigue on inter-limb synchrony and symmetry

A second ANCOVA was ran to determine the effect of fatigue on post-season interlimb temporal and spatial symmetry balance scores after controlling for pre-season interlimb synchrony scores. There was a poor linear relationship between pre- and post-season ML and AP inter-limb temporal synchrony and spatial symmetry for each group (none, post, pre, and both), as assessed by visual inspection of a scatterplot. There was homogeneity of regression slopes as the interaction term was not statistically significant for the temporal synchrony measures in the ML, $F(3, 79) = .617$, $p = .606$, and AP direction, $F(3, 79) = .453$, $p = .716$. For the spatial symmetry measures, the same can be said in the AP direction ($F(3, 71) = 1.391$, $p = 0.253$), but not in the ML direction ($F(3, 71) = 6.551$, $p = 0.001$) . Standardized residuals for the temporal measures in the ML and AP direction for the none, pre, and both fatigue groups were normally distributed ($p > .05$), however the scores of the post fatigue group were not normally distributed, as assessed by Shapiro-Wilk's test ($p < .05$). For the spatial measures, in the ML direction, the no-fatigue (none), fatigue prior to pre-season testing (pre), and fatigue prior to post-season testing (post) measures were normally distributed ($p > .05$), and fatigue prior to both pre- and post-season testing (both) measure was not ($p < .05$). There was homoscedasticity and homogeneity of variances, as assessed by visual inspection of a scatterplot and Levene's test of homogeneity of variance in the ML ($p = .500$) and AP direction ($p = 0.671$) for temporal measures. For spatial measures there was not homoscedasticity and homogeneity of variances in the ML direction ($p = .004$), but there was in the AP direction ($p = .832$). There were no outliers in the data for both ML and AP interlimb synchrony, as assessed by no cases with standardized residuals greater than ±3 standard deviations. After adjustment for pre-season interlimb synchrony scores, there wasn't a statistically significant difference in post-season ML (F(3, 82) =

0.049, $p = 0.791$) and AP inter-limb temporal synchrony ($F(3, 82) = 0.363$, $p = 0.780$) between the fatigue groups, or in ML ($F(3, 74) = 0.681$, $p = 0.566$) or AP ($F(3, 74) = 0.104$, $p = 0.958$) direction for spatial scores. A Post hoc analysis was not performed due to the non-significant findings from the ANCOVA. See Table 5.5 for adjusted and unadjusted means. See Figure 5.2 for a visual representation.

Effect of age on inter-limb synchrony and symmetry

A third ANCOVA was ran to determine the effect of age on post-season interlimb temporal and spatial symmetry balance scores after controlling for pre-season interlimb synchrony scores. There was a poor linear relationship between pre- and post-season ML and AP inter-limb temporal synchrony and spatial symmetry for each group (13, 14, 15, 16, 17, 18), as assessed by visual inspection of a scatterplot. There was not homogeneity of regression slopes as the interaction term was statistically significant for the temporal synchrony measures in the ML direction, $F(3, 56) = 3.002$, $p = .038$. In the AP direction ($F(3, 56) = .174$, $p = .914$) there was homogeneity of regression slopes. For the spatial symmetry measures, the same can be said in the AP direction ($F(3, 56) = 0.358$, $p = 0.783$), and ML direction ($F(3, 56) = 1.478$, $p = 0.230$) . Standardized residuals for the temporal measures in the ML were normally distributed ($p > .05$) within each age group (12-18), however in the AP direction the 13, 14, and 15-year-olds scores were not normally distributed ($p < .05$), as assessed by Shapiro-Wilk's test ($p < .05$). There was homoscedasticity and homogeneity of variances, as assessed by visual inspection of a scatterplot and Levene's test of homogeneity of variance in the ML ($p = .090$), but not in the AP direction ($p = 0.032$) for temporal measures. For spatial measures there was homoscedasticity and homogeneity of variances in the ML ($p = .268$) and AP direction ($p = .102$). There were no outliers in the data for both ML and AP interlimb synchrony, as assessed by no cases with standardized residuals greater than ±3 standard deviations. After adjustment for pre-season interlimb synchrony scores, there was not a statistically significant difference in post-season ML ($F(5, 82) = 0.321$, $p = 0.899$) and AP inter-limb temporal synchrony ($F(5, 82) = 0.117$, $p = 0.988$) between age groups, and in the ML ($F(5, 82) = 1.322$, $p = 0.263$) and AP ($F(5, 82) = 2.278$, $p = 0.054$) direction for spatial scores. A Post hoc analysis was not performed due to the non-significant findings from the ANCOVA. See Table 5.6 for adjusted and unadjusted means. See Figure 5.3 for a visual representation.

Table 5.4. Adjusted and Unadjusted Concussion Means and Variability for Post-season Inter-limb Temporal Synchrony and Spatial Symmetry Measures with Pre-season Inter-limb Temporal Synchrony and Spatial Symmetry Measures as a Covariate: Analysis for the influence of SRC on balance outcome scores

				Unadjusted		Adjusted	
			N	M	SD	M	SD
Inter-limb Temporal Synchrony	ML	No Concussion	92	-.588	.232	-.589	.240
		Concussion	12	-.587	.256	-.584	.236
	AP	No Concussion	92	.714	.174	.713	.173
		Concussion	12	.673	.199	.682	.177
Inter-limb Spatial Symmetry	ML	No Concussion	92	.725	.192	.725	.201
		Concussion	12	.739	.243	.740	.218
	AP	No Concussion	92	.751	.158	.751	.173
		Concussion	12	.744	.222	.744	.184

N = number of participants, M = mean, SD = standard deviation, No concussion = participants who did not sustain a concussion during the season, Concussion = participants who sustained a concussion during the season. Interlimb temporal synchrony and spatial symmetry measures a correlation value between -1 and 1, and therefore does not have a unit of measurement.

Table 5.5. Adjusted and Unadjusted Fatigue Means and Variability for Post-season Interlimb Temporal Synchrony and Spatial Symmetry Measures with Pre-season Interlimb Temporal Synchrony and Spatial Symmetry Measures as a Covariate: Analysis for the effect of fatigue on balance outcome scores

				Unadjusted		Adjusted	
			N	M	SD	M	SD
Inter-limb Temporal Synchrony	ML	None	26	-.579	.230	-.579	.224
		Post	21	-.618	.262	-.615	.225
		Pre	16	-.579	.186	-.583	.224
		Both	24	-.637	.195	-.637	.225
	AP	None	26	.732	.162	.739	.148
		Post	21	.737	.179	.734	.147
		Pre	16	.704	.176	.705	.148
		Both	24	.687	.187	.681	.167
Inter-limb Spatial Symmetry	ML	None	25	.764	.169	.767	.200
		Post	19	.738	.180	.740	.196
		Pre	14	.689	.178	.685	.198
		Both	21	.704	.246	.701	.197
	AP	None	25	.743	.162	.744	.165
		Post	19	.760	.147	.760	.166
		Pre	14	.759	.166	.757	.165
		Both	21	.735	.174	.734	.165

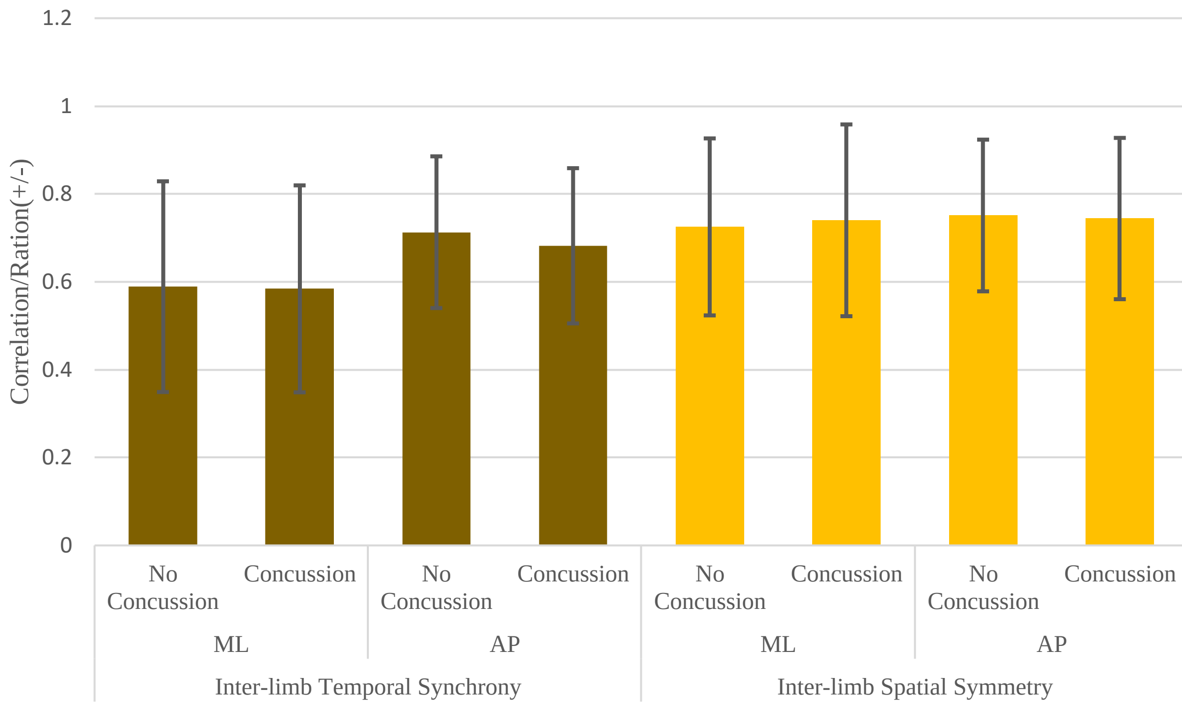
N = number of participants, M = mean, SD = standard deviation, None = participants who were not fatigued at pre- or post-season testing, Post = participants who fatigued at post-season testing but not pre-season, Pre = participants who were fatigued at pre-season testing but not post-season, Both = participants who were fatigued at both pre- and post-season testing. Interlimb temporal synchrony and spatial symmetry measures a correlation value between -1 and 1, and therefore does not have a unit of measurement.

Table 5.6. Adjusted and Unadjusted Age Means and Variability for Post-season Interlimb Temporal and Spatial Symmetry Measures with Pre-season Interlimb Temporal and Spatial Symmetry Measures as a Covariate: Analysis for the influence of age on balance outcome scores

				Unadjusted		Adjusted	
			N	M	SD	M	SD
Inter-limb Temporal Synchrony	ML	13	26	-.522	.262	-.537	.255
		14	30	-.578	.242	-.596	.241
		15	19	-.592	.214	-.571	.240
		16	17	-.639	.174	-.632	.247
		17	3	-.664	.419	-.604	.241
		18	1	-.873		-.658	
	AP	13	26	.651	.153	.712	.194
		14	30	.667	.136	.709	.181
		15	19	.701	.092	.708	.179
		16	17	.746	.145	.684	.186
		17	3	.704	.024	.660	.182
		18	1	.911		.768	
Inter-limb Spatial Symmetry	ML	13	26	.685	.221	.676	.214
		14	30	.776	.166	.793	.203
		15	19	.725	.192	.721	.201
		16	17	.679	.198	.677	.206
		17	3	.774	.258	.766	.201
		18	1	.987		.866	
	AP	13	26	.731	.191	.726	.173
		14	30	.797	.132	.795	.164
		15	19	.729	.151	.726	.166
		16	17	.679	.163	.689	.169
		17	3	.913	.066	.930	.166
		18	1	.969		.996	

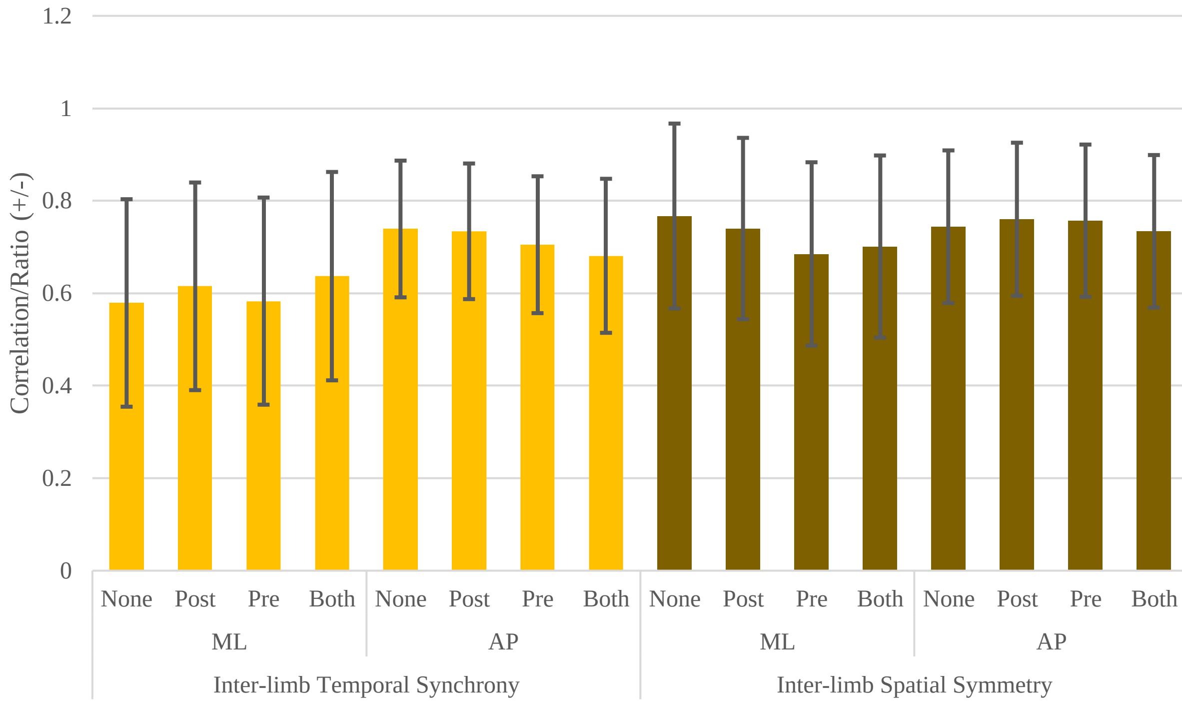
N = number of participants, M = mean, SD = standard deviation. Interlimb temporal synchrony and spatial symmetry measures a correlation value between -1 and 1, and therefore does not have a unit of measurement.

Figure 5.1. Adjusted Concussion Means for Post-season Inter-limb Temporal and Spatial Synchrony Measures: Analysis for the influence of concussion on balance outcome scores



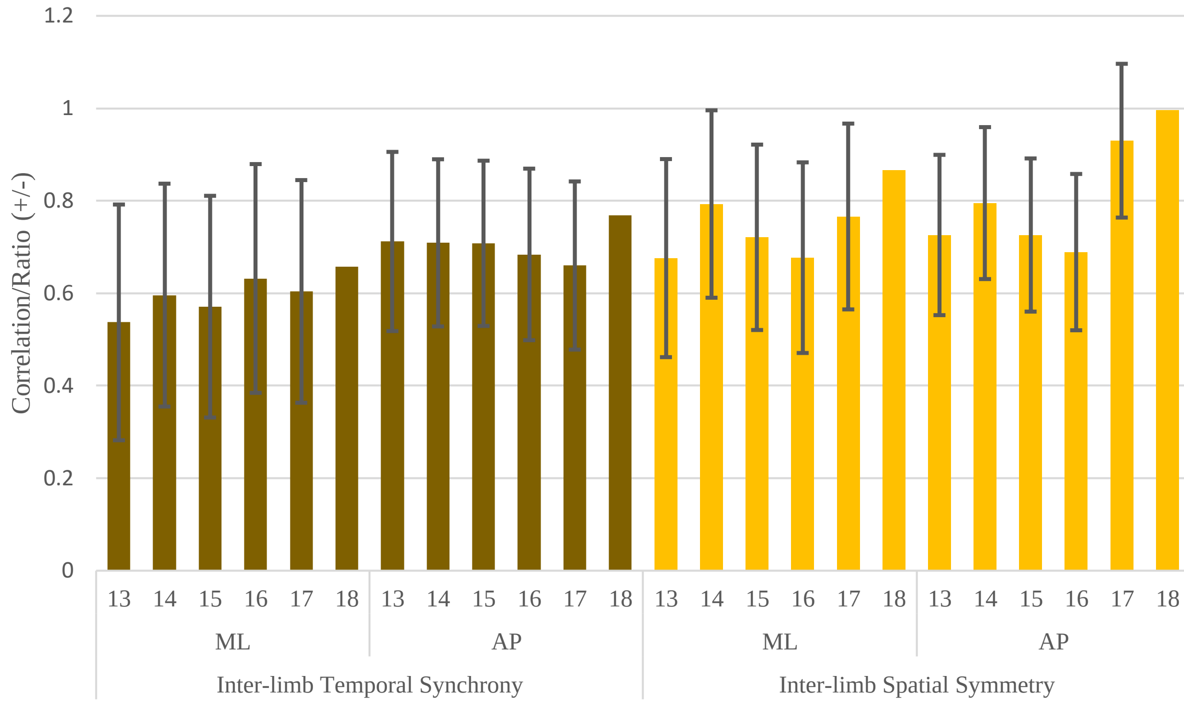
Note. Adjusted mean is graphed with error bars representing ±SD.

Figure 5.2.Adjusted Fatigue Means for Post-season Interlimb Temporal and Spatial Synchrony Measures: Analysis for the influence of fatigue on balance outcome scores



Note. Adjusted mean is graphed with error bars representing ±SD.

Figure 5.3. Adjusted Age Means for Post-season Interlimb Temporal and Spatial Synchrony Measures: Analysis for the influence of age on balance outcome scores



Note. Adjusted mean is graphed with error bars representing ±SD.

Effect of sport-related concussion on frequency decomposed inter-limb synchrony and symmetry

We next examined the wavelet decomposed high and low frequency interlimb temporal synchrony of CoP displacements. The first ANCOVA was ran to determine the effect of a suffering a SRC on post-season high and low frequency inter-limb temporal synchrony balance scores after controlling for pre-season interlimb balance scores. There was a poor linear relationship between pre- and post-season ML and AP inter-limb temporal synchrony for each group (concussion and no concussion) in both high and low frequency measures, as assessed by visual inspection of a scatterplot. There was homogeneity of regression slopes as the interaction term was not statistically significant in the ML for either high ($F(1, 100) = 0.117$, $p = 0.733$) or low frequency ($F(1, 100) = 1.776$, $p = 0.186$), and the AP direction for high ($F(1, 100) = 0.352$, $p = 0.554$) or low frequency ($F(1, 100) = 0.719$, $p= 0.399$) temporal synchrony scores. Standardized residuals for high and low frequency temporal synchrony in the ML and AP direction for the group that did sustain a concussion were normally distributed ($p > .05$), however the scores of the non-concussion groups were not normally distributed, as assessed by Shapiro-Wilk's test ($p < .05$). As the ANCOVA is fairly robust to deviations from normal, and this does not have a large effect on Type I error rate, the tests will continue. There was homoscedasticity and homogeneity of variances, as assessed by visual inspection of a scatterplot and Levene's test of homogeneity of variance in the ML high- ($p = 0.157$) and low-frequency ($p = 0.568$) measures, as well as in the AP high- ($p = 0.078$) and low-frequency ($p = 0.329$) temporal scores. There were no outliers in the data for both ML and AP inter-limb temporal and spatial symmetry, as assessed by no cases with standardized residuals greater than ±3 standard deviations. After adjustment for pre-season interlimb synchrony scores, there wasn't a statistically significant difference in post-season ML high- ($F(1, 101) = 0.202$, $p = 0.654$) or low-frequency ($F(1, 101) =

0.074, p = 0.786) interlimb temporal synchrony scores. The same can be said for AP inter-limb temporal synchrony in the high- (F(1, 101) = 2.263, p = 0.136) and low-frequency (F(1, 101) = 0.818, p = 0.368) scores between the concussion groups. A Post hoc analysis was not performed due to the non-significant findings from the ANCOVA. See Table 5.7 for unadjusted and adjusted means. See Figure 5.4 for a visual representation.

Effect of fatigue on frequency decomposed inter-limb synchrony and symmetry

Another ANCOVA was ran to determine the effect of fatigue on post-season frequency decomposed interlimb temporal synchrony balance scores after controlling for pre-season interlimb synchrony scores. There was a poor linear relationship between pre- and post-season ML and AP inter-limb temporal synchrony for each group (none, post, pre, and both) besides the AP pre group which had a moderate linear relationship, as assessed by visual inspection of a scatterplot. There was homogeneity of regression slopes as the interaction term was not statistically significant for the temporal synchrony measures in the ML high, F(3, 79) = 0.221, p = 0.881, and ML low, F(3, 79) = 0.578, p = 0.631, and AP high, F(3, 79) = 2.673, p = 0.053, and low measures, F(3, 79) = 0.151, p = 0.929. Standardized residuals for high- and low-frequency temporal measures in the ML and AP direction for the none and both fatigue groups were normally distributed (p > .05), however the AP and ML high-frequency scores of the pre fatigue group were not normally distributed, and the AP and ML low-frequency scores of the post-fatigue group as assessed by Shapiro-Wilk's test (p < .05). There was homoscedasticity and homogeneity of variances, as assessed by visual inspection of a scatterplot and Levene's test of homogeneity of variance in the ML high (p = 0.415), ML low (p = 0.353), AP high (p = 0.676), and AP low (p = 0.686) for temporal measures. There were no outliers in the data for both ML and AP interlimb synchrony, as assessed by no cases with standardized residuals greater than ±3 standard deviations. After adjustment for pre-season interlimb synchrony scores, there wasn't a statistically significant difference in post-season high-frequency ML ($F(3, 82) = 1.629$, $p = 0.189$) or low-frequency ML ($F(3, 82) = 0.472$, $p = 0.702$) and high- and low-frequency AP inter-limb temporal synchrony (High: $F(3, 82) = 1.109$, $p = 0.350$; Low: $F(3, 82) = 0.417$, $p = 0.741$). A Post hoc analysis was not performed due to the non-significant findings from the ANCOVA. See Table 5.8 for adjusted and unadjusted means. See Figure 5.5 for a visual representation.

Effect of age on frequency decomposed inter-limb synchrony and symmetry

A third ANCOVA was ran to determine the effect of age on post-season interlimb frequency decomposed temporal synchrony balance scores after controlling for pre-season interlimb synchrony scores. There was a poor linear relationship between pre- and post-season ML and AP inter-limb temporal synchrony for each group (13, 14, 15, 16, 17, 18) in both high- and low-frequency domains, as assessed by visual inspection of a scatterplot. There was not homogeneity of regression slopes as the interaction term was not statistically significant for the temporal synchrony measures in the ML direction for high-frequency ($F(1, 56) = 0.933$, $p = .431$), but was for low-frequency ($F(1, 56) = 3.107$, $p = 0.034$). In the AP direction, high- ($F(1, 56) = 1.309$, $p = .281$), and low-frequency ($F(1, 56) = 0.194$, $p = .900$) measures had homogeneity of regression slopes. Standardized residuals for high-frequency temporal measures in the AP and ML direction were normally distributed ($p > .05$) within each age group (12-18), however the high-frequency ML scores for the 13-year-old group were not normally distributed ($p < .05$), as assessed by Shapiro-Wilk's test ($p < .05$). Standardized residuals for low-frequency temporal measures in the AP and ML direction were normally distributed ($p > .05$) within each age group (12-18), except in the AP direction for the 13-, 14-, and 15-year-old groups where they were not ($p < .05$). There was homoscedasticity and homogeneity of variances, as assessed by visual inspection of a scatterplot and Levene's test of homogeneity of variance in the ML high- ($p = .300$), and low-frequency ($p = .112$) measures, and in the AP direction for high- ($p = 0.330$) and low-frequency ($p = 0.063$) temporal measures. There were no outliers in the data for both ML and AP interlimb synchrony, as assessed by no cases with standardized residuals greater than ±3 standard deviations. After adjustment for pre-season interlimb synchrony scores, there was not a statistically significant difference in post-season ML high- ($F(5, 82) = 2.203$, $p = 0.062$) or low-frequency ($F(5, 82) = 0.197$, $p = 0.963$) and frequency decomposed AP inter-limb temporal synchrony (High: $F(5, 82) = 0.875$, $p = 0.501$; Low: $F(5, 82) = 0.125$, $p = 0.986$) between age groups. A Post hoc analysis was not performed due to the non-significant findings from the ANCOVA. See Table 5.9 for adjusted and unadjusted means. See Figure 5.6 for a visual representation.

Table 5.7. Adjusted and Unadjusted Concussion Means and Variability for Post-season Frequency Decomposed Interlimb Temporal Synchrony Measures with Pre-season Interlimb Frequency Decomposed Temporal Synchrony Measures as a Covariate: Analysis for the influence of concussion on balance outcome scores

				Unadjusted		Adjusted	
			N	M	SD	M	SD
High-Frequency	ML	No Concussion	92	-.562	.173	-.561	.163
		Concussion	12	-.579	.116	-.584	.166
	AP	No Concussion	92	.688	.140	.687	.134
		Concussion	12	.742	.071	.749	.135
Low-Frequency	ML	No Concussion	92	-.590	.259	-.590	.269
		Concussion	12	-.569	.299	-.568	.267
	AP	No Concussion	92	.716	.190	.715	.192
		Concussion	12	.653	.236	.661	.197

N = number of participants, M = mean, SD = standard deviation, No concussion = participants who did not sustain a concussion during the season, Concussion = participants who sustained a concussion during the season. Interlimb temporal synchrony and spatial symmetry measures a correlation value between -1 and 1, and therefore does not have a unit of measurement.

Table 5.8. Adjusted and Unadjusted Fatigue Means and Variability for Post-season Frequency Decomposed Interlimb Temporal Synchrony Measures with Pre-season Frequency Decomposed Interlimb Temporal Synchrony Measures as a Covariate: Analysis for the influence of fatigue on balance outcome scores

				Unadjusted		Adjusted	
			N	M	SD	M	SD
High-Frequency	ML	None	26	-.560	.127	-.545	.153
		Post	21	-.578	.171	-.571	.156
		Pre	16	-.633	.215	-.652	.156
		Both	24	-.586	.160	-.598	.152
	AP	None	26	.698	.123	.683	.117
		Post	21	.699	.136	.699	.119
		Pre	16	.750	.153	.745	.120
		Both	24	.706	.106	.725	.122
Low-Frequency	ML	None	25	-.577	.257	-.577	.240
		Post	19	-.611	.292	-.608	.235
		Pre	14	-.569	.205	-.572	.232
		Both	21	-.604	.243	-.650	.229
	AP	None	25	.728	.162	.729	.185
		Post	19	.744	.196	.744	.179
		Pre	14	.687	.196	.688	.176
		Both	21	.716	.187	.695	.179

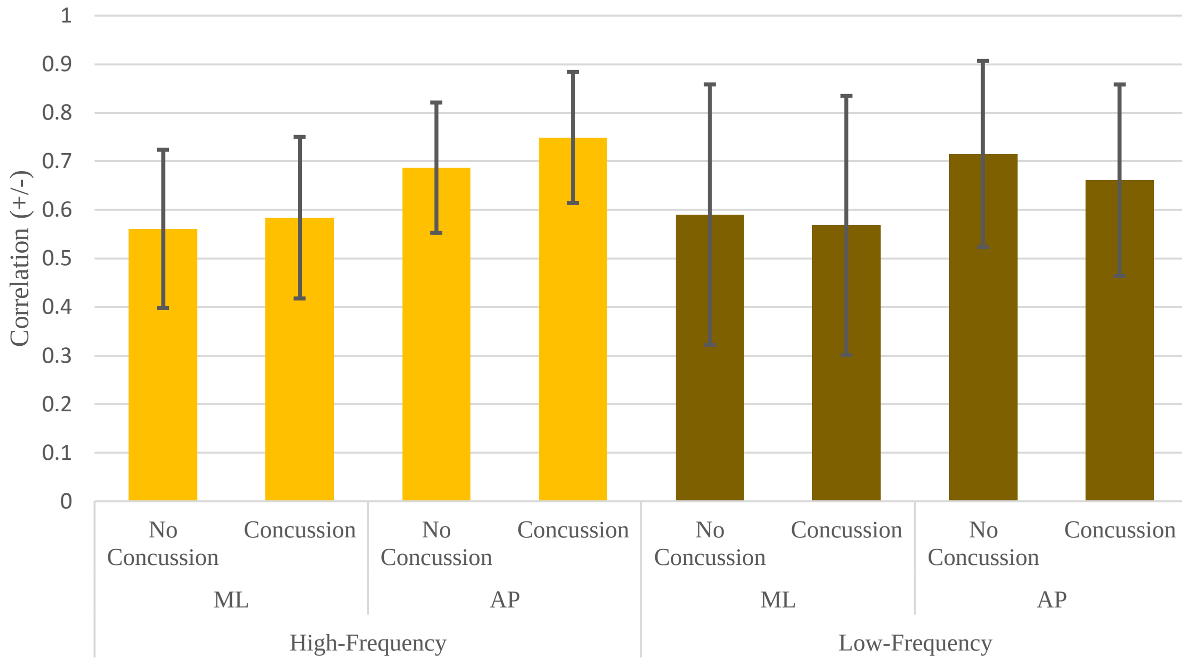
N = number of participants, M = mean, SD = standard deviation, None = participants who were not fatigued at pre- or post-season testing, Post = participants who fatigued at post-season testing but not pre-season, Pre = participants who were fatigued at pre-season testing but not post-season, Both = participants who were fatigued at both pre- and post-season testing. Interlimb temporal synchrony and spatial symmetry measures a correlation value between -1 and 1, and therefore does not have a unit of measurement.

Table 5.9. Adjusted and Unadjusted Age Means and Variability for Post-season Frequency Decomposed Interlimb Temporal Synchrony Measures with Pre-season Interlimb Frequency Decomposed Temporal Synchrony Measures as a Covariate: Analysis for the influence of age on balance outcome scores

				Unadjusted		Adjusted	
			N	M	SD	M	SD
High-Frequency	ML	13	26	-.457	.184	-.537	.255
		14	30	-.558	.149	-.596	.241
		15	19	-.584	.143	-.571	.240
		16	17	-.658	.143	-.632	.247
		17	3	-.580	.037	-.604	.241
		18	1	-.876		-.658	
	AP	13	26	.651	.153	.712	.194
		14	30	.667	.136	.709	.181
		15	19	.701	.092	.708	.179
		16	17	.746	.145	.684	.186
		17	3	.704	.024	.660	.182
		18	1	.911		.768	
Low-Frequency	ML	13	26	-.531	.304	.676	.214
		14	30	-.571	.272	.793	.203
		15	19	-.593	.239	.721	.201
		16	17	-.629	.199	.677	.206
		17	3	-.670	.439	.766	.201
		18	1	-.880		.866	
	AP	13	26	.687	.236	.726	.173
		14	30	.708	.187	.795	.164
		15	19	.732	.167	.726	.166
		16	17	.681	.138	.689	.169
		17	3	.698	.437	.930	.166
		18	1	.869		.996	

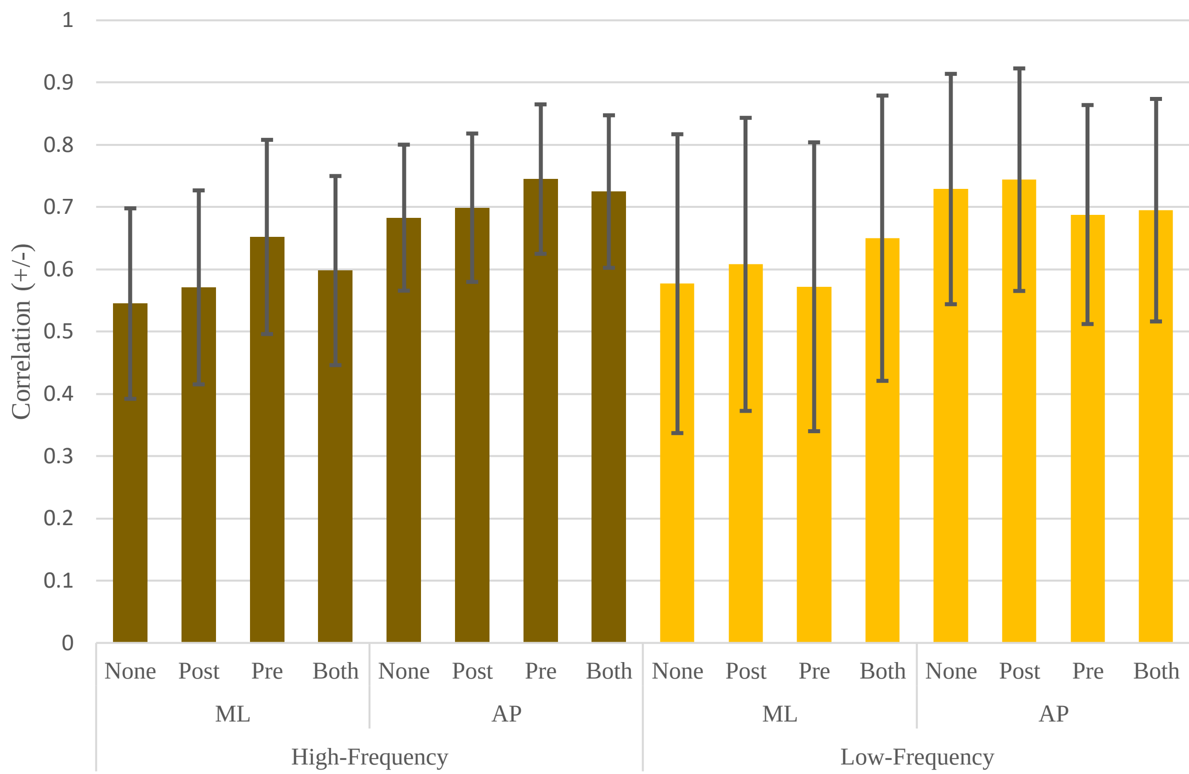
N = number of participants, M = mean, SD = standard deviation. Interlimb temporal synchrony and spatial symmetry measures a correlation value between -1 and 1, and therefore does not have a unit of measurement.

Figure 5.4. Adjusted Concussion Means for Post-season Frequency Decomposed Interlimb Temporal Synchrony Measures: Analysis for the influence of concussion on balance outcome scores



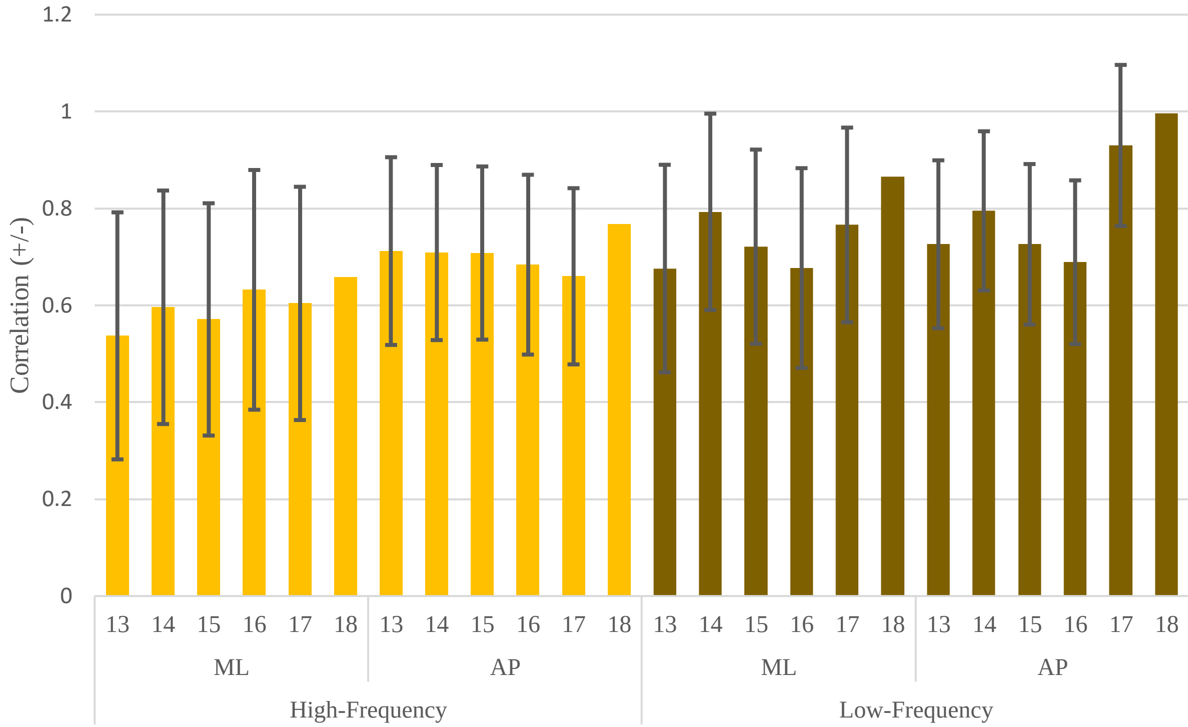
Note. Adjusted mean is graphed with error bars representing ±SD.

Figure 5.5. Adjusted Fatigue Means for Post-season Frequency Decomposed Interlimb Temporal Synchrony Measures: Analysis for the influence of fatigue on balance outcome scores



Note. Adjusted mean is graphed with error bars representing ±SD.

Figure 5.6. Adjusted Age Means for Post-season Frequency Decomposed Interlimb Temporal Synchrony Measures: Analysis for the influence of age on balance outcome scores



Note. Adjusted mean is graphed with error bars representing ±SD.

Table 5.10. Excluded (Outlier) Participant Inter-limb Synchrony and Symmetry Scores

	M	SD
Pre-season ML Inter-limb Temporal Synchrony	-0.886	0.090
Pre-season high-frequency ML Inter-limb Temporal Synchrony	-0.983	0.018
Pre-season low-frequency ML Inter-limb Temporal Synchrony	-0.937	0.056
Pre-season AP Inter-limb Temporal Synchrony	0.621	0.259
Pre-season high-frequency AP Inter-limb Temporal Synchrony	0.739	0.250
Pre-season low-frequency AP Inter-limb Temporal Synchrony	0.653	0.256
Post-season ML Inter-limb Temporal Synchrony	-0.546	0.319
Post-season high-frequency ML Inter-limb Temporal Synchrony	-0.554	0.139
Post-season low-frequency ML Inter-limb Temporal Synchrony	-0.538	0.351
Post-season AP Inter-limb Temporal Synchrony	0.648	0.282
Post-season high-frequency AP Inter-limb Temporal Synchrony	0.671	0.134
Post-season low-frequency AP Inter-limb Temporal Synchrony	0.633	0.319
Pre-season AP Inter-limb Spatial Symmetry	0.759	0.137
Pre-season ML Inter-limb Spatial Symmetry	0.754	0.158
Post-season AP Inter-limb Spatial Symmetry	0.740	0.193
Post-season ML Inter-limb Spatial Symmetry	0.698	0.191

M = mean, SD = standard deviation, SE = standard error. Interlimb temporal synchrony and spatial symmetry measures a correlation value between -1 and 1, and therefore does not have a unit of measurement.

Table 5.11. Mean values for between-limb measures of CoP temporal and spatial symmetry in young male top-level ice hockey players

Measure	Normative Score
ML Inter-limb Temporal Synchrony	-0.758 (0.142)
ML High-Frequency Inter-limb Temporal Synchrony	-0.777 (0.086)
ML Low-Frequency Inter-limb Temporal Synchrony	-0.774 (0.147)
AP Inter-limb Temporal Synchrony	0.713 (0.170)
AP High-Frequency Inter-limb Temporal Synchrony	0.763 (0.050)
AP Low-Frequency Inter-limb Temporal Synchrony	0.123 (0.183)
ML Inter-limb Spatial Symmetry	0.750 (0.158)
AP Inter-limb Spatial Symmetry	0.725 (0.180)

Variables are presented as mean (standard deviation). Interlimb temporal synchrony and spatial symmetry measures a correlation value between -1 and 1, and therefore does not have a unit of measurement.

Chapter 6 : Discussion

The main objective of the proposed research was to determine if newly developed indices of balance control (i.e., interlimb temporal synchronization and spatial symmetry of CoP displacements) can detect changes in balance control brought about by SRC. Based on the findings and after analysis, it can be speculated that concussion does not affect balance control, long term, using in the indices investigated over the time interval observed in the present work. However, these measures may not be sensitive enough to detect changes in CoP signal in long-term SRC follow-up. It was found that SRC did not influence AP or ML measures of temporal synchrony or spatial between-limb symmetry of CoP for young male top-level competitive ice hockey players who were 77.25±27.94 days post-concussion (see Table 5.2). This was also true when looking at frequency decomposed temporal synchrony measures (see Table 5.5). It was hypothesized that athletes who sustained a SRC over the season would show a reduced magnitude of between-limb CoP symmetry and synchrony, which will suggest greater instability then prior to the concussion. Due to the non-significance of our findings ($p > 0.05$), we failed to reject the null hypothesis, and it can be said that SRC has no effect on these measures at this time interval post-concussion. It was also hypothesized that athletes who sustain a SRC will have decreased between-limb synchrony in their higher-frequency components of the CoP signal, indicating impaired reactive control. Once again, due to the non-significance of our findings ($p > 0.05$), the null hypothesis was failed to be rejected, and it can be said that SRC has no effect on frequency decomposed measures, specifically high-frequency components of the CoP signal.

The investigation had five aims. The first was to determine if inter-limb CoP symmetry, synchrony, and time-frequency-based measures of postural control are sensitive to changes in stability control brought about by SRC. As previously mentioned, either the effects of concussion on balance control had dissipated by the time post-season measures were collected, or these measures are not sensitive enough to detect changes in CoP signals long-term following SRC ($p > 0.05$) (see Table 5.2 and 5.5). These findings agree with those of Guskiewicz (2011), Murray et al. (2014), and Powers, Kalmar, and Cinelli (2014), who stated that deficits only last for 3 to 10 days post-SRC. However, they do not agree with the findings from Pan et al. (2015) and Quatman-Yates et al. (2015), who suggest that balance and postural deficits may last months to years. This may be due to multiple factors. In the study by Pan et al. (2015), the findings were in an older population (median age = 26.5 years) of individuals who sustained a concussion during combat. The study by Quatman-Yates et al. (2015) involved younger athletes (13.23±1.28 years), however only those who were referred, “to physical therapy for a postconcussion postural control assessment while under the care of a physician for postconcussion symptoms,” were included in the study (p. 5). This introduces sampling bias into the study. It can be assumed that only athletes who had visually assessed impairments, or who complained of impairments to postural control were referred. The severity of concussion may also affect the ability of these measures to detect concussion/balance deficits. Individuals within the current study were not assessed for severity and there was a considerable timeframe between time of injury and post-season testing. This does not suggest that these variables are or may be sensitive, but represents a limitation of the study design, and may introduce noise/variability into the analyses that may obscure any actual changes post-SRC. It is unknown if all athletes returned to play following their SRC, or what signs and symptoms they reported at the time of injury and during their recovery. Finally, it can be suggested that inter-limb CoP symmetry, synchrony, and time-frequency-based measures of postural control are not sensitive enough to changes in stability control brought about by SRC, and therefore cannot be used in the assessment, management, and return to play decisions associated with SRC.

The second aim was to establish if intra-individual (compare to pre-concussed self) or inter-group comparison (compared to group mean values to determine if they fall outside cut-off value) needs to be used to assess for the effects of SRC on the measures of posture control. This was assessed using an ANCOVA. A repeated measures analysis of variance was not used to assess difference in individuals scores pre- and post-season due to the small sample size of concussed athletes versus non-concussed. It was found that neither comparison had statistically significant findings ($p < 0.05$), therefore it is not possible to determine if intra- or inter-individual comparisons need to be used. Many studies have been able to establish a difference in balance control between concussed and non-concussed groups (Guskiewicz, 2011; Murray et al., 2014; Powers et al., 2014). Majority of the studies found deficits only lasting 3-10 days post-concussion (Guskiewicz, 2011; Murray et al., 2014; Powers et al., 2014). The reason for different findings in this study compared to previous research may be due to methodological or sampling reasons that will be explored further in the limitations section.

The third aim was to provide baseline measures documenting the natural within-subject variation in these indices in the healthy controls for future work. When assessing the RMS CoP displacements and velocities to others in the literature, the displacements are lower than the average, and velocities are higher than the average (see Table 5.3 for values). This is based on a comparison to the graphs presented in Powers et al. (2014). Based on the analysis completed mean values have been established for this specific population in these measures to use in future research looking at this population (See Table 5.1-5.3). Prior results have been separated by concussion status, fatigue status, and age. However, since all findings were non-significant, these groups can be combined, as well, preseason and postseason scores can be combined to find baseline measures. See Table 5.11 for a summary of baseline measures for temporal and spatial between-limb CoP measures. However, there appears to be large within group variability across all age groups (see Table 5.3). This may suggest that these variables may not stabilize until early adulthood, and it may be challenging to disentangle the effects of growth/maturation from concussion even within participants. Future research should look at the large within group variability and finding a way to combat its effect on the statistical analysis – for example, a hierarchical linear growth curve model could fit to the data, which could help account for the within-individual variation. As well, future research assessing interlimb measures immediately post-concussion and throughout the recovery process may assist in disentangling the effects of growth/maturation from concussion.

This leads into the fourth aim, which was to explore if these measures are affected by confounding variables such as fatigue, and age. It was found that measures of temporal synchrony and spatial between-limb symmetry are not affected by fatigue or age, as assessed by an ANCOVA ($p < 0.05$). It was hypothesized that the effect of fatigue, that is associated with sport participation, may influence the testing outcomes as seen with other assessments of balance and postural control post-SRC where deficits last up to 15 minutes (Clifton et al., 2013; Schneiders et al., 2012). Our study showed that fatigue has no significant effect on interlimb temporal synchrony and spatial symmetry measures, which allows us to reject this hypothesis. These findings agree with Morissette et al. (2014), who found that only SCAT3 subjective measures were affected by fatigue due to maximal exercise, and not objective measures within the assessment such as the mBESS. It can be speculated that these measures were not affected by fatigue due to the static nature of the test, participants being able to stand on both feet with eyes open, and the ability of interlimb symmetry and synchrony measures to not be affected by path length or magnitude of the CoP signal. It should be noted that participants who were excluded based on having >20% BW asymmetries were not of a higher proportion from the fatigued group. There were more removed from the non-fatigued group based on this exclusion criteria. This ensures that we have not inadvertently excluded more fatigued individuals from analysis, which could bias the results. This is an impactful finding considering the potential future use of these measures in the population, if it can be established that these measures are sensitive to stability control changes brought about by concussion. Although they may be unable to detect concussion, these measures may be used to assess individuals with other neurological disorders as seen in older adults.

The other confounding variable under consideration within this study was age. It was hypothesized that age would have minimal effect on the measures. Our study found no significant differences between age groups for interlimb temporal synchrony or spatial symmetry measures. These findings oppose those made by Cordingley et al. (2019), who suggest that sport, age, and competition level may need to be taken into consideration when assessing other physiological findings in the same population. However, balance outcome variables may be well-practiced and so there may be a ceiling effect. This may be different than physiological outcome variables that may be influenced by training. This will allow for grouping of age groups in future research within this population using these measures. However, as mentioned previously, there appears to be a reduced within group variability across age groups, which may suggest that these variables may not stabilize until early adulthood.

The fifth and final aim, was to evaluate whether these measures have the potential for the use in the assessment, management, and return to play decisions associated with SRC in adolescents. It was hypothesized that difference would be found between the groups who sustained a SRC versus those who did not sustain a SRC over the course of the ice hockey season. Based on the results of the study, it can be said that interlimb temporal synchrony and spatial symmetry measures cannot be used to assess, manage, or make return to play decisions associated with SRC in long-term follow-up at the current time. All athletes who completed testing had been cleared to return to sport. These findings agree with previous research that states deficits in balance and posture control last anywhere from 3-10 days (Guskiewicz, 2011; Murray et al., 2014; Powers et al., 2014). However, they do not agree with findings that suggest balance and postural deficits may last months to years when using higher-level measures of balance and postural control such as non-linear measures (Pan et al., 2015; Quatman-Yates et al., 2013). The reasons for the findings not agreeing with the original hypothesis will be discussed the next section where limitations are examined.

Limitations

The following sections will examine and discuss the limitations of the study. These limitations may have contributed to the lack of significance when looking at the primary outcome of whether SRC influences interlimb temporal synchrony and spatial symmetry measures. Limitations to the study include study design, concussion diagnosis, and data collection methods used.

Study design

The first major limitation was study design. When the study was initially formulated, the intention was to have ongoing communication with study participants, such that they could be tested as soon as possible to the occurrence of concussion. Over time, it became evident that this study design was not possible and, as such, the final study design was a modified nonequivalent pretest-posttest control group design. Participants were collected via a convenience sample. Data as collected at two time points that were approximately equally spaced distance apart for all participants. For data analysis, the single group from the pre-season time point was divided in the post-season based on concussion status. Concussion status involved whether an individual sustained a SRC between the two data collection time points – the occurrence of concussion and the date at which the concussion was sustained were self-reported by the participant. In addition to the inaccuracy of self-reported concussion data, an additional limitation of this study design is its threat to the interaction of selection with history and maturation on interval validity (Portney & Watkins, 2015). The selection of the study design has its limitations when assessing the primary outcome. Based on previous research showing balance and postural control deficits may only last 3-10 days following a SRC, it would be beneficial to collect balance measures closer to the time of injury and follow the participant along at regular time intervals to monitor recovery (Guskiewicz, 2011; Murray et al., 2014; Powers et al., 2014). (McCrea et al., 2005), collected data at preseason baseline testing, then immediately following the SRC, 3 hours post-SRC, and 1, 2, 3, 5, and 7 days post-SRC. A data collection timeline like this would be beneficial in establishing if the measures are sensitive to concussion and, if so, when deficits in between-limb measures of CoP symmetry and synchrony cease to exist. Another time point of interest may be when an athlete gets clearance to RTP by a physician. This would assist in determining if athletes scores had returned to baseline, or if they still showed deficits when they RTP.

Concussion diagnosis

Another limitation of the study was how the diagnosis of a concussion was reported. Participants self-reported on an injury survey whether they sustained a concussion over the course of the season during the post-season data collection time point. This creates uncertainty in the number of concussions that were reported within the group. First, a definition was not provided to participants which allows for ambiguity in the definition of a concussion. As mentioned previously, what a concussion or SRC is defined as has changed over the years. Finally, also mentioned previously is the underreporting of SRC. Due to under-reporting, and the barriers associated with it, there may be many participants who sustained a concussion over the season but failed to report it.

Data collection methods

Another limitation of the study may be the differing data collection methods used at the pre- and post-season time points. First, there was different force platforms used for the collection of CoP measures. Although both sets of force platforms are sensitive enough to detect changes in CoP, they did not collect raw data at the same frequency or have the same outputs. Data collected at the post-season time point, needed to be down sampled from 200 Hz to 128 Hz to match pre-season data. This should not have an effect as both are above the Nyquist frequency. Post-season CoP locations were also calculated from forces and moments in post-processing in MatLab, as CoP location was not a part of the data exported from the AMTI software. Nevertheless, the calculation used to determine the CoP location is the same as the one used for pre-season data in the Kistler Bioware software. The use of different force platforms may contribute to difference in scores between the pre-and post-season, but this is unlikely. Second, the investigator was present for all pre-season data collection, but was only present for half of the post-season data collection. Detailed notes regarding data collection/force platform use, and participant set-up/instructions were given to the other assessors, however, little training or familiarization period was given. This can affect the rater reliability of measures (Portney & Watkins, 2015). During the processing of the post-season data there was a significant amount of movement during trials among many participants. In the exclusion process, the weight symmetry threshold was set at 20% of body weight, however this is still a significant amount of ML movement. It is common to see less than 5% variation in between limb weight distribution in quiet standing trials. This may have contributed a large amount of noise in the data and a reduced ability to distill anything from the results. Moreover, individuals were excluded from analysis on a listwise basis, a considerable reduction in the sample size resulted.

Future Directions

Though not supported by the present data, the application of spatial symmetry and temporal between-limb CoP synchrony in an acute SRC population may assist in the identification and monitoring of balance and postural control deficits. As mentioned previously, it has been shown that deficits in balance may only last for 3-10 days, however due to these measures being sensitive to proactive and reactive balance control, they may be able to detect deficits for longer, even after RTP clearance has been given to the athlete. The application of the measures in the players who are experiencing vestibulocular deficits post-concussion may be of greater value, as we know not all concussion present with the same symptomology. These measures may also be applied to other populations to determine if these findings are consistent across sports, sexes, and age groups. The measures may also be used with other pathologies, or to assist in the assessment of balance control training.

In the future, accessibility of measures studied could be done using the Nintendo Wii Balance Board (Nintendo of America, Inc., Redmond, WA). Reliable measures of CoP for quiet stance have been shown to be obtainable when compared to laboratory grade force plates from the board (Murray et al., 2014; Quatman-Yates et al., 2013). Using technology such as this, with user friendly software, may lead to the practicality of force plate measures outside the laboratory or clinical setting.

Chapter 7 : Conclusion

The effects of concussion on inter-limb synchrony and symmetry were not statistically significant and had either dissipated by the time post-season measures were collected, or these measures are not sensitive enough to detect changes in CoP signals long-term following. However, it was found that fatigue and age had little effect of inter-limb synchrony and symmetry. This finding is important as it shows these measures can be used immediately following sport, and do not need to be compared to means in players of the same age but can be compared to the mean of the entire population. These measures may be useful in studying athletes with vestibulocular deficiencies post-concussion, in athletes with other pathologies, or to assist in the assessment of balance control training.

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