The Use of Linear and Nonlinear Methods for Evaluating Balance on Collegiate Men's and Women's Ice Hockey Teams Throughout a Season

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Abstract

Participants in ice hockey have a great chance for injury since the sport incorporates physically aggressive play with high speeds of action. Balance assessment, whether through the use of a force plate or a clinical balance test, is useful in identifying impairments resulting from sport injuries and when the athlete is able to return-to-play. If objective data from balance assessments are to be used in assessing player's for returning to play, then it is also necessary to understand the in-season variability that can occur in these data. The linear dynamics framework has contributed to the development of commonly employed clinical measures of postural control, where postural stability is a focus (Cavanaugh et al., 2005). Nonlinear approaches can be used to evaluate either dynamic stability or complexity in the center of pressure time-series. Therefore, the purpose of this work was to determine if the time evolving nature of these measures can reveal new insights over the course of a full ice hockey season such that more effective return-to-play guidelines can be established.

Twenty-two men and Twenty-four women from their respective varsity ice hockey teams participated in this study during the 2014-2015 season. After two games into the regular season, all participants underwent baseline measurements using a ground mounted force platform and performed an upright standing test in 5 different conditions (eyes open, eyes closed, eyes closed/arms out, right leg up, and left leg up), each 120 s in duration, in a random order. In addition to baseline, participants were tested every 4 weeks throughout the season, plus one post-season session. Dependent linear (mean power frequency, mean velocity, and total excursion) and nonlinear (approximate entropy) measures were used to interpret force plate data.

Linear and nonlinear measures both showed significant main effects of time. Similar trends were demonstrated across most dependent measures. Monthly testing throughout the season demonstrated decreases in mean values for all measures with respect to baseline. The greatest decrease from baseline was: approximate entropy, eyes closed, baseline to fourth (0.219au, 68% decrease); mean power frequency, eyes open, baseline to third (0.096Hz, 77% decrease); mean velocity, eyes closed, baseline to post (0.006m/s, 67% decrease); total excursion, eyes closed, baseline to post (0.389m, 64% decrease). Regardless of the measure, or the standing condition, following the greatest decrease from baseline (at some subsequent point in the season testing) most conditions had a session with less of a decrease from baseline, representing a gradual increase (reflection) back towards baseline values. Post sessions for approximate entropy and mean power frequency had the smallest decreases from baseline (0.122au, eyes open trial; 0.057Hz, eyes closed/arms out trial, respectively) where third to baseline represented the smallest decrease from baseline for mean velocity and total excursion (0.004m/s, eyes closed trial; 0.287m, eyes closed trial, respectively). Mean velocity and total excursion (eyes closed arms out) trials and mean velocity (eyes open) trials were the only measures that did not demonstrate a session that appeared to return towards baseline values (less of a decrease from

baseline). Moreover, post-season sessions revealed that for all measures, participants never completely returned to initial baseline measures.

Balance training and adaptation along with accumulation of sub-concussive forces may have played a role in the pattern seen between linear and nonlinear measures over the course of a regular ice hockey season. The linear and nonlinear measures followed similar patterns through the course of the season, indicating that they can display similar patterns when measuring changes together over time. In-season variability of balance postures, recorded by these measures, can be used when comparing concussed athlete's baseline measures to their post-concussion measures. This will aid in assessing the appropriate time for an athlete to return-to-play.

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Statement of Originality

I hereby declare that this thesis is, to the best of my knowledge, original, except as acknowledged in the text, and that material has not been previously submitted either in whole or in part, for a degree at this or any other university and institution.

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Chapter 1: Introduction

Concussions are common in contact sports such as ice hockey (Helmer et al., 2014), yet are prevalent in all sports with the highest incidence found in football, hockey, rugby, soccer and basketball (Marar et al., 2012; Harmon et al., 2013). Particular attention has been focused on the criteria used to determine when an athlete who sustained a concussion is fully recovered and ready to resume play (Cavanaugh et al., 2005). Studies published using force plate technology and clinical balance tests (e.g. Balance Error Scoring System (BESS)), have identified postural stability deficits following sport-related concussions (McCroy et al., 2008). Balance is often affected by a concussion and should be evaluated when a concussion is suspected (Harmon et al., 2013). Balance assessment has been recommended as a primary measurement tool for monitoring recovery and for making return-to-play (RTP) decisions (Cripps and Livingston, 2013). While standardised sideline tests are a useful framework for examination, the sensitivity, specificity, validity and reliability of these tests among different age groups, cultural groups and settings is largely undefined (Harmon et al., 2013). Their practical usefulness with or without an individual baseline test is also largely unknown. Balance disturbance is a specific indicator of a concussion, but not very sensitive (Harmon et al., 2013).

"Postural steadiness" is a special case of "postural stability" which characterizes the ability to stand as motionless as possible (Goldie et al., 1989), through the dynamics of the postural control system associated with maintaining balance during quiet standing (Prieto et al., 1996). Postural stability has also been described as the ability to maintain a desired postural orientation in response to perturbations generated from either internal or external sources

(Cavanaugh et al., 2006). Cardiovascular function, and peristalsis are examples of internal integrated movements that create perturbations (Cavanaugh et al., 2006), with external perturbations resulting from the environment such as impacts from objects or wind resistance, which could affect static and dynamic postures. Control of integrated movements are likely distributed throughout many interacting systems working cooperatively (Bernstein, 1967). Predictive models of postural control systems output have evolved from both linear and nonlinear dynamics frameworks (Cavanaugh et al., 2005). Linear dynamic modeling is based on a stimulus-response, where a system output can be predicted from nonlinear equations. With this, the output of the entire system represents the summed output of local interactions (Onaral et al., 1995). Conventional linear statistics include range/distance, standard deviation and coefficient of variation. These are used to measure variability, providing information about the quantity (magnitude) of a signal from a given movement, not yielding the time-evolving nature of a signal (Rosenstein et al., 1993).

Fields studying movement generation, including robotics, psychology, cognitive science, and neuroscience utilize concepts and tools related to the pervasiveness of variability in biological systems (Stergiou and Decker, 2011). The nonlinear framework supports the idea that postural control emerges through the interactions of individual physiological systems, task demands and environmental constraints (Glass and Mackey, 1988; Riccio et al., 1988; Shumway-Cook, et al., 1995; Slobounov, et al., 1996), yielding estimates on the complexity of the system within one series of calculations (Rosenstein et al., 1993). The concept of variability and the measures for nonlinear dynamics used to evaluate this concept opens new vistas for research in movement dysfunction of many types (Stergiou and Decker, 2011). Variability itself

has a particular organization and is characterized by a chaotic structure (Stergiou and Decker, 2011). Deviations from this organized chaotic structure can lead to biological systems that are either overly rigid and robotic or noisy and unstable (Stergiou and Decker, 2011).

Linear and nonlinear measures can both be utilized to observe trends in centre of pressure (COP) through standing balance postures, over time In-season tracking of the change in balance postures through a regular ice hockey season, is lacking in current literature. Knowing how balance postures change in-season provides another objective measure to compare baseline tests with once an athlete has been concussed, aiding in return-to-play.

1.1 Purpose

The purpose of this study was to evaluate the time evolving nature of COP (measured at regular intervals throughout a hockey season) for both linear and nonlinear measures on healthy male and female hockey players.

1.2 Hypothesis

Summary metrics from linear and nonlinear measurements derived from centre of pressure balance testing throughout the course of a season will vary, making distinctions between the metrics evident.

Chapter 2: Literature Review

2.1 Head Injury Biomechanics

Sudden head motions can occur when the head is struck, when the head strikes a surface, or even indirectly when the body is suddenly displaced (Guskiewicz and Mihalik, 2006; Meaney and Smith, 2011). Biomechanical mechanisms of head injury can be divided into two categories: those related to head-contact injuries and those related to head-movement injuries (Guskiewicz and Mihalik, 2006). Two broad categories of forces—contact and inertial—encompass the important causal forces associated with TBIs (Guskiewicz and Mihalik, 2006; Meany and Smith, 2011). Understanding the biomechanics of sport-related concussion involves consideration of many factors but none more than that of acceleration and deceleration of the brain (Guskiewicz and Mihalik, 2006). There is considerable evidence showing that the primary cause of concussive injuries is movement or impact of the brain, caused by sudden violent head accelerations (Guskiewicz and Mihalik, 2006). Head impacts may cause rotational, shearing or compressive forces that act on the brain (Bigler et al., 1993). With the head/neck motions that occur during a typical impact, there are two components of acceleration that occur in nearly every instance of concussion — linear (or translational acceleration or deceleration) and rotational (or angular acceleration or deceleration) (Meaney and Smith, 2011). Linear or translational impacts in sport are seen as a direct blow to the face/head with rotation occurring when the head accelerates around its axis of rotation (Guskiewicz and Mihalik, 2006). Angular acceleration is common during either impact or impulsive head loading, with brain tissue deforming more readily in response to shear forces (Meaney and Smith, 2011). If the head motion is constrained to exclude any rotational motion, it is difficult to produce traumatic

unconsciousness (Meaney and Smith, 2011) with rotational movement's very likely leading to concussions (Guskiewicz and Mihalik, 2006). Experimental data shows the effect of rotational acceleration direction on the corresponding impairment, with lateral (coronal) plane accelerations in humans being the most likely for producing damage within the deep internal structures of the brain (Gennarelli et al., 1982; Meaney and Smith, 2011). Although it is possible to generate similar impairments with rotational motions along the horizontal and sagittal planes (Meaney and Smith, 2011).

It has been proposed that reducing an individual's head impact exposure is a practical approach for reducing the risk of brain injuries (Crisco and Greenwald, 2011; Wilcox et al., 2014b). With sport activities, falls produce the highest linear and angular acceleration, followed by ball and high-velocity stick impacts (Clark and Hoshizaki, 2016). Low-velocity stick impacts were found to produce the lowest linear and angular accelerations (Clark and Hoshizaki, 2016). Studying different impact mechanisms that occur in ice hockey, head impacts were classified into 8 categories: contact with another player; the ice, boards or glass, stick, puck, or goal; indirect contact; and contact from celebrating (Wilcox et al., 2014b). For men and women, contact with another player was the most frequent impact mechanism, and contact with the ice generated the greatest magnitude of peak rotational head accelerations (Wilcox et al., 2014b). Impacts of greater magnitude are more associated with concussion risk, and male hockey players are found to sustain head impacts that result in greater acceleration magnitudes than females (Dick, 2009; Beckwith et al., 2013). Wilcox et al. (2015) found that peak rotational accelerations are comparable in males and females and Elliot et al. (2015) echoed this when they found

strengthened relationship between rotational acceleration and injury risk, in concussion risk curves, in contact sports.

The common belief among users is that helmets protect the whole head, including the brain. However, current consensus among biomechanists and sports neurologists indicates that helmets do not provide significant protection against brain injuries (cerebral hemorrhages, concussion) (Karton et al., 2014; Lloyd and Conidi; 2015) since helmets may not be as effective at managing rotational acceleration (Karton et al., 2014). Men's lacrosse helmets significantly decreased linear and angular accelerations in all conditions, while unhelmeted impacts were associated with high accelerations (Clark and Hoshizaki, 2016). With or without helmets, an athlete is thought to reduce head acceleration after impact by contracting the cervical musculature, stiffening the joints and dampening the magnitude of head acceleration (Schmidt et al., 2014). Greater neck strength and activating the neck muscles to brace for impact are both thought to reduce an athlete's risk of concussion by attenuating the head's kinematic response after impact (Eckner et al., 2014). In a recent study, 49 high school and collegiate American football players completed a preseason cervical testing protocol that included measures of cervical isometric strength, muscle size, and response to cervical perturbation (Schmidt et al., 2014). Players with greater cervical stiffness had reduced odds of sustaining both moderate and severe head impacts compared with players with less cervical stiffness. However, the findings did not show that players with stronger and larger neck muscles mitigate head impact severity (Schmidt et al., 2014). Alternatively, Eckner et al. (2014) demonstrated in male and female contact athletes across an age spectrum (8-30 years of age), greater neck strength and anticipatory cervical muscle activation ("bracing for impact") can reduce the magnitude of the

head's kinematic response to an impact. This study also demonstrated an inverse relationship between neck strength and acceleration, which presented a moderately strong effect sizes (Eckner et al., 2014).

Hugenholtz and Richard (1982) reported that concussions can result from a blow to the head during linear accelerations 80 to 90 times the force of gravity for more than 4 milliseconds. The helmets of 335 football players were instrumented with accelerometers to measure head acceleration following head impacts during play (Rowson et al., 2012). The average sub-concussive impact (i.e. averages of forces that were not recorded in concussive impacts that resulted in diagnosed concussions) had a rotational acceleration of 1230 rad/s² and a rotational velocity of 5.5 rad/s, while the average concussive impact had a rotational acceleration of 5022 rad/s² and a rotational velocity of 22.3 rad/s (Rowson et al., 2012). Similar results were found by Brainard et al. (2012) using NCAA varsity ice hockey teams. The authors found that males were 1.9 times more likely to sustain an impact with a peak rotational acceleration greater than 5000 rad/sec². Studying the total number of daily head impacts sustained in NCAA ice hockey players, Wilcox et al. (2014a) found impacts to the side and back of the head were associated with the greatest peak rotational accelerations (males: 4256 rad/sec², females: 3784 rad/sec²). Additionally, female hockey players experienced a significantly lower number of impacts than males (females = 1.7 ± 0.7, males = 2.9 ± 1.2) (Wilcox et al., 2014a). The frequency of impacts by location was the same between genders for all locations except the right side of the head, where males received fewer impacts than females (Wilcox et al., 2014a). From their data, Rowson et al. (2012) developed an injury risk curve with a nominal injury value of 6383 rad/s², which represents a 50% risk of concussion. To maximize protection against head and brain

injuries for football players of all ages, Lloyd and Conidi (2015) proposed a threshold for all sports helmets based on a peak angular acceleration not exceeding 1700 rad/sec².

2.2 Physiological Measures & Psychological Burdens of Concussion

Concussion is a clinical diagnosis often depending on self-reporting, with no established biological marker or consistent symptoms/definitions (Dick, 2009). White matter microstructure evaluation using MR diffusion tensor imaging (DTI) has been an emerging technique used to more accurately identify mTBI's, by assessing brain white matter integrity following head injuries in ice hockey players (McAllister et al., 2011; Koerte et al., 2012; Sasaki et al., 2014) . There has been interest in using MRI diffusion imaging to provide information about the anatomical connectivity in the brain. By measuring the anisotropic (a property of being directionally dependent as opposed to directionally independent; diffusivity in all directions) diffusion of water in white matter tracts, with fractional anisotropy (FA) being one of the most commonly derived measures from diffusion data (Smith et al., 2006). FA and other diffusivity measures (axial diffusivity AD; radial diffusivity – RD), quantifies how strongly directional local brain tract structures are in one direction. Tract-Based Spatial Statistics (TBSS) is an approach used to improve the sensitivity, objectivity and interpretability of analysis of multi-subject diffusion imaging studies by aligning FA and other diffusivity measures properly, from multiple subjects (Smith et al., 2006). Ice hockey players with a history of clinically symptomatic concussion had their white matter microstructure compared to players without a history of concussion (McAllister et al., 2011; Sasaki et al., 2014). TBSS was used to test for group differences in FA, AD, RD, and the measure "trace," or mean diffusivity of water (McAllister et

al., 2011; Koerte et al., 2012; Sasaki et al., 2014). TBSS revealed a significant increase in FA and AD, and a significant decrease in RD and trace in several brain regions in the concussed group, compared with the non-concussed group (Sasaki et al., 2014). Results were similar in Koerte et al. (2012) where, compared with preseason data on ice hockey players, postseason images showed higher trace, AD, and RD values in the right pre-central region, the right corona radiata, and the anterior and posterior limb of the internal capsule. However, in Sasaki et al. (2014), the increased AD was observed in a small area in the left corona radiata. The regions with increased FA and decreased RD and trace included the right posterior limb of the internal capsule, the right corona radiata, and the right temporal lobe (Sasaki et al., 2014). No significant differences were observed between preseason and postseason for FA in the Koerte et al. (2012) study and post-season FA demonstrated a decrease in the amygdala in McAllister et al. (2011). There was a significant athlete-group (contact verse non-contact athletes) difference for mean diffusivity (MD) in the corpus callosum (McAllister et al., 2011). Interestingly, the DTI measures correlated with neither the ImPACT (Immediate Postconcussion Assessment and Cognitive Test) nor the SCAT2 (Sport Concussion Assessment Tool-2) scores (Sasaki et al., 2014). Increased FA based on decreased RD may reflect neuroinflammatory or neuroplastic processes of the brain responding to brain trauma (McAllister et al., 2011; Koerte et al., 2012; Sasaki et al., 2014). This led authors to conclude that the results of the current studies indicate that a history of concussion may result in physiological alterations of the brain's white matter microstructure in ice hockey players (McAllister et al., 2011; Koerte et al., 2012; Sasaki et al., 2014). Some authors did not indicate how many concussions would have to be suffered to lead to these changes or if these changes are reversible, following RTP guidelines with other forms of rehabilitation and training (Koerte et al., 2012; Sasaki et al., 2014). However, McAllister et al.

(2011) suggest a relationship between head impact exposure, white matter diffusion measures, and cognition over the course of a single season, even in the absence of diagnosed concussion, in a cohort of college athletes. Currently, there is no literature that investigates white matter changes (WMC) with DTI and postural stability alterations that result from concussions related to sports.

Other changes in brain tissue can be present with concussions. Cerebral microbleeds (CMBs), which appear as small, hypointense lesions on T2*-weighted images, can result from TBIs (Helmer et al., 2014). Helmer et al. (2014) studied 45 university-level adult male and female ice hockey players before and after a single Canadian Interuniversity Sports (CIS) season. A statistically significant increase in the hypointensity was observed for male subjects with concussions at the 2-week postconcussion time point, whereas a smaller, nonsignificant rise for female subjects with concussions was also observed within the same time period (Helmer et al., 2014). A gender difference in the peak burden of CMBs 2 week post-injury provides a tentative window of examine and possible physiological measure of diagnosis (Helmer et al., 2014). Multiple sustained sub-concussive events effects on the development and progression of CMBs was not examined. Neurometabolic changes in brain tissue could also result from concussions. Chamard et al. (2012) evaluated the effects that repetitive concussive and sub-concussive head impacts have on the neurometabolic ratio concentrations of glutamate/creatine-phosphocreatine (Cr), myoinositol/Cr, and N-acetylaspartate (NAA)/Cr in 25 men and 20 women CIS hockey players. Individuals sustaining a medically diagnosed concussion were sent for MRI at 72 hours, 2 weeks, and 2 months after injury (Chamard et al., 2012). No statistically significant longitudinal metabolic changes were observed among athletes who were diagnosed with a

concussion, however, results did demonstrated a predictable pattern of initial impairment, followed by a gradual return to ratios that were similar to, but lower than, baseline ratios (Chamard et al., 2012). Authors explain the few significant differences demonstrated between players who were diagnosed with a concussion and players who were not diagnosed with a concussion might be better described as a subgroup of the players who may have sustained a concussion but were not observed and diagnosed with a concussion (Chamard et al., 2012). To date there has been no published research into CMBs that result from concussions with associated balance alterations. The lack of associations of CMB with postural stability may be because of either a lack of sufficient number of lesions in locations important for balance (such as the cerebellum and subcortical structures) or alternatively because of insufficient sample power (Choi, et al, 2012). Nonetheless, speaking for a geriatric population, a person with brain infarcts or CMBs would be more likely to demonstrate gait difficulty or postural instability than a person without these lesions (Choi et al., 2012). Cerebrovascular lesions may also be directly associated with brain atrophy, which may have secondary effects on gait and balance (Choi, et al., 2012).

There has been some published research on speculated physiological measures of concussion (Stalnacke et al., 2003; Schneider et al., 2014; Shahim et al., 2014). Cervical musculature endurance and strength was evaluated as a risk factor for concussion in elite youth ice hockey players (Schneider et al., 2014). Researchers concluded that clinical tests of cervical flexor endurance and isometric cervical strength were not predictive of concussion risk. Physiological biomarkers have been shown to be more promising in identifying concussions, such as serum concentrations of the biochemical markers of brain damage S-100 (calcium

binding protein) B, neuron-specific enolase (NSE) (Stalnacke et al. 2003; Shahim et al., 2014) and total tau, which are proteins that stabilize microtubules in neurons of the central nervous system and nervous system pathologies are associated with defective tau proteins (Shahim et al., 2014). During competitive games of the Swedish Elite Ice Hockey League and the Swedish Elite Basketball League, S-100B was released into the blood of the players as a consequence of game-related activities (acceleration/deceleration events) (Stalnacke et al., 2003). Analysis of S-100B seems to have the potential of becoming a valuable additional tool for assessment of the degree of brain tissue damage in sport-related head trauma (Stalnacke et al., 2003). A similar study design with the professional Swedish ice hockey league, Shahim et al. (2014) came to a similar finding when researchers tested 28 players who suffered concussions and underwent repeated blood sampling at 1, 12, 36, and 144 hours and when the player's returned-to-play. Total tau, S-100B, and neuron-specific enolase concentrations in plasma and serum were measured (Shahim et al., 2014). Authors found that concussed players had increased levels of the axonal injury biomarker total tau and levels of the astroglial injury biomarker S-100B in players with sports-related concussion compared with preseason values. The highest biomarker concentrations of total tau and S-100B were measured immediately after a concussion, and they decreased during rehabilitation (Shahim et al, 2014). No significant changes were detected in the levels of neuron-specific enolase from preseason values to postconcussion values. These studies indicate that sports-related concussion in professional ice hockey players is associated with acute axonal and astroglial injury and that this can be monitored using blood biomarkers (Stalnacke et al., 2003; Shahim et al., 2014). In these studies, as previous studies discussed (Chamard et al., 2012; Helmer et al., 2014), the effects of sub-concussive events on the release and interaction of these markers is not known. Simple game play without any direct head contact could cause release or

increased activity of various cerebral markers. There is nothing in the current literature linking these markers (S-100B, NSE) specifically with changes in balance, that result from minor head injuries or concussions.

There is growing evidence of the psychological ramifications from concussions, such as depression and suicide (Chrisman and Richardson, 2003; Simpson and Tate, 2007). Chrisman and Richardson (2013) focused on analyzing the association between previous concussion and current depression diagnosis in a large nationally representative adolescent data set. A retrospective cohort study was implemented, using the National Survey of Children's Health 2007-2008, a nationally representative survey conducted via random digit dialing (Chrisman and Richardson, 2013). Data were obtained by parental report and included youth 12-17 years old without a current concussion (N = 36,060), and evaluated the association between previous concussion and current depression diagnosis using multiple logistic regression to control for age, sex, parental mental health, and socioeconomic status (Chrisman and Richardson, 2013). After controlling for age, sex, parental mental health, and socioeconomic status, history of concussion was associated with a 3.3-fold greater risk for depression diagnosis (Chrisman and Richardson, 2013). Sex was not significantly related to depression diagnosis. It is not known how many of the adolescences involved in study suffered concussions during sporting activities. Through a systematic literature search that addressed suicidality after traumatic brain injury (TBI) found that people with TBI have an increased risk of death by suicide (3-4 times greater than for the general population), as well as significantly higher levels of suicide attempts and suicide ideation (Simpson and Tate, 2007). Clinical studies have also reported high levels of suicide attempts (18%) and clinically significant suicide ideation (21-22%) in TBI samples (Simpson and Tate,

2007). It should be noted that the authors did not differentiate the rates by gender, age or relate the findings to specific causes of TBIs, such as sport related. Furthermore, at present, there are no studies linking depression (as a result of concussion or mTBI) with balance or postural control alterations.

2.3 Return-to-play (RTP)

Graded symptom checklists provide an objective tool for assessing a variety of symptoms related to concussions, while also tracking the severity of those symptoms (Harmon et al., 2013). According to the American Medical Society for Sports Medicine, concussion symptoms should be resolved before returning to exercise, with standardised assessment tools providing a helpful structure for the evaluation of concussion (Harmon et al., 2013). Sideline, baseline, and post-concussion assessments have become prevalent in documenting pre-injury and post-injury performance, tracking recovery rates, and assisting RTP decisions (McKeever and Schatz, 2003). Neuropsychological (NP) tests are an objective measure of brain-behaviour relationships and are more sensitive for subtle cognitive impairment than a clinical exam (Harmon et al., 2013). Various forms to administer neuropsychological tests via pencil and paper assessment forms (Echemendia et al., 2001) and through computerized test metrics (Brown et al. 2007). Higher neuropsychological scores with computerized testing reflect increased speed and accuracy of responses, indicating less cognitive impairment (Brown et al., 2007). neuropsychological tests appear to be more effective than subjective report of symptoms in differentiating between injured and non-injured athletes at 48 hours post-injury (Echemendia et

al., 2001). However, a battery of tests, rather than any single test, is necessary to capture the variability that exists among injured athletes (Echemendia et al., 2001).

Neurocognitive recovery following sport-related concussion is important for re-injury risk reduction and in elite youth hockey, it is unknown if neurocognitive function returns to baseline values at the time of medical clearance to RTP (Taylor et al., 2014). The Sport Concussion Assessment Tool (SCAT) is a commonly used paper neurocognitive tool for assessing concussion (Schneider et al., 2010). The SCAT2, which evolved from the 2008 Concussion in Sport Group (CISG) Consensus meeting, has been widely used internationally for the past 4 years (Guskiewicz et al., 2013). The 2012 CISG Consensus Meeting provided an opportunity for several of the world's leading concussion researchers and clinicians to present data and to share experiences using the SCAT2 to consider recommendations and to review the current literature, identifying the most sensitive and reliable concussion assessment components for inclusion in a revised version—the SCAT3 (Guskiewicz et al., 2013). Baseline symptoms and neurocognitive norms for non-concussed and previously concussed varsity athletes using the SCAT has been evaluated (Shehata et al., 2009). The five most frequently reported symptoms for all athletes were fatigue/low energy (37% of subjects), drowsiness (23%), neck pain (20%), difficulty concentrating (18%) and difficulty remembering (18%) (Shehata et al., 2009).

A RTP progression plan for concussed athletes involves a gradual, step-wise increase in physical demands and sport-specific activities (Harmon et al., 2013), with a gradual RTP being implemented once concussion symptoms subside. The primary concern with early RTP of an athlete is decreased reaction time, persisting cognitive and postural dysfunctions, which all pose

an increased risk of a repeat concussion (i.e. Second Impact Syndrome) and prolongation of symptoms (Harmon et al., 2013). Some currently utilized assessment tools for concussions have not been proven to be successful in RTP (Johnson et al., 2002). Test-retest reliability of ImPACT (a neurocognitive computerized assessment tool) in professional ice hockey players may not be sensitive (Bruce et al., 2014). A 1-year test-retest reliability on 305 professional ice hockey players indicated that the reliabilities for the Visual Motor and Reaction Time Composites ranged from low to high (.52 to .81), while the reliabilities for the Verbal and Visual Memory Composites were low (.22 to .58) (Bruce et al., 2014). Results provided mixed support for the use of Visual Motor and Reaction Time Composites, indicating the ImPACT may not be sensitive to clinical change (Bruce et al., 2014). Utilizing a prospective case study, concussed elite male and female youth (13-17 years) ice hockey players (n=68) and healthy controls (n=22) completed ImPACT and SCAT2 (Sport Concussion Assessment Tool-2) testing at baseline and RTP following concussion (Taylor et al., 2014). In the study cohort, approximately 25% of concussed players who were cleared to return to hockey had 1 composite score that had not yet returned to baseline (Taylor et al., 2014). Although the instrument is considered very practical and moderately effective for use by clinicians who manage concussion, the utility and sensitivity of a 100-point scoring system for the SCAT2 has been questioned (Guskiewicz et al., 2013). In addition to this, normative SCAT3 values in adolescent athletes can vary by gender (Brooks et al., 2014), which has been noted for the SCTA as well (Schneider et al., 2010). BESS scores were found to increase with age, ankle instability and external ankle bracing, and improving after training, which can affect BESS scores independently of remaining postural alterations as a result of a concussion (Bell et al., 2011). However, BESS has been found valid to detect balance deficits where large differences exist (concussion or fatigue), where it may not be valid when

differences are more subtle (Bell et al., 2011). Overall, the BESS has moderate to good reliability to assess static balance, correlates with other measures of balance using testing devices, and it can detect balance deficits in participants with concussion and fatigue (Bell et al., 2011). Neuropsychological tests aren't without their limitations either. Performance on computerized neuropsychological tests may be affected by a number of factors, including sex, Scholastic Assessment Test (SAT) scores, alertness at the time of testing, and the athlete's sport (Brown et al., 2007).

2.4 Training and Adaptation

The influence of training, preparedness, and musculoskeletal characteristics on injury biomechanics has yet to be systematically evaluated in sports-related concussion (Rabinowitz et al., 2014). However, injury prevention effects on neuromuscular training have been studied and partly attributed to postural control adaptations (Lloyd, 2001; Bressel et al., 2007; Taube et al., 2008; Hrysomallis, 2010; Zech et al., 2014). Superior balance of elite athletes may be the result of repetitive experience that influences motor responses and the athlete's ability to attend to relevant proprioceptive and visual cues (Bressel et al., 2007). Proprioception is a part of the sensory system that provides information on joint position sense or detecting joint motion and is a component of the balance system (Hrysomallis, 2010). Whether proprioception can really be improved by exercise has been questioned and it is speculated that athletes might just become more skilled at focusing and attending to important sensory cues with training and producing refined motor responses (Hrysomallis, 2010). Balance training may lead to task-specific neural adaptations at the spinal and supraspinal levels (Hrysomallis, 2010) and the training experience

might also improve coordination, strength and range of motion that may enhance balance ability (Bressel et al., 2007). Training may supress spinal reflex excitability such as the muscle stretch reflex during postural tasks which leads to less destabilizing movements (Taube et al., 2008), while improving balance such as needed in sports like gymnastics and rifle shooting (Hrysomallis, 2010). Moreover, the inhibition of muscle stretch reflexes may enhance agonist-antagonist muscle co-contraction which increases joint stiffness, stabilizing the joints against perturbations and therefore may improve balance (Lloyd, 2001). Neuromuscular training has not been shown to be effective in improving postural control in all balance measures (medial–lateral time to stabilization), suggesting that neuromuscular training does not influence all dimensions of postural control (Zech et al., 2014). Training of sport-specific skills could influence in-season variability of balance, through alterations of an athlete's biomechanics from the repetition of sport-specific skills. Normal in-season biomechanical adaptation(s) should be taken into account when assessing a suspected concussed athlete, since it can aid in determining proper RTP, by distinguishing abnormal posture (post-concussion) that are not similar to in-season patterns.

2.5 Accumulation of Subconcussive Forces

Athletes who participate in contact sports are trained to dampen impacts to the head with their shoulders and torso in order to minimize angular head accelerations (Rabinowitz et al., 2014). Repetitive impacts to the head that do not produce a concussion have been referred to as subconcussive blows (Rabinowitz et al., 2014). There is much speculation about the role of subconcussive impacts on acute and chronic neurological functioning in athletes (Rabinowitz et al., 2014). A recent review that examined subconcussive blows in athletes found that the

neurological/neuropsychological impact of subconcussive blows were quite limited and, in the short-term, have not been shown to cause significant clinical effects (Belanger, 2015). Furthermore, studies examining acute neurocognitive outcomes in non-concussed athletes exposed to subclinical levels of head trauma have generally failed to support this claim (McCrory, 2003; Miller et al., 2007). The link between subconcussive forces and clinical measures of concussion is also in debate. Researchers studying the role of subconcussive forces and concussion history on collegiate football players before and after the season expected to find that as total cumulative magnitude of head impacts increased, BESS scores would result in increased number of errors (worse BESS score) from preseason to postseason (Gysland et al., 2012). The researchers found, paradoxically, as the number of impacts increased, the BESS scores resulted in a decreased number of errors from preseason to postseason, with no reasonable explanation (Gysland et al., 2012). Despite this, other research has suggested that sub-concussive head impacts are a source of accrued damage (Rabadi and Jordan, 2001; Abbas et al., 2015). Indirect evidence of a relationship between subconcussive forces and neurological impairment comes from reports of increased risk of chronic neurological impairment in individuals exposed to contact sports for long durations or at high levels of competition (Rabadi and Jordan, 2001). In-season accumulation of sub-concussive forces could influence injury biomechanics. Understanding how these in-season patterns vary between nonlinear and linear metrics can lead to more thorough sport-related concussion evaluation, and therefore, more effective RTP.

2.6 Linear Approach to Calculating Centre of Pressure

Balance, which is often used synonymously with “equilibrium” (a state at which objects are at rest or constant speed), refers to equilibrium about a specific axis, such as vertical axis in upright standing (Schenkman, 1989). As such, postural control and balance control can be used interchangeably to refer to the process of maintaining or returning the body close to static or dynamic equilibrium (Schenkman, 1989). Balance can be evaluated using force plate technology (measuring centre of pressure - COP) as a static or dynamic platform (i.e. “unstable platform”; perturbations) and accelerometers. Balance testing on the sideline may be substantially different than baseline tests because of differences in shoe/cleat-type or surface, use of ankle tape or braces, or the presence of other lower extremity injury (Harmon et al., 2013).

Conventional linear approaches are tools (i.e. statistics of range, standard deviation, coefficient of variation) used to measure variability, providing information about the quantity (magnitude) of a signal from a given movement, not the structural nature of a signal. The linear dynamics framework and biomechanical models have contributed to the development of commonly employed clinical measures of postural control, where postural stability is a focus (Cavanaugh et al., 2005a). The medical assessment of postural control after injury often includes the determination of postural stability in quiet standing with the traditional Romberg’s postural stability assessment (Cavanaugh et al., 2005a).

The analysis of COP excursions is used as an index of postural stability in standing (Ruhe et al., 2010). According to Ruhe et al (2010), there has been conflicting data reported over the past 20 years regarding the reliability of COP measures and no standard procedure for COP measure use in study design has been established. The research group conducted a systemic

review of six online databases (January 1980 to February 2009). Thirty-two papers met the inclusion criteria with a majority of the papers (26/32, 81.3%) demonstrated acceptable reliability (Ruhe et al., 2010). According to the authors, COP mean velocity (mVel) demonstrated variable but generally good reliability throughout the different studies, no single measurement of COP appeared significantly more reliable than the others (Ruhe et al., 2010). Regarding data acquisition duration, a minimum of 90 seconds is required to reach acceptable reliability for most COP parameters. This review further suggests that while eyes closed readings may show slightly higher reliability coefficients, both eyes open and closed setups allow acceptable readings under the described conditions. Also averaging the results of three to five repetitions on firm surface is necessary to obtain acceptable reliability. A sampling frequency of 100Hz with a cut-off frequency of 10Hz is also recommended and no final conclusion regarding the feet position could be reached (Ruhe et al., 2010). The authors concluded that the studies reviewed show that bipedal static COP measures may be used as a reliable tool for investigating general postural stability and balance performance under specific conditions (Ruhe et al., 2010). This can allow COP to act as a baseline measurements for more in-depth biomechanical movement investigations, like postural sway. One recently developed method for assessing standing balance is the SWAY Balance Mobile Application (SWAY Medical, Tulsa, OK, USA) (Amick et al., 2015). It is a mobile device software application, which accesses mobile devices built-in accelerometer output to assess balance through a series of balance tests (Amick et al., 2015). Currently, the SWAY protocol consists of five stances (feet together, left foot forward, right foot forward, single leg stance right and left), each being performed for 10 s (Amick et al., 2015). The SWAY protocol applies similar methods utilized in other neurocognitive tests (i.e. BESS and SCAT1-3), namely, Romberg's balance (tandem stance, single leg stance and bilateral

stance) and sensory (eye's open and eye's closed trials). However, SWAY relying on new sensitive smart device technology could increase the sensitivity of identifying changes in balance since it does not rely solely on the practitioner in observing the alterations.

The concepts of variability and complexity and the nonlinear tools used to measure these concepts open new vistas for physical therapist practice and research in movement dysfunction of all types (Harbourne and Stergiou, 2009; Stergiou and Decker, 2011). Because mounting evidence supports the necessity of variability for health and functional movement, these authors argue for changes in the way therapists view variability, both in theory and in action. By providing clinical examples, as well as applying existing knowledge about complex systems, the Harbourne and Stergiou (2009) provide an article created as a springboard for new directions in physical therapist research and practice, utilizing nonlinear approaches. In Stergiou and Decker's 2011 review, a description of innovations in the exploration of variability, through nonlinear dynamics, and their importance in understanding the human movement is discussed.

2.7 Nonlinear Approach to Calculating Centre of Pressure

Approximate Entropy (ApEn) is an example of one type of nonlinear metric that has been used in research. ApEn has a larger probability associated with less complexity (i.e. greater regularity) in the COP time-series. Cavanaugh et al. (2005b; 2006) base their nonlinear analysis (using approximate entropy – ApEn, as the nonlinear measure) off a previously published nonlinear algorithm (Pincus, 1991; Stergiou et al., 2004), using nonlinear input calculations as (1) a series length (m) of two data points, (2) a tolerance window (r) normalized to 0.2 times the

standard deviation of individual times series, and (3) a lag value of 10. ApEn was chosen as the nonlinear measure in our research since it was previously used as a metric studying COP in ice hockey players (Cavanaugh 2005b; 2006).

The ApEn algorithm applies a moving window procedure to determine the probability that short sequences of data (points) are repeated (within a certain error tolerance) throughout the entire time series (Cavanaugh et al., 2007). ApEn expresses the average probability in log form (taking the inverse) and generates a unit-less real number from 0 – 2 (Pincus, 1991). Smaller ApEn values indicate a higher probability of regularly repeating sequences of observations (Pincus, 1991). A zero value corresponds to a time-series with perfect regularity (i.e. sine wave) (Cavanaugh et al., 2005b) and values approaching or at 2 is produced by random time series, for which any repeating sequences of points occur by chance alone (i.e. Gaussian noise) (Pincus, 1991).

ApEn was calculated using the following equation,

$$ApEn\ (m, r, N)\ =\ \Phi m(r)\ -\ \Phi m + 1\ (r)$$

Where the *r* represents the error tolerance, *m* the number of observations, and *N* data points for an ApEn time series (i.e. *u(1), u(2),...u(N)*) (Pincus, 1991). The definition of ApEn used was derived from,

$$Cmi(r)\ =\ (number\ of\ x(j)\ such\ that\ d[x(i), x(j)] \leq r)/(N - m + 1)$$

in four steps, where x represents a vector sequence, d is distance between vectors and Cmi is the regularity of the pattern similar to length m. The first step is to form vector sequences $x(1)$ through $x(N - m - 1)$ from the $\{u(i)\}$, defined by $x(i) = [u(i), ..., u(i + m - 1)]$ (Pincus, 1991). These vectors are basically m consecutive u values, beginning with the i-th point. The second step is to define the distance $d\ [x(i),x(j)]$ between vectors $x(i)$ and $x(j)$ as the largest difference in their respective scalar components. The third step is to use the vector sequences $x(1)$ through $x(N - m - 1)$ to create (for each $i \leq N - m + 1$). The $Cmi(r)$ values measure (within the tolerance r) the regularity of patterns similar to a given pattern of window length m. The fourth step is to define $\Phi^m(r)$ as the average value of ln $Cmi(r)$, where ln is the natural logarithm (Pincus, 1991), to get the definition of ApEn used.

2.8 Literature Review Findings

A sizable number of athletes may enter collegiate play with a previous concussion diagnosis, and many more are likely to have experienced symptoms suggestive of a mild head injury (Kaut et al., 2003). The fast, random nature and characteristics of ice hockey make injury prevention a challenge as high-velocity impacts with players, sticks and boards occur and may result in a variety of injuries, including concussion (Ruhe et al., 2014). Additional research is needed to validate current assessment tools, delineate the role of neuropsychological testing and improve identification of those at risk of prolonged post-concussive symptoms or other long-term complications. Evolving technologies for the diagnosis of concussion, such as newer neuroimaging techniques or biological markers, may provide new insights into the evaluation

and management of sports concussion (Harmon et al., 2013). Management of sport concussions are vital for proper safe RTP, which if rushed or improperly implemented, could jeopardize an athlete's life.

Chapter 3: The Use of Linear and Nonlinear Methods for Evaluating Balance on Collegiate Men and Women Ice Hockey Teams throughout a Season

3.1 Introduction

A number of studies have implemented force plate technology and clinical balance tests to identify postural stability deficits following sport-related concussions (McCroy et al., 2008). Balance is often affected and should be evaluated when a concussion is suspected (Harmon et al., 2013). Particular attention has been focused on the criteria used to determine when an athlete who sustained a concussion is fully recovered and ready to resume play (Cavanaugh et al., 2005a). Yet, return to play guidelines based on clinical balance tests remain elusive and data processing techniques for balance measures needs further attention.

Sport injuries are not commonly associated with "balance problems" since athletes generally are in excellent health or because most injuries are associated to a few musculoskeletal areas (Cavanaugh et al., 2005a). Sport activities do demand exquisite body control, such that even subtle impairments may interfere with optimal performance without producing obvious unsteadiness (Cavanaugh et al., 2005a). Studies have identified temporary or permanent deficits in static and/or dynamic balance in sports-related concussions (Erlanger et al., 1999; Riemann et al., 1999; McCrea et al., 2003; Peterson et al., 2003; McCrea et al., 2005). The pathophysiology of cerebral concussions has been a matter of dispute (McCrory and Berkovic, 2001) in the literature. However, recent studies have identified the neurophysiological cascade of changes that initiates post-concussion, but understanding the implications of the neurochemical cascade is still not fully realized (MacFarlane and Glenn, 2015). Other evidence suggests that concussions produce functional neurophysiological changes in the cortex and brainstem reticular formation

(Shaw, 2002) with subtle vestibular deficits possible (Mallinson and Longridge, 1998). The concussion induced pathophysiological changes might reflect alterations in the patterns of interaction among components of the central nervous system (Cavanaugh et al., 2005a). Brain regions might become less coupled to one another (Pincus, 1995) by the reduced or distorted interactions among neurons in the brain (McCrory et al., 2001). This can increase the regularity of cortical oscillations (Pincus, 1995) and makes it plausible that changes in patterns of COP after concussion reflect changes in cortical oscillatory activity (Cavanaugh et al., 2005a). COP is a compound signal that includes the position of the whole body CG, transformed by the multilinked system of the body to the support surface to control equilibrium (Blaszczyk and Klonowski, 2001). "Postural steadiness" is often measured or inferred from the amplitude of COP variation as a function of time (Cavanaugh et al., 2005a), collected during postural steadiness tests (Cavanaugh et al., 2006).

Linear dynamic framework and biomechanical models have contributed to the development of commonly employed clinical measures of postural control, where postural stability is a focus (Cavanaugh et al., 2005a). The medical assessment of postural control after injury often includes the determination of postural stability in quiet standing with the traditional Romberg's postural stability assessment (Cavanaugh et al., 2005a). Both non-instrumented (Romberg's Test and BESS), and instrumented force plate paradigms have been developed to asses postural stability (Cavanaugh et al., 2005a). These approaches assume that healthy mature individuals can regulate body position where there are slight variations in whole body CG about an equilibrium point (Cavanaugh et al., 2005a). While standardized sideline tests are useful for examination (Harmon et al., 2013), baseline values of commonly used sideline tests can vary

widely from athlete to athlete, and results are dependent on age, sport, sex, and confounding medical conditions. This makes the use of sideline tests without baseline results difficult (Covassin et al., 2006; Hunt and Ferrara, 2009; Jinguji et al., 2012; McLeod and Leach, 2012).

The human body can be seen as a complex mosaic of nonlinear dynamical systems (Glass and Mackey, 1988) organized within both spatial and temporal domains (Cavanaugh et al., 2005a). As outlined by Rosenstein (1993), nonlinear approaches take into account all available data in a system. The nonlinear framework supports the idea that postural control emerges through the interaction of individual physiological systems, task demands and environmental constraints (Glass and Mackey, 1988; Riccio et al., 1988; Shumway-Cook, et al., 1995; Slobounov et al., 1996). This yields estimates on the complexity of the system within one series of calculations (Rosenstein et al., 1993). Nonlinear models use the time evolving properties of an output signal to draw inferences regarding interactions within the underlying control system (Rosenstein et al., 1993; Newell, 1998). The measurement implications are that error magnitude is irrelevant, and the temporal structure is measured as patterns of variability (Cavanaugh et al., 2005a). This can yield a complex but highly accurate model of movements through time.

Balance disturbance is a specific indicator of a concussion, but not very sensitive (Harmon et al., 2013). The presence of a balance disturbance is not a sole indicator of a concussion. There could be natural disturbances in balance during a season (of any contact sport), that can result from normal day-to-day fluctuations in balance. Epidemiologic evidence, for example, indicates that postural instability after concussion, using clinical biomechanical measures, appears to resolve more quickly, on average, than either neurophysiological functions

or symptoms (McCrea et al., 2003). Other evidence has shown that not all athletes show reduced equilibrium scores (i.e. greater postural instability) after injury, even though concussion related symptoms were reported (Guskiewicz, 2002). An earlier study by Guskiewicz et al. (1996) showed results that indicated mild head injury (MHI) subjects appear to maintain their COP significantly farther away from their base of support 1 day after head injury. For injured athletes, the return of optimal postural control is an important rehabilitation goal being an indicator for recovery (Cavanaugh et al., 2005a; Cavanaugh et al., 2006). Fears have been expressed that current "traditional" linear approaches may be inadequate for helping athletes, coaches and medical professionals determine when absolute recovery has been reached and safe RTP is allowed (Cavanaugh et al., 2005a). Cavanaugh et al. (2005b) concluded that changes in approximate entropy (ApEn), a regularity statistic from nonlinear dynamics, may demonstrate clinically abnormal findings in COP oscillations for NCAA Division 1 athletes, tested 48 hours post-concussion (Cavanaugh et al., 2005b). This suggests that nonlinear analysis could be a valuable supplement to existing concussion assessment protocols (Cavanaugh et al., 2005b). Linear (Slobounov et al., 2008, Dorman et al., 2015) and nonlinear (Cavanaugh et al., 2005a; Cavanaugh et al., 2006) measures have been used to study COP on concussed and non-concussed athletes independently, and in tandem (Cavanaugh et al., 2007; Baltich et al., 2014). However, no study has examined both of these measures, on a collegiate population over the course of a season, to identify potential time evolving changes, in-season, which may be used to determine proper RTP guidelines for concussed athletes.

3.2 Methods

3.2.1 Subjects

Twenty-two men (age: 20-24 years, mean 22.59 ± 1.40 years; height: 1.82 ± 0.06m; and weight: 86.45 ± 6.6kg) and 24 women (age: 18-23 years, mean 19.63 ± 1.31 years; height: 1.67 ± 0.06m; and weight: 67.43 ± 9.0kg) from their respective varsity ice hockey teams participated in this study during the 2014-2015 season. Participants were excluded from participation based on self-reporting and/or previous history of TBI, suffered or diagnosed within one year of the project start date. This included athletes with a history of cerebellar or spinal cord injuries, muscular dystrophies and multiple sclerosis. This project was approved by the university Research Ethics Board and participants provided written informed consent prior to participation.

3.2.2 Data Acquisition

After two games into the 2014/15 regular season, all participants underwent baseline measurements. Baseline measures were collected using a ground mounted (0.46x0.51x0.08meters) force platform (OR6-7-1000, Advanced Mechanical Technology, Inc., Watertown, MA, United States) at a sampling rate of 1,000 Hz. Ground reaction forces (Fx, Fy and Fz) and moments (Mx, My and Mz) in three axis were simultaneously measured and recorded (AMTI NetForce®, software Version 3.51) during 5 conditions conducted in random order. Each condition was 120 seconds with a 5-10 second break between conditions. Participants were unshod (wearing socks and comfortable attire) during all trials and were told to perform the following trials while standing still (Figure 1). The five conditions included:

1. Eyes open (EO) - feet shoulder width apart, participant looking forward, with arms by side
2. Eyes closed (EC) - eyes closed, with the same stance as indicated above

3. Eyes closed with arms out (EC/AO) - eyes closed, arms stretched out in front at 90° shoulder forward flexion with feet shoulder width apart

4. Right leg up (RLU) – left single-leg stance, with right knee bent to 25°-30°, with the ankle in subtalar neutral, no dorsi-or plantar-flexion, arms by side and head facing forward

5. Left leg up (LLU) - same as #4, but opposite leg

Figure 1: Participant performing the standing balance test on force plate (EO condition).

Every participant went through each condition once, during each trial. Participants were tested every 4 weeks, throughout the season. This corresponded to 4 sessions during the season, plus a baseline and post-season session. In total there were 6 sessions. Figure 2 is a representative center of pressure trace for one participant. The post-season testing was conducted 4 and 5 weeks after the regular season ended for the men and women teams, respectively (Figure 3). There was no post-season competition for either team. Baseline measurements for the men's

team occurred after initial tryouts, 4 exhibition and 2 regular season games. The women's team baseline testing occurred after initial tryouts, 5 exhibition and 2 regular season games. There were no reported concussions from either team prior to baseline.

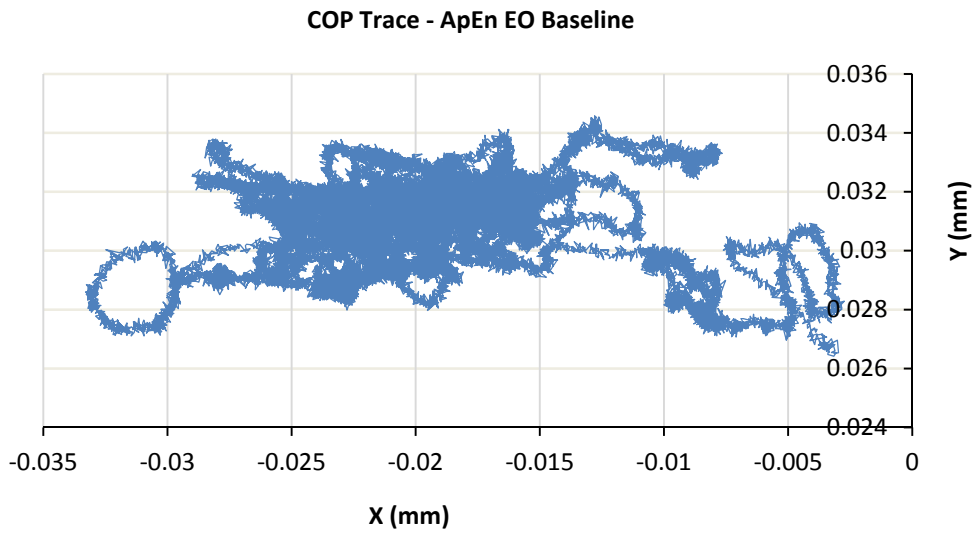

Figure 2: Representative COP trace for the EO baseline trial.

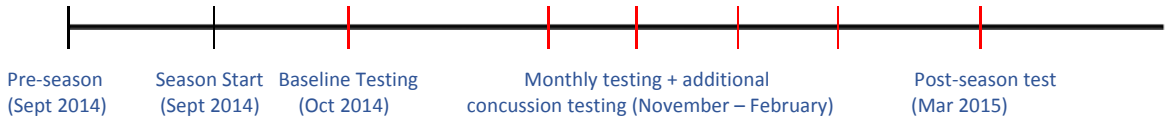

Figure 3: Testing timeline. Grey lines indicate events in the season, Red lines indicate testing sessions. Note: "Additional concussion testing" represents trials conducted on diagnosed concussed athletes, performed between monthly testing periods.

Due to scheduling conflicts, the number of participants from both teams varied per session and is highlighted in Table 1. If a participant was suspected of suffering a concussion (during practice or game), conformational screening was performed by a certified Athletic Therapist at the university Campus Recreation and Wellness Centre, as soon as possible. Subsequent study

testing was conducted at the participant's earliest convenience, while maintaining pre-scheduled monthly testing. Approximately, five men and two women suffered confirmed concussions during the testing period. Participants testing facts are indicated in Table 2.

Table 1: Number of athletes that participated in each session.

SESSION	MEN'S TEAM	WOMEN'S TEAM
Baseline	21	17
1	20	23
2	20	15
3	17	15
4	19	8
Post-season	7	8

3.2.3 Data Analysis

All COP calculations (both linear and non-linear) were performed using MATLAB (Matlab R2014, The Mathworks, Inc., Natick, MA, USA). Raw force plate data were low pass Butterworth filtered (Dual pass, 2nd order, 10Hz cut-off (Schmid et al., 2002)) and down sampled to 100Hz after filtering (Schmid et al., 2002; Rhea et al., 2015). ApEn was used as the nonlinear measure and calculated as per Cavanaugh et al. (2005b; 2006). The input parameters for the ApEn calculation were (i) a series length (m) of two data points, (ii) a tolerance window (r) normalized to 0.2 times the standard deviation of the individual time series, and (iii) a lag value of 10 (Pincus and Goldberger, 1994; Stergiou et al., 2004). The ApEn algorithm requires input of both the length of the short segments of data points and the error tolerance (Cavanaugh et al.,

2005b). Reliability of the algorithm output is best when input values (as well as the length of the entire time series) are identical for all subjects (Pincus et al., 1991).

In addition to ApEn, linear metrics were also used to measure COP. The linear measures included, mean velocity (MnVel), mean power frequency (MPF) and total excursion (TE). TE represents the total length of COP path, and is approximated by the sum of the distances between consecutive points on the COP path (Prieto et al., 1996), reported in meters. MnVel is the average velocity of the COP, which in effect, normalizes TE to the analysis interval (Prieto et al., 1996) and is reported in m/s. MPF was calculated using a Fast Fourier Transform (FFT). The AP and ML directions were combined (i.e. not separated from each other) for calculation of each linear and nonlinear measure.

ApEn was chosen as the nonlinear measure since it was used in previous studies (Cavanaugh et al., 2005b; 2006) to evaluate standing balance postures in collegiate level ice hockey players, which is the same study population used in our study. In the linear measures, TE was chosen since it gives insight into sway; which is how COP moves within the base of support. MnVel was chosen since is can be used to standardize force plate measures and has a high significance for separating visual conditions (i.e. EO and EC conditions) (Prietro et al., 1996). In addition to this, MnVel has a reliable "responsiveness" (Laroche et al., 2015), meaning MnVel can effectively detect changes in itself during standing balance postural trials. Lastly, MPF was chosen as a linear measure for the study since it was used in previous studies to evaluate COP excursion in EO and EC trials (Carpenter et al., 1999; Corbeil et al., 2003) and because MPF

reliability increases with increased sample duration (120s) (Carpenter et al., 2001). Our study used testing duration of 120s.

3.2.4 Statistical Computation

Due to the fact that there were an uneven number of participants in each testing period, a linear mixed model (LMM) analysis was performed on the changes of each measure (ApEn, MPF, MnVel, TE) with respect to baseline (that is, the difference between baseline and session 1, baseline and session 2, etc…) using SPSS (SPSS v23, IBM Corporation, Somers, NY, USA). A priori planned contrasts were used to compare across each time period. All data was collapsed across gender and only time period was compared. Normality for each of the dependent variables was confirmed using the Shapiro-Wilk test. Time was entered into the model as a fixed factor. The covariance structure for repeated measures was auto-regressive (AR1). Statistical significance for all analyses was set at an alpha level of <0.05. Data are presented as the mean ± standard error of the mean. A second statistical test was performed where the data from baseline and session 1 was combined for each participant as a session average. This was also done for session 2 and 3 and session 4 and post. A repeated measures ANOVA was performed to determine if there was a significant main effect of session with the combined trials. These results compared session 1, 2 and 3 and can be found in the appendix.

3.3 Results

During the course of the regular season, 7 (5 males; 2 females) athletes sustained diagnosed concussions (Table 2). Of the 7, only 2 (1 male; 1 female) attended all testing sessions

prior to and after sustaining injury. Partial data was obtained for 2 males and 1 female, who did not attend all planned sessions. Lastly, the remaining two (1 male; 1 female) athletes did not participate in the study. Data obtained (complete and partial) for concussed athletes was removed from the dataset prior to statistical computation. Baseline values are summarized for each measure in Table 3. Statistical results are summarized in Table 4.

Table 2: Number of athletes who completed all trials through the season, including Baseline and Post-season tests; with number of confirmed concussions and those concussed who participated in every trial, post-concussion

Testing Facts	MEN'S TEAM	WOMEN'S TEAM
Number of total participants	22	24
Number of participants that completed all sessions	4	5
Number of confirmed concussions	5	2
Number of concussed athletes that completed all trials	1	1

Table 3: Baseline raw average ±standard deviation for each linear and nonlinear measure, separated by gender.

	ApEn (au)	MnVel (m/s)	MPF (Hz)	TE (m)
EO				
Male	0.64 ±0.15	0.01 ±0.00	0.19 ±0.07	0.56 ±0.26
Female	0.41 ±0.11	0.00 ±0.00	0.12 ±0.04	0.25 ±0.04
EC				
Male	0.69 ±0.17	0.01 ±0.004	0.24 ±0.10	0.65 ±0.26
Female	0.41 ±0.13	0.01 ±0.00	0.12 ±0.05	0.31 ±0.06
EC/AO				
Male	0.75 ±0.17	0.01 ±0.01	0.29 ±0.12	0.81 ±0.28
Female	0.46 ±0.10	0.01 ±0.00	0.14 ±0.04	0.34 ±0.09
RLU				
Male	0.96 ±0.02	0.04 ±0.02	0.36 ±0.15	2.5 ±0.98
Female	0.68 ±0.12	0.02 ±0.00	0.19 ±0.05	1.1 ±0.25
LLU				
Male	0.96 ±0.17	0.04 ±0.12	0.36 ±0.15	2.6 ±1.0
Female	0.69 ±0.14	0.02 ±0.00	0.20 ±0.06	1.2 ±0.23

Eyes open (EO)

Pairwise comparison revealed that the mean difference from baseline to the third test session was the only time period to have a significant difference for all variables (ApEn $F_{5,111}$= 12.7, $p<0.001$; MnVel $F_{5,159} = 11.64$, $p<0.013$; MPF $F_{5,130} = 8.17$, $p<0.002$; TE $F_{5,150} = 11.58$, $p<0.014$). The baseline to third session demonstrated the largest decrease for the MPF (0.096Hz; 77% decrease), and ApEn (0.23au; 66% decrease) measures (Figure 4). For the TE measure, the largest decrease from baseline was during the fourth test session (0.332m or 61% decrease), the next largest decrease from baseline was found in the first session (Figure 4). The third to post test session represents the largest increase (from the lowest mean difference value) in ApEn (0.118au; 78% increase) and MPF (0.038Hz; 51% increase) (Figure 4). Post sessions for ApEn, MPF and TE had a smaller decrease from baseline (0.112au, 0.058Hz, 0.3m; respectively) than was evident from the fourth sessions (0.176au, 0.079Hz, 0.332m; respectively) (Figure 4). For TE, the largest increase was from the fourth to post test session (0.032m; 16% increase). For MnVel, the largest decrease from baseline was during the third session (0.005m/s; 60% decrease), however there were no changes during the fourth or post sessions (Figure 4).

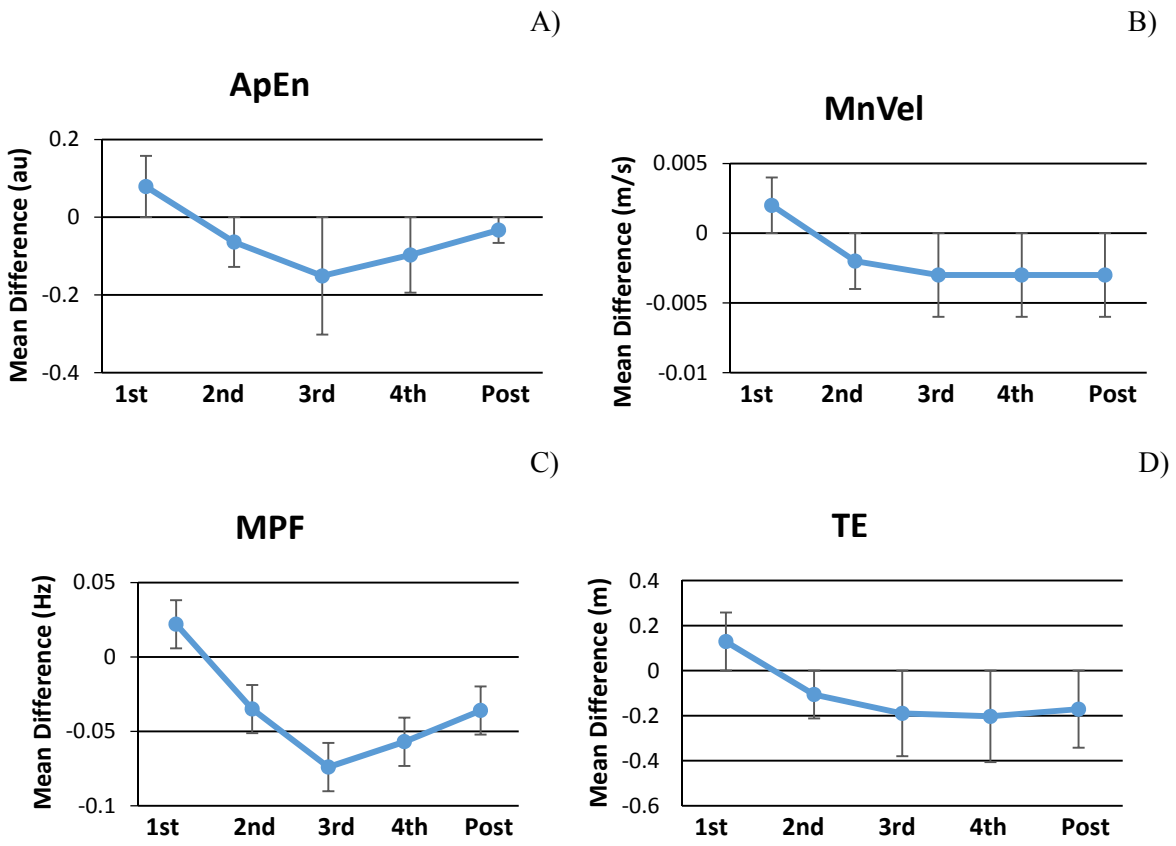

Figure 4: Mean difference from baseline for each time period for the eyes open condition. A) ApEn; B) MnVel; C) MPF; D) TE. Error bars represent Standard error SE.

Eyes closed (EC)

Pairwise comparisons demonstrated that the fourth test session had a significant decrease across all variables (ApEn $F_{5,120} = 17.55$, $p<0.001$; MnVel $F_{2,14} = 20.32$, $p<0.002$; MPF $F_{5,116} = 9.21$, $p<0.003$; TE $F_{5,99} = 20.29$, $p<0.002$) when compared to baseline. For ApEn and MPF, the largest decrease from baseline was found for the fourth test session (0.219au, 68% decrease; 0.094Hz, 74% decrease; respectively (Figure 5). For ApEn and MPF, the post-test session had a smaller decrease from baseline (0.174au, 0.069Hz; respectively) than the fourth (0.219au, 0.094Hz; respectively) session (Figure 5). For MnVel and TE, the largest decrease from baseline was found during the post-test session (0.006m/s, 67% decrease; 0.389m, 64% decrease; respectively) (Figure 5). TE and MnVel had their largest increase in mean difference towards baseline values at the second to the third test session (0.018m, 11% increase; 0.001m/s, 34% increase; respectively) (Figure 5). For TE and MnVel, the third test session had a smaller decrease from baseline (0.287m, 0.004m/s; respectively) than the second (0.305m, 0.005m/s; respectively) (Figure 5).

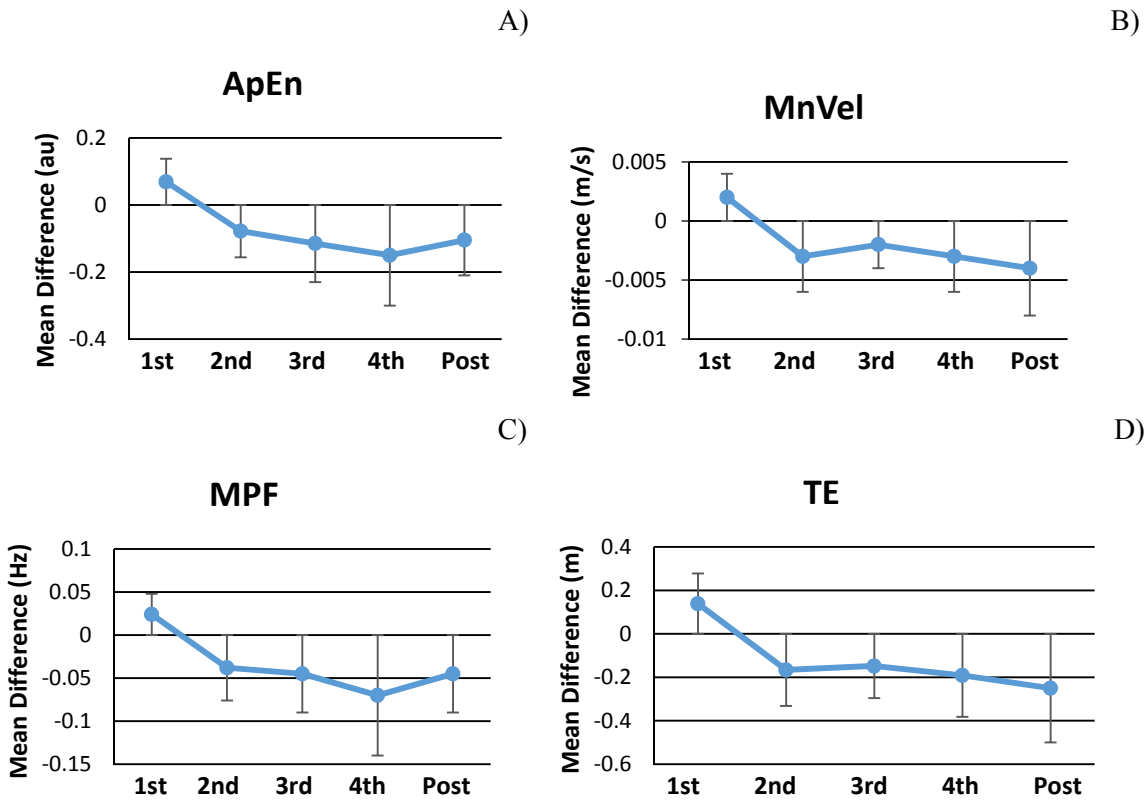

Figure 5: Mean difference from baseline for each time period for the eyes closed condition. A) ApEn; B) MnVel; C) MPF; D) TE. Error bars represent Standard error SE.

Eyes closed and arms out (EC/AO)

The mean difference from baseline to the first test session was significant for each variable in the EC/AO trial (ApEn $F_{5,118} = 19.19$, $p<0.006$; MnVel $F_{5,116} = 25.94$, $p<0.001$; TE $F_{5,115} = 25.9$, $p<0.001$), excluding MPF ($F_{5,111} = 8.71$, $p<0.402$). MPF was the only variable with no significant differences from baseline for any test session. ApEn (0.209au; 58% decrease), MPF (0.95Hz; 60% decrease) and TE (0.383m; 51%) had their greatest decrease in mean difference from baseline to the fourth test session, with progressive decrease for each previous session (Figure 6). The largest decrease for MnVel occurred from baseline to second test session (0.003m/s; 50%) (Figure 6). ApEn and MPF post sessions had a smaller decrease from baseline (0.157au, 0.057Hz; respectively) than the fourth sessions (0.209au, 0.095Hz; respectively) (Figure 6). TE and MnVel never increased in their mean difference values (Figure 6).

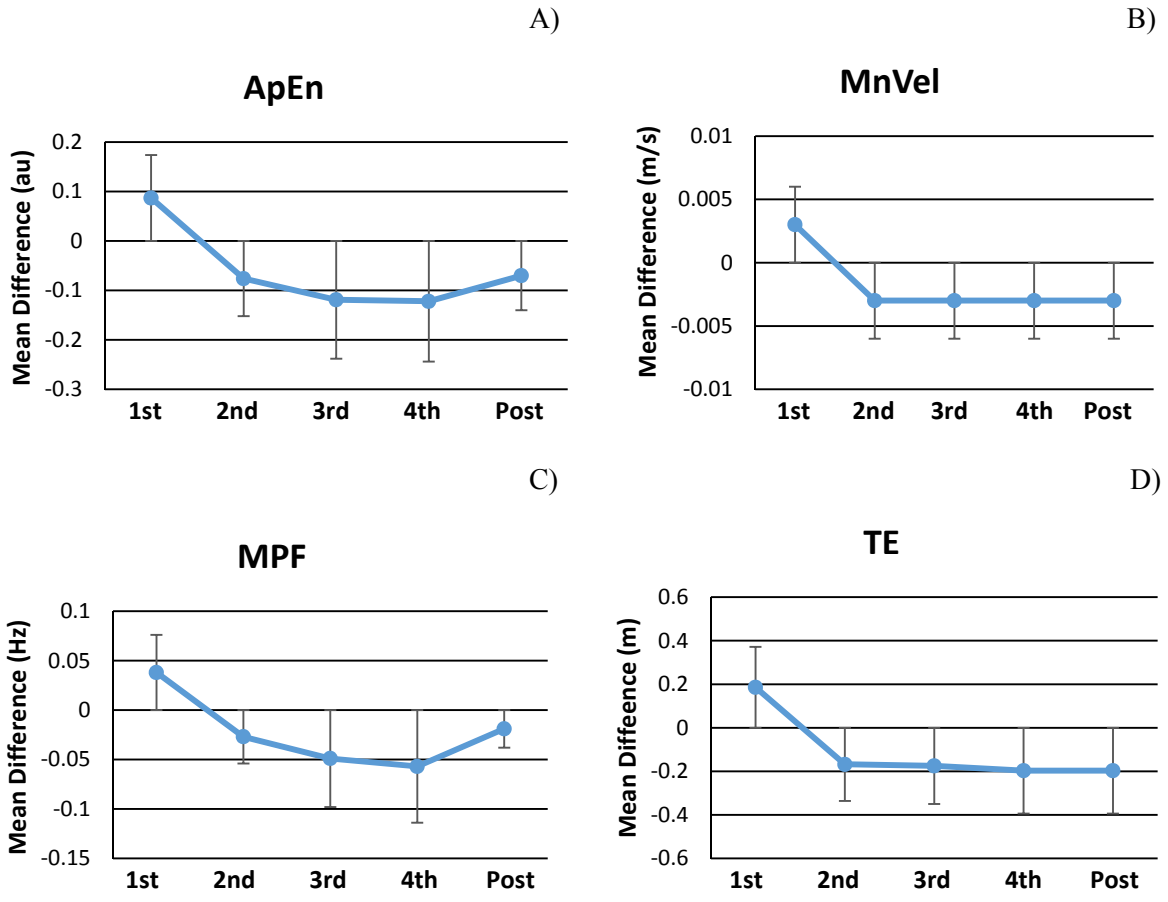

Figure 6: Mean difference from baseline for each time period for eyes closed and arms out condition. A) ApEn; B) MnVel; C) MPF; D) TE. Error bars represent Standard error; SE.

Right leg up (RLU)

The mean difference from baseline to the first test session was significant for each variable (ApEn $F_{5,35} = 27.41$, $p<0.000$; MnVel $F_{5,52} = 39.44$, $p<0.000$; MPF $F_{5,128} = 18.4$, $p<0.000$; TE $p<0.000$). The mean difference from baseline to the third test session (ApEn $p<0.031$; MnVel $p<0.000$; TE $p<0.000$) and post test session (ApEn $p<0.010$; MnVel $p<0.000$; TE $F_{5,129} = 34.64$, $p<0.001$) was significant for each trial, except MPF ($p=0.164$ baseline to the third test session; $p=0.201$ baseline to the post test session). However, for MPF the difference from baseline to the fourth test session ($p<0.002$) was significant. The baseline to post test session had the largest decrease in mean difference for ApEn (0.292au; 47% decrease), MnVel (0.021m/s; 52% decrease) and TE (1.223m; 52% decrease) (Figure 7). Subsequently, there were also decreases at baseline to first, with progressive decreases in all sessions. MPF demonstrated the largest decrease from baseline during the fourth session (0.174Hz; 50% decrease) (Figure 7). During the fourth test session, ApEn, MnVel and TE all had a smaller decrease from baseline (0.247au, 0.018m/s, 1.065m; respectively), than during the third session (0.248au, 0.02m/s, 1.197m; respectively) (Figure 7). MPF had its largest increase from the fourth to the post test session (0.022Hz; 25% increase), with the post session value having a smaller decrease from baseline (0.152Hz) than the fourth (0.174Hz) session (Figure 7).

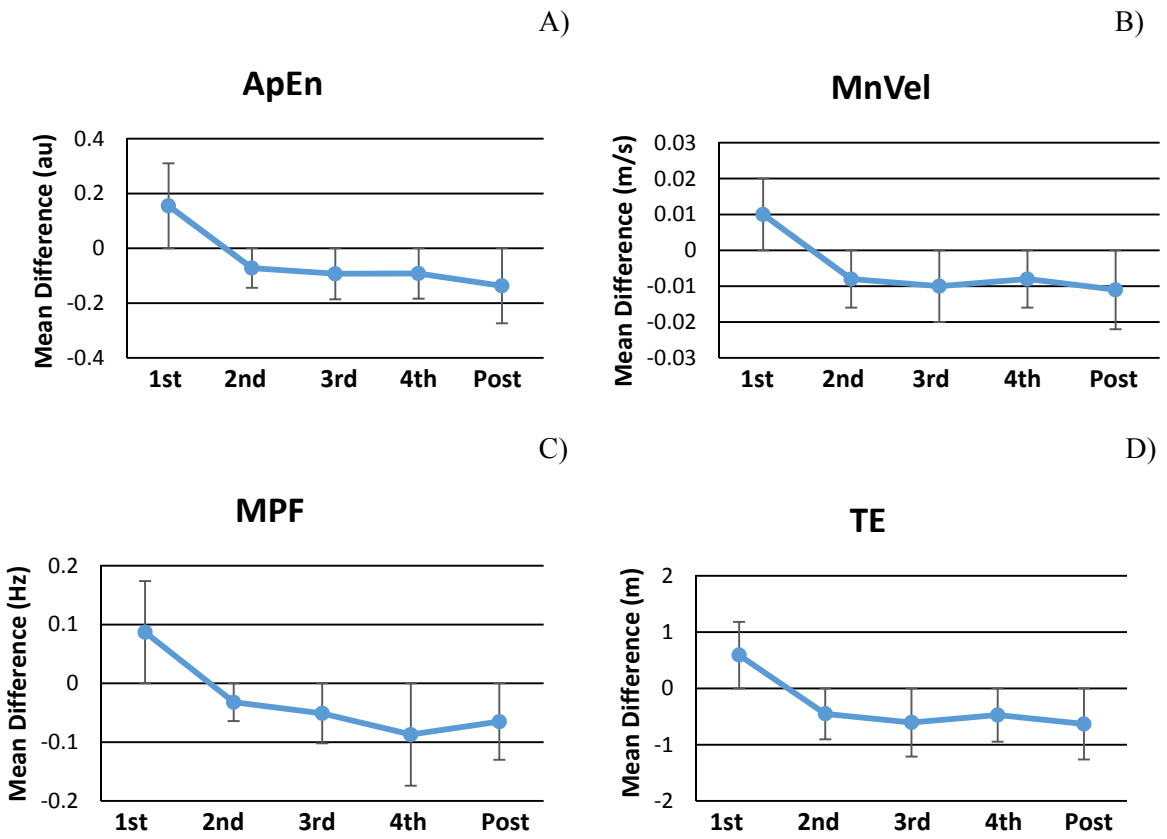

Figure 7: Mean difference for baseline for each time period for the right leg up condition. A) ApEn; B) MnVel; C) MPF; D) TE. Error bars represent Standard error; SE.

Left leg up (LLU)

The mean difference from baseline values to the first test session (ApEn $F_{5,79} = 27.84$, $p<0.000$; MnVel $F_{5,161} = 41.6$, $p<0.000$; MPF $F_{5,115} = 17.74$, $p<0.001$; TE $F_{5,137} = 37.31$, $p<0.000$) and third test session (ApEn $p=0.000$; MnVel $p<0.000$; MPF $p<0.002$; TE $p<0.000$) was significant for each variable. There was a significant decrease from baseline to the post test session for each variable (ApEn $p<0.023$au; MnVel $p<0.004$m/s; TE $p<0.028$m) except for MPF ($p=1.00$). The baseline to third test session represented the largest decrease for each measure (ApEn 0.283au, 54% decrease; MnVel 0.022m/s, 50% decrease; MPF 0.161Hz, 49% decrease; TE 1.292m, 51% decrease), followed by the baseline to first session and a progressive decrease in for each subsequent session (Figure 8). ApEn and MnVel fourth test sessions had a smaller decrease from baseline (0.241au, 0.02m/s; respectively), than third (0.283au, 0.022m/s; respectively) (Figure 8). MPF and TE post sessions had a smaller decrease from baseline (0.113Hz, 1.144m; respectively) than their third (0.161Hz, 1.292m; respectively) test sessions (Figure 8).

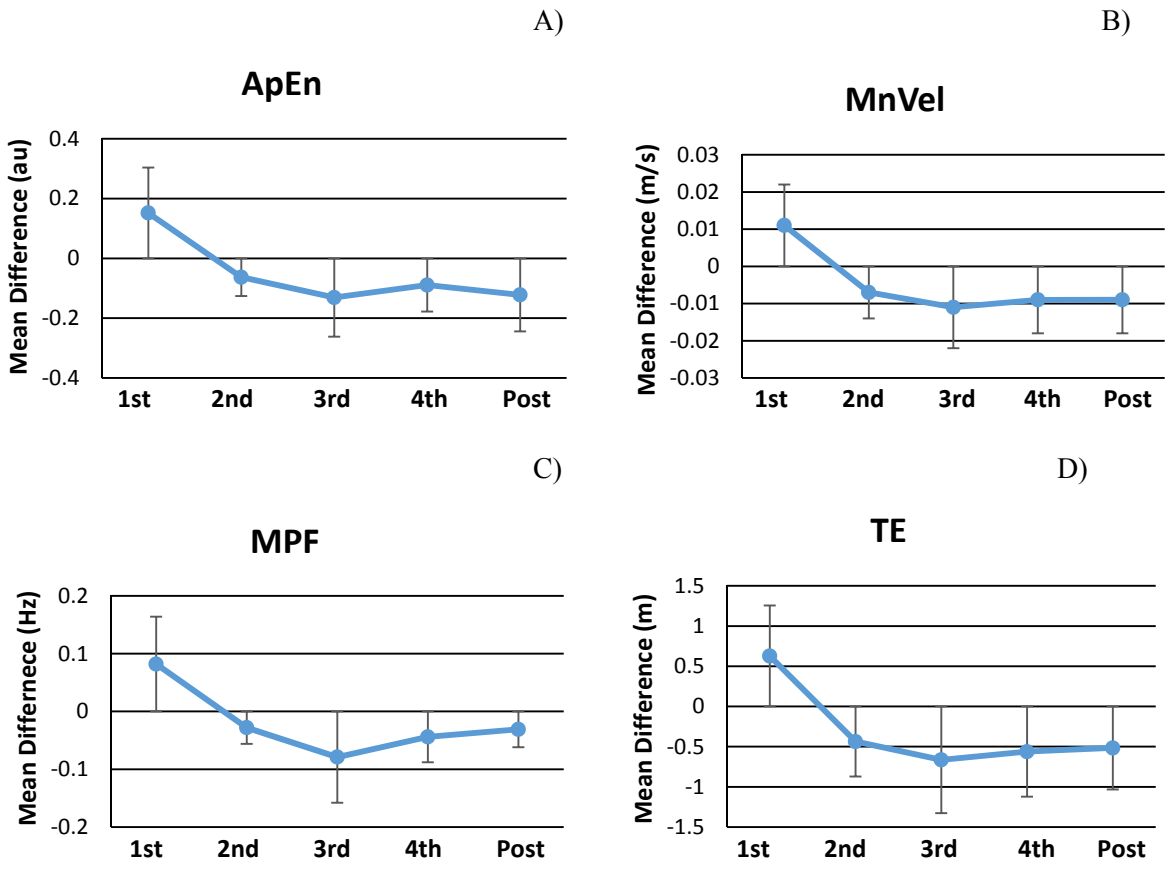

Figure 8: Mean difference for baseline for each time period for the left leg up condition. A) ApEn; B) MnVel; C) MPF; D) TE. Error bars represent Standard error; SE.

Table 4: Main effects of Time for each dependent variable with pairwise comparisons to baseline. The mean difference of each time point minus baseline is indicated for each session that was significant; S=significant main effect, p<0.05.

Variable	EO	EC	EC/AO	RLU	LLU
ApEn	S P=0.00 *(Third -0.151)	S p=0.00 *(Third, -0.115; Fourth, -0.150; Post, -0.105)	S p=0.00 *(First, 0.087; Third, -0.119, Fourth, -0.122)	S p=0.00 *(First, 0.155; Third, -0.093; Post, -0.137)	S p=0.00 *(First, 0.152; Third, -0.131, Post, -0.122)
MPF	S p=0.00 *(Third, -0.074)	S p=0.00 *(Fourth, -0.070)	S p=0.00	S p=0.00 *(First, 0.087; Fourth, -0.087)	S p=0.00 *(First, 0.082; Third, -0.079)
MnVel	S p=0.00 *(Third, -0.003; Fourth, -0.003)	S p=0.00 *(First, 0.002; Second, -0.003; Third, -0.002; Fourth, -0.003; Post, -0.004)	S p=0.00 *(First, 0.003; Second to Post, -0.003)	S p=0.00 *(First, 0.01, Second, -0.008; Third, -0.01; Fourth, -0.008; Post, -0.011)	S p=0.00 *(First, 0.011, Second, -0.007; Third, -0.011; Fourth, -0.009; Post, -0.009)
TE	S p=0.00 *(Third, -0.19, Fourth, -0.203)	S p=0.00 *(First, 0.139; Second, -0.166; Third, -0.148; Fourth, -0.191; Post, -0.25)	S p=0.00 *(First, 0.186; Second, -0.168; Third, -0.175; Fourth, -0.197; Post, -0.197)	S p=0.00 *(First, 0.591; Second, -0.452; Third, -0.606; Fourth, -0.474; Post, -0.632)	S p=0.00 *(First, 0.628; Second, -0.436; Third, -0.664; Fourth, -0.561; Post, -0.516)

3.4 Discussion

This study evaluated standing balance on a force plate for both men and women varsity ice hockey players over the course of 6 months, during the 2014/15 regular season. A baseline session, 4 months of sequential testing and a post testing session resulted in 6 measures across 5 common standing balance tests. Both nonlinear (ApEn) and linear (MnVel, MPF, TE) measures were used to interpret the COP data from each session. Every measure demonstrated a decrease in their mean difference values, with respect to baseline. We demonstrated that there was a decrease in ApEn and MPF mean values in the EO and LLU trials from first to third test sessions and first to fourth test sessions in the EC, EC/AO and RLU trials. Both measures appeared to

return toward baseline values at the post testing session (differences from baseline to each session, but no difference from baseline to the post test session), with ApEn displaying the closest return. In the RLU trial, MPF returned towards baseline values at the post test session with MnVel and TE returning earlier at the fourth test session. TE had the closest return to baseline values out of this trial. The LLU trial, MPF and TE values showed a return towards their baseline values at the post test session with TE having the closest return to baseline values. Decreases were demonstrated from baseline values to the third test session, where the greatest decrease was in EO compared to all other conditions. Both EC and EC/AO conditions had the greatest decrease in mean difference at the fourth test session from baseline values, with the EC condition having the greatest decrease magnitude. Lastly, the decrease from baseline to the post test session was the greatest in the RLU condition, occurring gradually through subsequent sessions. Linear and nonlinear measures both showed significant main effects of Time (testing session). This work demonstrated that ApEn, did not display an advantage over linear measures (MnVel, TE) in identifying significant changes in time through the testing period. However, it was found that ApEn, MnVel and TE were better indicators of change in time than the MPF measure.

Balance is the ability to maintain a base of support with minimal movement (Hrysomallis, 2010). Stability in a broad sense, refers to the ability of a system to resist perturbations (La Veau, 1992) and postural stability defines the ability to maintain a desired postural orientation, either at rest or during movement, in response to perturbations generated by internal or external sources (Cavanaugh et al., 2005a). Cavanaugh et al. (2005a) demonstrated that oscillations in a postural steadiness time series constituted a physiological rhythm associated

with postural control. In that study, postural steadiness was tested through time without external sources of perturbations, but to resist internal perturbations (for example: skeletal muscle activity, heartbeat, respiration) such that the centre of mass (COM) is maintained over the base of support (Cavanaugh et al., 2005a). Our work also tested postural steadiness (i.e. maintain a desired postural orientation against internal perturbations, with no external perturbations). We found that over time (between subsequent testing periods; every 4 weeks), all testing measures decreased (as demonstrated by mean differences from baseline). All testing measures appeared to have gradually decreased (Figures 4 – 8) from the first test session to the third, while returning towards baseline values at the third (EO, LLU, RLU), or fourth (EC, EC/AO) to the post test session, which results in the post testing session not being significantly different than baseline measures. The decreases with the early test sessions represented changes in postural steadiness (that are contradictory) as diminished ApEn and increased TE, MnVel and MPF. Baseline values compared to the first test session had the largest average mean value for all measures with all other subsequent testing sessions having lower mean values. With the linear variables (MnVel, MPF and TE), this corresponds to an increase in postural steadiness through the testing period, with the decrease in ApEn corresponding to a change in postural control. However, the decrease across all measures and trials, appeared to level off and to a certain degree, reflect back towards baseline over the course of the season. No measure fully returned back to baseline values after decreasing from baseline. This demonstrates that through the season, postural steadiness became unsteady, with the greatest difference being found from baseline to the first testing session, indicating that this was the greatest amount of unsteadiness during the whole testing period, which gradually became steady again through the testing period. Unsteadiness was present in the first to second, second to third and third to fourth test session, also (across all

measures) but with less change compared to the baseline to first test session time period. Natural philological changes in COP oscillations with effects of training and game play impacts (i.e. sub-concussive forces), could have led to the pattern seen in all measures through the season.

Entropies are among the most popular and often considered the most promising complexity measures for biological signal analyses (Gao et al., 2012). Various types of entropy measures exist, including Shannon entropy, Kolmogorov entropy, approximate entropy (ApEn), sample entropy and, multiscale entropy (Gao et al., 2012). According to Gao et al. (2012), a fundamental question to answer when using nonlinear dynamics, is which entropy should be chosen for a specific biological application. Gao et al. (2012) solved this by focusing on scaling laws of different entropy measures and introduced an ensemble forecasting framework to find the connections among them. In this study, ApEn was chosen since it was previously used in ice hockey player concussion studies (Cavanaugh et al., 2005a; Cavanaugh et al., 2006). Cavanaugh et al. (2005b) conducted a study to determine whether ApEn could detect changes in postural control after cerebral concussion among athletes with postural instability signs. They hypothesized that COP oscillations would become less random (more regular) in the acute stage following concussion (Cavanaugh et al., 2005b). Less random output is thought to be produced by systems that are relatively more constrained (Newell, 1998). None of the athletes in our study were tested within the same "acute" time frame as Cavanaugh et al. (2005b, 2006). However, focusing on non-concussed athletes data from baseline through to the post testing session, there was a decrease in ApEn values, representing increased COP regularity and changed postural control (Cavanaugh et al., 2004; 2005b; 2006). COP regularity was less random in all non-concussed athletes in the test period from baseline to post. Linear measures indicate (particularly

between the testing session periods of baseline to first and baseline to second, in all measures) decreased randomness, with decreased AP and ML movements (in TE), and deceased MPF and MnVel (velocity of sway during standing balance). Both linear and nonlinear measures appeared to have gone through a similar pattern with diminished postural randomness in their respective measures, during the periods indicated.

Previous studies have measured concussed athletes COP, at discrete time intervals, using linear and nonlinear measures (Cavanaugh et al., 2005a; 2005b; 2006). Cavanaugh et al. (2005b, 2006) observed if ApEn could detect changes in postural control in (men and women) concussed athletes during quiet standing, post-cerebral concussion. Athletes sustained their concussions during sport practice or competition from 1997-2003. Prior to the preseason training baseline measurements of the subjects were taken, in contrast to our study were baseline measures were taken after the regular season had begun. Subsequent balance assessment was performed within 48 hours post-concussion (Cavanaugh et al., 2005b) and in Cavanaugh et al. (2006) balance assessment was performed 48 hours and 48-96 hours post-concussion. Results showed that compared to healthy subjects, COP oscillations among athletes generally became more regular (lower ApEn values) after injury despite absence of postural instability (Cavanaugh et al., 2005b). Similar results were found in Cavanaugh et al., 2006 study with ApEn generally declining immediately after injury. According to Cavanaugh et al. (2004), sensory information can be withdrawn or degraded following concussions with COP oscillations becoming more regular (lower ApEn) and larger in amplitude (diminished postural stability). Collection of COP data with linear and nonlinear measures on all athletes (concussed and non-concussed) over the course of a regular season, to record the in-season change in COP, has not been previously

studied. This offers a unique chance to observe and record in concussed and non-concussed athletes, variations that can occur through a season. These variations should be acknowledged when force plate studies are used in concussion and non-concussion identification, for the purpose of RTP guideline specification. Our work removed any data from concussed athletes and even in so doing, ApEn values became more regular. Our results indicated that a similar trend existed across all trials as we demonstrated a significant decrease in ApEn mean values from the first to third test sessions. However, these findings were also shown in linear measures, across all trials. ApEn changes never occurred in isolation, with linear measures changing as well through the testing season. Our study did not test 48 hour or 48-96 hour post-concussion, focusing on testing "healthy" subjects every 4 weeks (regular intervals). The decrease in ApEn (which is especially prominent as the decrease from baseline to first test session, in all trials) represents a time interval of 4 weeks, where no athlete suffered a concussion, yet had significantly diminished postural steadiness. In Cavanaugh et al. (2005b; 2006) changes in COP became more apparent 48 hours to 48-96 hours post-concussion. Direct comparison of our findings to Cavanaugh et al. (2005b; 2006) is difficult, nonetheless, recording non-concussed athletes through a season, our study was able identify the in-season variability of balance postures, using measures utilized by Cavanaugh et al (2005b; 2006). Comparing baseline measures with post-concussion testing and in-season variability can more accurately tease out and confirm abnormal, clinically significant impairments the athlete may be still suffering with, that otherwise would not be apparent if just comparing post-concussive values with baseline for RTP determination.

Slobounov et al. (2012) implemented a concussion assessment protocol combining a series of EEG and balance measures throughout one-year post-concussion to document the

efficacy of EEG and balance measures as they relate to recovery from mTBI. Approximately 380 subjects at risk for mTBI were initially recruited for baseline testing, 49 (31 males; 18 females) suffered a single episode of a sport-related concussive blow and were tested 7, 15, 30 days, 6 months and 12 months post-injury (Slobounov et al., 2012). EEGs were recorded while subjects were sitting with various postures on a force plate, with some trials being performed with eyes closed (Slobounov et al., 2012). COP measures were obtained from a force plate and analyzed for eyes open verse eyes closed conditions (Slobounov et al., 2012). Postural analysis was obtained as a percent change in COP area. Percent alpha power suppression from sitting to standing postural conditions significantly increased shortly after injury, with the power suppression correlating with increased area of COP during standing postures with eyes closed (Slobounov et al., 2012). The authors did not indicate the time interval between tests, how long each subject was standing in each posture or if multiple trials were conducted on a given testing date. This could affect the reliability of COP data obtained. In our study, standing EO and EC trials were performed as independent trials, with linear and nonlinear measures being evaluated. EO and EC trials (for the linear measures) showed a gradual decreasing pattern through our testing time period (with some measures mildly returning) showing increased postural steadiness, even though no concussed athlete data was used. This can be readily seen with TE, which showed decreased AP and ML movements through the first half of sessions, across all trials. Slobounov et al. (2012) did not indicate if the increased area of COP during standing postures with eyes closed was an overall pattern seen at the end of the study or through particular time points of testing. Our study EO and EC trials, began to show return (in the linear measures) towards baseline (where COP area was highest) values at the third and fourth test sessions, establishing an increase in postural stability

The responsiveness of ApEn to evaluate the immediate, short-term effect of secondary cognitive task performance on postural control of healthy adults has been researched (Cavanagh et al., 2007). Thirty healthy young adults performed posture only and dual (posture plus cognitive) task, where ApEn, root mean square (RMS) displacement and equilibrium scores (ES) were calculated in the AP and ML directions (Cavanaugh et al., 2007). Results showed that COP AP time series generally became more random (higher ApEn value) during a dual task performance, but there was no significant effect of cognitive task for ApEn values of COP ML times series, RMS displacement (AP or ML) or ES (Cavanaugh et al., 2007). The authors concluded that during dual task performance, ApEn revealed a change in the randomness of COP oscillations, independent of changes in the amplitude of COP oscillations (Cavanaugh et al., 2007). This pattern appeared to have occurred in our study, where ApEn values were independent of changes in COP values during standing postures without dual task performance. In our study, without dual task performance, ApEn values decreased (i.e. become less random and more ordered) through the course of the testing season (Figures 4 - 8). Cavanaugh et al. (2007) determined that their findings added additional evidence to support ApEn as a potential means to detect subtle changes in postural control. Changes in postural control were evident in our study in ApEn on a healthy population. During performance of a secondary cognitive task, ApEn detected a change in COP variability that was not detected by RMS or ES (Cavanaugh et al., 2007). The authors explain that this is because ApEn considers the sequential order of neighboring data points in COP time's series and where RMS values and ES reflect the overall magnitude of COP displacement, without consideration of temporal order (Cavanaugh et al, 2007). Interestingly, the largest mean ApEn changes were only equivalent to approximately one

standard error of measurement (Cavanaugh et al., 2007). However, does the relatively small change indicate a clinical significance? This was not questioned by Cavanaugh et al. (2007). ApEn was shown to detect subtle changes that the linear measures could not, and the change detected was small (Cavanaugh et al., 2007). Clinically, this may not present as an overall gross balance disturbance from COP variability during standing postures. Our study showed conflicting changes in ApEn and linear (MnVel, MPF, and TE) measures through the testing time course that were statistically significant. This can be the result of subject adaptability through a regular season and building of sub-concussive forces. Utilizing both linear and nonlinear measures to evaluate COP together can present a "complete picture" of the overall COP variance.

There was a clear and consistent pattern seen in all of our measures, for each trial through the testing season (Figures 4 - 8). Generally, in all variables there was a gradual progressive decrease in mean difference values from baseline to first, third and fourth, with some measures showing a return back towards baseline values at the third and post test sessions. We propose two mechanisms to explain this pattern: training/adaptation and building of sub-concussive forces. From initial try-outs through the regular season, both the men and women's practices and training (i.e. dryland and on ice training) focused on hockey fundamentals reinforced through drills, such as passing, shooting and plays. Gradually over time through practices and games, athletes may have had their balance adapted and improved, as a result of the fundamental aspect of ice hockey; balancing and skating on two thin blades of metal on a sleek sheet of ice. This can explain the overall pattern indicted through all measures from first to post test session. The pattern seen in COP for the different measures in our study could also likely be due to repeated

subconcussive impacts, accumulating though the season. The subjects had their summer off from ice hockey and other sports that could involve contacts. When the ice hockey season started, contact sustained by most of the subjects would have risen dramatically. While it is still unclear if multiple impacts pre-dispose an athlete to injury (i.e. high number of impacts lowers a player's threshold of injury) or if the athlete simply has a higher risk of injury from a single event due to the higher number of impacts sustained (Gysland et al., 2012), it is clear that the number of impacts a player sustains is a key measure to consider when evaluating the link between head impact and injury (Beckwith et al., 2013). Since in our study, baseline measures were taken after preseason and a number of regular season were already played, multiple head impacts likely occurred to many athletes. Subconcussive impacts could have begun building, altering postural control, thus blurring the difference between injury and non-injury, since a true unbiased preseason, no previous impact baseline was taken. Through successive contacts (i.e. falling on ice, athlete-to-athlete contacts) and non-contact (quick stop and go), multiple sub-concussive forces could have built quickly from initial practices and pre-season games. Initial contact forces could have disrupted COP in the short term (as indicated by ApEn values being increased from baseline to first) with most athletes adapting over time, as seen in the pattern in all measures from second to post testing session. An inter-play between training/adaptation with sub-concussive forces may have impacted the measures, leading to the overall pattern seen through the season. Sub-concussive forces could have impacted the athletes early on in the season. The initial impacts could have affect motor control, with training/adaptation making a presence after a few months into play (i.e. practices and games), increasing motor control, through integration of motor patterns of skills used in hockey.

3.5 Conclusion

Both balance training and adaptation along with accumulation of sub-concussive forces may have played a role in the unique pattern seen between linear and nonlinear measures over the course of a regular season in the ice hockey teams. The linear and nonlinear measures followed similar patterns through time, indicating that even though the measures are different, they can display similar patterns, measuring changes together. Where significant changes were indicated, both linear and nonlinear measures were present. There was no discernible pattern of significance with the linear and nonlinear measures through the course of the study. Both measures should be utilized when recording baseline, in-season and post-concussive balance data. To our knowledge, no one has recorded the in-season variability of balance postures with measures utilized in this study. Understanding how COP can change (as recorded by linear and nonlinear measures) in-season between baseline and post-concussion balance tests, can create a more detailed picture of the injured athlete's current state, improving RTP guidelines. Combining pre-season and post-concussion measure values with patterns of variations of the measures, the overall change from where the athlete started (pre-season) verse post-concussion, could be better understood. Values of the measures would hold more weight in determining safe RTP, since the values would be better understood in terms of how they relate to true balance disturbance resulting from a concussion. Sport specific training and musculoskeletal demands required to perform particular skills of the sport, along with acute to sub-acute injuries associated with the physicality of play, will affect in-season metrics (as used in this study) uniquely for a sport. Future studies should focus on in-season variability in different sports. The in-season variability may be sport specific since training, and musculoskeletal demands vary from sport-to-sport.

Chapter 4: Future Considerations

The current study is not without considerations. None of the participants had independent medical orthopedic or neurological examination prior to commencement of the study. This was not evaluated in similar studies (Cavanaugh et al., 2005b; Cavanaugh et al., 2006; Cavanaugh et al., 2007). The implications are that present and ongoing undiagnosed neurological conditions could predispose the subject to balance inequalities, may have been present, biasing results. Moreover, none of the subjects were screened (tested and/or questioned) for alcohol consumption, medication use, level of alertness or other variables (i.e. lower extremity weight training, caffeine consumption) that would compromise or interfere with postural performance tests, prior to each testing session. In Cavanaugh et al. (2007) all subjects were non-smokers and denied ingesting within 24 hours prior to testing any substances (dietary, pharmacological, or recreational drug) that might affect motor performance. In addition to that, to avoid potential physiologic confounders, subjects were required to avoid vigorous physical activity within 2-hours of testing and to be free of pain, dizziness, or unusual fatigue (Cavanaugh et al., 2007). Without instituting these measures prior to testing, participants could have altered postural steadiness that did not result from participation in hockey, potentially skewing results.

Subject lifetime history of concussion or participation in other sports during the 2014/15 school year, was not inquired prior to commencement of the study as in Cavanaugh et al. (2005b). Previous history of mTBI's could have altered subjects COP, being recorded as "normal" during baseline measurements. Altered COP oscillation patterns that are still present during time of study. Musculoskeletal injury sustained either before baseline, between monthly

testing periods, or at the time of concussion (if athletes sustained a diagnosed concussion) was not recorded. Participation in others sports during the season, such as football, soccer, rugby or basketball can increase risk injury (Marar et al., 2012; Harmon et al., 2013), skewing standing balance posture measurements. In addition, these sports also have high incidence of sport concussions. Athletes could have sustained concussive blows during other sport activities, not reporting to their hockey trainers, coaches or researchers altering results of recorded standing postures. Furthermore, balance impairments have been shown to occur in the initial postconcussion period, from 1-10 days (Cripps and Livingston, 2013). In the course of this study, 2 of the 5 concussed men and no concussed women had their first post-concussion testing performed within this time period (5-days and 6-days post-concussion). When viewing individual data, specifically of the concussed athletes, discernible patterns in differences in their COP over the trials could have been identified when compared to the rest of the uninjured study population.

Participants foot outlines were not traced on the force plate to ensure consistent foot positioning between standing trials, as done in similar COP studies (Cavanaugh et al., 2007; Kooij et al., 2011). Foot placement was standardized based on subject height according to manufacture guidelines in Cavanaugh et al., (2007). Shifting feet position within and between testing session, on the same subject, could have altered COP during standing postures. Consistency in foot position could have ensured more accurate COP data. The potential confounding effect of fatigue was not accounted for in the study as well. Kooij et al. (2011), repeated their analysis on the same data, but in reverse order, with incrementally longer sample durations beginning at 600 s, and extending backwards in time, on standing balance EO and EC.

Their results demonstrated that fatigue had little effect on overall findings. The Kooij et al. (2011) study also revealed that the range of COP movements is noticeably larger when recorded over a 600 s compared to 60 s sampling duration. Furthermore, differences between EC (eyes closed) and EO (eyes open) become obvious only when considering the entire 600 s sample. The present study utilized 120 s sampling duration for each session, including EO and EC. Even though the 120 s is substantially shorter in time compared to 600 s, noticeable differences were found in mean values for all measures (except mean velocity) for EO and EC.

The number of participants varied per session, ranging from a max of 21 participants (baseline) for the men and 23 (Second) in women to a minimum of 7 (Post) in the men and 8 (Post) for the women. Inconsistency of participant numbers through each trial could have skewed data by under or over estimating tested variables resultant values. Moreover, conducting baseline measurements after the start of the regular season (and not during pre-season) could have impacted the data recorded. The several practices and games prior to baseline recordings offered an opportunity for head trauma that could have led to mTBI's or at the very least, a building of sub-concussive forces that may have altered standing postures and COP, resulting in skewed or non-typical baseline recording for athletes, compared to non-injured or altered states.

Other studies where standing balance data was recorded for increasing durations from 10-60 s showed that at least 30 s would be sufficient for data reliability (Le Clair and Riach, 1996). Alternative studies have suggested durations greater than 60 s (Carpenter et al., 2000; Lafond et al., 2004; Doyle, et al., 2007). To ensure reliable DMs (descriptive measures), averaging together a number of shorter trials whose net duration exceeds 300 s has been proposed as an effective

alternative to collecting a single long standing trial (Kooij et al., 2011). The length of time for all five standing balance trials in our study was 120 s. This time frames falls into some previous study recommendations for accurate COP data.

During our trials, participants were not given any specific instructions while performing the various standing balance postures, as per previous literature, other than to “stand still” (Yardley et al., 1999; Zok et al., 2008). The kind of standing posture a subject is instructed to maintain can influence the postural exam conducted (Zok et al., 2008). This study investigated whether instructions issued in traditional posturographic test influence outcome (Zok et al., 2008). Two groups were issued one of two common instructions, “stand quietly” or “stand as still as possible”, by means or projected instructions. Results indicated instructions strongly influence outcomes (Zok et al., 2008). Yardley et al. (1999) determined that increased postural instability produced by mental task was due to perturbation of posture by articulation. Articulation by participants resulted in significant sway (Yardley et al., 1999). During the trials, participants remained as silent as possible, with no verbal communication between the participant and researcher. This interpretation was also suggested that instructions to "stand as still as possible" during the posture-only task placed a somewhat unusual (novel) constraint on what commonly is a well learned yet unrestricted task (standing quietly). By focusing attention on the task of standing still, subjects may have artificially constrained the interactions among underlying postural control system components, thereby increasing the regularity of the output signal (Vuillerme et al., 2000; Roerdink et al., 2006; Cavanaugh et al., 2007).

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APPENDIX

Name: _____

DOB: _____

Height: _____

Weight: _____

1 – Eyes Open
2 – Eyes Closed
3 – Eyes Closed/Arms Out
4 – Left Leg up
5 – Right Leg up

File Number	Trial Number

VERBAL RECRUITMENT SCRIPT

I am informing you that my research team is currently recruiting male and female UOIT collegiate ice hockey players for our study. We are studying the use of nonlinear analysis techniques to improve postural stability measurements and movement variability recordings, which result from concussions and sub-concussive forces. We predict that the analysis techniques used can lead to improved safe return-to-play guidelines. Your coaching staff are have already been informed of this work and are supportive of it.

If you would like to know more about the study, the researchers have copies of the consent form to be viewed and researchers will be available to answer any questions you may have prior to signing the informed consent. Participation is strictly voluntary, being free to withdraw or discontinue the study at any time, without consequence. Any participant that withdrawals from this study will have their data permanently discarded and all paper copies (consent form, etc.) will be destroyed. Participants will be asked to provide contact information if they would like to receive additional information about the outcome of the study, including a summary of the results.

Your participation will require your involvement throughout the hockey season. You will be required to come to the lab for approximately 15 minutes, once a month throughout the season. We will try our best to schedule this at convenient times for you (i.e. immediately before practice). We would like you to know that your coaches are supportive of this work, so you do not have to worry about them being concerned with the small time commitment. However, it is equally important for you to know that you do not need to participate. Participation is completely voluntary and the coaches will not be aware of who participated.

If you have any questions, please feel free to contact me via email or phone. Thank you for listening,

Marco De Ciantis
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INFORMATION CONSENT FORM

Research Title: ***Evaluating a standing balance test using nonlinear dynamic analysis to appraise safe return-to-play from concussion***

You are invited to participate in a research study entitled "**Evaluating a standing balance test using nonlinear dynamic analysis to appraise safe return-to-play from concussion**". This study (REB#: 14-018) has been reviewed by the UOIT Research Ethics Board and has been approved as of (Date: September 9th, 2014). Please read this form carefully, and feel free to ask any questions you might have. If you have any questions about your rights as a participant in this study, please contact the Compliance Officer at 905-721-8668 ext. 3693 or compliance@uoit.ca

Researchers

Dr. Marco G De Ciantis, BSc (Hons), DC, Sports Science Resident, MSc (Candidate), Faculty of Health Sciences, University of Ontario Institute of Technology, Phone: (647) 688-8852, email: marco.deciantis@uoit.net

Dr. Michael Holmes, Assistant Professor, Faculty of Health Sciences, University of Ontario Institute of Technology, Phone: (905) 721-8668 ext. 6587, email: michael.holmes@uoit.ca , Fax: (905) 721-3179

Purpose of the Study
The fast and random nature of ice hockey makes injury prevention a challenge and to date there have been no studies on the accuracy and/or reliability of one particular data analysis technique (nonlinear dynamic testing) using an ice hockey population. This study will record standing balance data from hockey players over the course of the season and then use this analysis technique to determine if the technique can be used to better identify dysfunctions resulting from diagnosed concussions in collegiate ice hockey athletes.

Potential Benefits to Participants and/or to Society
By participating in this study you will contribute to our goal of improving the safe return-to-play (RTP) prediction measures through stricter testing.

Participation and Withdrawal
Your participation in this study is voluntary. You may withdraw from this study at any time without penalty. To do so, indicate this to the researcher or one of the research assistants by saying, "*I no longer wish to participate in this study*". If you wish to withdrawal from this study your data will be permanently discarded and all paper copies (consent form, etc.) will be destroyed.

If you wish to withdraw consent after the study has ended, please contact one of the researchers on this project and they will remove you from the study.
Rights of Research Participants

You are free to ask any questions that you may have about your rights as a research participant. You may withdraw your consent at any time and discontinue participation without penalty. If any questions come up during or after the study or if you have a research-related injury, contact the study researchers listed on the first page.

Should you have any questions or concerns regarding your rights as a participant in this research study, or if you wish to speak with someone who is not related to this study, you may contact the UOIT Research Ethics Board through the Compliance Office (905) 721-8668 ext. 6393.

Eligibility

Twenty-two male and female participants (age range, 17-25 years) are being recruited from the UOIT ice hockey teams. We are also only seeking individuals who have no previous history of traumatic brain injuries (TBI), suffered within 12 months of the project start date. In addition to any athlete with a history of cerebellar or spinal cord injuries, muscular dystrophies and Multiple Sclerosis.

Procedures Involved in this Study and Time Commitment

Description

Overview: Standing balance tests will be performed on a force platform throughout the regular ice hockey season and a nonlinear dynamic testing analysis will be implemented as a data analysis technique. The goal is to improve safe RTP prediction measures through stricter testing.

Simulated tasks: Prior to the beginning of the 2014 fall extramural Male and Female ice hockey season; participants will undergo baseline measurements. Preceding the initial measurements, upon arrival to the laboratory, you will be familiarized with the lab equipment and protocols. Baseline measures will be conducted in the UOIT Kinesiology laboratory by study investigators.

Once familiarized with all tasks, postural sway will be measured using a ground mounted force platform (Advanced Mechanical Technology, Inc., Watertown, MA, United States) by tracking centre of pressure (COP) in the anterior-posterior and medial-lateral directions, over the base of support, during simple tasks such as standing posture and other balance tests.

Protocol: You will be required to stand on a force plate and perform a series of trials, each lasting for 2 minutes. Participants will stand on the force plate in a variety of conditions, including:

1. standing - feet shoulder width apart, participant is looking forward, with arms down by their side
2. standing - eyes closed, with the same stance as indicated above
3. standing - eyes closed, arms stretched out in front at 90 degrees forward flexion with feet shoulder width apart
4. standing - on one foot; with contralateral leg bent to 25-30 degrees, with the ankle kept in sub-talar neutral with no dorsi- or plantar-flexion, and arms down by the participants side and eyes facing forward
5. standing - on one leg, on other foot, in same stance as indicated above

These tests will take approximately 15 minutes in total, but you will return to the lab once a month over the course of the season to perform these tests.

The COP data will be analyzed by using non-linear dynamic analysis calculations to identify postural sway differences over time. Concussion assessment will be carried out by a third party qualified Sports Medicine Practitioner (MD) present at every regular season game, utilizing common practice sideline concussion objective measures (SCAT3). The practitioner will have no connection to the proposed study either academically or monetarily. Subsequent suspected concussion investigation with injured subjects will be set with the Sports Medical Practitioner at a later date. Regardless of suspected concussion, all participants will be re-tested at the end of the study, post-season in the lab.

Upon completion of the study, each participant will be given a feedback letter that reiterates the details of the study and implications of the findings. Anticipated results will also be provided. Participants will be asked to provide contact information if they would like to receive additional information about the outcome of the study, including a summary of the results.

Timeline
Including instrumentation and experimental setup, it is expected that you will be in the UOIT Kinesiology Laboratory for approximately 10-15 minutes (including set-up time, instructions before each stance and 30second rest between different stances) for each in lab testing session (baseline pre-season, season and post-season). A schedule for dates and times will be coordinated through the PI, respective coaches and Kinesiology Lab coordinator prior to the beginning of the regular playing season. Dates will be booked well in advance so you will be aware of the testing schedule, after baseline measurements have been done, through a verbal reminder and schedule sheet.

Risks and Discomforts
There may be minimal risk associated with this study. All tasks being simulated in the lab will be the same as those encountered in activities of daily living and considered to be minimal risk to the participants.

None of the study investigators teach the athletes that are being recruited, so there is no potential for participants to feel coerced into contributing to this research.

Compensation for Participation
No monetary compensation will be given for volunteering in the study.

Disclosure
Your identity will be kept confidential and only made available to the researchers. You will be identified only by a subject identification code during the data collection phase of this study. Only the researchers will have access to the actual identities of the participants, even during release of the study findings. All data will be stored in a secure area (UAB 346), locked in the investigator's filing cabinet or on a secured computer. We will use arbitrary ID numbers for linking your longitudinal data over the duration of the study. We will then delete the master key of those ID numbers 30 days following the final data-collection session, to ensure that the data remains anonymous. Therefore, after this time, your data will be complete anonymous and we will not be able to dispose of it.

Please read the following before signing the consent form and remember to keep a copy for your own records.

By signing this form, I agree that:

- The study has been explained to me. All my questions were answered to my satisfaction.
- The possible harms and discomforts and the possible benefits (if any) of this study have been explained to me.
- I know about the alternatives to taking part in this study. I understand that I have the right not to participate and the right to stop at any time.
- The data collected in this study will be kept in a locked filing cabinet, and/or stored on a password protected computer at UOIT, Oshawa, Ontario.
- I hereby consent to participate.
- By consenting to participate, I do not waive any legal rights or recourse in the event of research related harm.

I, ……..... agree to take part in this research.

- I have read and I understand the information for volunteers taking part in the study "**Evaluating a standing balance test using nonlinear dynamic analysis to appraise safe return-to-play from concussion**". I have had the opportunity to discuss this study. I am satisfied with the answers I have been given.

Thank you very much for your time and help in making this study possible. If you have any queries or wish to know more please contact Dr. Michael Holmes, an Associate Professor at the University of Ontario Institute of Technology, Faculty of Health Sciences, 2000 Simcoe St North, Oshawa, Ontario, L1H 7K4
Phone (905) 721-8668 ext. 6587 Fax (905) 721-3179 email : michael.holmes@uoit.ca

For any other queries regarding this study, please contact the UOIT Research and Ethics Committee Compliance officer (compliance@uoit.ca and 905-721-8668 ext. 3693).

I, the undersigned, have fully explained the relevant details of this research study to the participant named above and believe that the participant has understood and has knowingly given their consent.

_____ _____

Printed Name Date

_____

Signature

_____

Role in the Study (only authorized / qualified member of the research team)

Signing this form gives us your consent to be in this study. It tells us that you understand the information about the research study. When you sign this form, you do not give up your legal rights. Researchers or agencies involved in this research study still have their legal and professional responsibilities.

AVERAGE TABLES

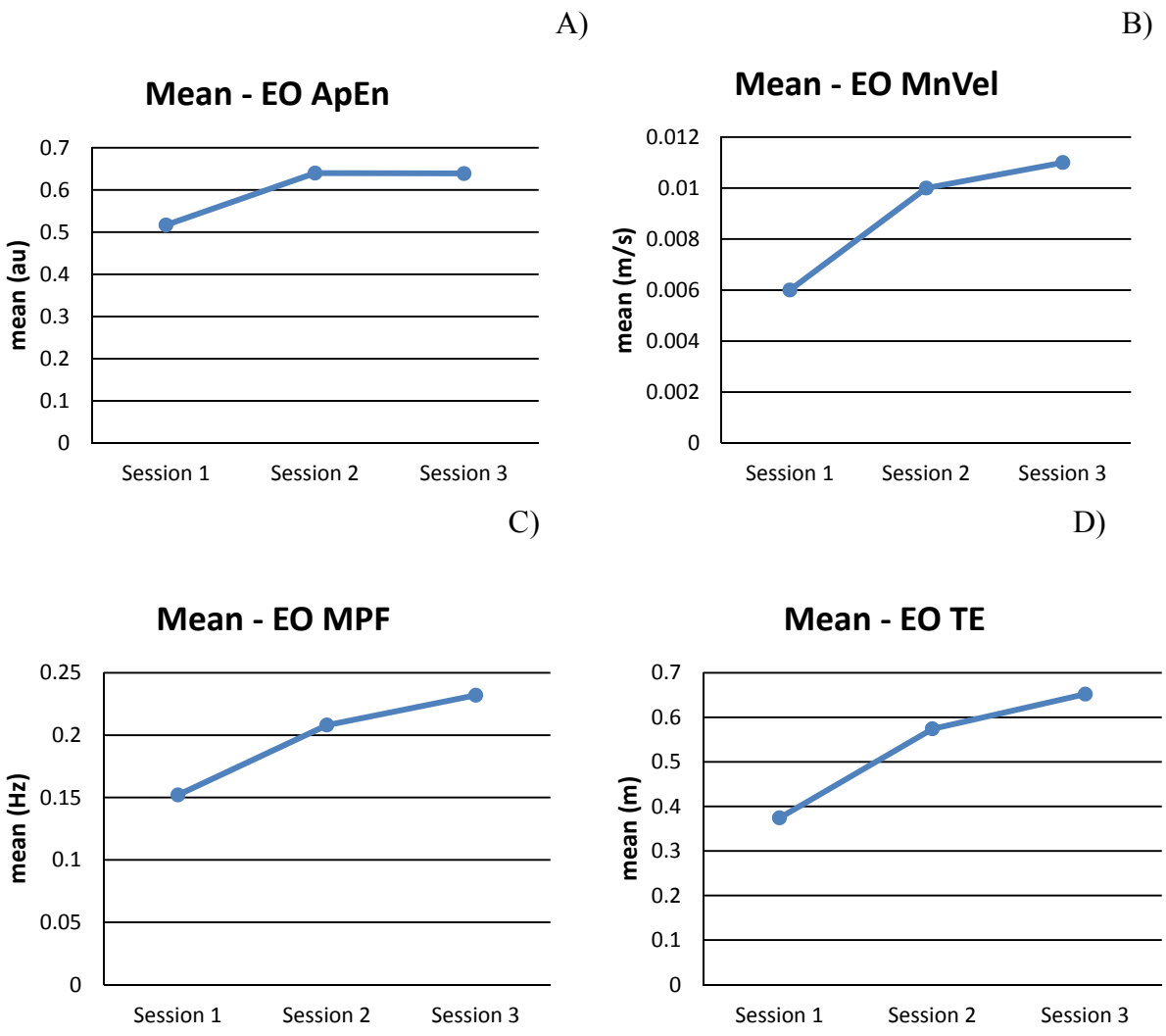

Figure 9: Average for baseline with session 1, session 2 with session 3, and session 4 with post, for the eyes open condition. A) ApEn; B) MnVel; C) MPF; D) TE.

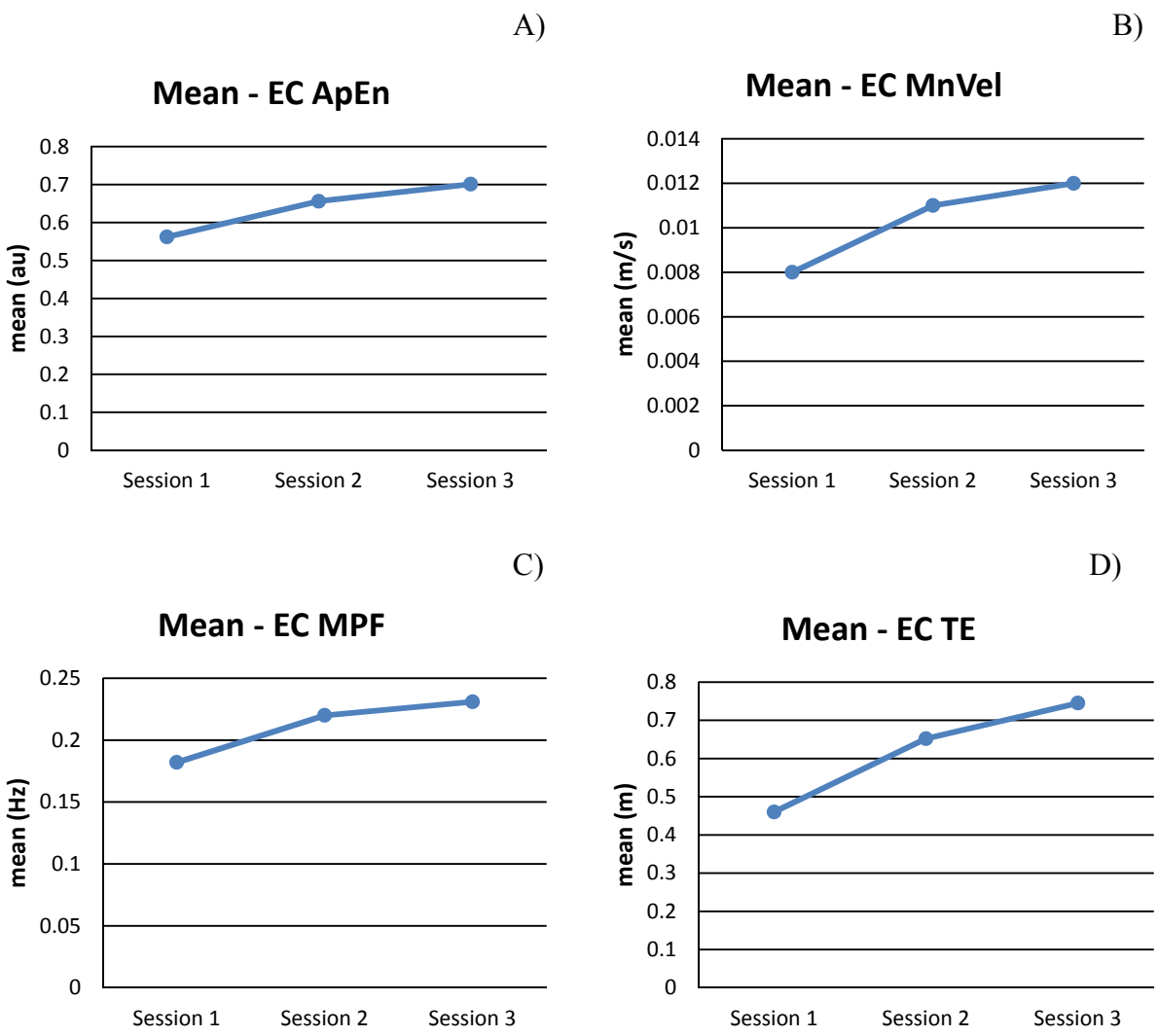

Figure 10: Average for baseline with session 1, session 2 with session 3, and session 4 with post, for the eyes closed condition. A) ApEn; B) MnVel; C) MPF; D) TE.

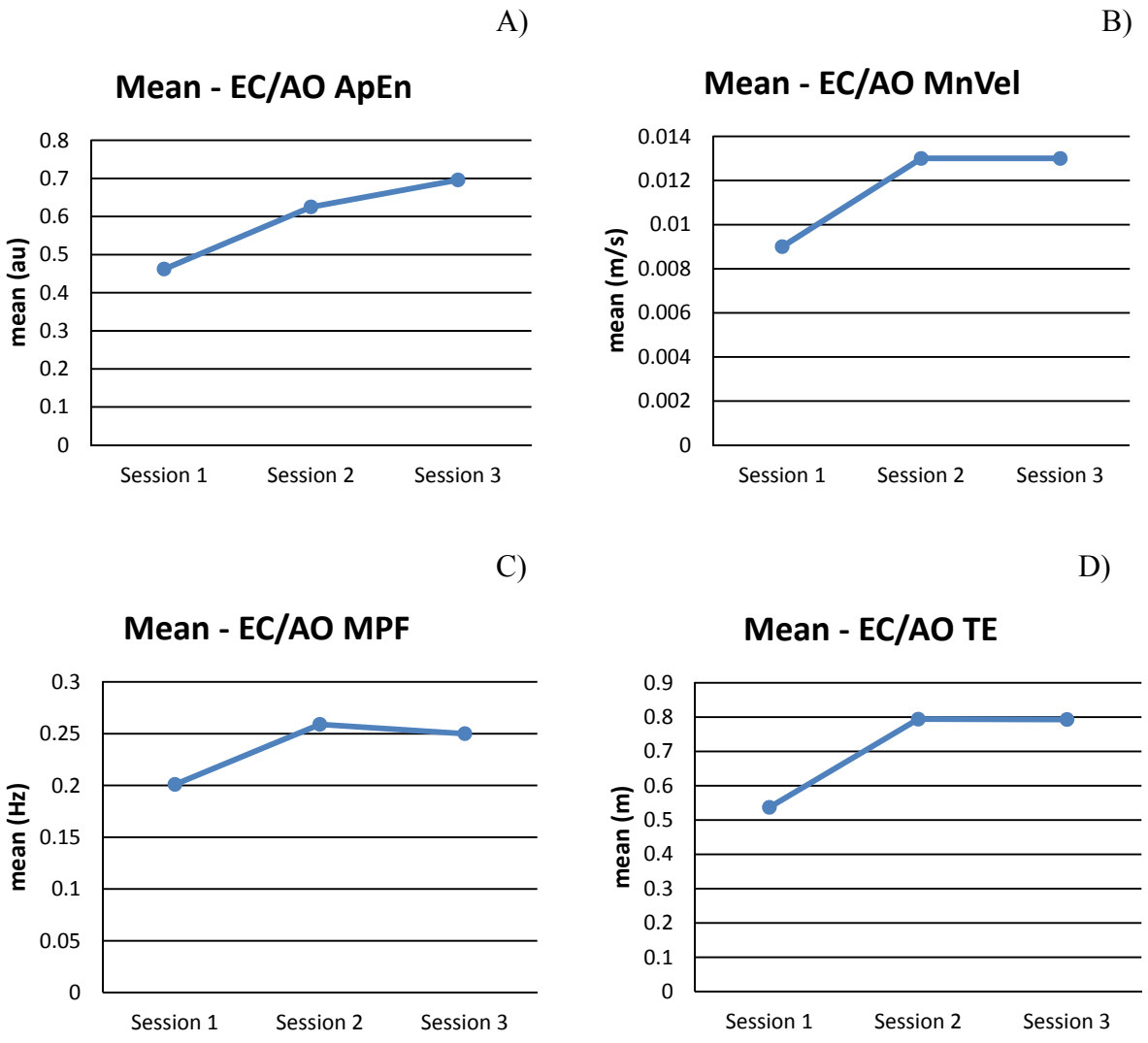

Figure 11: Average for baseline with session 1, session 2 with session 3, and session 4 with post, for the eyes closed and arms condition. A) ApEn; B) MnVel; C) MPF; D) TE.

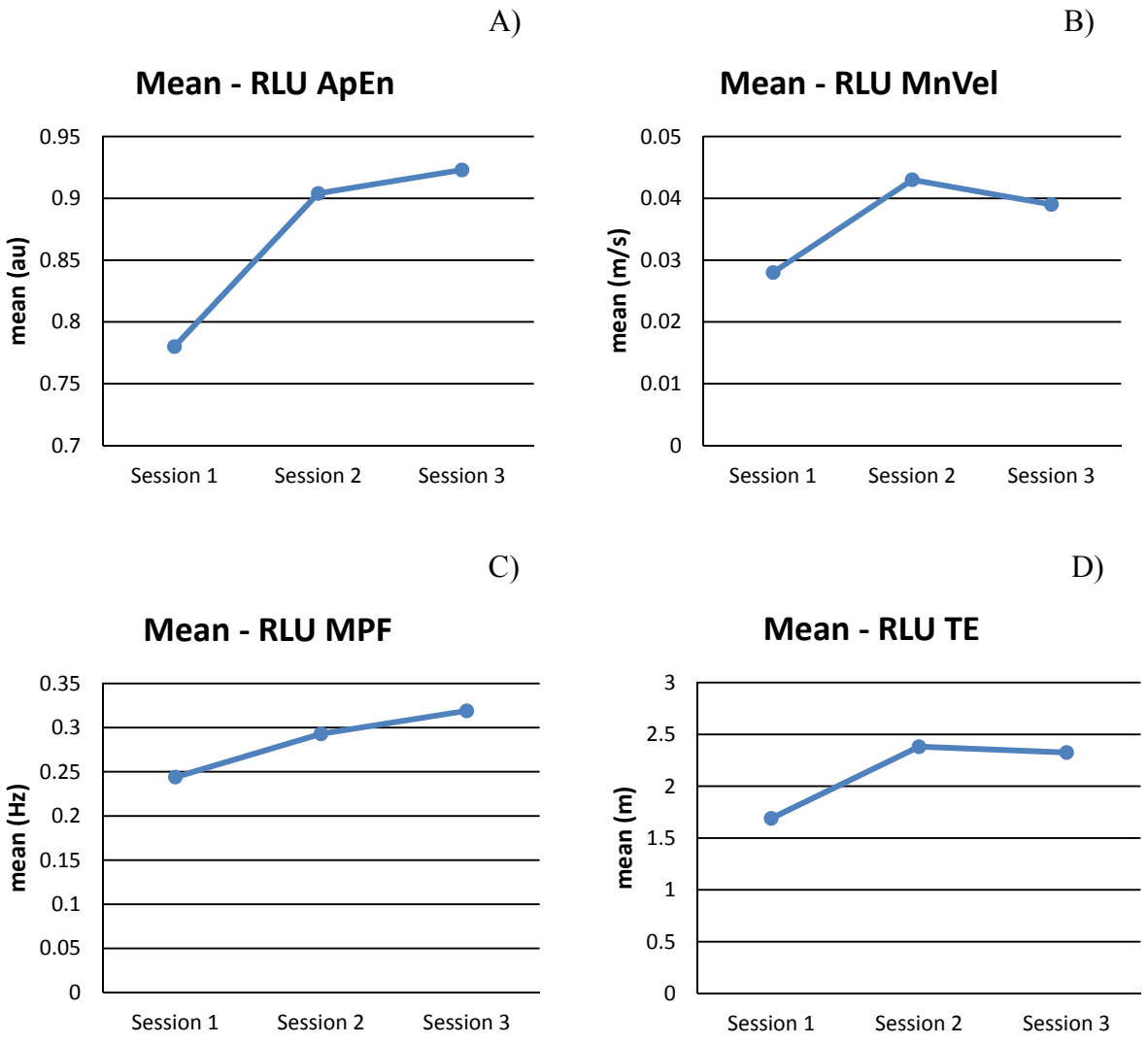

Figure 12: Average for baseline with session 1, session 2 with session 3, and session 4 with post, for the right leg up. A) ApEn; B) MnVel; C) MPF; D) TE.

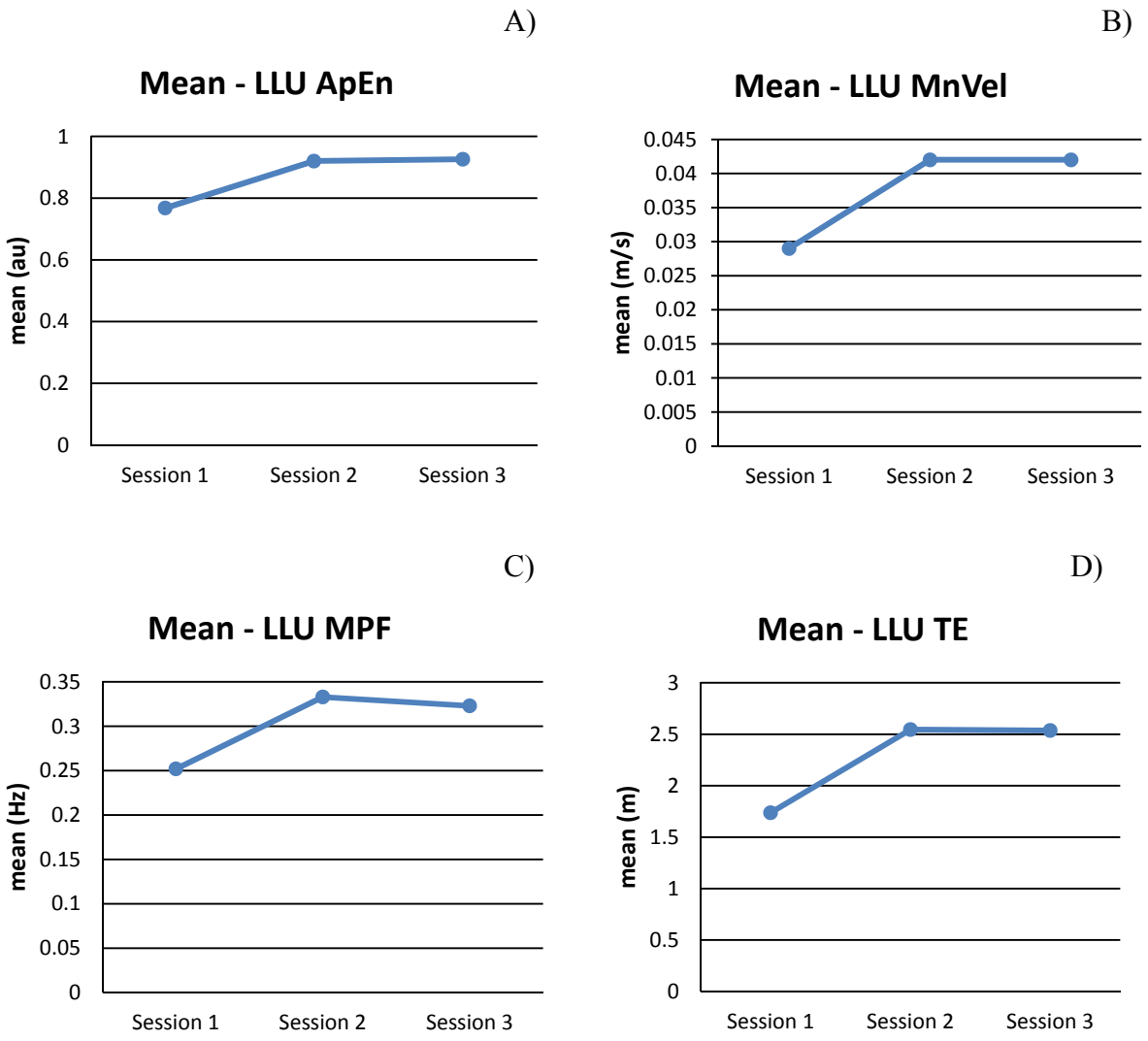

Figure 13: Average for baseline with session 1, session 2 with session 3, and session 4 with post, for the left leg up. A) ApEn; B) MnVel; C) MPF; D) TE.