The Recovery of Postural Control Following a Concussion in Adults from the General Population

by

Michelle Sweeny

A thesis submitted in conformity with the requirements for the degree of Master of Science
Rehabilitation Sciences Institute
University of Toronto

© Copyright by Michelle Sweeny 2018
Abstract

Following concussion, dizziness and balance deficits are commonly reported symptoms. Although evidence in the athletic population exists, limited knowledge exists regarding balance deficits and recovery timelines in adults from the general population with concussion. Currently, the Balance Error Scoring System (BESS) is widely used for assessment of balance following a concussion in athletes. Limitations associated with the BESS have encouraged work using center-of-pressure (COP) metrics during quiet standing. This thesis determined balance deficits were present acutely following concussion (on average, 5-days post-injury) in self-reported symptoms, BESS score, and COP metrics. However, objective balance deficits did not accurately reflect self-perceived symptoms of balance problems or dizziness. When examining recovery longitudinally across 3-months post-concussion, limited recovery was observed in BESS score or COP metrics. This work highlights the importance of standardizing the assessment of postural control following a concussion. Future work should include measures of dynamic balance in the concussion assessment battery.
Acknowledgments

I would like to thank my supervisor, Dr. George Mochizuki for all of his invaluable guidance, mentorship, and support over the course of this degree. I would also like to thank the scientists on my committee including Drs., Elizabeth Inness, Mark Bayley and Paul Comper for their support and guidance over the past two years. To my fellow lab members including: Tyler Saumur, Myles Resnick, and Olinda Habib Perez, thank you for all of your support and for your friendship. I would like to thank everyone from the Hull-Ellis Concussion Clinic including: Tharshini Chandra, Evan Foster, Ryan Lyn, and Jane Cosgrove for their contributions to this work. I would like to thank Cynthia Danells for her help and mentorship in data collection. This work could not have been completed without each of these individuals’ contributions. Finally, I would like to thank all of my participants for their time in completing this study.
# Table of Contents

Acknowledgments................................................................................................................... iii

Table of Contents.................................................................................................................... iv

List of Tables ............................................................................................................................ viii

List of Figures ............................................................................................................................ x

List of Appendices ....................................................................................................................... xii

Chapter 1 Introduction ................................................................................................................ 1

1 Introduction ............................................................................................................................ 1

1.1 Background ......................................................................................................................... 1

1.2 Concussion .......................................................................................................................... 2

1.3 Balance and Postural Control............................................................................................... 4

1.3.1 Movement Strategies .................................................................................................... 5

1.3.2 Sensory Strategies .......................................................................................................... 5

1.3.3 Cognitive Processing ...................................................................................................... 6

1.4 Posturographic Measures of Balance ............................................................................... 7

1.5 Balance Deficits Following Concussion ............................................................................ 10

1.5.1 BESS ............................................................................................................................... 11

1.5.2 Posturographic Measures .............................................................................................. 12

1.5.3 Self-Reported Symptoms .............................................................................................. 14

1.5.4 Recovery ......................................................................................................................... 16

1.6 Rationale and Objectives ................................................................................................... 19

Chapter 2 Characterizing Balance Deficits Following Acute Concussion in Adults from the General Population: A Cross-Sectional Analysis .................................................. 23

1 Introduction ............................................................................................................................ 23

2 Methods.................................................................................................................................. 26

2.1 Participants......................................................................................................................... 26
2.2 Experimental Protocol ........................................................................................................27
  2.2.1 SCAT-3 Self-Reported Symptoms ...............................................................................27
  2.2.2 Equipment Set-Up .........................................................................................................27
  2.2.3 Quiet Standing ...............................................................................................................27
  2.2.4 BESS .............................................................................................................................28
2.3 Data Analysis .......................................................................................................................28
  2.3.1 Spatial Analysis .............................................................................................................29
  2.3.2 Spectral Analysis ..........................................................................................................29
2.4 Statistical Analyses ..............................................................................................................29
  2.4.1 Secondary Analysis .......................................................................................................30

3 Results ...................................................................................................................................30
  3.1 BESS .................................................................................................................................32
  3.2 COP Metrics ......................................................................................................................32
  3.2.1 RMS ...............................................................................................................................32
  3.2.2 Velocity .........................................................................................................................33
  3.2.3 Power Spectrum Density ...............................................................................................34
  3.3 Secondary Analysis ..........................................................................................................35
  3.4 Individual Data ..................................................................................................................37
  3.5 Cognitive Motor Dual-Task ..............................................................................................40

4 Discussion ..............................................................................................................................40
  4.1 Clinical Measures of Balance Revealed Deficits .............................................................41
  4.2 COP Measures During Quiet Standing Revealed Deficits .................................................41
  4.3 Self-Reported Symptoms is not a Reliable Method of Identifying Balance Deficits ........44

5 Conclusions ............................................................................................................................45

Chapter 3 The Recovery of Postural Control Following a Concussion in Adults from the General Population .................................................................46
1.3 Self-Reported Symptoms.................................................................75
2 Differences between Athletes and General Population Following Concussion.............76
3 Revisiting the Conceptual Model........................................................................78
4 Limitations ........................................................................................................79
5 Implications for Rehabilitation ...........................................................................80
6 Future Directions...............................................................................................81
7 Final Conclusions...............................................................................................82
References.............................................................................................................84
Appendices............................................................................................................99
List of Tables

Table 1. Methodological manipulations and measures used in this thesis to probe underlying mechanisms of postural control deficits. .............................................................. 21

Table 2. Demographics for CONC and HC. Significant differences are represented with *. .... 31

Table 3. Demographics for groups based on self-reported measures. .................................. 36

Table 4. Proportion of participants in the Both, Bal/Dizz and None groups, relative to upper limit of the 95% CI of HC. Participants in the ‘Within Both’ quadrant fall within 95% CI during the EO and EC or DT conditions. Participants that were within the 95% CI during EO but above the 95% CI for EC/DT are represented as ‘Within EO/ Above EC/DT’. Participants that were above 95% CI during EO but inside 95% CI for EC/DT are listed in ‘Above EO/ Within EC/DT’. Participants who were above the 95% CI for EO and EC/DT are represented in ‘Above Both’. 39

Table 5. Demographics and self-reported symptom score for CONC participants included in the Hierarchical Growth Curve Model. ................................................................. 55

Table 6. Residual and intercept covariance parameters and ICC values obtained from the Unconditional Means Model. Bolded values represent significance at the p<0.05 level. ........ 56

Table 7. Model parameters obtained from the Hierarchical Growth Curve Model. Bolded variables represent significance at the p<0.05 level. Standard error (SE) is included in parentheses. ............................................................................................................. 

Table 8. Proportional reduction in variability associated with Level-1 covariates (Within-Individual) and Level-2 covariates (Between-Individual). ........................................... 61

Table 9. Normative data for n=19 HC including mean, standard deviation (SD) and the upper limit of the 95% confidence interval (CI). ......................................................... 62

Table 10. Participant demographics and self-reported symptom score for CONC participants across time. ........................................................................................................... 63

Table 11. Average CV values across Week 1, 2, 4, 8 and 12 for n=19 HC. .......................... 63
Table 12. Proportion of participants who were dichotomized as ‘recovered’ across Week 2, 4, 8 and 12, as determined by reduction in dependent variable by an amount greater than the CV, relative to the Week 1 value................................................................. 64

Table 13. Proportion of participants who were dichotomized as recovered based on CV calculation and the 95% CI of HC ........................................................................................................... 64
List of Figures

Figure 1. Conceptual framework outlining the balance-related concussion literature that has previously been established in the athletic population (solid lines). What remains to be examined are balance-related deficits in adults from the general population (broken lines). This thesis will examine deficits using self-reported symptoms, clinical (BESS), and posturographic measures of balance and the recovery of them across time. ................................................................. 20

Figure 2. Total BESS test score for CONC and HC. Values are represented as means and SD. ................................................. 32

Figure 3. AP RMS (left) and ML RMS (right) for CONC (grey) and HC (white) in EO, EC, and DT conditions. Values are represented as means and SD .................................................. 33

Figure 4. AP velocity (left) and ML velocity (right) for CONC (grey) and HC (white) in EO, EC and DT conditions. Values are represented as means and SD. Group differences are denoted by * .......................................................... 34

Figure 5. AP high-frequency PSD (left) and ML high-frequency PSD (right) for CONC (grey) and HC (white) in EO, EC and DT conditions. Values are represented as means and SD. Group differences are denoted by * . .......................................................... 35

Figure 6. CONC grouping based on self-reported symptoms of balance and dizziness. Participants are allocated based on reporting ≥1 on both (Both), either (Bal/Dizz) or neither (None). BESS score (top left), AP velocity (top right), ML velocity (bottom left) and ML high-frequency PSD (bottom right) showed significant group differences. Values are represented as means and SD. Post-hoc group differences are represented by * .......................................................... 36

Figure 7. Scatterplots depicting the relationship between EO (x-axis) and EC/DT (y-axis) for RMS (top), velocity (middle) and high-frequency PSD (bottom) in the AP (left) and ML (right) directions, relative to the 95% confidence intervals of HC (black lines). Each CONC participant is represented based on self-reported symptoms grouping. ........................................................................ 38

Figure 8. Growth curve (line) and individual data (dots) for total BESS score ........................................................... 58
Figure 9. Growth curves (lines) and individual data (dots) for AP RMS (top left), ML RMS (top right), AP Velocity (bottom left), and ML Velocity (bottom right) in the Eyes Open condition. 59

Figure 10. Growth curves (lines) and individual data (dots) for AP RMS (top left), ML RMS (top right), AP Velocity (bottom left), and ML Velocity (bottom right) in the Eyes Closed condition. 60

Figure 11. Growth curves (lines) and individual data (dots) for AP RMS (top left), ML RMS (top right), AP Velocity (females=pink, bottom left), and ML Velocity (bottom right) in the Dual Task condition. 60

Figure 12. Revised conceptual model summarizing this thesis. Balance-related deficits were probed using self-reported symptoms, BESS score, and COP metrics (eyes closed and dual task), including a measure of reactive balance control. Recovery trajectories are represented for self-reported symptoms, BESS score, and COP measures for adults in the general population with concussion. This thesis highlighted differences in recovery timelines between concussed athletes and adults from the general population. 78
List of Appendices

Appendix 1. Pearson correlations for velocity (vel) and high-frequency power. Significant correlations are denoted with *. .......................................................... 99
Chapter 1
Introduction

1 Introduction

1.1 Background

At the onset of concussion, a multitude of symptoms present themselves (Broglio & Puetz, 2008). Some of the most important symptoms in terms of safety when completing activities of daily living include dizziness and balance problems. In addition to the physical symptoms of concussion, cognitive and attentional deficits are often self-reported (McCrea, Guskiewicz, Marshall, Barr, Randolph, Cantu, Onate, & Kelly, 2003; Register-Mihalik, Littleton, & Guskiewicz, 2013; Van Donkelaar, Osternig, & Chou, 2006). As most activities of daily living require a division of attention, the interaction of these symptoms may have serious implications in terms of fall risk or risk of re-injury during activities of daily living (Register-Mihalik, Littleton, & Guskiewicz, 2013).

Though the risk factors for falls are multifactorial (Horak, 2006; Woollacott & Shumway-Cook, 1996), a fall occurs as a result of inappropriate execution of reactive balance responses (Horak, 2006; Maki & McIlroy, 1997; Mansfield et al., 2015). Reactive balance control is the task of recapturing the center of mass (COM) within the base-of-support (BOS) in response to a destabilizing movement (Horak, 2006). This control occurs by adjusting the centre of pressure (COP), which is driven by sensory information from the three sensory systems that control posture; the visual, vestibular, and somatosensory systems (Horak, 2006). Intact cognition is also important to appropriately allocate attention to the task of postural control (Maki & McIlroy, 1996; Woollacott & Shumway-Cook, 2002). However, concussion can impair the ability to process sensory information or allocate attention needed to generate appropriate balance responses (Register-Mihalik et al., 2013).

Playing contact sports is associated with an increased incidence of concussion (Clay, Glover, & Lowe, 2013). As a result, much of the current balance-related concussion literature involves athletes who have sustained a sport-related concussion. Limited knowledge exists in adults from the general population who have sustained a concussion. As athletes make up a small subset of the general population, the current knowledge regarding the effects of concussion is not
representative of what happens to the general population. In addition, some evidence suggests that exercise reduces concussion burden (Lawrence, Richards, Comper, & Hutchison, 2018; Leddy et al., 2010). Due to the differences in physical activity levels between the general population and high-level athletes, the need to determine the real-life effects of concussion is apparent. This thesis will examine deficits in postural control following a concussion in adults from the general population. Specifically, deficits in sensory strategies, movement strategies and cognitive processes will be explored. In addition, the interaction of self-reported symptoms and balance deficits will be explored in order to enable characterization of balance-related recovery following concussion.

1.2 Concussion

Concussion is defined as a traumatic brain injury induced by biomechanical forces inflicted to the head or body (McCrory et al., 2017) and the term concussion is often used interchangeably with mild traumatic brain injury (mTBI) in the literature. The biomechanical forces dissipate through the head, neck or body and cause the brain to move within the skull resulting in microstructural injury (Giza & Hovda, 2015). Upon concussive injury there is an absence of macroscopic brain damage; therefore, conventional imaging techniques such as computerized tomography (CT) cannot reliably diagnose concussions (Giza & Hovda, 2015). Rather, concussion is diagnosed through clinical evaluation of symptom burden, the level of consciousness and physical and neurological function. Merritt et al (2015) reported dizziness, headache, feeling in a fog, visual disturbance, disorientation, balance problems, pressure in the head, attention, nausea and, numbness as the 10 most common symptoms in concussed athletes (Merritt, Rabinowitz, & Arnett, 2015). Symptoms typically subside within 1-2 weeks for 80-90% of people with concussion (McCrory et al., 2013a). Often, the Glasgow Coma Scale (GCS) (Jones, 1979) is performed within the first 24 hours of injury for traumatic brain injury severity classification based on a score for 3 behaviours; eye opening, verbal and motor responses. For a traumatic brain injury to be considered mild, a score of 13-15 on the GCS is typically associated with a concussion diagnosis.

The clinical symptoms that present after concussion are thought to be caused by a disruption in neurometabolic processes (Giza & Hovda, 2001, 2014). In response to physical
damage to the axons in the brain, neurotransmitters are released to cause a global depolarization of neuronal activity, coupled with a release of calcium and potassium into the cell (Giza & Hovda, 2001, 2014). The brain attempts to restore this ionic imbalance by increasing ionic pump activity, which requires adenosine triphosphate (ATP) (Giza & Hovda, 2001, 2014). Glucose metabolism increases and ultimately results in a period of hyper-metabolism in the brain immediately following injury (Giza & Hovda, 2001, 2014). Simultaneously, there is a reduction in cerebral blood flow (Giza & Hovda, 2001, 2014). Coupled with the hyper-metabolism occurring in the brain, these processes result in a mismatch between energy supply and demand (Giza & Hovda, 2001, 2014). Following this period of hyper-metabolism, there is a period of depressed metabolism (Giza & Hovda, 2001, 2014). Additional intracellular calcium is taken up by the mitochondria, which ultimately reduces oxidative metabolism (Giza & Hovda, 2001, 2014). Reduction in mitochondrial metabolism results in a period of diminished glucose metabolism, which lasts for days-to-weeks following injury (Giza & Hovda, 2001, 2014).

As a result of this energy imbalance, axonal dysfunction and altered neurotransmission, a wide range and highly variable set of neurological deficits, cognitive impairments, and somatic symptoms can be present following concussion (Giza & Hovda, 2001, 2014). Despite the growing body of literature identifying deficits following concussion, little evidence exists regarding the effects of concussion and recovery timelines for adults from the general population who have sustained a concussion. The literature suggests that for athletes who have sustained a concussion, it takes approximately 7 days for post-concussive symptoms, cognitive function and clinical measures of balance to return to baseline (McCrea, Guskiewicz, Marshall, Barr, Randolph, Cantu, Onate, & Kelly, 2003). However, use of more sensitive measures to assess these deficits has found lasting deficits beyond the expected clinical timelines for recovery of concussion, lasting greater than 4 months post-injury (Buckley, Oldham, & Caccese, 2016; Cavanaugh et al., 2006; Degani et al., 2017; Kleffelgaard, Roe, Soberg, & Bergland, 2012; Powers, Kalmar, & Cinelli, 2014; Rochefort et al., 2017). This implies that limitations in traditional assessment methods may impact accurate measurement of recovery trajectories.

The Center for Disease Control and Prevention (CDC) reported 2.8 million cases of TBI-related Emergency Department (ED) visits, hospitalizations and deaths in the United States in 2013 (Taylor, Bell, Breiding, & Xu, 2017). And, since concussion accounts for 70-90% of all TBI cases, the high incidence of concussion is apparent (Taylor et al., 2017). However, this
number is likely largely under-represented as a majority of people who have sustained a concussion do not seek medical attention (Voss, Connolly, Schwab, & Scher, 2015). Although a global incidence of concussion is difficult to estimate due to discrepancies in diagnostic criteria and operational definitions of concussion, examination of health records from 12 ED and 19 family practice clinics in Ontario puts the incidence of concussion between 426-535/100,000 (2001 data) (Ryu, Feinstein, Colantonio, Streiner, & Dawson, 2009; Voss et al., 2015).

1.3 Balance and Postural Control

Postural control is the task of controlling the body’s position in space for the purposes of orientation and equilibrium (Horak, 2006). Orientation refers to the positioning of the body with respect to gravity (Horak, 2006). Equilibrium refers to the coordination of movement strategies to keep the center-of-mass (COM) within the base-of-support (BOS) in response to internal and external destabilizing forces on the body (Horak, 2006). Postural control and balance are often used interchangeably in the literature; however, for the purposes of this thesis, balance refers to an overall global measure of controlling the body’s position, whereas postural control represents the neural process necessary for orientation and equilibrium. Postural control is measured using the center-of-pressure (COP) which is a single point representation of all the ground reaction forces within the BOS (Winter, Patla, Prince, Ishac, & Gielo-Perczak, 1998). In contrast, the COM represents the average position of the centers of mass of each body segment (Winter et al., 1998). During quiet standing, the COP and COM are in-phase with each other and the COP oscillates around the COM to keep it within a neutral position within the BOS (Winter et al., 1998). The BOS is defined as the area enclosed beneath the points of contact with the support surface, and in the case of bipedal stance, is the area enclosed beneath the feet (Horak, 2006). The COP keeps the COM within the BOS by modulating muscle torque in response to information from three sensory systems: the visual, vestibular and, somatosensory systems (Horak, 2006). Sensory strategies, along with biomechanical factors, movement strategies, orientation in space, control of dynamics and cognitive processing are suggested to be the key resources which, when intact, controls balance (Horak, 2006). This thesis will focus on identifying deficits in movement strategies, sensory strategies and cognitive processing following a concussion.
1.3.1 Movement Strategies

In response to phases of COM instability, the central nervous system (CNS) elicits movement strategies, which can be anticipatory or reactive (Horak, 2006). Anticipatory postural control strategies are typically produced prior to voluntary movement, such as moving a limb or prior to gait initiation (Frank & Patla, 2003). Prior to the movement, the COP moves in the opposite direction of the movement and acts to minimize the destabilization (Frank & Patla, 2003; Maki & McIlroy, 1997). Reactive postural adjustments, on the other hand, are movements made in response to phases of postural instability (Frank & Patla, 2003). During quiet standing, when the COM reaches the limits of the BOS, reactive postural control strategies are engaged to move the COM (via the COP) back within a neutral position within the BOS (Winter et al., 1998). During quiet standing, the COM must stay within the BOS in order to prevent a loss of balance (Horak, 2006). The COP does this by oscillating around the COM to stabilize it within some neutral position (Winter et al., 1998). The CNS is able to generate sufficient muscle torque to enable these ‘fixed-support’ responses (Maki & McIlroy, 1997). Reactive balance control is activated by sensory cues that provide the CNS with information that the COM is moving to the limits of stability (Winter et al., 1998). In response to larger bouts of instability and destabilizing forces, the BOS is expanded to recapture the COM. This occurs by taking a step or reaching out to a hand rail to prevent a fall, resulting in a ‘change-in-support’ response (Maki & McIlroy, 1997).

1.3.2 Sensory Strategies

Previous work has determined that stimulation of the visual, vestibular or somatosensory systems results in body sway (Horak, Nashner, & Diener, 1990; Inglis, Horak, Shupert, & Jones-Rycewicz, 1994; Mauritz & Dietz, 1980; Nashner, Black, & Wall, 1982; Nashner, 1982; Paulus, Straube, & Brandt, 1984). These sensory systems aid in spatial orientation and navigation to the surrounding environment (Horak, 2006). Despite this, individuals with visual, vestibular or somatosensory impairments are able to maintain upright stance and ambulate through their environment (Nashner, 1982). This is because the contributions from these three systems can be re-weighted, in a context and environment-dependent manner (Inglis et al., 1994). In a healthy individual, in response to changing environments, the weighting of the contribution from each
sensory system to control upright posture is altered (Nashner, 1982). As the environment and sensory stimuli change, individuals must be able to re-weight the sensory inputs in order to maintain postural control.

Under normal conditions of a fixed support surface and presence of visual input (eyes open), postural control is maintained mostly by somatosensory inputs in contact with the support surface (Nashner, 1982). These inputs, including proprioceptive information from muscle spindles and joint position, along with mechanoreceptors from the foot, detect where the body is in space (Inglis et al., 1994). These sensory inputs are able to detect when the COM is reaching the limits of stability and produce reactive muscle torques to stabilize the COM (Horak et al., 1990; Inglis et al., 1994; Nashner, 1982). The visual and vestibular systems also contribute to postural stability under normal conditions, although the relative contributions of these systems is minimal compared to somatosensory input (Nashner et al., 1982; Nashner, 1982). In these conditions, the visual system provides fixation information relative to the central and peripheral visual fields and the vestibular afferents provides linear and angular acceleration information (Nashner, 1982). Although contributions of the visual and vestibular systems are marginally less than the somatosensory systems during normal vision and fixed-support conditions, manipulation of sensory input has been the focus of many postural control studies. Commonly, the contributions of the somatosensory and vestibular systems are probed through the use of an eyes closed condition. This causes a re-weighting of sensory inputs towards the somatosensory and vestibular systems in the absence of visual input.

1.3.3 Cognitive Processing

Until 1985, the relationship between cognition and postural control had not been characterized. Kerr et al (1985) demonstrated that a balance task interfered with a visual memory task but not a verbal memory task, as the visual system was involved in postural control (Kerr, Condon, & McDonald, 1985). Kerr et al (1985) concluded that postural control was an attentionally demanding task that resulted in reduced performance of a simultaneous task. In the context of this thesis, attention will be defined as the information processing capacity of an individual (Woollacott & Shumway-Cook, 2002). If two tasks are performed together and the total capacities of these tasks are greater than the processing capacity of an individual, a
reduction in performance in either or both of the tasks will occur (Woollacott & Shumway-Cook, 2002). During dual-task paradigms, the postural control task is considered the primary task while a secondary cognitive task is performed simultaneously (Woollacott & Shumway-Cook, 2002). The amount of performance decline in both or either task represents the demand for attentional resources (Woollacott & Shumway-Cook, 2002).

The dual-task paradigm has been widely accepted by researchers to determine age-related cognitive decline and the relationship between attention and postural control (Woollacott & Shumway-Cook, 2002). However, the validity of the assumption that dual-task paradigms probe attentional resources has been questioned in the literature (Woollacott & Shumway-Cook, 2002). Some dual-task paradigms have been shown to elicit arousal, as measured by skin conductance during completion of an arithmetic task (Maki & Mcilroy, 1996). When measures of anxiety were controlled for, the negative influence of the cognitive task on postural control was reduced (Maki & Mcilroy, 1996). In addition, the role of speaking and respiration on measures of quiet standing have been questioned (Woollacott & Shumway-Cook, 2002). During a dual-task paradigm, participants are often instructed to verbally articulate their answers so the researcher can determine accuracy of responses. In a study that compared silently counting to counting aloud, postural sway was significantly higher when participants articulated their answers. This may be a result of two factors: that speech and balance share common pathways in the brain or that participants were not actively attempting to complete the cognitive task to the best of their ability during the silent conditions (Woollacott & Shumway-Cook, 2002). Despite these limitations associated with the dual-task paradigms, previous work has found deficits in dual-task paradigms are associated with increased fall risk (Ashburn, Stack, Pickering, & Ward, 2001; Woollacott & Shumway-Cook, 2002). In addition, the dual-task paradigm has proven to be sensitive enough to track recovery or improvement as a result of a clinical intervention (Woollacott & Shumway-Cook, 2002).

1.4 Posturographic Measures of Balance

Posturographic analysis allows for an objective method of assessing postural control (Duarte & Freitas, 2010; Horak, 2006; Palmieri, Ingersoll, Stone, & Krause, 2002; Winter et al., 1998). Most commonly, the COP is calculated from ground reaction forces and moments
measured by force plates and is used to measure the amount of postural control (Duarte & Freitas, 2010; Winter et al., 1998). However, there is no universal agreement on which variables to extract from the COP signal and there is discussion surrounding which variables are the most sensitive and reliable in detecting changes in postural control (Palmieri et al., 2002). Variables derived from the COP can represent spatial, temporal or spectral aspects of the signal (Duarte & Freitas, 2010; Palmieri et al., 2002). Certain COP variables have been found to represent different aspects of the postural control system. Often, measures of postural control derived from the COP are reported in the anteroposterior (AP) and mediolateral (ML) directions separately as the neural and biomechanical control of posture is regulated differently in each direction (Winter, Prince, Frank, Powell, & Zabjek, 1996). The psychometric properties some of these variables have been determined in healthy and clinical populations with some measures showing greater reliability than others (Geurts, Nienhuis, & Mulder, 1993; Moghadam et al., 2011; Palmieri et al., 2002). Optimal data collection lengths have been previously determined as 45-60 seconds to extract reliable parameters (Carpenter, Frank, Winter, & Peysar, 2011; Le Clair & Riach, 1996). In addition, standardized foot placement has been adopted into many studies in order to make comparisons across studies (McIlroy & Maki, 1997). However, slight differences in trial length, foot placement, dependent variable, and task condition make it difficult to compare findings between studies. Lastly, although the COP analysis allows for a sensitive and objective measure of postural control, limited knowledge exists on the clinically important differences associated with change in these measures across time.

1.4.1.1 Spatial Measures

Two commonly reported COP variables are root-mean-square (RMS) amplitude and mean velocity. RMS represents the standard deviation of the displacement of the COP and is therefore a measure of COP variability (Duarte & Freitas, 2010; Lucy & Hayes, 1985; Palmieri et al., 2002). Mean velocity represents the distributions of displacements over time (Palmieri et al., 2002). In either parameter, a larger value indicates reduced ability to control posture (Palmieri et al., 2002). Reliability of these measures has been determined in healthy young and older adults. Test-retest values of within-day values for RMS and velocity have been found to be strong, with interclass coefficients (ICC) around 0.80 (Lin, Seol, Nussbaum, & Madigan, 2008).
However, test-retest values for between-day variability lowers the reliability of RMS and velocity to around 0.70 (Lin et al., 2008). This indicates that highly sensitive force plate technology can detect day-to-day fluctuations in balance in healthy adults. In addition, elevated RMS and velocity in the mediolateral direction have been related to fall-risk in older adults (Piirtola & Era, 2006). However, the fall-risk relationship in these measures and the concussed population has not been determined.

1.4.1.2 Spectral Measures

The COP signal can be transformed from the time domain to the frequency domain through the Fast Fourier Transform (FFT) (Duarte & Freitas, 2010; Lucy & Hayes, 1985). The FFT allows for a decomposition of sine and cosine signals with differing wave properties and provides an estimate of the frequency composition of the signal, represented as power spectrum density (Duarte & Freitas, 2010; Lucy & Hayes, 1985; Zatsiorsky & Duarte, 2000; Zatsiorsky & Duarte, 1999). The frequency spectrum of the COP has been previously used to determine age and condition-related changes in postural control (Kanekar, Lee, & Aruin, 2014; Lucy & Hayes, 1985; McClenaghan et al., 1996; Oppenheim, Kohen-Raz, Alex, Kohen-Raz, & Azarya, 1999; Singh, Taylor, Madigan, & Nussbaum, 2012). Power spectrum density curves show that the majority of COP movement during quiet standing occurs within 0-2 Hz (Duarte & Freitas, 2010; McClenaghan et al., 1996; Vieira, Oliveira, & Nadal, 2009; Zatsiorsky & Duarte, 2000). Previously, the frequency of the COP has been divided into low, middle, and high frequency bands which are thought to respectively represent the visual, vestibular, and somatosensory contributions to postural control (Kanekar et al., 2014; Mauritz & Dietz, 1980; Palmieri et al., 2002). While this method may allow for quantification of the contributions of each sensory system, there is large variation between the cut-off frequencies of each band in previous work.

In contrast, it has been recognized that the COP signal contains two main frequency components; low-frequency components that represent the exploratory migration of the COP and high-frequency components that represent stabilizing corrections (Mansfield et al., 2015; Winter et al., 1998; Zatsiorsky & Duarte, 2000). Zatsiorsky and Duarte (1999, 2000) proposed the low and high components of the frequency COP signal as rambling and trembling, respectively (Zatsiorsky & Duarte, 2000; Zatsiorsky & Duarte, 1999). During quiet stance, the COP is
constantly in motion as a result of internal and external forces acting on the body (Zatsiorsky & Duarte, 1999). However, there are phases of instantaneous equilibrium when all forces and moments acting on the body are equal to zero (Zatsiorsky & Duarte, 1999). The rambling component of the COP signal represents the movement of this instantaneous equilibrium point (Zatsiorsky & Duarte, 1999). When the body deviates from this equilibrium point, restoring forces return the body to a position of equilibrium, which is represented by the trembling component of the COP signal (Zatsiorsky & Duarte, 1999). The rambling and trembling components have different frequency characteristics. Zatsiorsky and Duarte (1999, 2000) found the mean frequency of the rambling component was 0.2 Hz whereas the mean frequency of the trembling component was 0.9 Hz. The peak frequencies were at 0.16 Hz and 0.57 Hz for rambling and trembling, respectively (Zatsiorsky & Duarte, 1999). Therefore, previous work has used the 0.4 Hz mark as a cut-off to separate the two components of postural control (Schinkel-Ivy, Singer, Inness, & Mansfield, 2016; Singer & Mochizuki, 2015).

In agreement with this view, Schinkel-Ivy et al. (2016) found a significantly greater high-frequency (trembling, >0.4 Hz) RMS amplitude in participants with stroke who could not successfully respond to an external perturbation. No significant differences were found between the group that could successfully respond and the group that could not successfully respond in the low-frequency (rambling, <0.4 Hz) amplitude, which is thought to be indicative of exploratory migrations of the COP (Schinkel-Ivy et al., 2016). This work adds to the evidence that the high-frequency band of the COP represents reactive balance control. During quiet standing, these participants were exerting more stabilizing moments to keep the COP within the limits of stability (Schinkel-Ivy et al., 2016). This was represented as an elevated high-frequency COP band. This component of balance control is important to characterize as deficits in reactive balance control have been related to fall risk in the stroke population (Mansfield et al., 2015).

### 1.5 Balance Deficits Following Concussion

As a result of the multifaceted symptoms that present themselves following concussion, best practices guidelines include assessments that are multifactorial in nature and include aspects of self-reported symptoms, cognition and balance (Broglio, Macciocchi, & Ferrara, 2007). This approach is more sensitive at detecting concussion than any single measure alone (Broglio et al.,
Balance deficits following concussion can be a result of many aspects of the postural control system (Horak, 2006). However, previous work has aimed to identify deficits in the vestibular control of balance as dizziness is one of the most commonly reported symptoms following concussion (Chamelian & Feinstein, 2004; Reneker, Cheruvu, Yang, James, & Cook, 2018; McLeod & Hale, 2015). Although dizziness can describe a range of pathophysiological processes, previous work has found vestibular dysfunction in participants with concussion who self-report the symptom of dizziness (Reneker et al., 2018). In agreement with this finding, although subjective symptom reports do not always align with objective measures of balance, previous work has found associations between the complaint of dizziness and objective balance deficits (Kaufman et al., 2006).

The Balance Error Scoring System (BESS) is the most commonly used clinical assessment of balance following concussion. The BESS was created for use as a sideline assessment in concussed athletes (Bell, Guskiewicz, Clark, & Padua, 2011); however, the BESS is prone to learning effects and lacks sensitivity in identifying individuals with concussion (Bell et al., 2011; Iverson & Koehle, 2013; Mulligan, Boland, & McIlhenny, 2013; Murray, Salvatore, Powell, & Reed-Jones, 2014). In contrast to these limitations, analysis of the COP allows for clinicians and researchers to objectively examine balance deficits under conditions that probe different aspects of the postural control system that may be negatively impacted by concussion. Commonly, postural control tasks included in the assessment of concussion probe the vestibular system and attentional processes through the use of an eyes-closed condition and dual-task paradigm, respectively. These will be discussed in detail in subsequent sections.

1.5.1 BESS

The BESS was developed as an inexpensive and quick assessment of postural control in concussed athletes and is currently the most widely used balance assessment for concussion (Murray et al., 2014). It includes measurement of 3 stances: feet together, unipedal and tandem stance repeated on a firm surface and secondly on a foam surface. All conditions are performed with eyes closed and held for 20 seconds (Bell et al., 2011). Participants are scored for errors which include: opening the eyes, moving hands off iliac crest, moving feet out of position, lifting the forefoot or heel, abducting the hip >30 degrees, staying out of position for >5 seconds and
failing to maintain the testing position for >5 seconds (Bell et al., 2011). A score of 3 represents the reliable change index (RCI) of the BESS (Valovich Meleod, Barr, Mccrea, & Guskiewicz, 2006). However, the validity of the BESS test can be questioned when considering the observed learning effects over repeated administrations (Bell et al., 2011; Mulligan et al., 2013; Sheehan, Lafave, & Katz, 2011). It is possible that the reduction of BESS test scores is a result of learning and not true recovery related to concussion. McLeod et al (2004) found learning effects of a 4-point improvement in score when athletes were administered the BESS test 3 times over 5 days. These learning effects are likely the result of improved balance strategies. In addition to learning effects, the BESS test relies upon rater interpretation when scoring participants for errors and the subjective nature of the BESS test results in interclass coefficient scores that range from poor to moderate and below the clinically acceptable level of 0.80 (Bell et al., 2011). The BESS test shows low sensitivity (0.34) but high specificity (0.96) in concussed athletes (Murray et al., 2014). However, it should be noted that the BESS test was designed for athletes and due to the challenging postural conditions, the specificity of the BESS test may be drastically reduced for people with lower athletic ability.

Previous work in the athletic population has assessed athletes at baseline then re-assessed athletes following concussion using the BESS test (Bell et al., 2011; Guskiewicz, Ross, & Marshall, 2001; McCrea et al., 2003; Ruhe, Fejer, Gänsslen, & Klein, 2014). In general, athletes typically score 12 errors at baseline, which increase by 6-20 errors immediately following injury. Deficits have been found using the BESS test acutely following concussion in athletes. These deficits have been attributed to deficits in sensory interaction, where concussed athletes fail to rely on the vestibular and somatosensory systems to maintain posture in the absence of visual input (Guskiewicz, 2003). As a result of learning effects and low sensitivity associated with the BESS, previous concussion-related balance literature has identified balance deficits using COP measures of balance.

1.5.2 Posturographic Measures

Relative to the magnitude of studies that use clinical measures of balance to identify deficits following concussion, fewer studies have identified deficits using posturographic measures of balance. The majority of studies record the COP during conditions that manipulate
different sensory systems or some use a cognitive-motor dual-task in order to probe deficits in sensory integration and cognitive processing, respectively. Few balance-related studies exist that determine deficits in postural control following acute concussion (within 1-2 weeks). Although posturographic measures allow for a direct quantification of postural control, variation in the size of the base-of-support, test condition, dependent variable, length of data collection, number of days post-concussion, and symptom severity contribute to a large variation in the conclusions of these studies. For example, Powers et al (2014) found elevated variability of COP velocity in acutely concussed athletes (Powers et al., 2014), whereas other work in concussion found reduced COP velocity in participants with a history of concussion (Degani et al., 2017). A key difference between these studies is the BOS in which the participants were standing, where Degani et al (2017) used a BOS that was 10 cm wide and arms crossed, whereas Powers et al (2014) used a feet-together BOS with arms held at the side. In comparing these studies, the smaller BOS in Powers et al (2014) presents a greater postural challenge. Additionally, Degani et al (2017) used participants who had a history of concussion (on average 20-months post-concussion) whereas Powers et al (2014) used acutely concussed participants (on average 5-days post-concussion). Other work has found postural control deficits as defined by movement of the COP away from an average neutral position in acutely concussed (on average 3-days) adults with eyes open when compared to controls (Lin et al., 2015). In a study using recently concussed children (on average, 6-hours post-concussion), postural deficits in the eyes open condition were observed when compared to controls (Rhine, Byczkowski, Clark, & Babcock, 2016).

Other researchers have used a non-linear dynamics approach in detecting balance deficits following sport-related concussion, in light of the view that traditional spatial COP analyses may not be sensitive enough at detecting sport-related concussion (Cavanaugh et al., 2005, 2006). Non-linear dynamics uses measures of COP irregularity, such as approximate entropy (ApEn). ApEn detects the amount of randomness of the COP, where less regularity in COP fluctuations has been shown to increase risk of falls (Busa & van Emmerik, 2016). Previous work has found postural control deficits when using ApEn in concussed athletes (on average 48 hours post-injury), but no deficits in spatial measures of the COP, such as displacement amplitude (Cavanaugh et al., 2005).

While measures of postural control are necessary to guide recovery and return-to-play decisions in athletes, the assessment of postural control alone may not be sufficiently sensitive to
detect concussion (Broglio et al., 2007). Rather, a comprehensive assessment of postural control, cognition, and self-reported symptoms may be over 90% sensitive in detecting concussion and monitoring recovery (Broglio et al., 2007). Most activities-of-daily living require a division of attention (Register-Mihalik, Littleton, & Guskiewicz, 2013). And, as concussion is a multifaceted neurological injury that affects both cognition and balance, previous work has found deficits in postural control under these conditions following concussion through the use of visual or auditory Stroop tasks, mental arithmetic tasks or switching tasks (Register-Mihalik et al., 2013).

1.5.3 Self-Reported Symptoms

Self-reported symptoms are used by clinicians to diagnose concussion and guide recovery decisions (Alla, Sullivan, Hale, & McCrory, 2009; Broglio et al., 2007; Broglio & Puetz, 2008; Lovell et al., 2006). Self-reported symptoms are often presented as a list of physical, emotional, and cognitive symptoms (Lovell et al., 2006). Many symptom scales and derivatives exist; however, the symptom evaluation section of the Sport Concussion Assessment Tool (SCAT) is commonly used by clinicians and researchers. The symptom evaluation section of the SCAT includes 22 different symptoms on a Likert scale with the following severity groupings; 0 (none), 1-2 (mild), 3-4 (moderate) and 5-6 (severe) (Lovell et al., 2006). The symptom evaluation section of the SCAT was developed to provide a method of documenting concussion symptoms and severity perceived by athletes, and their resolution over time (Lovell et al., 2006). Previous work has determined moderate reliability [interclass coefficient (ICC)=0.62] of the symptom evaluation section of the SCAT in acutely concussed high-school athletes over a 7-day interval (Chin, Nelson, Barr, McCrory, & McCrea, 2016). In addition, a significant change in symptom score has been determined to be 3 points (Chin et al., 2016). The moderate reliability of the self-reported symptom scale is likely related to the subjective nature of concussion symptoms. Concussion-related symptoms are often experienced in everyday life in people who have not experienced a concussion (Lovell et al., 2006; Zimmer, Marcinak, Hibyan, & Webbe, 2015). In addition, previous work has highlighted that athletes have a tendency to under-report symptoms following concussion in order to return-to-play earlier (Kroshus et al., 2016). In contrast, people
who have experienced life stressors have a tendency to somaticize these stressors and over-report symptoms (Lovell et al., 2006).

Between-individual differences in concussion symptom reporting has previously been determined. Some factors that contribute to these differences include; number of previous concussions, sex, age, and history of mental illness (Brown, Elsass, Miller, Reed, & Reneker, 2015; Hugentobler et al., 2016; Kroshus et al., 2016). In a meta-analysis by Brown et al. (2015), high-school and collegiate-aged females tend to report more symptoms than men at baseline (Brown et al., 2015). These sex differences may be due to hormonal fluctuations that occur in females and may be associated with the menstrual cycle (Brown et al., 2015). It should be noted these studies use high-school or collegiate aged athletes as participants, who may differentially display sex differences, compared to middle age or older adults. In addition, adults from the general population may not have the same motivation to return-to-play/work/learn as athletes do and therefore may report symptom severity differently than athletes.

Although there is variation regarding the most-frequently endorsed post-concussion symptoms, following sport-related concussion, 76% report dizziness and 30% report balance as a debilitating symptom (Murray et al., 2014). Previous work has also found low correlations between self-reported measures of balance and objective measures of balance (Kleffelgaard et al., 2012; Rochefort et al., 2017). No significant correlations were found between self-reported balance symptoms and deficits in COP metrics during eyes open, eyes closed, tandem or unipedal stance in participants with a history of concussion (on average 4 years post-injury) (Kleffelgaard et al., 2012). However, a moderate (r=0.43), statistically significant correlation was found between COP measures during a dual-task and self-reported balance problems (Kleffelgaard et al., 2012). This further suggests the dual-task condition may be more sensitive in detecting deficits compared to the eyes open or eyes closed conditions. Rochefort et al (2017) found significantly larger COP area and velocity during a dual-task condition in concussed adolescents that self-reported no balance symptoms, compared to controls 1-month following injury. No differences were found between the group of concussed participants that reported balance symptoms and those who did not. Lastly, in acutely concussed children (on average 6 hours post-injury), subjective complaints of balance deficits were not predictive of deficits in postural control (Rhine et al., 2016). These findings may be a result of the balance assessments not capturing the full postural control system or may be related to lack of symptom reporting in
order to return-to-play earlier. Taken together, this evidence suggests that self-reported measures should not be the only measures used in the diagnosis of concussion-related balance deficits.

1.5.4 Recovery

Concussion recovery is a dynamic process where, in 80-90% of cases, spontaneous recovery occurs within the first week (McCrory et al., 2013a). Most of what we know about concussion recovery comes from measures of self-reported symptoms and clinical measures of cognition and balance (McCrea, Guskiewicz, Marshall, Barr, Randolph, Cantu, Onate, & Kelly, 2003). McCrea et al (2003) baseline tested n=1631 football players at the beginning of the season. Players that received a concussion (n=79) were reassessed longitudinally following injury. Concussed participants returned to baseline values for self-reported symptoms, cognition, and balance (as measured by the BESS) within 1 week of injury.

Specific to balance recovery, previous work has used the BESS or the Sensory Organization Test (SOT) to measure recovery across time. The SOT manipulates sensory input in a similar manner to the BESS in that vision and somatosensory inputs are reduced (Guskiewicz, 2001). Using the scoring systems of these studies, it has been determined that recovery of clinical measures of balance occurs, on average, within 3-5 days post-injury in collegiate level athletes (Cavanaugh et al., 2005; Guskiewicz, 2001; Guskiewicz, Riemann, Perrin, & Nashner, 1997; Riemann & Guskiewicz, 2000). It should be noted that these study used collegiate-level athletes who may have experienced neuroprotective effects of intense, regular physical activity (Cotman & Engesser-Cesar, 2002). In addition, previous work has determined low to moderate reliability and learning effects associated with the BESS and SOT over repeated administrations (Mulligan et al., 2013; Murray et al., 2014).

In an effort to minimize the limitations associated with clinical measures of balance, previous work has aimed to identify the recovery of postural deficits using more sensitive COP measures. Few studies identify deficits during acute concussion and additionally assess participants at multiple time-points across the recovery trajectory. Some evidence suggests that deficits in postural control persist beyond the 1-week timeframe associated with clinical recovery. Powers et al (2014) assessed concussed athletes acutely following injury (mean=5
days) and again upon return to play (range: 10-49 days) (Powers et al., 2014). Compared to non-concussed controls, elevation in COP RMS velocity (variability of velocity) persisted upon return-to-play (RTP) (Powers et al., 2014). This is significant as these players have been cleared to RTP but may have lasting deficits (Powers et al., 2014). The authors found these deficits during the eyes closed condition, suggesting that this deficit may be a result of the vestibular system having not yet recovered (Powers et al., 2014). More evidence of prolonged postural control deficits comes from work by Slobounov et al (2012) (Slobounov, Sebastianelli, & Hallett, 2012). When assessing concussed athletes, Slobounov et al (2012) used an index of proportional increase in COP area in the eyes closed condition, relative to the eyes open condition (Slobounov et al., 2012). Proportional increase in COP area did not recover to pre-injury baseline values until 6-months post-concussion (Slobounov et al., 2012). Despite these deficits using linear metrics of the COP, some evidence suggests these metrics are not sensitive enough to detect recovery of deficits following concussion. Fino et al (2016) found postural control deficits, using a nonlinear dynamics approach (Fino, Nussbaum, & Brolinson, 2016). The authors collected the COP of concussed athletes with feet together and eyes open on a weekly basis between 1-6 weeks post-concussion (Fino et al., 2016). Reduced high-frequency (1.1-33.3 Hz) COP randomness was observed when compared to controls, which persisted until 6-weeks post-injury. However, interpretation of this finding is limited as the high-frequency band used in this study is typically associated with noise. Other work has used ApEn measures and determined residual deficits 4 days post-injury, which is only slightly longer than the time-frame in which BESS score recovers (Cavanaugh et al., 2006). Unfortunately, this study did not assess participants beyond this acute time-frame.

Aside from these longitudinal studies, knowledge related to lingering deficits in postural control comes from cross-sectional studies examining deficits in participants with a history of concussion. These studies have also identified residual deficits beyond the recovery timelines of clinical measures of balance and suggest deficits in postural control may persist months following injury (Cavanaugh et al., 2006; Cavanaugh et al., 2005; Beaumont et al., 2011; Powers et al., 2014; Slobounov et al., 2008; Sosnoff et al., 2011). Rochefort et al (2017) assessed both symptomatic and non-symptomatic concussed adolescents 1-month post-injury. Significant deficits in both concussion groups were found in COP area and ML velocity during a dual task condition, compared to controls (Rochefort et al., 2017).
found deficits 1-month post-injury in concussed athletes when using a measure which assesses position, velocity, and acceleration of the COP, despite no significant differences found in traditional COP metrics. Degani et al (2017) found elevation in COP area and range in formerly concussed participants (on average 29-months post-injury). Beaumont et al (2011) found deficits in COP displacement amplitude and nonlinear dynamic metrics in participants who had sustained a concussion 9-34 months prior to assessment. Sosonoff et al (2011) also found deficits in ApEn during conditions of the SOT (Sosnoff et al., 2011). Taken together, these studies illustrate that deficits in posturographic measures during quiet standing are observable in months to years following concussion.

Paralleling clinical measures of balance, self-reported symptoms also recover, on average, within 1-week of concussion in the athletic population (Broglio & Puetz, 2008; Chin et al., 2016; Lovell et al., 2006; McCrea, Guskiewicz, Marshall, Barr, Randolph, Cantu, Onate, Kelly, Page, et al., 2003). As suggested above, this may be a result of the motivation for athletes to return-to-play and should not be the only measure used to determine true recovery from concussion. On the other hand, emotional and life-stressors may prolong recovery of self-reported symptoms. As previous work has identified that people with no history of concussion experience concussion-related symptoms during everyday life, it is difficult to determine if prolonged symptoms are associated with lack of concussion recovery or alternatively, remain elevated as they are symptoms which naturally occur in everyday life (Zimmer et al., 2015).

This work suggests that clinical measures of balance and self-reported symptoms lack sensitivity associated with determining balance-related concussion recovery. In contrast, due to differences in COP metrics and postural conditions used in the assessment, posturographic measures of balance do not show a consistent or conclusive recovery pattern. Therefore, a combined approach using measurement of self-reported symptoms and objective measures of balance should be used to determine concussion-related balance recovery. In addition, the assessment battery used in the measurement of postural control should be standardized within the concussion literature.
1.6 Rationale and Objectives

Much of our knowledge about the effects of concussion on balance comes from literature in elite athletes. Athletes differ from adults from the general population in many ways that may influence severity of concussion deficits and prolong recovery. For example, the neuroprotective effects of intense, regular physical activity have been well-characterized and may mask larger detrimental effects of concussion (Cotman & Engesser-Cesar, 2002). Specific to balance-related deficits, previous work has found lasting beneficial effects of exercise including; increased muscular strength, improved sensory awareness, and cognitive abilities (Brauer, Neros, & Woollacott, 2008). In addition, the effect of physical activity alone stimulates the visual, vestibular, and somatosensory systems (Brauer et al., 2008). As these sensory systems are used in the control of posture, this may result in a better ability to control posture in athletes. In addition, concussion affects the Autonomic Nervous System (ANS) and results in altered cerebral blood flow and cardiac and vascular function (Giza & Hovda, 2001, 2014; Leddy et al., 2010). Exercise has been shown to regulate the ANS following acute concussion and may have a positive impact in restoring cerebral blood flow and cardiac and vascular function (Leddy et al., 2010). While traditional best practices guidelines recommend complete physical rest following concussion, RTP protocols require a graded return to activity where athletes firstly return to light activity, then practice, then sport. In contrast, adults from the general population exercise at significantly reduced rates compared to athletes and are likely not exposed to this early physical activity post-concussion. Evidence suggests that early post-injury physical activity results in sooner recovery (Lawrence et al., 2018). In addition, in comparison to non-athletes, athletes recover from concussive symptoms faster and with a greater magnitude in response to an exercise intervention (Leddy et al., 2010). As the majority of concussion-related balance literature characterizes deficits in high-level athletes, it is possible these factors are masking detrimental balance deficits that may subject non-athletic people to more severe balance-related deficits. As another example, everyday activities vary between adults from the general population and collegiate-level athletes. Adults from the general population may be subjected to more frequent life-stressors related to work and family that may influence the presentation and recovery of concussion symptoms. As concussion recovery is a dynamic and variable task, these stressors may negatively influence recovery trajectories.
Previous literature explores postural control deficits following a concussion in high-level athletes. The previous methodological approaches used to determine balance-related deficits and recovery timelines in athletes following concussion are outlined in the conceptual model for this thesis (presented in Figure 1). These include self-reported symptoms, BESS score, and COP metrics during conditions of eyes open, eyes closed, and dual-task. What remains to be examined is how postural control is affected in adults from the general population following a concussion. In addition, deficits in reactive balance control have yet to be explored in the concussion population. As deficits in postural control have been shown to increase fall risk and fall-related injury, determining the real life consequences of concussion is needed. Of importance to clinicians and researchers is the mechanisms of balance deficit, as these mechanisms can guide rehabilitation strategies. Posturographic analysis allows for an objective quantification of these deficits. In addition, methodological manipulations probe different aspects of the postural control system in order to determine specific concussion-related balance deficits.

**Figure 1.** Conceptual framework outlining the balance-related concussion literature that has previously been established in the athletic population (solid lines). What remains to be examined are balance-related deficits in adults from the general population (broken lines). This thesis will examine deficits using self-reported symptoms, clinical (BESS), and posturographic measures of balance and the recovery of them across time.
Accordingly, the objectives of this thesis were to:

1. Determine balance deficits using self-reported, posturographic, and clinical measures of balance
2. To identify the mechanisms that contribute to balance deficit in concussion in adults from the general population
3. Characterize the recovery trajectories of balance deficits across time

The specific research questions were:

1. What deficits in self-reported symptoms, BESS score, and COP exist in adults from the general population with concussion?
2. What underlying mechanisms contribute to deficits exist during quiet standing in adults from the general population with concussion (Table 1)?
3. When do self-reported symptoms, BESS score, and COP metrics recover in adults from the general population with concussion?

Table 1. Methodological manipulations and measures used in this thesis to probe underlying mechanisms of postural control deficits.

<table>
<thead>
<tr>
<th>Task</th>
<th>Pathways</th>
<th>Measures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eyes Open</td>
<td>Postural control system with contributions from visual, vestibular and somatosensory systems</td>
<td>RMS (sway variability), velocity (extent of COP displacements over time), high-frequency power (reactive balance control)</td>
</tr>
<tr>
<td>Eyes Closed</td>
<td>Vestibular and somatosensory contributions to postural control</td>
<td></td>
</tr>
<tr>
<td>Dual Task</td>
<td>Attentional capacity of an individual</td>
<td></td>
</tr>
</tbody>
</table>

It was hypothesized that concussion will result in postural instability, as measured by posturographic measures and clinical measures of balance. Further, that these postural deficits will be exacerbated during the eyes closed and during the dual-task conditions, suggesting deficits in the vestibular control of posture and attentional processes, respectively (Table 1). And,
during the completion of these tasks, reactive postural adjustments will be greater (increased high-frequency power) and not effective in controlling the COP, as determined by increased RMS and velocity. It was also hypothesized that these deficits will be greater for participants who self-report balance and dizziness symptoms. Lastly, due to differences in activity level between the general population and high-level athletes, it was hypothesized that these deficits will take longer to recover than what has been characterized in the concussed athletic population.

Deficits in balance and postural control following a concussion have been characterized in high-level athletes. However, due to the differences in everyday lives between a high-level athlete and an adult from the general population, the implications of concussion may be more serious in adults from the general population as a result of symptom burden interfering with activities of daily living and life stressors. By characterizing deficits in postural control and their recovery over time, return-to-work and return-to-activity guidelines can be informed within this cohort. In determining the effects of subjective self-reported symptoms on objective measures of balance and posture, this work will inform clinicians about the interaction of self-reported symptoms and objective posturographic measures of balance. Through the identification of specific deficits in postural control, this work will inform clinicians on potential rehabilitation strategies used for adults from the general population with concussion.
Chapter 2
Characterizing Balance Deficits Following Acute Concussion in Adults from the General Population: A Cross-Sectional Analysis

1 Introduction

Concussion is a mild traumatic brain injury defined as a complex pathophysiological process affecting the brain, which is induced by biomechanical forces (McCrory et al., 2013a). Although a reliable concussion-severity grading system has yet to be widely accepted by clinicians and researchers, severity is often reported in the literature in terms of the magnitude and duration of self-reported symptoms (Niskala & Walter, 2012). Due to the heterogeneity of concussion, clinicians rely on self-reported symptoms to make recovery decisions (Lovell et al., 2006). Most commonly, this is reported using the self-reported symptom section of the Sport Concussion Assessment Tool (SCAT-3) (McCrory et al., 2013b). The self-reported symptoms section includes 22 different symptoms, which include physical, somatic, and cognitive deficits commonly reported following a concussion. While clinical decisions based on symptoms enables delivery of care based on self-perceptions, it is possible that a more quantitative assessment of behaviour and the impact of concussion can be more informative of persisting subtle deficits.

One of the most relevant issues in regards to safety while completing activities-of-daily living is balance impairment. Balance is an essential element of common tasks, such as maintaining upright stance, rising from a seated position, ambulation, and reacting to a slip or trip (Horak, 2006; Pollock, Durward, Rowe, & Paul, 2000; Woollacott & Shumway-Cook, 1996). Self-reported symptoms related to balance (i.e. balance, dizziness) are common following sport-related concussion (Broglio, Sosnoff, & Ferrara, 2009; Kleffelgaard et al., 2012; McCrea, Guskiewicz, Marshall, Barr, Randolph, Cantu, Onate, Kelly, & Page, 2003; Rochefort et al., 2017). Thus, there has been a growing focus on measuring balance deficits in the context of concussion. Previous work has identified the relationship of balance deficits to fall risk; therefore, it is vital that balance deficits be identified to minimize risk of re-injury and risk of falls (Horak, 2006; Woollacott & Shumway-Cook, 2002).
While subjective, self-reports of balance-related symptoms provide insight into self-perceived balance ability, instrumented measures may provide more specific information as to balance deficits or the mechanism that may be contributing to the balance problem. The Balance Error Scoring System (BESS) offers a relatively quick assessment of postural control following concussion. Because the BESS is conducted with the eyes closed and includes conditions of standing on foam, visual and somatosensory contributions of balance are manipulated, leaving only vestibular sensory inputs as the primary balance control mechanism. As the balance-related deficits following concussion have been attributed to vestibular injury, the BESS has been the focus of prior work (Powers et al., 2014; Ruhe et al., 2014).

Despite the apparent utility and widespread use of the BESS, it has low to moderate reliability and is prone to learning effects over repeated administrations (Bell et al., 2011; Mulligan et al., 2013; Sheehan et al., 2011). Additionally, the BESS was created for the athletic population and may be too difficult for an adult from the general population to complete and therefore may lack specificity of identifying individuals with concussion in the general population. Alternatively, posturographic measures of balance can be obtained from the center-of-pressure (COP) signal, as measured by force plates. The COP is a single point representation of the weighted average of the ground reaction forces within the base-of-support (BOS) (Winter, Patla, Prince, Ishac, & Gielo-Perczak, 1998). The COP represents the neuromuscular response to the movement of the center-of-gravity (COG), which is the downward projection of the center-of-mass (COM) (Winter et al., 1998). The COM, the average position of the body’s total mass, is controlled by the COP to keep it within the BOS (Winter et al., 1996).

The ability to control the COM within the BOS can be characterized using measures of the COP obtained from force plates. Commonly reported measures include root-mean-square (RMS) and velocity. RMS represents the variability of the COP, whereas velocity represents the distribution of displacements over time (Duarte & Freitas, 2010). In either parameter, a large value indicates greater postural instability. Additionally, the COP can be transformed into the frequency domain and split into low (<0.4 Hz) and high (>0.4 Hz) frequency bands (Zatsiorsky & Duarte, 2000). Previous work has identified the low-frequency band as representing exploratory COP migrations, whereas the high-frequency band represents reactive movements in response to instability (Schinkel-Ivy et al., 2016; Zatsiorsky & Duarte, 2000). Reactive balance control occurs following an unexpected destabilization and is the task of recovering the COM
within the BOS (Frank & Patla, 2003). During quiet standing, reactive balance control can occur in response to phases of instability when the COP reaches the limits of stability. Previous work in stroke identified increased high-frequency power of COP RMS during quiet standing in participants who could not successfully respond to an external perturbation, compared to participants who could successfully respond (Schinkel-Ivy et al., 2016). This finding implies that the individuals who could not successfully respond to an external perturbation have a reduced capacity for reactive balance control and this impairment is being captured in the high-frequency COP band during quiet standing (Schinkel-Ivy et al., 2016). COP parameters obtained during quiet standing conditions offer an objective and quantitative method of assessing the postural control system (Duarte & Freitas, 2010; Horak, 2006; Palmieri et al., 2002; Winter et al., 1998; Woollacott & Shumway-Cook, 1996). Manipulation of sensory systems within quiet standing can probe the function of the postural control system. In the eyes closed condition, the function of the vestibular system at controlling posture can be assessed without the subjective nature associated with scoring the BESS. In addition, the role of cognition in postural control can be probed through the use of a cognitive-motor dual-task paradigm. Cognitive-motor dual-task paradigms require a division of attention between simultaneous tasks (Register-Mihalik et al., 2013). As attentional deficits are a commonly reported symptom of concussion, dual task paradigms may reveal deficits in this population (Register-Mihalik et al., 2013).

Many concussed athletes present with balance deficits following concussion (Ruhe et al., 2014). In an effort to diagnose and monitor concussion, postural stability assessments have been included in the diagnostic battery of concussion (Ruhe et al., 2014). As a result, much of the knowledge related to balance deficits following concussion is based on observations of athletes who have sustained a concussion. In contrast, less is known about the extent to which concussion affects adults from the general population. Athletes who have sustained a concussion would likely be better able to benefit from the neuroprotective effects of exercise (Griesbach, 2011). However, statistics Canada reported that only 15% of Canadian adults aged 20-79 years accumulate 150 minutes per week of moderate to vigorous exercise (Colley et al., 2011). It is possible that due to the differences in exercise levels between high-level athletes and adults from the general population, that the impact of concussion will be greater for someone with lower fitness levels. Due to the differences in everyday activities between a high-level athlete and
adults from the general population, the need to characterize these deficits in people from the general population is apparent.

The objective of this work was to characterize deficits in balance and postural control following acute concussion in adults from the general population using self-reported, clinical, and posturographic measures of balance. In addition, this study aimed to identify potential mechanisms that contribute to balance deficits after concussion. It was hypothesized that participants with concussion will show increased errors on the BESS test, elevated RMS, velocity, and high-frequency power of the COP compared to controls. In addition, it was hypothesized that these impairments in RMS, velocity, and high-frequency power of the COP will be exacerbated in the absence of vision (eyes closed) and during cognitive-motor dual task conditions. Lastly, it was hypothesized that these deficits would be greater for participants who self-report a greater amount of balance-related symptoms (i.e. balance and dizziness versus balance or dizziness alone).

2 Methods

2.1 Participants

Participants with concussion were recruited for the study following referral to the Hull-Ellis Concussion Clinic at the Toronto Rehabilitation Institute from Emergency Department (ED) physicians at 3 participating hospitals upon diagnosis of concussion. Participants were included if: there was a diagnosis of concussion at ED visit, they were 18-75 years old, were assessed within 8 days of concussion, and had a Glasgow Coma Scale (GCS) score of 13-15. Exclusion criteria for the study were: admission to the hospital for the current concussion, positive head imaging, history of other neurological conditions, pre-morbid vestibular disorders or any current lower limb injuries that would affect balance, lastly, participants with concussion were excluded if the origin of injury was a result of a motor vehicle accident. Professional and elite athletes were also excluded from the study. Twenty age and sex-matched participants who had no history of concussion participated in the study as a control group. Exclusion criteria for the control group was the same as the concussion group. All participants provided written
informed consent prior to study participation. This study was approved by the Research Ethics Board at the University Health Network (REB #17-5348).

2.2 Experimental Protocol

2.2.1 SCAT-3 Self-Reported Symptoms

Symptoms were self-reported using the SCAT version 3, which measures self-reported symptom severity on 22 concussion symptoms including symptoms of dizziness and balance impairment (McCrory et al., 2013b). The SCAT-3 categorizes symptoms from 0 (none) to 1-2 (mild) to 3-4 (moderate) to 5-6 (severe) for a total possible score of 132 (McCrory et al., 2013b). Concussed participants completed the self-reported symptoms portion of the SCAT-3 on a computer prior to the balance assessment.

2.2.2 Equipment Set-Up

Quantitative balance measures were collected while individuals stood with each foot on adjacent AMTI force plates (1mm between plates, Y axes in parallel) to record the ground reaction forces and moments from each plate using a custom program in LabView 12 software (National Instruments, Austin TX). Participants were positioned to stand in a standardized BOS as determined by McIlroy and Maki (1997) as 10cm between heel centres and feet turned 14° from midline (McIlroy & Maki, 1997). Each foot was positioned on a separate force plate. Signals from each plate were sampled at 256 Hz.

2.2.3 Quiet Standing

Three quiet standing conditions were included in the analysis. Quiet standing trials were collected on force plates for 50 seconds. During the first task, participants were instructed to stand with their arms at their side, maintain a fixed gaze on a point on a wall 5m away, and stand as still as possible with their eyes open (EO). During the second task, participants were instructed to stand in the same position with their eyes closed (EC) as still as possible. Lastly,
during the dual task (DT) condition, participants were instructed to complete the Backwards Sevens task (counting backwards by 7) with eyes open while trying to be as still as possible (Hayman, 1942). Participants were reminded to avoid breathing deeply or to use fingers to count for the dual-task during data collection.

2.2.4 BESS

Participants completed the BESS battery which included standing with feet together, unipedal (non-dominant foot) and tandem (non-dominant foot at the back) stances (Riemann & Guskiewicz, 2000). Stances were performed once on a firm surface and then repeated on a medium density foam (10 cm height Airex Balance Pad 81000) surface. Each stance was held for 20 seconds. All trials were completed with hands placed on the iliac crests and eyes closed. Errors were scored retrospectively using video-recording. An error was given for any of the following; opening the eyes, moving the hands off the iliac crest, abducting the hip greater than 30 degrees, lifting the forefoot or heel, taking a step, stumble or fall or remaining out of the testing position for greater than 5 seconds. A maximum score of 10 was given if the position was not attempted for a total of 5 seconds throughout the 20 second period (Riemann & Guskiewicz, 2000).

2.3 Data Analysis

Force plate data recorded during quiet standing were filtered using a low-pass, zero-lag, 2nd order Butterworth filter with a 10 Hz cut-off. The net COP signal was calculated in the antero-posterior (AP) and medio-lateral (ML) directions. Dependent variables (RMS, velocity, high-frequency PSD) were calculated using a code written in MatLab v.8.3 (The MathWorks Inc., Natick, USA).
2.3.1 Spatial Analysis

RMS and velocity were calculated in the AP and ML directions using the mean-removed net COP data. Using mean-removed data, RMS represents a measure of the standard deviation (SD) of the displacement (Equation 1, Duarte & Freitas, 2010). Velocity represents a measure of the distribution of the displacements over time (Equation 2, Duarte & Freitas, 2010).

Equation 1: \[ RMS = \frac{\sqrt{\sum(COP^2)}}{\text{length}(COP)} \]

Equation 2: \[ Velocity = \frac{\text{sum}(\text{abs}(\text{diff}(COP))) \times \text{freq}}{\text{length}(COP)} \]

2.3.2 Spectral Analysis

A Fast-Fourier Transform (FFT) was applied to the COP signal and the power spectrum density (PSD) was estimated using the Welch method (Welch, 1967). The integral of the PSD was computed using the trapezoid method in bins of 0.04 Hz. The mean power in the low (0-0.4 Hz) and high (0.4-3 Hz) frequency band were calculated.

2.4 Statistical Analyses

All statistical tests were performed using IBM SPSS Statistics 23 (IBM, Armonk USA). Descriptive statistics were used to characterize the study cohorts. The Shapiro-Wilk test for normality identified that none of the continuous dependent variables (RMS, velocity, high-frequency PSD) were normally distributed. The continuous dependent variables were subsequently log-transformed. All dependent variables were normalized after the log transformation with the exception of 4: ML RMS (EC), AP Velocity (DT), ML Velocity (DT), AP High-frequency PSD (DT). BESS test score is an ordinal variable and therefore no transformations were performed. To test the hypothesis that participants with CONC will show increased RMS, velocity, and high-frequency PSD, a 2 x 3 mixed analysis of variance (ANOVA) was conducted with group (HC or CONC) as the between-subjects factor and condition (EO, EC, DT) as the within-subject factor. A univariate ANOVA was used to test the hypothesis that
participants with concussion will show increased BESS score compared to HC. An independent samples t-test was used to determine differences in age, years of education, number of responses, and number of errors for the two groups (HC or CONC). The Greenhouse-Geisser correction for degrees of freedom was used for analyses that failed Mauchly’s Test of Sphericity. Age and sex was controlled for in analyses. Statistical significance was set at \( p \leq 0.05 \).

2.4.1 Secondary Analysis

The concussion group was subdivided based on presence of zero, one, or two symptoms on self-reported symptom scores. Participants who scored \( \geq 1 \) (mild, moderate or severe) on either the balance or dizziness subsections were classified in the ‘Bal/Dizz’ group. Only 6 participants scored \( \geq 1 \) on the balance subsection and 0 for the dizziness subsection. These participants were grouped with participants who exclusively reported \( \geq 1 \) on dizziness and 0 on balance deficit. Participants who scored \( \geq 1 \) on both balance and dizziness were grouped as ‘Both’. Participants who reported no symptoms (score=0) on both balance and dizziness were allocated to the ‘None’ group. Healthy controls represented their own group. A 4 x 3 repeated measures ANOVA was performed to test the hypothesis that participants who self-report greater symptoms will show elevated RMS, velocity, and high-frequency PSD in the EO, EC and DT conditions. A univariate ANOVA was used to test the hypothesis that participants who reported greater symptoms will show elevated BESS score. Age and sex were controlled for in analyses.

3 Results

Fifty-three participants were excluded from the analysis. Fifty-two participants were excluded for the following reasons: >8-days post-concussion at the time of the assessment (n=5); professional or elite athletes (n=3); not following instructions or producing an accessory movement during one of the conditions (n=18); pre-morbid vestibular problems (n=3); current lower limb musculoskeletal injuries (n=16); concussion within the year (n=4); multiple concussions (n=2); multiple strokes (n=1). One person withdrew from the study. Thus, 104 participants with concussion (CONC) were included in the analysis. Twenty healthy controls (HC) were included in the analysis. One healthy control (female; age 26) was excluded from the
COP analysis for producing an accessory movement during the DT condition, but was included in the demographics and BESS analysis. Demographics are reported in Table 1.

Table 2. Demographics for CONC and HC. Significant differences are represented with *.

<table>
<thead>
<tr>
<th>Variable</th>
<th>CONC N=104</th>
<th>HC N=20</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sex (number (%))</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Men</td>
<td>47 (45%)</td>
<td>8 (40%)</td>
</tr>
<tr>
<td>Women</td>
<td>57 (55%)</td>
<td>12 (60%)</td>
</tr>
<tr>
<td><strong>Age (Mean (SD))</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Range)</td>
<td>32.7 (11.8)</td>
<td>31.9 (10.1)</td>
</tr>
<tr>
<td><strong>Years of Education (Mean (SD))</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>15* (2.36)</td>
<td>18*(1.39)</td>
</tr>
<tr>
<td><strong>Dual Task (Mean (SD))</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Responses</td>
<td>12* (6.13)</td>
<td>16* (5.2)</td>
</tr>
<tr>
<td>Errors</td>
<td>1 (1.34)</td>
<td>0.5 (0.77)</td>
</tr>
<tr>
<td><strong>Days post-injury (Mean (SD))</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>5.0 (1.74)</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Method Of Injury (%)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sport-Related</td>
<td>28%</td>
<td>N/A</td>
</tr>
<tr>
<td>Fall</td>
<td>28%</td>
<td>N/A</td>
</tr>
<tr>
<td>Transportation</td>
<td>25%</td>
<td>N/A</td>
</tr>
<tr>
<td>Violence</td>
<td>7%</td>
<td>N/A</td>
</tr>
<tr>
<td>Other</td>
<td>12%</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>SCAT3 [Median (Range)]</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>37 (0-128)</td>
<td>N/A</td>
</tr>
<tr>
<td>Balance</td>
<td>1 (0-6)</td>
<td>N/A</td>
</tr>
<tr>
<td>Dizziness</td>
<td>1 (0-6)</td>
<td>N/A</td>
</tr>
</tbody>
</table>
3.1 BESS

BESS score showed to be a sensitive test to identify balance-related differences between adults with concussion and controls, with individuals with concussion (CONC) producing, on average, 3.5 more errors than HC \([F(1,120)=5.555, p=0.020, \text{ Figure 2}]\). No significant effect of sex on total BESS score was observed. Age was found to be a significant covariate for BESS score \([F(1,120)=8.73, p=0.004]\).

\[
\begin{align*}
\text{Figure 2.} & \quad \text{Total BESS test score for CONC and HC. Values are represented as means and SD.}
\end{align*}
\]

3.2 COP Metrics

3.2.1 RMS

Specific to the AP direction, RMS showed to be sensitive at determining group differences between CONC and HC and task differences between EO and DT conditions and EC and DT conditions. The results showed a main effect of task \([F(2, 238)=4.29, p=0.015, \text{ Figure 3}]\). Bonferroni adjusted post-hoc analysis identified significantly larger RMS in the EO condition compared to DT \([p=0.010]\) and significantly larger RMS during EC compared to DT \([p=0.001]\); however, no significant difference between EO and EC was present. No task-by-group interaction was identified. A trend toward larger AP RMS for the CONC group was identified, compared to HC \([F(1,119)=3.33, p=0.070]\). Age or sex were not significant covariates. Analysis
of ML RMS revealed the absence of statistically significant main or interaction effects. In addition, no significant effects of age or sex were observed.

![Graph showing AP RMS and ML RMS for CONC (grey) and HC (white) in EO, EC, and DT conditions. Values are represented as means and SD.](image)

**Figure 3.** AP RMS (left) and ML RMS (right) for CONC (grey) and HC (white) in EO, EC, and DT conditions. Values are represented as means and SD.

### 3.2.2 Velocity

COP velocity showed to be sensitive in identifying differences between participants with concussion and controls and for determining differences between tasks during quiet standing. A significant main effect of task was found for AP Velocity \([F(1.66, 197.93) = 11.65, p = 0.001, Figure 4]\). Bonferroni adjusted post-hoc analysis revealed a significant difference between all tasks \([p < 0.002]\) where AP velocity was significantly larger in EC and DT conditions, compared to EO. A trend towards a group effect (CONC tending to have larger AP velocity than HC) was identified for AP Velocity \([F(1, 119) = 3.28, p = 0.072]\). Sex was not a significant covariate, however a significant effect of age \([F(1, 119) = 11.12, p = 0.001]\) was present. Analysis in the ML direction revealed no task differences. However, the CONC group produced significantly larger ML velocity compared to HC \([F(1, 119) = 8.60, p = 0.004]\). No significant sex or age effects were found.
3.2.3 Power Spectrum Density

High-frequency PSD was sensitive in differentiating between individuals with concussion and non-concussed controls. A main effect of task was observed for AP high-frequency PSD \[F(1.783, 212.07) = 10.71, p = 0.001, \text{Figure 5}\]. Bonferroni adjusted post-hoc analysis revealed significant differences between all conditions \(p < 0.001\), such that individuals produced significantly larger AP high-frequency power in the EC and DT conditions, compared to EO. AP high-frequency PSD was significantly larger in CONC participants compared to HC \[F(1, 119) = 4.67, p = 0.033\]. AP high-frequency PSD showed no group-by-task interaction or effect of sex. Age was a significant covariate of AP high-frequency PSD \[F(1, 119) = 9.52, p = 0.003\]. No significant task effects were found for ML high-frequency PSD. The CONC group produced significantly larger ML high-frequency PSD compared to HC \[F(1, 119) = 8.18, p = 0.005\]. No group-by-task interaction or effects of covariates (age, sex) were observed.

**Figure 4.** AP velocity (left) and ML velocity (right) for CONC (grey) and HC (white) in EO, EC and DT conditions. Values are represented as means and SD. Group differences are denoted by *.
3.3 Secondary Analysis

Subdividing the CONC group based on symptom reporting (self-reporting >1 on balance or dizziness, scoring >1 on both, or 0 on both), did not reveal any further task, group, or interaction effects when comparing the entire CONC group to HC. However, pairwise comparisons between groups were explored that showed a significant main effect of group including; BESS score, AP velocity, ML velocity, and ML high-frequency power. A trend towards a group effect was present in AP RMS and AP Velocity when analyzing the CONC group overall; however, these trends were no longer significant when categorizing the CONC group based on self-reported symptoms.
Table 3. Demographics for groups based on self-reported measures.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Both</th>
<th>Bal/Dizz</th>
<th>None</th>
<th>HC</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>45</td>
<td>30</td>
<td>29</td>
<td>20</td>
</tr>
<tr>
<td>Sex (number (%))</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Men</td>
<td>19 (58%)</td>
<td>15 (40%)</td>
<td>13 (45%)</td>
<td>8 (40%)</td>
</tr>
<tr>
<td>Women</td>
<td>26 (42%)</td>
<td>15 (50%)</td>
<td>16 (55%)</td>
<td>12 (60%)</td>
</tr>
<tr>
<td>Age (years (SD))</td>
<td>32.0 (10.7)</td>
<td>31.3 (10.2)</td>
<td>36.1 (15.0)</td>
<td>31.9 (10.1)</td>
</tr>
</tbody>
</table>

Figure 6. CONC grouping based on self-reported symptoms of balance and dizziness. Participants are allocated based on reporting ≥1 on both (Both), either (Bal/Dizz) or neither (None). BESS score (top left), AP velocity (top right), ML velocity (bottom left) and ML high-frequency PSD (bottom right) showed significant group differences. Values are represented as means and SD. Post-hoc group differences are represented by *.
A main effect of group was present for total BESS score \(F(3, 118)=2.69, p=0.049\), Figure 6]. The average number of errors performed by all groups was; 17.1 (Both), 15.5 (Bal/Dizz), 15.5 (None) and 12.7 (HC). Bonferroni adjusted post-hoc analysis revealed the participants that reported both balance and dizziness symptoms (Both) produced significantly more errors than controls \(p=0.006\). AP velocity revealed a main effect of group \(F(3, 117)=2.88, p=0.039\), Figure 6. However, when adjusting for multiple comparisons, no pairwise comparisons were significant. A main effect of group was found in ML Velocity \(F(3, 117)=4.26, p=0.007\), Figure 6. Pairwise comparisons (Bonferroni adjusted) revealed significantly larger ML velocity in the group that reported no balance or dizziness symptoms (None) and HC \(p=0.005\). A main effect of ML high-frequency power was present \(F(3, 117)=3.07, p=0.031\), Figure 6. Bonferroni adjusted pairwise differences were observed between the None group and HC, where the group that reported no symptoms had significantly larger high-frequency ML PSD compared to HC \(p=0.034\).

3.4 Individual Data

Individual data for the concussion participants are represented in scatterplots based on their self-reported symptom groupings, relative to the upper limit of the 95% confidence interval (CI) of HC (Figure 7). Data were displayed in both the EC and DT conditions (y-axis), relative to EO (x-axis) for each dependent variable. The proportion of participants in each quadrant was calculated to explore condition-dependent deficits on an individual level. If participants were within the 95% CI of HC on both EO and EC/DT they were allocated under ‘Within Both’. If participants were within the 95% CI in the EO condition however fall above the 95% CI in the EC/DT conditions they were categorized as ‘Within EO Above EC/DT’. Similarly, if they were above of the 95% CI during EO but below the 95% CI during EC/DT they were included in the ‘Above EO Within EC/DT’. Lastly, if they were above of the 95% CI during EO and EC/DT they were included in ‘Above Both’.
Figure 7. Scatterplots depicting the relationship between EO (x-axis) and EC/DT (y-axis) for RMS (top), velocity (middle) and high-frequency PSD (bottom) in the AP (left) and ML (right) directions, relative to the 95% confidence intervals of HC (black lines). Each CONC participant is represented based on self-reported symptoms grouping.
Table 4. Proportion of participants in the Both, Bal/Dizz and None groups, relative to upper limit of the 95% CI of HC. Participants in the ‘Within Both’ quadrant fall within 95% CI during the EO and EC or DT conditions. Participants that were within the 95% CI during EO but above the 95% CI for EC/DT are represented as ‘Within EO/ Above EC/DT’. Participants that were above 95% CI during EO but inside 95% CI for EC/DT are listed in ‘Above EO/ Within EC/DT’. Participants who were above the 95% CI for EO and EC/DT are represented in ‘Above Both’.

<table>
<thead>
<tr>
<th></th>
<th>Within Both</th>
<th>Within EO Above EC/DT</th>
<th>Above EO Within EC/DT</th>
<th>Above Both</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Both</td>
<td>Bal/Dizz</td>
<td>None</td>
<td>Both</td>
</tr>
<tr>
<td>AP RMS</td>
<td>EC 38%</td>
<td>47%</td>
<td>48%</td>
<td>22%</td>
</tr>
<tr>
<td></td>
<td>DT 33%</td>
<td>33%</td>
<td>48%</td>
<td>27%</td>
</tr>
<tr>
<td>ML RMS</td>
<td>EC 47%</td>
<td>43%</td>
<td>52%</td>
<td>4%</td>
</tr>
<tr>
<td></td>
<td>DT 40%</td>
<td>47%</td>
<td>38%</td>
<td>11%</td>
</tr>
<tr>
<td>AP Velocity</td>
<td>EC 40%</td>
<td>70%</td>
<td>38%</td>
<td>20%</td>
</tr>
<tr>
<td></td>
<td>DT 44%</td>
<td>60%</td>
<td>34%</td>
<td>16%</td>
</tr>
<tr>
<td>ML Velocity</td>
<td>EC 36%</td>
<td>50%</td>
<td>40%</td>
<td>27%</td>
</tr>
<tr>
<td></td>
<td>DT 36%</td>
<td>40%</td>
<td>30%</td>
<td>27%</td>
</tr>
<tr>
<td>PSD High AP</td>
<td>EC 42%</td>
<td>63%</td>
<td>53%</td>
<td>24%</td>
</tr>
<tr>
<td></td>
<td>DT 51%</td>
<td>57%</td>
<td>53%</td>
<td>16%</td>
</tr>
<tr>
<td>PSD High ML</td>
<td>EC 51%</td>
<td>60%</td>
<td>66%</td>
<td>22%</td>
</tr>
<tr>
<td></td>
<td>DT 47%</td>
<td>43%</td>
<td>52%</td>
<td>27%</td>
</tr>
</tbody>
</table>

The individual data show that 30-70% of participants fall within the upper limit of the 95% CI of HC (Within Both), regardless of task (EC or DT). Previously, AP velocity, ML velocity and ML high-frequency PSD were found to show significant mean differences (Figure 6) where the ‘None’ group had significantly larger ML velocity and ML high-frequency PSD compared to HC. This is reflected in the proportion of participants in the ‘Above Both’ group, where the participants that reported no symptoms (‘None’ group) represent the largest proportion in these measures. As 9-33% of participants with concussion fall above the 95% CI of HC, these scatterplots suggest that concussion does not always result in postural instability. Rather, there is heterogeneity in balance deficits throughout this cohort.
These scatterplots additionally reflect condition-dependent postural deficits. Participants that fall within healthy values during EO but above the 95% CI in the EC condition (‘Within EO Above EC’) may have deficits in the vestibular control of balance. Participants that fall within healthy values during EO but fall above healthy values during DT (‘Within EO Above DT’) may have deficits in attentional processes and are therefore unable to divide attention between the simultaneous tasks. In contrast, participants who are in the ‘Above EO Within EC/DT’ group may be using a different strategy to control the COP within the BOS. Perhaps these participants are constricting the movement of the COP within a smaller area during the EC and DT conditions, compared to EO.

3.5 Cognitive Motor Dual-Task

The number of responses given during the DT condition was significantly higher $[t(123)=-2.715, p=0.008]$ in the HC (16 responses) than in the CONC group (12 responses). The HC had significantly more years of education (18 years) than the CONC group (15 years) $[t(38.63)=-6.443, p=0.001]$. However, no significant difference was found between number of errors made, where HC made 0.5 errors and the CONC group made 1 error, on average. There were no significant correlations between years of education and number of responses or number of errors made.

4 Discussion

The present study aimed to characterize deficits in postural control following acute concussion in adults from the general population. The main findings of this study were: (1) compared to age- and sex-matched healthy controls, individuals with concussion produced more errors during the BESS and showed deficits during quiet standing in COP velocity and high-frequency power, (2) altering task difficulty (EC or DT) did not result in a greater postural instability than in healthy controls, (3) subjective self-reporting symptoms did not align with objective measures of balance deficits. The findings of this study will be discussed further in subsequent sections.
4.1 Clinical Measures of Balance Revealed Deficits

Previous studies have identified recovery trajectories of the BESS test in high-level athletes (Ruhe et al., 2014). At baseline, athletes score an average of 12 errors. This increases to 16 errors after concussion (Ruhe et al., 2014). Although the present study did not collect baseline values for participants with concussion, an age-and sex-matched control group was used for comparison. The difference in BESS scores between groups in the present study parallel the pre-post injury differences previously reported in high-level athletes. It is important to note that the reliable change index (RCI) of the BESS test is 3 points (Valovich Mcleod et al., 2006). On average, the difference in BESS between the CONC and HC groups was 3 points, indicating that the CONC group was impaired on the BESS and that there is capacity for the CONC group to recover in a clinically meaningful way.

What remains unclear is an understanding of the specific balance deficits that are reflected in the BESS. Because the BESS is performed in the absence of vision and with altered proprioceptive information (foam conditions), the BESS may be an indicator of vestibular dysfunction. Indeed, more errors occur while standing on foam than on the firm surface (Iverson, Kaarto, & Koehle, 2008; Iverson & Koehle, 2013), although this finding may be attributed to the difficulty and unfamiliarity in relying solely on the vestibular system to control posture during these challenging positions. In contrast, the positions employed in the BESS reduce the BOS, resulting in reduced space for the COM to move within before reaching the limits of stability. Errors made during the BESS may represent balance reactions that are too late or too small and represent deficits in appropriate execution of reactive balance responses.

4.2 COP Measures During Quiet Standing Revealed Deficits

The COP is a measure of the net neuromuscular control of the position of the COM within the BOS (Winter et al., 1998). The more variable (RMS) and faster (velocity) the COP moves, the greater amount of postural instability (Palmieri et al., 2002). One of the ways in which the central nervous system controls the COP is through the information from relevant sensory systems (i.e. visual, vestibular, and somatosensory systems). Previous work has found vestibular dysfunction following concussion as a result of the mechanism of concussive injury
causing damage to the sensitive sensory organ in the inner ear (McLeod & Hale, 2015). This is reflected by the common complaint of dizziness that occurs following concussion that is self-reported in 67-77% of concussions (Lovell et al., 2006; McLeod & Hale, 2015). Dizziness can result from a range of pathophysiological processes; however, previous work in concussion has determined that complaints of dizziness reflects true vestibular dysfunction (Reneker et al., 2018). In addition, previous concussion-related balance literature has found deficits in the vestibular control of posture. Previous work has identified interactions between concussed athletes and controls when using the eyes closed condition (Powers et al., 2014). Additional work using the Sensory Organization Test (SOT), which probes postural control while manipulating different sensory contributions, has found deficits when visual inputs are absent or inaccurate, through the use of a sway-referenced visual field in athletes with concussion (Cavanaugh et al., 2005, 2006; McLeod & Hale, 2015). Although significant task effects between eyes open and eyes closed were found in the present study (reflecting the difficulty associated with maintaining postural control when relying more heavily on the vestibular system), these deficits were not significantly larger for participants with concussion compared to controls. As a result, conclusions regarding deficits in the vestibular control of posture cannot be made. Alternatively, the task of standing within the standardized BOS may not cause an adequate postural challenge to distinguish this cohort from controls. Powers et al. (2014) found group differences in the feet together position when assessing concussed athletes. The balance tasks in this study were all completed within a BOS that was standardized to a comfortable foot position for 262 men and women (McIlroy & Maki, 1997). Consistent with other null findings in the eyes closed condition within a ‘comfortable’ BOS, the BOS used in the present study may not be difficult enough to determine deficits in individuals with concussion (Kleffelgaard et al., 2012). This point further supports the position that the reduced BOS employed by the BESS increases postural challenge. Within the standardized BOS during the eyes closed condition, the control of the COM within the limits of stability may not be restricted enough to elicit large contributions of the vestibular system such that deficits are revealed in this cohort.

As concussion is a multimodal neurological injury that affects both balance and cognition, the cognitive-motor dual task was used to probe attentional processes and postural resources simultaneously (Register-Mihalik et al., 2013). The individual may prioritize the arithmetic task or postural control task. When the information processing capacity of an
individual is limited following concussion, performance in either the postural control or
cognitive task may decline (Woollacott & Shumway-Cook, 2002). In the AP direction,
significantly larger variability (RMS) was found in the EO condition, compared to the DT
condition. Previous studies have found similar strategies (Broglio, Tomporowski, & Ferrara,
on the balance task during the EO condition, participants may unconsciously increase muscle
tension of the lower limbs, leading to increased COP variability (Hunter & Hoffman, 2001).
Although increasing muscle tension may lead to a tighter control strategy and smaller COP
movement, the variability around this COP movement may be increased.

No task-by-group interactions were found in any of the COP measures; however, the
concussion group produced significantly fewer responses than controls. In spite of this, when
controlling for number of responses, no significant differences were observed in the number of
errors made. Years of education was also statistically significant between the two groups (i.e.
controls had 3 more years of education on average); however, no significant correlations were
found between years of education and number of responses or number of errors made. The
differences in response rate, coupled with the absence of a significant correlation between years
of education and response rate, may reflect deficits in attention, mental tracking, and
computation specific to the concussion group. Taken together, the observation of fewer
responses yet no significant difference in COP measures between the groups indicates that
individuals with concussion may have prioritized the balance task over the mental arithmetic
task.

Elevated high-frequency power was found in both the AP and ML directions for
participants with concussion. This implies that participants with concussion exert more
stabilizing moments in order to keep the COM around a neutral position within the BOS
(Schinkel-Ivy et al., 2016). The elevated RMS and velocity in individuals with concussion
suggests that the reactive postural adjustments in response to phases of instability made by
individuals in the concussion group do not effectively control the COP. Previous work in
individuals with stroke identified a high-frequency RMS amplitude in individuals who could not
respond to an external perturbation, compared to those who could successfully take a stepping
response (Schinkel-Ivy et al., 2016). This implies there is reduced capacity for reactive balance
control in these individuals and is being captured in the high-frequency COP signal during quiet
standing (Schinkel-Ivy et al., 2016). This finding suggests that participants with concussion may have a reduced capacity to reactively control their COM within the BOS.

4.3 Self-Reported Symptoms is not a Reliable Method of Identifying Balance Deficits

As there is no reliable and widely-accepted grading scale for concussion, the self-reported symptom section of the SCAT was developed to inform athletes and clinicians about post-concussive symptoms and their resolution over time (Alla et al., 2009). Previous studies have determined a high internal consistency for post-concussion symptom scales in athletes who are high-school and university-aged; however, no study has determined the reliability of the measure in adults from the general population (Lovell et al., 2006). In the present study, there was a significant difference between the group that reported both balance and dizziness symptoms on BESS test score. Despite statistically significant differences between both the Bal/Dizz group and None group in comparison to controls, the concussed participants in these groups produced 3 more errors (reliable change index of the BESS test) than controls, suggesting that this difference is clinically meaningful. Posturographic measures revealed concussed participants who reported no balance or dizziness symptoms had significantly larger ML velocity and high-frequency PSD, compared to controls. Significant elevation of COP measures during quiet standing were not observed in concussion participants who reported ≥1 on balance and dizziness or participants that reported ≥1 on either symptom. It is possible that the task of standing within the standardized BOS may not be challenging enough to reveal deficits in this population. Alternatively, it is also possible that these participants have a tendency to over-report symptoms. This is reflected in the total self-reported symptom score (Table 1) where the median score 5-days post-concussion was 37. This is, on average, double than what athletes with concussion report 5 days post-concussion (Lovell et al., 2006). Lovell and colleagues (2006) reported that people with depression, anxiety, life stress, or pain self-report a greater magnitude of symptoms on the PCS (Lovell et al., 2006). One potential explanation for this finding could be that the participants in this study are experiencing these stressors and have the tendency to over-report greater symptoms without any objective impairment. If clinical decision-making was based simply on the resolution of symptoms, these people would take longer to make a clinical
recovery from concussion despite objective measures reporting opposite findings. The present findings suggest that the PCS should not be the only measure to characterize balance deficit following a concussion in adults from the general population.

5 Conclusions

The present study demonstrated that within 1-week following injury, individuals from the general population who sustain a concussion experience deficits in clinical and posturographic measures of balance when compared to healthy individuals. Participants who do not self-report symptoms of dizziness or balance problems showed significantly larger COP variables than controls and participants who reported either balance or dizziness symptoms or both balance and dizziness showed no differences to controls. In addition, all groups, regardless of self-reported symptoms, produced a minimum of 3 more errors than controls which is the reliable change index of the BESS. This finding suggests that self-reported symptoms should not be used in isolation for determining concussion-related balance deficit. Instead, self-reported symptoms should be used in parallel with other tools to fully characterize post-concussion balance deficits.
Chapter 3
The Recovery of Postural Control Following a Concussion in Adults from the General Population

1 Introduction

Concussion consensus guidelines suggest that recovery from concussion is a spontaneous process that occurs within the first 1-2 weeks in 80-90% of injuries (McCrory et al., 2017; McCrory et al., 2013a). In agreement with this are studies that identify recovery of balance using self-reported symptoms or clinical measures in high-level athletes (McCrea, Guskiewicz, Marshall, Barr, Randolph, Cantu, Onate, & Kelly, 2003; Ruhe et al., 2014). However, there are limitations associated with the use of self-reported symptoms and clinical measures of balance. The validity of self-reported symptoms has been questioned in the athletic literature as athletes have the tendency to under-report symptoms in order to return-to-play earlier (Broglio et al., 2009; Rochefort et al., 2017). On the other hand, individuals may somaticize life stressors when reporting concussion symptoms (Lovell et al., 2006). In Chapter 2, participants who self-reported both balance deficits and dizziness or either balance deficits or dizziness showed no significant difference in balance measures during quiet standing. In contrast, concussed participants that reported neither symptom showed significant balance deficits when compared to controls. Alongside self-reported symptoms, clinical measures of balance are often used to measure concussion recovery across time (Buckley et al., 2016; Guskiewicz, 2003; Guskiewicz, 2001; Mulligan et al., 2013; Ruhe et al., 2014). The Balance Error Scoring System (BESS) offers a quick and low-cost assessment of balance following a concussion (Bell et al., 2011). Previous studies have identified recovery of balance following concussion using the BESS test, which occurs within 5-7 days (Ruhe et al., 2014). However, the BESS test has been found to have low to moderate reliability, and low sensitivity after 3-5 days (Mulligan et al., 2013; Murray et al., 2014; Sheehan et al., 2011). In addition, the BESS test is prone to learning effects over repeated administrations (Mulligan et al., 2013). This questions the validity of whether these studies are capturing recovery of balance or if reduction in score is a result of learning effects following a concussion. However, athletes have previously been shown to have neurophysiological differences compared to non-athletes, which makes athletes better motor learners than non-
athletes (Nakata, Yoshie, Miura, & Kudo, 2010). Because non-athletes demonstrate reduced motor learning abilities, it is possible the observed learning effects in the athletic population may not be observed in adults from the general population.

The limitations associated with self-reported symptoms and the BESS make it difficult to draw reliable conclusions regarding the recovery of postural control following a concussion. As a result, researchers have used posturographic measures to determine recovery of postural control following concussion (Buckley et al., 2016; Cavanaugh et al., 2005, 2006; Degani et al., 2017; Powers et al., 2014; Slobounov et al., 2008). Posturographic analyses allow researchers to characterize different aspects of the postural control system (Horak, 2006; Woollacott & Shumway-Cook, 1996). Previous work that has used posturographic measures to determine recovery find prolonged recovery trajectories compared to what has been found for BESS score and self-reported symptoms (Powers et al., 2014; Slobounov et al., 2008; Sosnoff et al., 2011). Powers et al (2014) assessed concussed collegiate-level football players acutely following concussion and secondly upon return-to-play (Powers et al., 2014). Upon return-to-play, which ranged from 10-48 days, athletes had significantly elevated RMS COP velocity during quiet standing with the eyes closed condition. In addition, Slobounov et al (2008) found deficits in COP measures 30-days post-injury (Slobounov et al., 2008). Postural control deficits have additionally been observed in athletes with a history of concussion ranging from 6-150 months post-injury (Sosnoff et al., 2011). Studies that use posturographic measures to determine recovery often rely on values returning to pre-injury baseline values or non-concussed control values. However, questions often arise as to the real-world interpretation of these measures that may be limited in their clinical significance or in their association with risk of injury or risk of falls. Although the COP allows for a sensitive and objective measure of balance, limited evidence exists regarding clinically meaningful change associated with these measures.

Although these recovery trajectories of BESS and COP variables exist, the majority of the current concussion-related balance literature identifies recovery in high-level athletes. Recovery of postural control following concussion has not been determined in adults from the general population. The recovery of postural control in adults from the general population may be different from what has been characterized as the recovery trajectory of athletes as a result of the neuroprotective effects of exercise on the brain (Cotman & Engesser-Cesar, 2002; Leddy et al., 2010). The neuroprotective effects may mask concussion-related deficits in athletes and lack
of neuroprotective effects of exercise may prolong recovery in adults from the general population. In addition, as return-to-play protocols require graded return to physical activity, these early differences in exercise levels post-injury may be beneficial in increasing recovery rates of concussion-related balance deficits (Leddy et al., 2010). Recent work has shown faster rates of recovery in athletes who returned to aerobic exercise sooner following concussion (Lawrence et al., 2018). Taken together, this evidence suggests that exercise may have a beneficial role on recovery from concussion. Apart from the differences in activity level, the everyday lives of an adult from the general population and an elite athlete differ. The stress associated with returning to work, completing activities of daily living, and taking care of family members may have a negative impact on the recovery of concussion. If postural control deficits are prominent when returning to these activities too early, this may put individuals at increased risk of re-injury or falls. The need to characterize the recovery of postural control deficits in adults from the general population is apparent.

The purpose of this work was to determine recovery of postural control longitudinally over time following a concussion in adults from the general population using BESS score and posturographic measures during quiet standing. Recovery was determined using a Hierarchical Growth Curve Model. In order to determine recovery that is both clinically meaningful and individualistic (i.e. person-specific), an analysis using a reduction in BESS score and COP measures was completed using the reliable change index (BESS) and coefficient of variation of healthy controls (COP measures). It was hypothesized that the Hierarchical Growth Curve Model will show significant reduction in these variables across time. Additionally, it was hypothesized that using the reliable change index and coefficient of variation approach to determine recovery of BESS score and COP measures will yield a greater proportion of participants recovering across time.

2 Methods

2.1 Participants

Concussion (CONC) participants were referred to the Hull-Ellis Concussion Clinic by physician referral by 3 emergency departments from hospitals in the downtown Toronto, Canada
area and were assessed within the first 8 days of injury to mark the Week 1 visit. Participants were re-assessed at Weeks 2, 4, 8 and 12 post-concussion. Healthy, age- and sex-matched controls (HC) were recruited from the university and hospital community and were assessed at the same time points. Exclusion criteria for the CONC participants included: admission to the hospital for the current concussion, showed positive head imaging, history of other neurological conditions, pre-morbid vestibular disorders or any lower limb injuries within 1 year of assessment date that would affect balance. Exclusion criteria for HC included: history of concussion or other neurological conditions, pre-morbid vestibular disorders or any lower limb injuries within 1 year of assessment date that would affect balance. Lastly, professional and elite athletes were excluded from the study. All participants provided written informed consent prior to study participation. This study was approved by the Research Ethics Board at the University Health Network (REB #17-5348).

2.2 Experimental Protocol

2.2.1 Self-Reported Symptoms

CONC participants self-reported symptoms using the Sport Concussion Assessment Tool (SCAT-3) (McCrorry et al., 2013b) prior to the balance assessment at each time-point. The SCAT-3 requires the participant rate their symptoms based on ‘how they are feeling on that day’ on a likert scale [0 (none), 1-2 (mild), 3-4 (moderate), 5-6 (severe)] for 22 different symptoms including balance problems and dizziness.

2.2.2 Equipment and Set-Up

All assessments included 3 quiet standing trials of EO, EC, and DT (backwards sevens) for 50 seconds within a standardized BOS, as determined by McIlroy and Maki (1997) as 10 cm between heel centres and feet turned 14° from midline (McIlroy & Maki, 1997). Participants were instructed to keep their hands at their side and to remain as still as possible. Participants also completed the BESS test. The order of quiet standing or BESS test was counterbalanced between participants.
2.2.2.1 Quiet Standing

Measures of quiet standing were quantified using separate AMTI force plates under each foot (1 mm between force plates, Y axes in parallel). Ground reaction forces and moments were recorded using LabView 12 software (National Instruments, Austin TX). Signals from each force plate were sampled at 256 Hz.

2.2.2.2 BESS

Participants were video recorded while completing the BESS battery (feet together, unipedal, and tandem stances repeated on firm and foam surface with eyes closed) and were retrospectively scored for errors (Riemann & Guskiewicz, 2000). Errors included; opening the eyes, moving the hands off the iliac crest, abducting the hip greater than 30 degrees, lifting the forefoot or heel, taking a step, stumble or fall or remaining out of the testing position for greater than 5 seconds (Riemann & Guskiewicz, 2000).

2.3 Data Analysis

The COP was calculated using the forces and moments collected by two adjacent force plates during quiet standing. Data were filtered using a low-pass, zero-lag, 2nd order Butterworth filter with a 10 Hz cut-off. The net COP signal was calculated in anteroposterior (AP) and mediolateral (ML) directions. Mean-removed COP was used to calculate RMS and velocity (Equations 1 and 2, respectively) using a custom code written in MatLab v.8.3 (The MathWorks Inc., Natick, USA) (Duarte & Freitas, 2010).

Equation 1: \[ RMS = \frac{\sqrt{\sum (\text{COP}^2)}}{\text{length(COP)}} \]

Equation 2: \[ Velocity = \frac{\text{sum(abs(diff(COP))) \times freq}}{\text{length(COP)}} \]
2.3.1 Hierarchical Growth Curve Model

A Hierarchical Growth Curve Model was used to determine recovery across all dependent variables during quiet standing (RMS, velocity in the AP and ML directions) across each condition (EO, EC, DT), and for total BESS score. A Hierarchical Growth Curve Model was used instead of an ANOVA as the growth curve model allows for missing data points and irregularity of timing in between assessments (Curran, Obeidat, & Losardo, 2010; Shek & Ma, 2011; Singer, Nishihara, & Mochizuki, 2015). The Hierarchical Growth Curve Model is a 2-level model that assesses within-individual change (Level 1) and between-individual change (Level 2) (Shek & Ma, 2011; Singer et al., 2015; West, 2009). As a result, the Hierarchical Growth Curve Model allows for both time-variant (Level 1) and time-invariant (Level 2) covariates. The model can be conceptualized by the following equations (DeLucia & Pitts, 2006):

**Level 1 model:**

\[ Y_{ij} = b_{0i} + b_{1i}(time_{ij}) + e_{ij} \]

**Level 2 model:**

\[ b_{0i} = \beta_{00} + v_{0i} \]

\[ b_{1i} = \beta_{10} + v_{1i} \]

where Level 1 represents an ordinary least square regression model (DeLucia & Pitts, 2006). The outcome (Y) is dependent on intercept (\( b_{0i} \)), slope (\( b_{1i} \)) and a residual estimate (\( e_{ij} \)). Subscript \( i \) represents measurement at the individual level. Therefore, these values differ for each individual, unlike ordinary regression models in which these factors are fixed. In this equation, time is linear. However, the Hierarchical Growth Curve can assess curvilinear effects of time through inclusion of quadratic or cubic effects of time. Level 2 represents deviation in intercept and slope parameters (\( b_{0i}, b_{1i} \)) as a function of population-level estimates of intercept or slope (\( \beta_{00}, \beta_{10} \)) plus individual deviation from population intercept or slope (\( v_{0i}, v_{1i} \)). Population-level estimates are fixed effects, therefore constant across each individual in the sample. Individual-level deviations are random effects and can vary across each individual in the sample.

First, an Unconditional Means Model was used to determine if there was systematic variation in the dependent variables, irrespective of time (Hedeker, 2004). The interclass correlation (ICC) is calculated from the Unconditional Means Model and represents the amount of variation in the dependent variable that is attributed to individual differences (Hedeker, 2004).
The Unconditional Means Model confirmed there was systematic variation in each dependent variable worth exploring and was calculated by the following equation:

\[ ICC = \frac{\text{Intercept}}{\text{Residual} + \text{Intercept}} \]

Next, the Unconditional Growth Curve Model assessed if there was a linear effect of time in the dependent variables without the inclusion of covariates. Values of missing data points were estimated using the Maximum Likelihood (ML) estimation (Hedeker, 2004). The ML approach estimates missing data by weighting participants with a larger number of data points more heavily than participants with fewer data points (Curran et al., 2010). Covariance parameters were estimated using an Unstructured matrix which assumes no relationship in covariance parameters. Time post-concussion was scaled in Weeks and centered at Week 0 (the week the concussion occurred) to account for any recovery that may have happened between the onset of concussion and the first balance assessment. Intercept was held as a random factor. Slope was held as random depending on the model fit; if model fit was improved holding slope as only a fixed factor and if the covariance parameter for slope was non-significant, then slope was held as a fixed factor only (the same trajectory occurs in each participant). If the covariance parameter for slope was significant (i.e. slope significantly differed between participants), slope was additionally held as a random factor. Model fit was assessed using the Log Likelihood Ratio and significance was determined using the Chi-Square statistic. Significance levels for slope (time) were assessed using the t-statistic with a Satterthwaite approximation for degrees of freedom (Singer et al., 2015). If the linear effect of time was significant, quadratic effects of time were explored for significance. If the quadratic effect of time was not significant, the model with the better fit was retained for the analysis.

Lastly, the Conditional Growth Model assessed the addition of Level 2 covariates and interactions (Age, Sex, Age x Time, Sex x Time). Age was centered on the mean (age subtracted the mean) to determine if there were any differences at the mean age (rather than age 0). Sex was coded as males=0 and females=1. No additional Level 1 covariates (within-individual covariates) other than time were added to the model. If covariates or interactions were not statistically significant, they were removed from the model. Model fit was assessed using Log Likelihood Ratio and the Chi-Square statistic. Removal of non-significant covariates did not significantly
reduce model fit. For dependent variables that had significant covariates, final between-
individual variance parameters were obtained from this model and proportional reduction in
variance was calculated using the variance parameters from the Unconditional Growth Curve
Model. For variables that had no significant covariates, the Unconditional Growth Curve Model
was retained as the final model and therefore between-individual reduction in variance was not
calculated as there were no between-individual covariates. Within-individual reduction in
variance was calculated using the variance parameter from the Unconditional Means Model as
time was the only within-person covariate in this analysis. Proportional reduction in within and
between-individual variance was calculated using the following equation:

\[
\text{Proportional Reduction in Variance} = \frac{\text{Variance}_{\text{Initial}} - \text{Variance}_{\text{Final}}}{\text{Variance}_{\text{Initial}}}
\]

### 2.3.2 Coefficient of Variation

An individualized (person-specific) approach to determine recovery was completed using
the coefficient of variation (CV) across 5 balance assessments in controls. HC completed the
balance assessment at the same time points as CONC and therefore, the natural variation that
exists in RMS and velocity over time could be determined for each task. The CV was calculated
across Week 1, 2, 4, 8 and 12 for HC for each dependent variable. The average CV was obtained
across the sample of \( n = 19 \) HC participants. These values were used to determine if
individualized recovery occurred in CONC participants relative to Week 1 values. The CV
determined by HC was multiplied by the Week 1 value for CONC participants and subsequently
subtracted from the Week 1 value to represent a new value that has decreased by natural
variation. This is represented by the following equation:

\[
x = W_1 - (W_1 \times CV)
\]

If the Week 2, Week 4, Week 8 or Week 12 value was less than \( x \), the participant was
dichotomously categorized as ‘recovered’. If the Week 2, 4, 8 or 12 value was not reduced by
this amount, the participant was categorized as ‘not-recovered’ at that time-point. Essentially, if
the dependent variable reduced greater than the natural variation that was determined by controls
across time, it was hypothesized this variation is a result of something apart from the natural day-
to-day fluctuation associated with these measures and can be assumed this reduction is attributed to concussion-related recovery. As the RCI exists for total BESS score (a reduction in 3 errors), a similar approach was taken for BESS score however using the RCI rather than the CV.

Therefore, relative to the Week 1 BESS score, if Week 2, 4, 8 or 12 had reduced by 3 or more errors, the participant was determined to be recovered. A second level of analysis was completed using the 95% confidence interval (CI) of HC. The upper limit of the 95% CI was used as a cut-off in determining if the recovered CONC participants were within 95% CI of HC. If the participant recovered by greater than the CV and this value was within the 95% CI, they were determined to be recovered.

3 Results

3.1 Hierarchical Growth Curve Model

In order to best estimate recovery within individuals, participants were included in the Hierarchical Growth Curve Model if they had completed 3 or more assessments (Curran et al., 2010). Ninety-four CONC participants had completed 3 or more balance assessments. Thirty-two participants were excluded from the analyses for the following reasons: athlete (n=2), history of stroke (n=2), previous concussion within the year (n=5), current lower musculoskeletal injury (n=10), previous vestibular injury (n=5), involved in a motor vehicle accident (n=2) or not following instructions (n=6). Sixty-two CONC participants were included in the analyses. Sample size varied across weeks with n=61 at Week 1, n=58 at Week 2, n=53 at Week 4, n=51 at Week 8 and n=39 at Week 12. Participant demographics are reported in Table 4. Residual and intercept parameters used to calculate ICC values from the Unconditional Means Model are represented in Table 5. These values confirmed that exploration of variability in these measures was warranted. Growth model parameters are reported in Table 6. The intercept value represents the group mean at Week 0. The slope of the growth curve is represented by the fixed effect variable of time. For variables in which slope was additionally included as a random factor, the covariance parameter for slope is represented as time under random effects. This value represents the amount each individual fluctuates around the fixed effect of time. All variables have covariance parameters for intercept (between-person variability) and for the residual (within-person variability).
Table 5. Demographics and self-reported symptom score for CONC participants included in the Hierarchical Growth Curve Model.

<table>
<thead>
<tr>
<th>Variable</th>
<th>CONC (N=62)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sex [Number (%)]</td>
<td></td>
</tr>
<tr>
<td>Men</td>
<td>29 (47%)</td>
</tr>
<tr>
<td>Women</td>
<td>33 (53%)</td>
</tr>
<tr>
<td>Age [Mean (SD)]</td>
<td>32.8 (11.6)</td>
</tr>
<tr>
<td>Years of Education</td>
<td>15.4 (2.5)</td>
</tr>
<tr>
<td>Days Post Injury</td>
<td>5.0 (2.2)</td>
</tr>
<tr>
<td>Method Of Injury</td>
<td></td>
</tr>
<tr>
<td>Sport-Related</td>
<td>31%</td>
</tr>
<tr>
<td>Fall</td>
<td>30%</td>
</tr>
<tr>
<td>Transportation</td>
<td>25%</td>
</tr>
<tr>
<td>Violence</td>
<td>2%</td>
</tr>
<tr>
<td>Other</td>
<td>12%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>W1</th>
<th>W2</th>
<th>W4</th>
<th>W8</th>
<th>W12</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCAT3 [Median (Range)]</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>36 (0-128)</td>
<td>28 (0-104)</td>
<td>19 (0-99)</td>
<td>6 (0-104)</td>
<td>4 (0-97)</td>
</tr>
<tr>
<td>Balance</td>
<td>0.5 (0-6)</td>
<td>0 (0-6)</td>
<td>0 (0-5)</td>
<td>0 (0-6)</td>
<td>0 (0-3)</td>
</tr>
<tr>
<td>Dizziness</td>
<td>1 (0-6)</td>
<td>1 (0-5)</td>
<td>0 (0-6)</td>
<td>0 (0-4)</td>
<td>0 (0-6)</td>
</tr>
</tbody>
</table>
Table 6. Residual and intercept covariance parameters and ICC values obtained from the Unconditional Means Model. Bolded values represent significance at the p<0.05 level.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Residual</th>
<th>Intercept</th>
<th>ICC</th>
</tr>
</thead>
<tbody>
<tr>
<td>BESS</td>
<td>14.955</td>
<td>26.172</td>
<td>64%</td>
</tr>
<tr>
<td>Eyes Open</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AP RMS</td>
<td>0.022962</td>
<td>0.014471</td>
<td>39%</td>
</tr>
<tr>
<td>ML RMS</td>
<td>0.004722</td>
<td>0.002027</td>
<td>30%</td>
</tr>
<tr>
<td>AP Velocity</td>
<td>0.005701</td>
<td>0.010243</td>
<td>64%</td>
</tr>
<tr>
<td>ML Velocity</td>
<td>0.003341</td>
<td>0.005995</td>
<td>64%</td>
</tr>
<tr>
<td>Eyes Closed</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AP RMS</td>
<td>0.018253</td>
<td>0.017815</td>
<td>49%</td>
</tr>
<tr>
<td>ML RMS</td>
<td>0.006592</td>
<td>0.003567</td>
<td>35%</td>
</tr>
<tr>
<td>AP Velocity</td>
<td>0.018327</td>
<td>0.040635</td>
<td>69%</td>
</tr>
<tr>
<td>ML Velocity</td>
<td>0.029367</td>
<td>0.012672</td>
<td>30%</td>
</tr>
<tr>
<td>Dual Task</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AP RMS</td>
<td>0.016077</td>
<td>0.018207</td>
<td>53%</td>
</tr>
<tr>
<td>ML RMS</td>
<td>0.006318</td>
<td>0.006688</td>
<td>51%</td>
</tr>
<tr>
<td>AP Velocity</td>
<td>0.017981</td>
<td>0.027749</td>
<td>61%</td>
</tr>
<tr>
<td>ML Velocity</td>
<td>0.006079</td>
<td>0.015647</td>
<td>72%</td>
</tr>
</tbody>
</table>
Table 7. Model parameters obtained from the Hierarchical Growth Curve Model. Bolded variables represent significance at the p<0.05 level. Standard error (SE) is included in parentheses.

<table>
<thead>
<tr>
<th>Ears Open</th>
<th>Eyes Closed</th>
<th>Dual Task</th>
</tr>
</thead>
<tbody>
<tr>
<td>BESS</td>
<td>AP RMS</td>
<td>ML RMS</td>
</tr>
<tr>
<td>AP Vel</td>
<td>ML Vel</td>
<td>AP RMS</td>
</tr>
<tr>
<td>AP Vel</td>
<td>ML Vel</td>
<td>AP RMS</td>
</tr>
</tbody>
</table>

**Fixed Effects**

**Time Invariant**

| Intercept | 15.4 (0.71) | 0.43 (0.021) | 0.19 (0.009) | 0.55 (0.014) | 0.37 (0.011) | 0.49 (0.021) | 0.20 (0.011) | 0.81 (0.030) | 0.43 (0.022) | 0.40 (0.021) | 0.22 (0.013) | 0.74 (0.033) | 0.42 (0.018) |
| Age       | 0.15 (0.052) | 0.0024 (0.0011) | - | - | - | - | - | - | - | - | - | - | - |
| Sex       | 0.0016 (0.0025) | 0.00015 (0.0011) | -0.0015 (0.0013) | -0.0014 (0.001) | -0.0029 (0.002) | -0.0011 (0.0013) | -0.0085 (0.0022) | -0.0038 (0.0028) | -0.0009 (0.0021) | -0.0002 (0.0013) | -0.0002 (0.0013) | - | - |

**Time Variant**

| Time      | -0.046 (0.078) | 0.0016 (0.0025) | 0.00015 (0.0011) | -0.0015 (0.0013) | -0.0014 (0.001) | -0.0029 (0.002) | -0.0011 (0.0013) | -0.0085 (0.0022) | -0.0038 (0.0028) | -0.0009 (0.0021) | -0.0002 (0.0013) | - | - |

**Random Effects**

| Intercept | 24.3 (16.13) | 0.015 (0.0036) | 0.0213 (0.001) | 0.0094 (0.0019) | 0.006 (0.0012) | 0.018 (0.0019) | 0.004 (0.0009) | 0.044 (0.01) | 0.0127 (0.0036) | 0.0182 (0.0039) | 0.0067 (0.0015) | 0.025 (0.0052) | 0.016 (0.003) |
| Time      | 0.132 (0.073) | 0.0000004 (0.00002) | - | - | - | - | - | - | - | - | - | - | - |
| Residual  | 12.9 (1.53) | 0.023 (0.0023) | 0.00465 (0.0005) | 0.0057 (0.00057) | 0.0033 (0.00033) | 0.018 (0.0016) | 0.007 (0.0007) | 0.017 (0.002) | 0.029 (0.0029) | 0.016 (0.0016) | 0.0063 (0.0006) | 0.018 (0.0018) | 0.0061 (0.0006) |
3.1.1 BESS Score

Total BESS score did not show significant recovery (reduction in score) across time \[ t(49.4) = -0.59, p=0.558 \] nor did a reduction in a score of 3 errors (the RCI of the BESS test) occur across Week 0 to Week 12 (Figure 8). Age was a significant covariate \[ t(78.6) = 2.88, p=0.05 \] suggesting older participants had a higher BESS score at Week 0. Both within (represented by residual random effect) and between (represented by intercept random effect) individual covariance parameters were significant in the final model, suggesting there was variance in BESS score that was not being accounted for in linear time and age, respectively. Proportional reduction in variability is represented in Table 4. Linear time accounted for 14% of the within-person variability and age accounted for 23% of the between-person variability.

![Figure 8. Growth curve (line) and individual data (dots) for total BESS score.](image)

3.1.2 COP Measures

Individual data and linear growth lines are represented for EO (Figure 9), EC (Figure 10), and DT (Figure 11). No significant recovery occurred in AP RMS, ML RMS, AP Velocity or ML Velocity in EO, EC or DT, with the exception of a significant effect of time (recovery) found in AP Velocity in the EC condition \[ t(31.0) = -3.82, p=0.001 \]. No significant covariates were found in the dependent variables across conditions with the exception of; age in AP velocity in EO \[ t(63.4) = 2.14, p=0.037 \], and sex in AP velocity in DT \[ t(62.5) = -2.54, \]
p=0.014], suggesting participants with age above the mean have higher initial status in AP Velocity (EO) and females have lower initial status in AP velocity (DT). No significant age-by-time or sex-by-time interactions were found, suggesting older participants or female participants do not recover differently across time. Within- and between-individual covariance parameters were significant in the final models. Proportional reduction in variance was calculated between the nested model (without covariates) and the final model and represented in Table 7. Linear effect of time accounted for very little amount of variability (0-8%). Between-person variability was not calculated for variables that did not have age or sex as covariates in the final model.

Figure 9. Growth curves (lines) and individual data (dots) for AP RMS (top left), ML RMS (top right), AP Velocity (bottom left), and ML Velocity (bottom right) in the Eyes Open condition.
Figure 10. Growth curves (lines) and individual data (dots) for AP RMS (top left), ML RMS (top right), AP Velocity (bottom left), and ML Velocity (bottom right) in the Eyes Closed condition.

Figure 11. Growth curves (lines) and individual data (dots) for AP RMS (top left), ML RMS (top right), AP Velocity (females=pink, bottom left), and ML Velocity (bottom right) in the Dual Task condition.
Table 8. Proportional reduction in variability associated with Level-1 covariates (Within-Individual) and Level-2 covariates (Between-Individual).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Within-Individual</th>
<th>Between-Individual</th>
</tr>
</thead>
<tbody>
<tr>
<td>BESS</td>
<td>14%</td>
<td>23% (Age)</td>
</tr>
<tr>
<td>Eyes Open</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AP RMS</td>
<td>0.3%</td>
<td></td>
</tr>
<tr>
<td>ML RMS</td>
<td>1.4%</td>
<td></td>
</tr>
<tr>
<td>AP Velocity</td>
<td>0.8%</td>
<td>8% (Age)</td>
</tr>
<tr>
<td>ML Velocity</td>
<td>1.3%</td>
<td></td>
</tr>
<tr>
<td>Eyes Closed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AP RMS</td>
<td>0.6%</td>
<td></td>
</tr>
<tr>
<td>ML RMS</td>
<td>0.2%</td>
<td></td>
</tr>
<tr>
<td>AP Velocity</td>
<td>8%</td>
<td></td>
</tr>
<tr>
<td>ML Velocity</td>
<td>0.8%</td>
<td></td>
</tr>
<tr>
<td>Dual Task</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AP RMS</td>
<td>0.07%</td>
<td></td>
</tr>
<tr>
<td>ML RMS</td>
<td>0.02%</td>
<td></td>
</tr>
<tr>
<td>AP Velocity</td>
<td>0.9%</td>
<td>10% (Sex)</td>
</tr>
<tr>
<td>ML Velocity</td>
<td>0%</td>
<td></td>
</tr>
</tbody>
</table>

3.2 Healthy Control Values

As the Hierarchical Growth Curve Model did not include HC, the mean, standard deviation (SD), and the upper limit of the 95% CI of HC were calculated, in order to make a comparison to values found in the models. Twenty HC completed the study protocol. However, one HC was excluded from analysis (female, 26 years) because of the production of accessory movement during DT conditions at multiple time-points. Data were extracted using the Week 1 visit for n=19 HC participants (Table 8). Demographic information for HC are presented in Table 9. Mean values of HC data are similar in magnitude to the intercept value found in the Growth Curve Models (Table 6).
Table 9. Normative data for n=19 HC including mean, standard deviation (SD) and the upper limit of the 95% confidence interval (CI).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean (SD)</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>BESS</td>
<td>12.6 (3.8)</td>
<td>14.2</td>
</tr>
<tr>
<td>Eyes Open</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AP RMS (cm)</td>
<td>0.42 (0.13)</td>
<td>0.49</td>
</tr>
<tr>
<td>ML RMS (cm)</td>
<td>0.16 (0.05)</td>
<td>0.22</td>
</tr>
<tr>
<td>AP Velocity (cm/s)</td>
<td>0.52 (0.15)</td>
<td>0.59</td>
</tr>
<tr>
<td>ML Velocity (cm/s)</td>
<td>0.32 (0.09)</td>
<td>0.39</td>
</tr>
<tr>
<td>Eyes Closed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AP RMS (cm)</td>
<td>0.44 (0.15)</td>
<td>0.52</td>
</tr>
<tr>
<td>ML RMS (cm)</td>
<td>0.18 (0.07)</td>
<td>0.23</td>
</tr>
<tr>
<td>AP Velocity (cm/s)</td>
<td>0.73 (0.26)</td>
<td>0.82</td>
</tr>
<tr>
<td>ML Velocity (cm/s)</td>
<td>0.35 (0.11)</td>
<td>0.42</td>
</tr>
<tr>
<td>Dual Task</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AP RMS (cm)</td>
<td>0.33 (0.07)</td>
<td>0.36</td>
</tr>
<tr>
<td>ML RMS (cm)</td>
<td>0.16 (0.06)</td>
<td>0.21</td>
</tr>
<tr>
<td>AP Velocity (cm/s)</td>
<td>0.63 (0.18)</td>
<td>0.72</td>
</tr>
<tr>
<td>ML Velocity (cm/s)</td>
<td>0.35 (0.09)</td>
<td>0.40</td>
</tr>
</tbody>
</table>

3.3 Coefficient of Variation

Of the individuals who were included in the Hierarchical Growth Curve Model, 25 participants had full a data set. Three participants had been discharged from physician care at Week 2 and purposely missed the Week 4 balance assessment (a procedure directed by the Clinic). To avoid bias towards participants who remain symptomatic, these 3 participants were included in the CV analysis despite missing Week 4. Nineteen controls (HC) were used to calculate the average CV (across time, Table 10) and 95% confidence interval (at Week 1, Table 8) in order to determine recovery to normal values. Demographics are listed in Table 9. The proportion of participants who were determined recovered through the CV calculation are listed in Table 11. The proportion of participants that were determined recovered based on the CV and the 95% CI of HC are listed in Table 12.
Table 10. Participant demographics and self-reported symptom score for CONC participants across time.

<table>
<thead>
<tr>
<th>Variable</th>
<th>CONC</th>
<th>HC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N=28</td>
<td>N=19</td>
</tr>
<tr>
<td>Sex [Number (%)]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Men</td>
<td>10 (35%)</td>
<td>8 (43%)</td>
</tr>
<tr>
<td>Women</td>
<td>18 (64%)</td>
<td>11 (57%)</td>
</tr>
<tr>
<td>Age [Mean (SD)]</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>34.8 (11.1)</td>
<td>31.9 (10.1)</td>
</tr>
<tr>
<td></td>
<td>(21-63)</td>
<td>(22-56)</td>
</tr>
<tr>
<td>SCAT3 [Median (Range)]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>W1</td>
<td>38 (0-94)</td>
<td>25 (0-104)</td>
</tr>
<tr>
<td>W2</td>
<td>23 (1-99)</td>
<td>8 (0-104)</td>
</tr>
<tr>
<td>W4</td>
<td>8 (0-104)</td>
<td>7 (0-96)</td>
</tr>
<tr>
<td>W8</td>
<td>7 (0-96)</td>
<td>7 (0-96)</td>
</tr>
<tr>
<td>W12</td>
<td>0 (0-1)</td>
<td>0 (0-1)</td>
</tr>
<tr>
<td>Balance</td>
<td>1 (0-4)</td>
<td>1 (0-5)</td>
</tr>
<tr>
<td>Dizziness</td>
<td>0 (0-4)</td>
<td>0 (0-4)</td>
</tr>
</tbody>
</table>

Average CV of HC across 5 time-points are presented in Table 7. On average, velocity showed less variability than RMS. It was hypothesized the proportion of participants who were determined to be recovered should increase across time (Table 11). This trend occurs in 5 variables; BESS, AP Velocity (EO), AP RMS (EC), AP Velocity (EC), and ML RMS (DT). However, within these measures, the proportion of participants defined as recovered varies across time and does not steadily increase with time. Using this approach to determine recovery, the proportion of participants determined to be recovered ranged between 11-32%, 4-40%, 18-46% and 14-43% across Week 2, 4, 8 and 12, respectively. Table 12 shows that the majority of participants who were determined recovered by the CV calculation also had values that were within the 95% CI of HC. Using this approach to determine recovery yields a range of 7-29%, 0-36%, 14-39%, 14-39% across Week 2, 4, 8 and 12, respectively.

Table 11. Average CV values across Week 1, 2, 4, 8 and 12 for n=19 HC.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Eyes Open</th>
<th>Eyes Closed</th>
<th>Dual Task</th>
</tr>
</thead>
<tbody>
<tr>
<td>AP RMS</td>
<td>24%</td>
<td>23%</td>
<td>18%</td>
</tr>
<tr>
<td>ML RMS</td>
<td>27%</td>
<td>31%</td>
<td>28%</td>
</tr>
<tr>
<td>AP Velocity</td>
<td>11%</td>
<td>16%</td>
<td>13%</td>
</tr>
<tr>
<td>ML Velocity</td>
<td>12%</td>
<td>16%</td>
<td>14%</td>
</tr>
</tbody>
</table>
### Table 12. Proportion of participants who were dichotomized as ‘recovered’ across Week 2, 4, 8 and 12, as determined by reduction in dependent variable by an amount greater than the CV, relative to the Week 1 value.

<table>
<thead>
<tr>
<th></th>
<th>Eyes Open</th>
<th></th>
<th>Eyes Closed</th>
<th></th>
<th>Dual Task</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>W2</td>
<td>W4</td>
<td>W8</td>
<td>W12</td>
<td>W2</td>
</tr>
<tr>
<td>AP RMS</td>
<td>29%</td>
<td>40%</td>
<td>32%</td>
<td>21%</td>
<td>25%</td>
</tr>
<tr>
<td>ML RMS</td>
<td>29%</td>
<td>32%</td>
<td>25%</td>
<td>29%</td>
<td>21%</td>
</tr>
<tr>
<td>AP Vel</td>
<td>21%</td>
<td>28%</td>
<td>36%</td>
<td>36%</td>
<td>21%</td>
</tr>
<tr>
<td>ML Vel</td>
<td>43%</td>
<td>40%</td>
<td>36%</td>
<td>39%</td>
<td>29%</td>
</tr>
<tr>
<td>BESS</td>
<td>11%</td>
<td>4%</td>
<td>26%</td>
<td>19%</td>
<td></td>
</tr>
</tbody>
</table>

### Table 13. Proportion of participants who were dichotomized as recovered based on CV calculation and the 95% CI of HC.

<table>
<thead>
<tr>
<th></th>
<th>Eyes Open</th>
<th></th>
<th>Eyes Closed</th>
<th></th>
<th>Dual Task</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>W2</td>
<td>W4</td>
<td>W8</td>
<td>W12</td>
<td>W2</td>
</tr>
<tr>
<td>AP RMS</td>
<td>29%</td>
<td>36%</td>
<td>29%</td>
<td>21%</td>
<td>21%</td>
</tr>
<tr>
<td>ML RMS</td>
<td>25%</td>
<td>28%</td>
<td>21%</td>
<td>29%</td>
<td>21%</td>
</tr>
<tr>
<td>AP Vel</td>
<td>11%</td>
<td>24%</td>
<td>29%</td>
<td>29%</td>
<td>18%</td>
</tr>
<tr>
<td>ML Vel</td>
<td>29%</td>
<td>32%</td>
<td>32%</td>
<td>25%</td>
<td>29%</td>
</tr>
<tr>
<td>BESS</td>
<td>7%</td>
<td>0%</td>
<td>26%</td>
<td>15%</td>
<td></td>
</tr>
</tbody>
</table>

### Discussion

The present study aimed to identify the recovery of postural control following concussion in adults from the general population using a Hierarchical Growth Curve Model and an individualistic approach using the RCI (BESS) and coefficient of variation of controls (RMS, velocity). The main findings of this study were: (1) significant recovery across time occurred in AP velocity in the eyes closed condition and (2) when using an individualistic approach using the coefficient of variation, it is evident that recovery is a variable process which fluctuates across time. The findings of this study will be discussed further in subsequent sections.
4.1 Hierarchical Growth Curve Model

Due to difficulties with attrition in longitudinal analyses, partially missing data within individual trajectories is common. Standard statistical approaches to determine time-effects in outcome measures includes the use of the ANOVA (Curran et al., 2010; DeLucia & Pitts, 2006; Kwok et al., 2008; Singer et al., 2015). However, the ANOVA excludes participants with missing data points. In contrast, the Hierarchical Growth Curve Model allows for missing data within individual trajectories. The Hierarchical Growth Curve Model estimates between-individual differences in within-individual change over time through the inclusion of time-invariant and time-variant covariates (Curran et al., 2010; Singer et al., 2015). In the present study, age and sex were added to the model as time-invariant covariates, which were significant and therefore retained in 3 models. Time was the only time-variant covariate included in the models. Self-reported symptom score was not used as a time-variant covariate as self-reported symptom score has poor agreement with objective measures of balance (Rochefort et al., 2017). In addition, BESS was not used as a time-variant covariate due to low reliability and established learning effects of the BESS (Mulligan et al., 2013; Murray et al., 2014; Sheehan et al., 2011). HC were not included in the Hierarchical Growth Curve Model because control data were assumed to remain reasonably constant across time and if included, would have artificially changed the trajectory of the growth curve. As a result, group effects between CONC and HC were not characterized in this study. However, the CONC values in the growth model at Week 0 (intercept values) are nearing control values. Thus, it is possible that no recovery occurred across time (with the exception of AP velocity in EC) because there are negligible postural control deficits following concussion in this cohort to begin with.

The Unconditional Means Model confirmed there was significant variability in the dependent variables worth exploring using the Hierarchical Growth Curve Model. However, the inclusion of Level 1 or Level 2 covariates did not result in a large reduction in variability for within-individual and between-individual variability, respectively. In addition, significant variability existed in the final models. Time accounted for 0-8% variability in COP measures and 14% variability in BESS score. This is likely attributed to limited time-related change, as evident by the small magnitude of values for slope. Age or sex accounted 8% and 23% (age) and 10% (sex) variability in models in which they were included. No significant age or sex interactions with time were found, suggesting that females do not recover differently than males and older
participants do not recover differently than young participants. This contrasts with previous literature that suggests concussed female athletes report more symptoms, perform worse on measures of postural control, and take longer to recover than male athletes (Covassin, Elbin, Harris, Parker, & Kontos, 2012; Lovell et al., 2006).

The significant intercept covariance parameters in the final model suggest there is a between-individual covariate that may explain the variability but that was not included in this analysis. One possible candidate is concussion severity; however, there are currently no reliable scales in identifying severity of concussion apart from self-reported symptoms. Chapter 2 showed self-reported symptom reporting was not a reliable method of determining balance deficits and therefore was not explored in this chapter. Alternatively, it is possible that balance deficits present heterogeneously following concussion. Recent work has used symptoms and physical examination findings to classify concussion-type (Ellis, Leddy, & Willer, 2015). These differences in concussion-type may explain the heterogeneity in balance measures. For example, it is possible some participants received damage to the vestibular or ocular nuclei, whereas others may have received damaged to the cervical muscles (Ellis et al., 2015). While participants with cervicogenic-type concussion may experience concussion symptoms, this type of concussion may not result in balance deficits, compared to someone with damage to the vestibular or ocular centres. (Ellis et al., 2015).

It was hypothesized that the Growth Curve Model would yield significant reduction in BESS score and COP measures across time (negative slope). This significant finding occurred only in AP velocity in the EC condition. Powers et al (2014) found significant elevation of the variability of AP velocity in the EC condition upon return-to-play in athletes, which ranged from 10-49 days (Powers et al., 2014). In the present study, significant recovery was observed over 12-weeks. However, the total reduction across Week 0 to Week 12 was 0.1 cm/s. Despite statistical significance, a reduction in 0.1 cm/s does not likely translate to a clinically meaningful reduction. In the absence of RCI values for COP measures, we cannot confirm this hypothesis. The lack of significant recovery observed is discussed further in subsequent sections.
4.2 Coefficient of Variation Analysis

In longitudinal analyses, researchers often rely on a statistically significant finding to indicate recovery across time. Specifically, in studies using posturographic measures of balance, recovery is often characterized by a statistically significant reduction in COP parameters. However, despite statistical significance, the reduction in these measures may not be clinically meaningful (Jaeschke, Singer, & Guyatt, 1989). No previous literature has identified the RCI for reduction in COP measures across time. To address this limitation, balance-related recovery in concussion was determined to have occurred if the dependent variable reduced by an amount larger than natural variation in healthy, age- and sex-matched controls.

Although the Growth Curve Model takes into account within-individual change, the majority of the dependent variables included in this study held the effect of time as a fixed factor (the same across all participants) and negates this. For the dependent variables in which slope was held as a random factor, the covariance parameter for slope was small and non-significant, suggesting the individual variability around the fixed effect of slope is null. As a result, the Hierarchical Growth Curve Model assumed all participants have the same trajectory across time. However, the intercept value and covariance parameter were significant across all dependent variables. This suggests that participants are significantly different in outcome variable at the onset of concussion. In an effort to determine individualistic recovery relative to Week 1 (which is significantly different in each participant), the RCI (BESS) and CV (RMS, velocity) analysis was used. This approach assumes CONC participants will have balance deficits at the Week 1 visit that would not have recovered to a complete extent by the initial visit. Participants were subsequently categorized as recovered if the reduction in outcome variable was within the 95% CI of HC. This analysis showed the majority of participants who had reduced by more than the CV were within healthy boundaries.

Dependent variables that showed increasing proportion of participants recovering across time include BESS, AP Velocity (EO), AP RMS (EC), AP Velocity (EC), and ML RMS (DT). The Hierarchical Growth Curve Model also found significant recovery in AP Velocity in EC however no significant recovery in the other variables. Although a net increase in proportion of participants recovered occurred across Week 2 to Week 12, this increase was variable across time with some measures showing a reduction between weeks. This may reflect the variability in
concussion recovery, in which life stressors can trigger an onset of symptoms and can vary day-by-day (Lovell et al., 2006). Alternatively, this finding may reflect the sensitivity of COP measures, which are variable across-time even in healthy adults. That is, the COP measures may be prone to inaccurate measurement as a result of subtle accessory movement that is not associated with concussion or reflective of the recovery process.

4.3 BESS

Despite the known learning effects that occur after repeated administrations of the BESS, no significant recovery across time occurred. A total reduction of 0.55 errors was found across Week 0 to Week 12. Previous work in athletes found recovery of BESS score to pre-injury values to occur within 5-7 days (Bell et al., 2011; McCrea, Guskiewicz, Marshall, Barr, Randolph, Cantu, Onate, Kelly, Page, et al., 2003; Ruhe et al., 2014). However, athletes have been found to have neurophysiological differences that make them able to learn a motor task faster and with greater accuracy, compared to non-athletes (Nakata et al., 2010). It is possible that the learning effects observed in the athletic population over repeated administrations (Mulligan et al., 2013) is not observed in adults from the general population with concussion as they are not able to learn a motor task as quickly or as effectively as athletes can.

Alternatively, the lack of recovery observed in the BESS may be related to low specificity in adults from the general population. The BESS was created for the assessment of concussion in athletes (Bell et al., 2011). Differences in physical activity levels and muscular strength between an athlete and adults from the general population may allow athletes an advantage in maintaining balance during these challenging positions (Brauer et al., 2008). In addition, regular exercise has been shown to have a positive impact on the sensory systems that control balance, specifically the vestibular and somatosensory systems (Brauer et al., 2008). Since the BESS probes the vestibular control of posture through the elimination of vision on a foam surface (Bell et al., 2011), athletes may have a better ability to maintain posture when having to rely on only the vestibular system. The BESS is likely lacking specificity in adults from the general population and may explain why no statistically or clinically significant recovery occurred in BESS score across time.
4.4 COP Measures

COP measures during quiet standing allow for characterization of different aspects of postural control. However, regardless of condition (EO, EC, DT), significant recovery across time occurred in only one variable, AP velocity (EC). Although COP measures offer a sensitive and objective measure of postural control, the task of quiet standing within the standardized BOS may not have been difficult enough to reveal deficits, and therefore limited recovery was observed due to small effect sizes in initial deficit. This is contrast to other studies in which a narrow BOS was used and where recovery over time was observed (Powers et al., 2014; Rhine et al., 2016). The feet together position increases postural challenge by reducing the BOS and therefore reducing the area available for COM movement within the limits of stability. Although no group differences between CONC and HC were tested through the addition of the HC in the Hierarchical Growth Curve Model, the CONC values for RMS and velocity are similar to values of HC. Future work should use a feet-together position in order to identify balance deficits during quiet standing following concussion.

5 Limitations

The Hierarchical Growth Curve model assumes the data are normally distributed (Curran et al., 2010). The raw data in this study were negatively skewed. In an effort to normalize negatively skewed data, the log-transformation is typically applied. However, if the data were to be log-transformed, the output of the Growth Curve Model, which provides intercept and slope values, would be in log-units, making interpretation of graphs non-intuitive. Reverse transforming intercept and slope values do not retain negative signs. For these reasons, data for the Hierarchical Growth Curve Model were not transformed but rather left in raw format as negatively skewed data. Although the data were not normally distributed, previous work has determined parametric statistical tests are robust in handling non-normally distributed data (Lumley, Diehr, Emerson, & Chen, 2002).
6 Conclusions

The present study demonstrated that recovery of postural control, measured by BESS score and COP measures during EO, EC, and DT, does not occur across 12-weeks following concussion in adults from the general population. Using an individualized (i.e. person-specific) approach using the RCI of BESS score and coefficient of variation of controls in COP measures, this study demonstrated that recovery of postural control following concussion in adults from the general population is a variable process. Lack of statistically significant or clinically meaningful recovery is likely due to low specificity of the BESS score and lack of task difficulty during quiet standing within a standardized BOS. These findings suggest that the assessment of balance following a concussion in adults from the general population should not include BESS score as it may lack specificity. In addition, measures of quiet standing may be more useful when task challenge is increased through the use of a feet together position.
Chapter 4
General Discussion and Conclusions

1 Summary of Findings

The purpose of this thesis was to identify balance-related deficits and recovery across 12-weeks following concussion in adults from the general population. Balance-related deficits were measured using self-reported symptoms, BESS score, and COP measures during eyes open, eyes closed, and dual-task conditions. Following acute concussion (5-days post-injury on average), adults from the general population produced significantly more errors on the BESS and demonstrated elevated ML Velocity and AP and ML high-frequency power, compared to controls. However, participants who reported no balance or dizziness symptoms had significantly larger ML velocity and ML high-frequency power, compared to controls. In contrast, participants who reported both balance and dizziness symptoms or either balance or dizziness had no significant difference in COP measures compared to controls. All groups performed worse on the BESS, compared to controls. At the Week 1 assessment, participants with concussion did not perform worse than controls in conditions which probed the vestibular system and attentional processes.

When examining the recovery of BESS score and COP metrics across 12-weeks following concussion, no significant recovery was observed using a Hierarchical Growth Curve Model, with the exception of AP velocity in the eyes closed condition. When using an individualistic approach to determine recovery, on average, less than half of the cohort was recovered by Week 12 on BESS score and COP metrics. However, the low rates of recovery observed in this study was likely attributed to low specificity associated with the BESS in this cohort and lack of task difficulty associated with the quiet standing tasks within the standardized base-of-support. Overall, this thesis determined that balance deficits exist acutely following concussion; however, limited recovery occurs across 12-weeks post-injury in adults from the general population with concussion. Subsequent sections will explore these findings and their limitations, as well as the future directions and the implications to rehabilitation of this work.
1.1 BESS

Comparing BESS score at baseline and 1-day following concussion, BESS score increases by 3-5 errors in athletes (Ruhe et al., 2014). Concussed athletes quickly return to baseline values within 3-5-days post-concussion (Ruhe et al., 2014). Although no baseline values were measured in this thesis, age- and sex-matched controls were used for comparison. A similar trend was observed acutely following injury, where concussed participants scored, on average, 4 more errors than controls. However, BESS score did not recover as it does in athletes. Rather, BESS score remains elevated at Week 12 post-concussion. In the athletic population, the BESS has been shown to have low sensitivity, moderate-to-low reliability, and learning effects over repeat administrations (Bell et al., 2011; Mulligan et al., 2013; Murray et al., 2014; Ruhe et al., 2014). Taking into account the learning effects that have been observed with repeat administrations of the BESS, it was expected that BESS should decrease across time, even if reduction in score was not representative of true recovery. Lack of reduction in BESS score across time may be due to variability in scoring between raters. Although each BESS score rater was trained on BESS scoring, some differences in scoring between raters may have occurred. Difficulty in determining forefoot or heel elevation and other scoring interpretation may contribute to the lack of recovery observed across time. Future work should determine the inter-rater reliability in adults from the general population with concussion. Alternatively, differences in recovery rates in the BESS could be attributed to the observation that athletes are able to learn and adapt to a motor task faster than non-athletes (Nakata et al., 2010). It is possible this enhanced ability to learn a motor task in the athletic population may not occur in adults from the general population as rapidly. This may explain why reduction in score did not occur across time. Due to the difficulty associated with the BESS, it is likely that the BESS lacks specificity in adults from the general population with concussion. Therefore, balance-related deficits may have recovered in this cohort, but were masked due to lack of specificity of the BESS.

1.2 COP Metrics

In the athletic literature, there are a wide range of conditions and COP variables used to measure the recovery of postural control following concussion (Buckley et al., 2016). Because of the large variation in task, condition, and outcome measures in previous concussion literature,
there is no definitive timeline in which COP metrics recover in concussed athletes. Previous work has used a non-linear dynamics approach to determine postural control deficits, under the assumption that traditional COP metrics (COP area, RMS, velocity, etc.) are not sensitive enough in determining deficits following sport-related concussion (Cavanaugh et al., 2005, 2006). However, other work has found deficits in these traditional linear measures lasting beyond return-to-play timelines in concussed athletes (Kleffelgaard et al., 2012; Powers et al., 2014; Rochefort et al., 2017). In our work, RMS did not show any significant difference between participants with concussion and controls following acute concussion or any significant recovery across time. This suggests that RMS may not be sensitive enough to determine deficits following concussion in adults from the general population. Alternatively, this finding may be related to lack of task difficulty within the standardized base-of-support. Previous work in concussed athletes has found significant elevation of RMS in the AP direction under the eyes closed condition with feet together acutely following concussion, which recovered upon return-to-play (Powers et al., 2014). In addition, we found significant elevation of velocity in the AP and ML directions in participants with concussion following acute injury. AP velocity in the eyes closed condition was the only significant variable that showed significant recovery across time. Whereas, in the concussed athletic population, previous work has found elevation of COP velocity upon return-to-play during the eyes closed condition with feet together (Powers et al., 2014). Taken together, these findings suggest that traditional, linear COP metrics are sensitive enough in determining differences following concussion. This work suggests the use of non-linear dynamics is not necessary to determine balance-related deficits following concussion, rather, task challenge should be increased in order to reveal deficit.

No previous concussion literature has quantified deficits in reactive balance control following concussion. Chapter 2 identified deficits in high-frequency power during quiet standing, which is indicative of deficits in reactive balance control. However, the recovery of reactive balance control was not directly quantified due to large variation within the measure across time. No previous work has determined the reliability of high-frequency power across multiple assessments. This thesis determined the coefficient of variation of high-frequency power greater than 40% across time-points for healthy adults. Although high-frequency power allows for quantification of reactive balance control during quiet standing without having to expose acutely injured individuals to external perturbations, the large variability in the measure
should be considered when interpreting findings. Due to the large variability in high-frequency power in the concussion group, the Hierarchical Growth Curve Model procedure generated errors and was not able to produce an output. In attempts to overcome this challenge, a proxy measure for high-frequency power (which would not generate errors in the analysis) was sought. A strong, statistically significant correlation (Appendix 1) ranging from 0.76 to 0.8, between high-frequency power and velocity was identified. Thus, velocity was used in the Hierarchical Growth Curve Model. Velocity showed less variability and coefficient of variation measures were ~20% within controls. Using velocity as a proxy for high-frequency power, AP velocity showed significant recovery across time. Previous work has found elevation of COP metrics in the high-frequency power band in the stroke population (Schinkel-Ivy et al., 2016). Specifically, elevated high-frequency power was found in participants with stroke who could not successfully respond to an external perturbation, suggesting these participants have deficits in reactive balance control which is quantified in the high-frequency power band during quiet standing (Schinkel-Ivy et al., 2016).

Following acute concussion, participants did not perform worse on eyes closed or dual task conditions, compared to controls. Previous work has found lasting deficits in eyes closed conditions and under dual-task conditions. Our work found recovery in AP velocity during eyes closed. No recovery was observed in the dual task condition; however, consistent with null findings following acute concussion, minimal differences between concussed participants and controls were observed. This was likely attributed to the lack of task difficulty associated with the base-of-support, which therefore did not differentiate concussed participants from controls under these conditions. This is consistent with other work that found deficits in these conditions, in which the authors increased task challenge by using the feet together position (Powers et al., 2014). Similarly, the backwards sevens task used in this thesis may not be difficult enough to differentiate concussed participants from controls. Previous work has found deficits using a visual Stroop task (Rochefort et al., 2017) at 1-month post-concussion. As the visual system is used in the control of posture, this visual Stroop cognitive task may not accurately probe attentional resources but rather cause postural instability as a result of interference with the visual system (Kerr et al., 1985).

The lack of recovery and large variability found in this thesis may be attributed to the highly sensitive nature of force-plate data. Prior to this work, no previous literature had
examined the stability of COP measures across multiple time-points and under different postural conditions in healthy adults. This work determined that although the force plate measures are highly sensitive, traditional measures such as RMS and velocity are relatively stable and reliable across time-points. While other measures, such as high-frequency power, is less reliable and highly variable across time-points.

1.3 Self-Reported Symptoms

Acutely following concussion in adults from the general population, the median self-reported symptoms score is 0.5 and 1 from balance problems and dizziness, respectively. These contributions are minimal and equate to none-mild on the self-reported symptom scale (Chin et al., 2016). As a result of symptom burden during the acute phase of concussion and the low levels of physical activity of adults from the general population, the cohort in this study are likely not exposing themselves to compromising balance positions during this acute phase and may not detect balance deficits following concussion. Chapter 2 found significant deficits in concussed participants who self-reported no balance or dizziness symptoms. It is possible that the magnitude of these deficits were minimal and therefore were not detected by the participants when performing activities of daily living and ultimately not translated when reporting symptoms. In addition, with the exception of the BESS, no significant differences were found between the group that reported both or either balance problems or dizziness, compared to controls. This may be a result of the postural control assessment. The assessment probed aspects of static postural control and perhaps these participants experience balance deficits or dizziness during dynamic tasks, such as walking, or getting up from a seated position.

Prolonged recovery (reduction) of total symptom score may indicate the participants in this cohort experienced more severe concussions than what is being compared to in the athletic literature. In athletes, self-reported symptoms recover within 3-5 days following injury (Chin et al., 2016; Lovell et al., 2006; McCrea, Guskiewicz, Marshall, Barr, Randolph, Cantu, Onate, Kelly, & Page, 2003). Alternatively, this difference likely lies within the motives behind symptom reporting between the two groups (Lovell et al., 2006). In athletes, previous work has reported athletes have a tendency to under-report symptoms in order to return-to-play earlier (Kroshus et al., 2016). In contrast, people who experience life stressors may have a tendency to
over-report concussion symptoms (Lovell et al., 2006). In addition, the majority of concussion symptoms are experienced in everyday life by people who have never experienced a concussion (Zimmer et al., 2015). Prolonged elevation of concussion symptoms may be a result of participants from this cohort somaticizing everyday symptoms into concussion-related symptoms (Zimmer et al., 2015).

2 Differences between Athletes and General Population Following Concussion

This thesis found elevated self-reported symptoms in adults from the general population, compared to what has been published in the athletic literature. Initial symptom severity has been shown to predict prolonged symptom recovery (Meehan, Mannix, Monuteaux, Stein, & Bachur, 2014). Differences in physical activity levels at baseline likely play a role in the faster resolution of symptoms and BESS score in concussed athletes. Physical activity has been shown to have neuroprotective and neuroplastic effects in response to brain injury (Cotman & Engesser-Cesar, 2002; Griesbach, 2011; Lawrence et al., 2018). Further, recent work has shown that earlier return to physical activity is associated with faster return to sport/ school/ work in concussed athletes (Lawrence et al., 2018).

Alternatively, the differences between concussed athletes and adults from the general population may be related to mechanism of injury or concussion severity as related to neck strength (Eckner, Oh, Joshi, Richardson, & Ashton-Miller, 2014). Sex-related differences have been previously characterized in the concussion literature (Covassin et al., 2012). Females are more severely affected by a concussion in terms of symptom burden and objective measures of balance or cognition (Covassin et al., 2012). These differences are thought to be a result of differences in neck strength between male and females (Eckner et al., 2014). Greater neck strength is thought to reduce concussion incidence and severity as muscles in the neck are able to deaccelerate the kinetic impact (Eckner et al., 2014). Recent work has focused on classifying the type of concussion based on pathophysiology (Ellis et al., 2015). Generally, concussion and persistent post-concussion symptom disorders are classified as physiological, vestibulo-ocular, or cervicogenic based on physical examination, predominant symptoms and response to exercise testing (Ellis et al., 2015). Typically, vestibulo-ocular concussions are caused by trauma to the
vestibular and ocular systems and typically result in dizziness, vertigo, and postural instability (Ellis et al., 2015). In contrast, cervicogenic concussions are caused by muscle trauma and inflammation and can result in neck pain, stiffness and decreased range of motion (Ellis et al., 2015). It is possible that adults from the general population with concussion have weaker neck muscles compared to athletes and therefore exhibit the pathophysiology associated with cervicogenic concussion. In agreement with this, recent work regarding head impact in athletes indicate that the magnitude of concussive impact forces range from 60-170 g (Mihalik, Bell, Marshall, & Guskiewicz, 2007). As the sensitive vestibular system is able to detect subtle body movements, these large impacts are likely to damage the vestibular organs. In contrast, in adults from the general population, the magnitude of head impacts which caused the concussive injury are likely lower than what has been found in athletes. This becomes evident when comparing the method of injury. In athletes, concussions are often induced by a hit during a game by another athlete. The momentum transferred by a high-level athlete to cause a concussion is likely larger than what would be caused by a non-athlete during recreational sport, or a fall. Compared to adults from the general population, where the method of injury is commonly related to recreational sport activity or falls, one would expect the magnitude of these concussive impacts to be greatly reduced in comparison to what has been observed in athletes.

Adults from the general population self-reported more symptoms following concussion, which may suggest this theory is incorrect. However, in agreement with this are findings that head impact magnitude does not correlate with self-reported symptoms, measures of balance, or cognitive deficits (Guskiewicz et al., 2007). Therefore, it is possible that adults from the general population receive their concussions with lesser magnitude and that weaker neck muscles contribute to a cervicogenic-type concussion in a larger proportion of this cohort than in athletes. This would also explain the lack of differences observed in the eyes closed condition in this cohort, compared to significant findings in the eyes closed condition previously observed in athletes (Powers et al., 2014; Rochefort et al., 2017). However, as observed throughout this thesis, balance-related deficits following concussion appears to be heterogeneous across individuals. Diagnosing concussed individuals based on their perceived concussion-type may help reduce this variability.
3 Revisiting the Conceptual Model

The initial conceptual model highlighted deficits and recovery timelines that have previously been explored in the athletic population following concussion. What remained to be explored was the extent to which these deficits exist in adults from the general population with concussion, in addition to specific deficits in reactive balance control following concussion. The final conceptual model is represented in Figure 12. Recovery timelines found in adults from the general population are listed in the final conceptual model. However, only the median score of self-reported symptoms showed recovery across time. Other measures did not recover across 12-weeks post-concussion. Due to large variation in high-frequency power, reactive balance control was not measured across time. Comparing these timelines to what is known from the athletic literature, BESS scores remain elevated at 12-weeks post-concussion in adults from the general population with concussion, whereas in the athletic population recovers within 1-week. Self-reported symptoms also recover within 1-week in athletes, however, in adults from the general population, recovered between 4 and 8 weeks. No definitive recovery timeline exists regarding COP measures in concussed athletes. In adults from the general population, limited recovery of COP metrics was observed across 12 weeks.

Figure 12. Revised conceptual model summarizing this thesis. Balance-related deficits were probed using self-reported symptoms, BESS score, and COP metrics (eyes closed and dual task), including a measure of reactive balance control. Recovery trajectories are represented for self-reported symptoms, BESS score, and COP measures for adults in the general population with concussion. This thesis highlighted differences in recovery timelines between concussed athletes and adults from the general population.
4 Limitations

There are some limitations associated with the balance tasks used in this thesis that should be considered when interpreting findings. First, the BESS was designed for the assessment of concussion in athletes (Bell et al., 2011). The stances used in the BESS include: feet together, unipedal, and tandem stance which are completed on a firm and foam surface with eyes closed (Bell et al., 2011). These positions (particularly unipedal and tandem stances) greatly reduce the base-of-support and ultimately the space in which the COM can move before reaching the limits of stability (Horak, 2006; Woollacott & Shumway-Cook, 1996). In addition, in the absence of vision (all tasks) and reduced somatosensory input (foam conditions), the control of posture must be regulated within a small base-of-support and under the control of sensory input from the vestibular system (Nashner, 1982). As the vestibular contributions to postural control are minimal during upright stance under normal conditions (well-lit environment, stable support surface) (Nashner, 1982), using the vestibular system to control posture is likely unfamiliar to participants in this cohort. Taken together with the reduced base-of-support, ultimately, these sensory manipulations make it increasingly difficult to maintain postural control. In an athlete, experiences positive stimulation of the vestibular system through increased physical activity (Brauer et al., 2008) and therefore a better ability to maintain postural control, the BESS may be valid to use in this population. However, in an adult from the general population, who is likely not exercising at the same rates (Colley et al., 2011), nor are subjected to compromising balance tasks on a daily basis as an athlete, the BESS may be too difficult to complete. For these reasons, the BESS likely lacks specificity in an adult from the general population with concussion. Under the hypothesis that clinical measures of balance recover within 1-week for athletes, in tandem with the documented learning effects of the BESS, it was hypothesized the BESS would recover faster than recovery of COP metrics. However, in reality, little recovery was observed across time. This finding may be explained by a lack of specificity associated with the BESS test in adults from the general population.

Measurement of the COP under eyes open, eyes closed, and dual-task conditions was completed in order to negate the limitations of the BESS and allow for an objective quantification of postural control deficits. Quiet standing trials were completed within a base-of-support that as standardized to a comfortable stance position of 262 participants in previous work by McIlroy and Maki (McIlroy & Maki, 1997). Lack of differentiation between concussed
participants and controls in eyes closed and dual task conditions, along with lack of recovery across time, may be explained by the base-of-support being too wide to reveal deficits. Within this base-of-support, the COM has a large area to move within before reaching the limits of stability (Horak, 2006; Palmieri et al., 2002). Narrowing the base-of-support ultimately constricts the stability limits of the COM (Horak, 2006). Under these more challenging positions, balance-related deficits and recovery may have been observed. An additional limitation in using these tasks is that quiet standing does not capture the entire postural control system. As quiet standing is a static task, the assessments completed in this study fails to capture the dynamic aspect of the postural control system. In addition, as all tasks were completed in a well-lit room on a stable surface, the tasks used in this thesis do not capture how participants with concussion would respond to changing conditions and are not representative of postural control in everyday situations.

5 Implications for Rehabilitation

The findings of this thesis have many implications for rehabilitation. Firstly, this work demonstrated that objective balance deficits exist in participants who self-report no balance or dizziness symptoms. Although the effect sizes present in this cohort are small and may not lead to increased risk of fall, these deficits may be exacerbated during more challenging conditions (feet together during quiet standing or during dynamic tasks). This finding suggests that self-reported symptoms should not be the only measure used in the assessment of post-concussion balance deficits (Broglio et al., 2007). Rather, an objective assessment of balance should be considered when determining balance-related deficits following concussion. The widespread use of force plates in clinical settings is unrealistic due to cost and complicated technological interpretation; however, clinical observations can be made under dynamic tasks which may provide insight into the postural control system following concussion. Secondly, increased high-frequency power was observed in participants with concussion, which represents deficits in reactive balance control (Schinkel-Ivy et al., 2016; Zatsiorsky & Duarte, 2000; Zatsiorsky & Duarte, 1999). This finding was observed during quiet standing. Under dynamic conditions, such as responding to an external perturbation, these deficits may be exacerbated. As failure to reactively control balance leads to increased risk of falls (Horak, 2006), reactive balance control
deficits should be explored under dynamic situations. In order to reduce these deficits, rehabilitation strategies should include perturbation-based training in this cohort.

Due to the small effect sizes and relative absence of recovery observed in this cohort, it is difficult to make recommendations as to when adults from the general population should return-to-activity following concussion. Similar to protocols in the athletic population, adults from the general population should gradually return-to-activity. Currently, no evidence exists suggesting that physical activity should be restrained following concussion (Lawrence et al., 2018; Leddy et al., 2010). And, recovery increases with sooner return to physical activity (Lawrence et al., 2018). Therefore, there are no reasons why individuals from the general population should refrain from physical activity following concussion if symptoms are not aggravated upon return-to-activity. Although, deficits during dynamic tasks should be explored in this population to confirm safety related to fall-risk. This will be discussed in the subsequent section.

6 Future Directions

This thesis highlighted the importance of tasks used in the assessment of balance following concussion in adults from the general population. As highlighted in Chapter 1, there is little agreement among previous studies regarding COP metrics used in the athletic population following concussion, nor is there agreement about which tasks or conditions to include in the assessment battery. Although there is agreement regarding the use of the BESS to measure balance-related deficits and recovery across time in the athletic population, the limitations associated with the BESS in terms of learning effects and low specificity, suggest that using the BESS in assessment of balance following concussion should be reconsidered, especially in the general population. Previous work has found the modified BESS (which removes foam conditions) has higher reliability (Hunt, Ferrara, Bornstein, & Baumgartner, 2009). Since then, the modified BESS has been adapted into the Sport Concussion Assessment Tool (version 3) (Guskiewicz et al., 2013; McCrory et al., 2017). Despite increased reliability, the modified BESS does not capture components of dynamic balance control (Johnston, Coughlan, & Caulfield, 2017). Based on the findings of the studies in this thesis, along with previous negative findings of balance deficits during quiet standing, future work should include aspects of dynamic balance control in the assessment of balance following concussion. Dynamic balance tasks require a
synchronization of limb movement and requires greater motor planning and processing of sensorimotor integration (Johnston et al., 2017; Maki, McIlroy, & Fernie, 2003). This aligns with recent work which finds deficits when using measures of tandem gait or dual-task gait deficits (Lee, Sullivan, & Schneiders, 2013; Oldham, DiFabio, Kaminski, DeWolf, & Buckley, 2017). Further, when probing aspects of static balance control, the feet together base-of-support should be adopted when assessing this cohort. Due to the mild nature of concussion, the standardized base-of-support as outlined by McIlroy and Maki (McIlroy & Maki, 1997) is likely too wide to reveal deficits in concussed participants. In contrast, reducing the size of the base of support by employing a ‘feet together’ stance would reduce the area within which the COM could move without experiencing a loss of balance. This more challenging foot position may reveal deficits in this population. Lastly, COP velocity showed to be sensitive in differentiating concussed participants from controls in this work and previous work in participants with concussion (Powers et al., 2014; Rochefort et al., 2017). Therefore, COP velocity may be used as a valid metric to use in the measurement of static postural control following a concussion. However, it should be noted that other work suggests that these linear metrics may not be sensitive enough to determine deficits following concussion (Buckley et al., 2016; Cavanaugh et al., 2005, 2006; Fino et al., 2016; Sosnoff et al., 2011). As a result, some groups have used a non-linear dynamics approach to analyze COP data (Buckley et al., 2016; Cavanaugh et al., 2005, 2006; Fino et al., 2016; Sosnoff et al., 2011). This approach was not explored in this thesis and may reveal further deficits; however, the real-world implications of these measures is unknown.

7 Final Conclusions

To conclude, this thesis determined balance deficits are present following acute concussion in adults from the general population. This thesis found subjective measures of self-reported symptoms do not align with objective measures of balance deficit. In addition, little recovery was observed across 3-months post-concussion. The lack of recovery present in this study is likely attributed to low specificity of the BESS and small effect sizes in COP metrics due to lack of task difficulty. This thesis highlighted the importance of standardizing the assessment of balance following concussion in adults from the general population and to
integrate aspects of dynamic balance control in the assessment of balance following concussion in adults from the general population.
References


Eckner, J. T., Oh, Y. K., Joshi, M. S., Richardson, J. K., & Ashton-Miller, J. A. (2014). Effect of


96. https://doi.org/10.1016/j.jneumeth.2013.10.020


concussion syndrome. *Clinical Journal of Sport Medicine, 20*(1), 21–27. https://doi.org/10.1097/JSM.0b013e3181c6c22c


Appendices

**Appendix 1.** Pearson correlations for velocity (vel) and high-frequency power. Significant correlations are denoted with *.

<table>
<thead>
<tr>
<th>Pearson Correlation</th>
<th>AP High EO</th>
<th>AP High EC</th>
<th>AP High DT</th>
<th>ML High EO</th>
<th>ML High EC</th>
<th>ML High DT</th>
</tr>
</thead>
<tbody>
<tr>
<td>AP Vel EO</td>
<td>0.766*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AP Vel EC</td>
<td></td>
<td>0.851*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AP Vel DT</td>
<td></td>
<td></td>
<td>0.859 *</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ML Vel EO</td>
<td></td>
<td></td>
<td></td>
<td>0.831*</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ML Vel EC</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.847*</td>
<td></td>
</tr>
<tr>
<td>ML Vel DT</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.873*</td>
</tr>
</tbody>
</table>