EXPLORING THE RELATIONSHIP BETWEEN NECK STRENGTH, ANTHROPOMETRY, AND SYMPTOM SCORES ON CONCUSSION RISK AND RECOVERY IN UNIVERSITY ATHLETES

EXPLORING THE RELATIONSHIP BETWEEN NECK STRENGTH, ANTHROPOMETRY, AND SYMPTOM SCORES ON CONCUSSION RISK AND RECOVERY IN UNIVERSITY ATHLETES

By

ERIN ELIZABETH COLE, BSc.

A Thesis

Submitted to the School of Graduate Studies

In Partial Fulfillment of the Requirements

For the Degree

Master of Science

McMaster University

McMaster University MASTER OF SCIENCE (2018) Hamilton, Ontario
(Rehabilitation Science)

TITLE: Exploring the relationship between neck strength, anthropometry, and symptom score on concussion risk and recovery time in university athletes.

AUTHOR: Erin Cole, B.A., BSc. (McMaster University) SUPERVISOR: Professor Carol DeMatteo. NUMBER OF PAGES: vii, 146

Abstract

Concussion incidence in university athletes has been increased drastically over the last two decades. Prevention of concussion injuries is still elusive and scarcely reported in the literature. Certain athletes are at greater risk for concussion than others. Identifying these risk factors is an important first step in identifying those who are at highest risk for concussion. Concussions are biomechanical injuries therefore addressing the strength of the neck musculature might be a significant modifiable risk factor in concussion prevention. Greater neck strength may help to attenuate the forces that cause concussion and either prevent injury or decrease the severity.

There are some known risk factors for concussion, including age and female sex, however this does not account for all of the variability in concussion incidence in university athletes. Further exploration into the importance of neck strength and concussion in university athletes is required to identify alternative prevention strategies available to athletes.

The purpose of this research was to examine if neck strength and anthropometric variables are significant predictors of concussion risk and concussion recovery time in Canadian university athletes.

Chapter One provides a review of the current literature on concussion. It presents the background information for concussion risk, etiology, assessment, and management in university athletes. This chapter also reviews the literature to date on neck strength in concussion and assessments of neck strength in athletes.

Chapter Two presents a study evaluating the risk of concussion in a group of Canadian university varsity athletes (n = 246). Neck strength and anthropometric variables are assessed for their significance in predicting concussion risk in this cohort along with published covariates.

Neck pain and past concussion history were found to be the most significant predictors of concussion in this population.

Chapter Three provides an exploration into the importance of neck strength and anthropometric variables in length of recovery in concussed athletes (n = 35). The Sport Concussion Assessment Tool, 3rd edition was used to evaluate symptom intensity in these athletes. A multiple linear regression model was used to predict recovery time. Symptom score and neck pain were the only significant predictors of concussion recovery time in varsity athletes.

Chapter Four presents the implications of the two aforementioned studies for clinical practice, future research, and policy recommendations. More in-depth assessments prior to the beginning of competition should be considered in identifying athletes who are at greatest risk for concussion. Athletes with significant past concussion history should be evaluated more closely and informed of their heightened risk for subsequent injury.

Acknowledgements

The time I spent doing research at the School of Rehabilitation Science has been one of the most rewarding experiences in my academic career. I would like to express my appreciation to the faculty and my colleagues for the encouragement and support throughout the process.

First to my supervisor, Professor Carol DeMatteo, who always encouraged me to be curious, explore my interests, and push forward. Her enthusiasm and belief in me was often the inspiration needed to continue my inquiry. Her guidance, mentorship, and patience was steadfast as I navigated the challenges of research and for that I am truly grateful.

I was privileged to have committee members who provided invaluable contributions and insight to this body of work; Anita Gross, asked the tough questions and always challenged my thinking in the most supportive way. A committed and persistent editor, she elevated my work. Dr. Ira Price, one of my first teachers and mentors in this field, has been so generous in sharing his clinical expertise on concussion and has been pivotal to my development as a student.

I owe much of my experiences in sports injuries and concussion to Chris Puskas, long-term mentor and head athletic therapist at McMaster University. His wealth of knowledge and selfless nature were integral in nurturing my passion for rehabilitation and igniting my interest in concussions. I would like to acknowledge the athletes in the Department of Athletics and Recreation at McMaster University, for without them this project would not be possible.

I undoubtedly owe everything to my family and friends for their continual support. My dear friend Colby was invaluable in the editing of this project. She was always available to review my work and critique my writing. She made my work better. Finally, to my parents, Sue and Derek, and my little brother, Liam, I truly believe I won the family lottery! Thank you for so fiercely believing in me and everything I do. Your unrelenting support has made this possible.

Table of Contents

List of Figures

Chapter 1

Chapter 2

List of Tables

Chapter 1

Chapter 2

Chapter 3

List of Appendices

CHAPTER 1: INTRODUCTION

Overview

Concussions, common in high impact sports such as boxing and football, result in acute physical (headache, dizziness and vomiting), somatosensory (balance), cognitive (concentration, memory), emotional (depression, irritability), and sleep related symptoms that are incapacitating for athletes (Guskiewicz et al., 2000; Halstead & Walter, 2010; Powell & Barber-foss, 1999) and can result in disabling long-term consequences (early onset dementia, mood disturbances, personality changes, and chronic mental health issues) (Stern et al., 2011). Concussion incidence is at its highest in athletes between the ages of nine and 22 (Zemek, Farion, Sampson, & McGahern, 2013). A 2010 study demonstrated a 200% increase in the number of concussed youth aged 14 to 19 presenting to emergency rooms between 1997 and 2007 (Bakhos, Lockhart, Myers, & Linakis, 2010). According to Daneshvar and colleagues (2011), the incidence of concussions in university athletes doubled between the 1988/1989 and 2003/2004 athletic seasons from 0.17 to 0.34 per 1000 athlete-exposures.

More alarming than the rising incidence of concussions is the 50 to 75 percent of injuries that go unreported (Harmon et al., 2013; McCrea, Hammeke, Olsen, Leo, & Guskiewicz, 2004; McCrory et al., 2013). Barriers to reporting concussions in varsity athletics have been identified as a lack of awareness of concussion symptoms, the athletes' desire to continue participation, and external pressures to participate (McCrea et al., 2004). These barriers, and the chronic underreporting of concussions, implicate a higher incidence of concussion in college athletes than what is published in the literature. Underreporting potentiates premature return to competition prior to adequate recovery. Early return to sport puts athletes at a heightened risk for repeat injuries and permanent damage, thus illustrating the importance of effective primary prevention strategies for concussion in sport.

The current concussion literature investigates the areas of assessment, injury diagnosis, and management. There is a paucity of literature examining risk factors and preventative strategies for concussions in sport. Research that examines prevention strategies for concussion focuses mainly on the education of athletes, coaches and parents, rule regulation, and protective equipment (B W Benson et al., 2013; Emery et al., 2017a) albeit, the effectiveness of these strategies remain inconclusive (Emery et al., 2017; Harmon et al., 2013; Scopaz & Hatzenbuehler, 2013). One physical training preventative strategy suggests that absorbing forces that cause concussions may reduce the injury-inducing impact. Biomechanically addressing the strength of an athlete's neck musculature can supposedly limit these forces. Recent studies have examined how the anticipatory responses of the neck musculature in response to an impact to the head, plays a role in concussion prevention. Greater strength and anticipatory activation of the neck muscles were able to reduce the head's kinematic response to spontaneous loads in both males and females (Angelica & Fong, 2008; Eckner, Oh, Joshi, Richardson, & Ashton-Miller, 2014). Athletes who were better able to brace themselves upon impact were less likely to sustain a concussion (Eckner, Oh, Joshi, Richardson, & Ashton-Miller, 2014). Therefore, athletes with greater overall neck strength may have a biomechanical advantage to resist or absorb potentially concussive impacts, thus decreasing their risk of concussion.

A review published in 2013 indicates that further research must be conducted on physical training and neck strength as a potential predictive factor or prevention mechanism in concussions (Harmon et al., 2013; Hrysomallis, 2016; Williams, Puetz, Giza, & Broglio, 2015). Such a prevention strategy needs to be economical, clinically applicable, and completely under athlete control (Collins et al., 2014; Hrysomallis, 2016). There is sparse data exploring 1) neck strength and its protective ability against concussion injuries in university athletes, 2) gender and age-based comparisons of neck strength and associated concussion risk within a varsity athlete population, and 3) the interaction between neck strength and other known risk factors for concussion such as sport and past concussion history. The primary objective was to examine neck strength as a determinant of concussion risk and injury severity with respect to recovery time in a varsity athlete population over the course of one academic year.

This objective is examined across four chapters:

Chapter 1: Evidence and theory underpinning concussion injuries in athletes, including the related pathophysiological processes and the relevance of neck strength in injury prevention is reviewed. The psychometric properties underpinning concussion assessment tools, and evidence for concussion prevention and risk in a university-aged population is explored. Effect modifiers and confounding factors are considered and specified *a priori*.

Chapter 2: The extent to which deep neck flexor and neck extensor endurance strength is predictive of concussive injuries in athletes who play high risk for concussion sports is examined.

Chapter 3: The relationship between neck strength, past concussion history, and concussion symptom scores measured on the Sports Concussion Assessment tool, 3rd edition (SCAT3) and how these characteristics contribute to the time needed to return-to-play for a university athlete following a concussion is examined.

Chapter 4: The final chapter examines the relationships between the current literature, the findings of this thesis, and how they relate to real clinical applications of concussion evaluation and management in varsity athletes. Next steps in the field of concussion research are noted.

Chapter One

Concussion in Athletes

The 5th International Consensus Statement on Concussions in Sport defines concussion as "a brain injury, of complex etiology, resulting from a biomechanical force applied to the head or the body" (McCrory et al., 2017). The incidence of sports-related concussion (SRC) is shown to be highest in a younger athlete population. Athletes between the ages of nine and 22 report the greatest number of concussions (Zuckerman et al., 2015). Proper concussion diagnosis and management across all levels of competition is imperative with new evidence constantly emerging on the vast long-term consequences of SRC. Studies examining the incidence of concussion within the National Collegiate Athletic Association (NCAA) demonstrate substantial increases in the rate of concussions among athletes over the last two decades however, data examining the epidemiological presence of concussion in Canadian university athletes is limited. Early studies examining concussion incidence in Canadian varsity athletics looked at sport specific incidence of SRC in a cohort of men's football and hockey players. These studies reported the incidence rate in this group of athletes to be 0.50 and 0.90 per 1000 athletic exposures, respectively (Black, Sergio, & Macpherson, 2017; Meeuwisse, Hagel, Mohtadi, Butterwick, & Fick, 2000; Rishiraj, Lorenz, Niven, & Michel, 2009). A 2008, study examined the incidence across university basketball, football, soccer, lacrosse, and rugby athletes over a span of 12-months (Bloom, Loughead, Shapcott, Johnston, & Delaney, 2008). The authors of this study reported the number of concussions experienced by males was significantly greater than those experienced by females. This finding contradicts the current concussion literature that cites a higher prevalence in female athletes (Covassin, Swanik, and Sachs 2003; Gessel et al. 2007; Tierney et al. 2008a). The discrepancies in this article could be due to the retroactive questionnaire used to identify potentially concussive events within the last 12 months, which relies strongly on proper documentation from the clinical team. Furthermore, the Sport History Questionnaire, used to assess these athletes, has very limited use in other studies examining SRC. Nonetheless, the rates reported for male and female athletes were 3.39 and 2.58 concussions, respectively (Bloom et al., 2008). A more recent study by Black, Sergio, and Macpherson (2017) evaluated the incidence of concussions in Canadian university athletes at one university between 2008 and 2011. Concussion incidence, in this study, was reported as incidence density, referring to the number of concussions per 100 athlete-seasons. The highest incidence of concussion was found to be in women's rugby and men's basketball with an incidence density reported to be 20.00 per 100 athlete-seasons (Black, Sergio, & Macpherson 2017). The limitations to the aforementioned studies are mostly surrounding the retrospective nature of the methodology. The authors used a retrospective chart analysis to determine the presence of concussion in athletes over three athletic seasons. However, it is unclear on the diagnostic criteria used to determine a possible concussion and if that criteria was used consistently among all athletes screened in the study. The methodology used in determining the presence of their primary outcome may have led to misidentification of injuries and a misrepresentation of the number of concussions over the three study years. Despite these limitations, some of the results reflect similar conclusions reported by larger scale studies completed on NCAA athletes. A combination of systematic reviews indicate approximately 10% of athletes who play high risk sports sustain a concussion in one single athletic season (Emery et al., 2017; Zuckerman et al., 2015). Several studies on college and university athletes have demonstrated differences in concussion incidence among specific sports and between genders (Black et al., 2017; Covassin, Swanik, & Sachs, 2003; Zuckerman et al., 2015). Collision and contact sports report the highest rates of concussed athletes (Emery et al., 2017). Studies examining epidemiology of sports concussion in college athletes indicate the greatest number of concussions occurs in the following sports: basketball, cheerleading, football, ice hockey, lacrosse, rugby, and soccer (Black et al., 2017; Covassin et al., 2003; McCrea et al., 2004; Zuckerman et al., 2015). Furthermore, a summary of the data on the NCAA injury surveillance system indicates female athletes report higher rates of concussion compared to their male counterparts who participate in sports with the same rules (Daneshvar et al., 2011). However, evidence on concussion reporting differences between sexes within the collegiate athlete population does not currently exist.

There are a variety of reasons that explain the rising incidence of concussion in athletes. One explanation is an increase in the number of people participating in athletics exposing more individuals to potentially injurious environments (The Physical Activity Council, 2016). Furthermore, the awareness of the detriments of concussive injuries has fostered the implementation of various concussion education resources for athletes (Williamson et al., 2014). This increase in concussion awareness may be a contributor to the growing incidence of concussion (Daneshvar et al., 2011). Although The NCAA implemented a mandatory athlete education program on concussion prior to the start of competition each year, the rates of unreported concussion are still high (NCAA, 2013-2014). One study, evaluating the implementation of this education program in collegiate ice hockey players, saw no changes in athlete knowledge of SRC (Kroshus, Daneshvar, Baugh, Nowinski, & Cantu, 2014). In March 2018 the Ontario government implemented concussion safety legislation enforcing the use of concussion education resources for all coaches, parents, and athletes of high-risk sports (Rowan's Law, 2018). Concussions have been an elusive injury with respect to identification and diagnosis. Yet, the growing recognition of possible long-term consequences of concussion including depression, anxiety, and chronic traumatic encephalopathy, has indicated the need for better assessment tools in determining the presence of concussion in an athletic population.

Concussion Pathophysiology

The pathophysiology of concussion injuries is a hypothesized cerebral energy crisis. This is the result of the brain jostling inside of the skull leading to a functional injury, which includes impaired neurotransmission, and disruptions to metabolic processes affecting cerebral blood flow and ionic shifts (Giza, 2014). Until recently, structural damage to the neural tissue has been undetectable on regular brain imaging techniques, however, new studies using diffusion tensor imaging, have been able to depict signs of axonal damage post-concussion (Bazarian et al., 2007; Koerte, Ertl-Wagner, Reiser, Zafonte, & Shenton, 2012; Virji-Babul et al., 2013). This disruption of cellular processes in the brain triggers a cascade of neurochemical changes that alters homeostasis of the cerebral environment (Giza & Hovda, 2001; Holbourn, 1943). Simply stated, the metabolic processes taking place in the brain requires an abundance of blood flow to meet energy demands, however, due to the injury, there is an overall reduction in cerebral blood flow. Therefore, creating an imbalance in the supply and demand of blood to the brain resulting in a cerebral energy crisis (Giza, 2014; Seifert & Shipman, 2015).

Following the biomechanical impact to the brain, the intracranial movement forces potassium out of the cell creating a surplus in the concentration of extra-cellular potassium (Giza, 2014; Giza & Hovda, 2001; Seifert & Shipman, 2015). This increase in potassium induces depolarization or neural firing, which, in turn, results in the release of the excitatory neurotransmitter glutamate. Glutamate release, in combination with the potassium efflux and sodium influx, signals a crisis. This initiates mechanisms to restore equilibrium to the cerebral environment. The energy demands of these metabolic processes necessitates an increase in glucose metabolism through glycolysis (Giza, 2014). Consequently, an increase in the demand for glucose dictates an increase in mitochondrial oxidative phosphorylation - a process that governs energy production. However, an influx of calcium inhibits oxidative phosphorylation. Coupled with a decrease in cerebral blood flow, the energy demands needed to restore stability to the cerebral environment are not met. This exacerbates the brain's state of vulnerability towards further injury (see Figure 1.0).

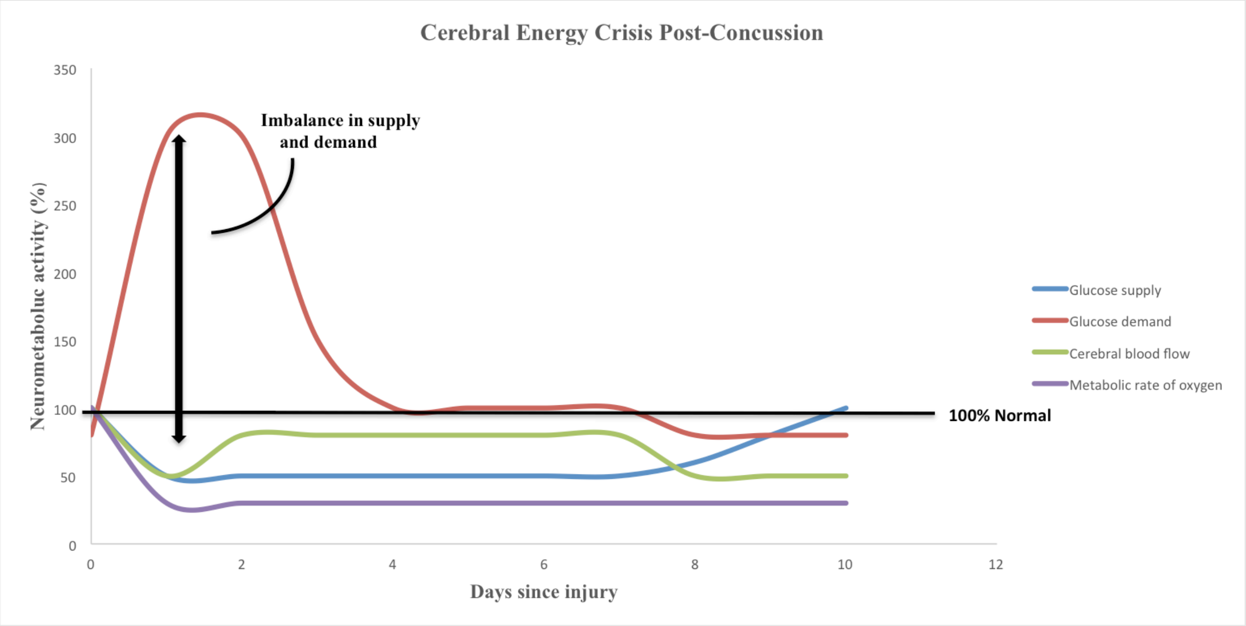


Figure 1.0 – Post-concussion there is a period of cerebral vulnerability, characterized by an increase in glucose demand but a decrease in glucose production along with decreased cerebral blood flow and oxygen delivery. Adapted from Giza, C., & Hovda, D. (2014). The new metabolic cascade of concussion. *Neurosurgery, 75*(4).

To date, much of the evidence on concussion pathophysiology has only been corroborated in fluid percussion models in animals; further study must be done on the neurometabolic changes that occur post-concussion in humans. Efforts have been made to try and pair pathophysiology with clinical symptom presentation. Headache is one of the defining symptoms of concussion. This is evident due to more than 85% percent of varsity athletes who sustained a concussion reporting symptoms of headache (Guskiewicz et al., 2000). The ionic flux of sodium, potassium, and calcium that have been shown in fluid percussion injury models on rats is extremely similar to the ionic flux that has been reported in the presence of patients who have suffered from migraines unrelated to mTBI (Giza, 2014). Furthermore, the reported symptoms of migraine sufferers such as nausea, dizziness, and sensitivity to light and noise are also commonly reported concussion symptoms (Giza, 2014; Seifert & Shipman, 2015). As a result, there is speculation that some of the somatic symptoms experienced by athletes who have sustained concussions are in part due to the ionic shift that takes place at the cellular level in the brain (Giza, 2014).

Standard clinical care for concussion injuries is removal from competition and a delayed return to play following a specific graduated protocol and physician clearance (Harmon et al., 2013; McCrory et al., 2013, 2017). This is in part due to the increased vulnerability of the brain should subsequent injury occur. Some animal studies in rats and mice have shown the imbalance between the supply and demand of cerebral blood flow post injury to be part of the cause of heightened susceptibility to subsequent injury (Barkhoudarian, Hovda, & Giza, 2011). Two studies on rats and mice examined the temporal vulnerability following concussive injuries. The results demonstrated that mice were subjected to greater metabolic stress, neurocognitive impairment, and axonal dysfunction when injuries occurred three or five days apart (Longhi et al., 2005; Tavazzi et al., 2007; Vagnozzi, 2007).The study on rats found the period of vulnerability immediately post injury corresponded with a deterioration in working memory as a result of decreased glucose metabolism and increased glucose demand. Subsequent injuries that occurred within one-day post injury resulted in even further impairment to working memory and further depreciation into a hypermetabolic state (Giza, 2014; Prins, Alexander, Giza, & Hovda, 2013).

A comprehensive understanding of the long-term consequences of concussions is still elusive. Diffusion tensor imaging has been able to pick up signs of axonal damage and decreased white matter density in the brain (Koerte et al., 2012; Stern et al., 2011; Virji-Babul et al., 2013). These structural damages provide better understanding of potential long-term consequences. Axon damage or death is thought to be associated with delayed reaction time and cognitive impairments, while a decrease in the amount of white matter is thought to contribute to the onset of depression, dementia, or Alzheimer's following repeated head injury (Stern et al., 2011).

Recent explorations in to the effect of repeated head trauma on athletes has revealed the presence of symptoms of depression, mood disturbances, suicidal ideation, Alzheimer's Disease, and Parkinson's. These symptoms often develop years after an athlete has sustained their injuries and are ultimately a result of a neurodegenerative disease called chronic traumatic encephalopathy (CTE) (Safinia et al., 2016; Stern et al., 2011). CTE has been shown to develop in high impact sports following multiple blows to the head. CTE is characterized as a tauopathy that includes a degeneration and atrophy of several areas of the brain (Safinia et al., 2016; Stern et al., 2011). The frontal and temporal lobes, the thalamus, and the mammillary body are the most commonly atrophied areas. In addition to a decrease in brain mass, CTE is associated with several microscopic changes made up of a variety of neurofibrillary tangles, beta amyloid deposits, and changes to white matter (Omalu et al., 2005; Safinia et al., 2016; Stern et al., 2011). These pathophysiological changes to neurological tissue, in combination with a decline in neurological function, results in the clinical presentation of the disease. Early signs of CTE include issues with short-term memory and executive functioning, including organization and planning, emotional disturbances, apathy, substance abuse, and suicidal behaviours (Stern et al., 2011). As the disease progresses, it presents clinically through a worsening impairment to executive functioning and memory, difficulties with speech and motor control, further mood and behavioural disturbances, and dementia (Stern et al., 2011). The development of CTE often occurs in middle-aged athletes, far earlier than the typical onset of dementia and Alzheimer's Disease. Although this may be the case, there are some reported cases of CTE presentation in younger individuals (Stern et al., 2011).

Both the acute and chronic pathophysiological processes of concussions provide adequate support for the development of appropriate physical prevention strategies in order to protect athletes immediately and in the long-term once their athletic career has ended.

Concussion Diagnosis, Assessment and Psychometric Properties

Several physical and cognitive indicators have been used in order to determine the presence of a concussion. Concussion symptomology can be separated into four distinct categories: physical (somatic), cognitive, emotional, and sleep-related (Table 1.0). The current standard for determining the presence of concussion is through physician diagnosis as per the Berlin Consensus Statement on Sports Concussion (McCrory et al., 2017). Physicians diagnose the presence of concussion based upon the presence of symptoms across the domains noted in Table 1 using various grading tools and checklists, mechanism of injury, combined with a clinical examination and various neuropsychological tests (McCrory et al., 2017).

One of the biggest concerns with concussion injuries is how debilitating the acute symptoms can be to athletes and the physical, psychological, and emotional sequelae that follow. Concussion symptoms are typically short lived in adults, with 90% of all injuries spontaneously resolving within seven to ten days (Gessel et al., 2007; Guskiewicz et al., 2003). However, the symptoms of concussion make it difficult for those affected to perform activities of daily living.

This is of great concern for student athletes as they are expected to meet both the cognitive demands of a full academic course load and the physical demands of competing in high-level athletics, both of which may worsen concussion symptoms (Harmon et al., 2013; McCrory et al., 2013). Improper concussion management after an initial injury can result in repeated injury or an exacerbation of concussion symptoms, longer recovery time, and an increased vulnerability for subsequent brain injuries (Giza, 2014; McCrea et al., 2004; McCrory et al., 2017).

A subset of concussed athletes will experience persistent concussion symptoms beyond one month. Athletes who experience this type of prolonged recovery are considered to have post-concussion syndrome (PCS). The exact criteria for post-concussion syndrome is still widely debated. The World Health Organization's *International Statistical Classification of Diseases and Related Health Problems, 10th Revision* considers post-concussion syndrome to be the presence of three or more symptoms lasting greater than one month. However, a 2015 study reported that in a survey of over 500 physicians the majority of them gave athletes a PCS diagnosis if they experienced one or more concussion symptoms for at least four weeks (Rose, Fischer, & Heyer, 2015). Epidemiological data on the course of recovery in college athletes is still limited, as most of the literature has examined recovery in either high school student-athletes or professional athletes. The sparse literature that does exist on recovery in college athletes reports recovery time of more than four weeks in 6.25 – 8.0 percent of athletes over one year (Yengo-kahn, Allen, & Kerr, 2016; Zuckerman et al., 2015). In addition to the lowered quality of life and challenges completing activities of daily living associated with prolonged concussion recovery, athletes who experience post-concussion syndrome are at greater risk of developing depression and anxiety than those who recover within the typical two-week timeframe. Risk factors including female sex, past concussion history, and pre-existing mental illness have been reported as indicators of possible post-concussion syndrome in athletes (Iverson et al., 2017). A review by Scopaz et al. published a list of potential indicators of prolonged concussion recovery time that included sex, age, past concussion history, type of sport, and history of headaches, amnesia, and migraines (Scopaz & Hatzenbuehler, 2013). It was found, however, that the level of support for these risk factors is variable. The strongest evidence in the review suggests females and those with a history of past concussions are at greatest risk for prolonged recovery (Scopaz & Hatzenbuehler, 2013). A 2003, study on a cohort of college football athletes demonstrated a statistically significant correlation between multiple past concussions and a prolonged recovery greater than seven days, however, further evidence is needed to evaluate concussion history as a risk modifier for prolonged concussion recovery (Guskiewicz et al., 2003). Another cohort study of college athletes examined the sex differences in concussion incidence over the span of three years. The findings of this study reveal that concussed female athletes experienced greater symptom presentation and cognitive deficits than their male counterparts, which may indicate a prolonged recovery time for females (Covassin, Swanik, & Sachs, 2003). The effect of concussion on cognition and mood, along with a potential increase in depression rates following concussion injuries, has provided some support for mental health issues, mood disorders, and learning disabilities to be potential risk factors for delayed concussion recovery as well. At this time, however, further exploration is required (Williams et al., 2015).

There is no definitive scale for concussion severity and how injury severity relates to recovery time. A prospective cohort study examined the relationship between concussion symptom scores on prolonged recovery time in a younger population (mean age 15.02 years, range 7.6 – 26.7) (Meehan, Mannix, Stracciolini, Elbin, & Collins, 2013). This study found that there was a significant independent relationship between an athlete's symptom score on the post-concussion symptom scale of the SCAT3 and prolonged recovery. Athletes with a greater total symptom score following concussion were more likely to take more than 28 days to recover from a concussion (Meehan et al., 2013).This study provides a foundation that symptomology may indicate a longer recovery time, although the extent to which this holds true in a varsity athlete population has not been verified. Therefore, the goal of chapter 3 is to determine whether or not there is a correlation between SCAT3 symptom score, neck muscle endurance, and time to recovery in a university athlete population.

There is much debate regarding the use of concussion assessment batteries and symptom scales, as a primary diagnostic tool as they are typically developed clinically without the necessary empirical evidence to support them (Alla, Sullivan, Hale, & McCrory, 2009; Johnston et al., 2001; Schatz, Pardini, Lovell, Collins, & Podell, 2006). There are reportedly over 25 published injury severity scales and checklists that have been used to help assess and manage concussion symptoms (Johnston et al., 2001; Schatz et al., 2006). These assessments are all various forms of self-reported symptom scales or checklists that are used to evaluate the presence and intensity of common concussion symptoms. While these assessment batteries can help indicate injury severity and guide return-to-activity decisions, there are limited psychometric properties published on these scales limiting the validity of their use in wholly determining the presence of concussion (Broglio, Macciocchi, & Ferrara, 2007).

Psychometric properties of grading tools and checklists.

There have been several grading tools and checklists presented as possible methods to identify the presence of concussion. The tools most commonly used in university athletics are the Sport Concussion Assessment Tool, 3rd edition (SCAT3), the Immediate Post-Concussion

Assessment and Cognitive Test (ImPACT) and the Graded Symptom Checklist. Despite these tools, no one tool has been shown to have adequate sensitivity and specificity to single-handedly determine the presence of concussion (Alla et al., 2009; Yengo-kahn et al., 2016). Therefore, a multidimensional approach to diagnosis is encouraged.

Physical	**Cognitive**	**Emotional**	**Sleep-related**
• Headache • Nausea • Vomiting • Tinnitus • Sensitivity to light or noise • Issues with balance • Vision impairment	• Difficulty concentrating • Difficulty remembering/amnesia • Feeling mentally foggy/slowed down • Reduced reaction time • Mental confusion	• Irritability • Sadness • Generally more emotional • Anxiety • Depression • Feeling nervous	• Difficulty falling and staying asleep • Sleeping more or less than usual • Drowsiness • Restlessness

Table 1.0 – List of physical, cognitive, emotional, and sleep-related concussion symptoms.

Concussion injuries are also considered to be a disruption in brain function without structural injury. Detection of structural damage on traditional brain scans has not been possible following concussion injuries until the recent use of diffusion tensor imaging (DTI) (Gardner et al., 2012; Giza, 2014; Johnston et al., 2001). DTI is able to detect microstructural injury damage to the brain's white matter, as well as any axonal damage that may have occurred (Khong, 2016). These changes may correspond with symptoms experienced in patients with prolonged concussion recovery (Khong, Odenwald, Hashim, & Cusimano, 2016). The use of this technique, however, is not available immediately post injury and has been explored, almost exclusively, in patients with post-concussion syndrome. Therefore, DTI is of greater use in determining structural injury and predicting prolonged recovery than initial diagnosis (Borich et al., 2013; Virji-Babul et al., 2013). Still, there is significant difficulty in determining objective, quantifiable measurement tools that identify the acute presence of concussion and indicate the removal of athletes from competition to prevent further injury. As such, several concussion assessment batteries have been developed as a way to try to more accurately detect the presence of concussion on the sideline.

A systematic review conducted by Alla et al. (2009) examined the psychometric properties of the most common self-report concussion symptom checklists and scales. They identified the six different checklists and scales most commonly used in concussion assessment and noted minimal peer-reviewed data on the psychometric properties of these scales (Alla et al., 2009). Several more scales have been derived or modified from theses original six, all of which have similar issues surrounding their psychometric properties. Given the lack of published validity and reliability values on the most frequently used concussion symptom checklists, it is not possible to use these tools in isolation to determine the presence of concussion (Alla et al., 2009; Schatz et al., 2006).

As indicated by the lack of psychometric validation of concussion symptom scales and checklists, symptom reporting alone is insufficient for accurate concussion diagnosis. This is largely due to the variability in symptom presentation (Yengo-kahn et al., 2016). Therefore, accurate diagnosis of concussion requires objective assessment of neurocognitive and neurological functions. The need for a more comprehensive assessment of concussion in athletes led to the development of the Standardized Assessment of Concussion (SAC) as a way to evaluate an athlete's mental status on the sideline. According to Capruso, attention and concentration, memory issues, disorientation, and delayed reaction time are among the characteristics most susceptible to deficit in concussive injuries (1992). The SAC was developed to be a short tool that informs on the mental status of an athlete and is to be used to help guide clinical decisions on the sideline (McCrea et al., 1998). The SAC provides immediate evaluation of concentration, short-term memory, delayed recall, and orientation (McCrea et al., 1998). This tool also provides therapists and physicians with a better understanding of an athlete's neurocognitive impairment on the sideline to allow for better clinical decision making with respect to acutely concussed athletes.

Balance issues are common symptoms found in concussed athletes. The injury creates an environment that impedes communication between the visual, somatosensory, and vestibular systems responsible for maintaining postural control (Guskiewicz, 2011). Balance requires input from the somatosensory, vestibular, and visual systems in order to maintain stability (Guskiewicz, 2011). A study published in 2000 demonstrated balance issues in 30% of concussed athletes (Guskiewicz et al., 2000). Two methodologies have been identified in assessing balance in concussed athletes: 1) Sensory organization test (SOT) and 2) Balance Error System Scoring (BESS) (Guskiewicz, 2011). The SOT is a high technology force plate system used to evaluate an athlete's balance by disrupting the somatosensory and visual input information as they attempt to maintain their balance within a dynamic, or moving, environment (Bell, Guskiewicz, Clark, Padua, 2011; Guskiewicz, 2011). The system measures the athletes change in center of gravity throughout the test trials (three trials under six conditions) where an overall composite equilibrium score is produced. Higher scores indicate better performance on the test (Guskiewicz, 2011). A 2008 study evaluated the sensitivity and specificity of the SOT in concussed individuals and found that while the SOT showed moderate to excellent specificity, the test has low sensitivity to concussion detection. The authors concluded that balance evaluation should not be the sole basis for concussion diagnosis and should be used concurrently with other assessments (Broglio, Ferrara, Sopiarz, & Kelly, 2008). A full overview of the psychometric properties of the SOT may be found in Table 2.0. Furthermore, the sophistication of this equipment has minimal clinical utility and would only be of use in helping to guide recovery and return to competition decisions (Bell, Guskiewicz, Clark, & Padua, 2011).

The BESS is a clinically relevant and cost-effective method of providing an objective assessment of balance (Bell, Guskiewicz, Clark, & Padua, 2011). Similar to the SOT, the BESS has three different stances, double-leg, single-leg, and tandem, performed on two separate surfaces with the athletes' eyes closed performed for 20 seconds. A modified version of the BESS is included in the SCAT3 for its sideline utility. Balance testing, while an important consideration in a concussion assessment, does not provide a complete picture on its own and therefore must be used in conjunction with other assessments.

One of the most frequently used assessment tools is the SCAT3 published by the Concussion in Sport Group (CISG) at the International Consensus on Sports Concussion (McCrory et al., 2017). The SCAT3 combines the scoring of the Glascow Coma Scale, the modified BESS, the Standardized Assessment of Concussion (SAC), and the Maddocks score to provide a brief sideline snapshot of the state of an athlete's mental capacity, symptom presentation, and vestibular functioning immediately following injury (McCrory et al., 2013). The SCAT3 was the primary outcome tool used for this thesis. At the time of data collection, the SCAT3 was the most current assessment tool for concussion assessment however, since then, the 5th International Consensus Statement has updated the SCAT 3 to the SCAT5. This thesis will report data on the SCAT3 as this is the assessment tool used by McMaster University Athletics and Recreation at the time of my thesis.

Several international sports associations, including the International Ice Hockey Federation (IIHF), the International Olympic Committee (IOC), World Rugby, and the Fédération International de Football Association (FIFA) endorse the use of this tool (McCrory et al., 2013). The SCAT3 is also the concussion assessment tool used in the McMaster University Department of Athletics and Recreation. This tool is used for its utility on the sideline during practice or competition as 18 of its items are to be used immediately post injury. The remaining seven items are to be evaluated at a follow-up assessment, as concussions, although typically transient injuries, require monitoring over a period of time.

The SCAT3 begins with an assessment of injury severity using the Glasgow Coma Scale (GCS). However, the utility of the GCS is questionable given that a large majority of sports-related concussions do not result in loss of consciousness (Guskiewicz et al., 2003; Guskiewicz et al., 2000). The most recent systematic review on the use of SCAT3 in concussions did not include studies that used the GCS due to the lack of literature in athletic head injuries and the significant use in traumatic brain injuries (Yengo-kahn et al., 2016). Following the assessment of an athletes' level of consciousness, the Maddocks Score is used to establish their orientation and understanding of their current environment and has been validated for sideline concussion assessment (McCrory et al., 2017; Yengo-kahn et al., 2016). Athletes are asked to provide their own personal demographic information including age, past concussion history, medications, and history of mental health issues. A subsequent evaluation on the presence and severity of concussion symptoms takes place using the post-concussion symptom scale (PCSS). The 22 symptoms are ranked on a 7-point likert scale in terms of intensity. Following symptom evaluation athletes are subjected to brief cognitive evaluation, balance and coordination tests. The scores on each sections are tallied at the end of the assessment (Sport Concussion Assessment Tool, 2013; McCrory et al., 2013). A copy of the SCAT3 and its scoring can be found in Appendix E. Multiple SCAT3 assessments over the course of the athlete's recovery may be able to provide information to guide return to play decisions as no normative values for college athletes based on sport exist.

The SCAT3 is one of the only symptom checklists to have published face/content validity although the reliability, sensitivity, and specificity with respect to concussion diagnosis are unknown at this time (McLeod & Leach, 2012). Furthermore, a systematic review published in 2016 evaluated the use of SCAT3 and its components in the detection of concussion in athletes (Yengo-kahn et al., 2016). The review found variability in studies that used the m-BESS and SAC in their ability to detect concussion. These tools were used mostly in football players. One study reported a decrease in SAC by 2.94 points below baseline following a concussion (McCrea et al., 2003; Yengo-kahn et al., 2016). However, the sensitivity and specificity of the SAC is scarcely reported. One study from 2001 indicated that a one point decrease in SAC score was 94% sensitive and 76% specific at detecting concussion (Barr & McCrea, 2001). A more recent study published in 2015 noted no significant differences in SAC scores between baseline and post-injury assessment in a mixed gender sample of rugby athletes (Putukian et al., 2015). The use of the m-BESS as a sole indicator of concussion has only been used in one study. The authors reported a significant decline in m-BESS scores from baseline following concussion injury (Putukian et al., 2015). The sensitivity and specificity on this modified version of the BESS is not reported. Most studies that included the m-BESS use this tool as part of a SCAT3 assessment (Yengo-kahn et al., 2016). There are few studies that have examined the psychometric properties of the SCAT3. A study by Putukian et al. examined the sensitivity and specificity of an earlier version of the SCAT (SCAT2). This study found a 3.5 point drop in SCAT2 score from baseline was 96% sensitive and 81% specific at detecting concussion. However, similar studies of smaller cohorts have indicated no significant changes in the total SCAT2 score from baseline post-injury (2015). Additionally, the 2017 Berlin Consensus Statement on concussion assessment stipulates that baseline testing for athletes is not required. Baseline testing is often challenging to do in varsity athletes due to the time and cost associated with performing the assessments. The 2017 Berlin Consensus Statement has also indicated that no one item in a specified tool is adequate to distinguish the presence of concussion (McCrory et al., 2017). The International Consensus Statement indicates an exploration and assessment of balance, memory and other neurocognitive processes should be included following a suspected concussion injury (McCrory et al., 2017). A summary of the psychometric properties for the SCAT3, mBESS, SAC, SOT and the ImPACT test is found in table 2.0.

Scale	Reliability	Validity	Sensitivity	Specificity	Positive Predictive Values, %	Negative Predictive Value, %
PCSS	Cronbach α = 0.88-0.93	Construct	N/A	N/A	N/A	N/A
SAC	Cronbach α = 0.44-0.65	N/A	0.94	0.76	N/A	N/A
BESS/ mBESS*	ICC = 0.78-0.96	Criterion Content	0.60/0.71*	0.66*	N/A	N/A
SOT	ICC = 0.15-0.70	Concurrent	0.73	0.95	N/A	N/A
SCAT2/3	Cronbach α = 0.94	Face/Content	0.83-0.96	0.81-0.93	N/A	N/A
ImPACT	ICC= 0.26-0.88	Construct Criterion	0.29-0.82	0.75-0.89	83-89.4	70-81.9

Table 2.0 – Overview of the published psychometric properties of the most common concussion assessment tools.

Neuropsychological assessments in concussions.

Concussion injuries can result in impairments to certain cognitive functions, including memory, attention, information processing, and visual-motor reaction time (Collie, 2006) . While resolution of these impairments often follow the recovery timeline of other somatic symptoms, cognitive impairment may endure beyond an athlete’s time of recovery of physical concussion symptoms (Bleiberg et al., 2004; McCrea et al., 2003; Sandel, Lovell, Kegel, Collins, & Kontos, 2013). As such, the International Consensus Statement advises that neuropsychological testing be included in a complete concussion assessment and used to help advise return-to-play decisions (McCrory et al., 2013).

Some concussion assessment tools, such as the SCAT3, include brief, simple, verbal cognitive testing to establish impairment in athletes. However, these tools have several limitations including floor and ceiling effects, and practice bias (McCrea et al., 1998). Thus, more thorough testing is often warranted to better assess the level of impairment. Currently, the most widely used neuropsychological concussion assessment is the Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT) battery. The ImPACT test is a computer neurocognitive screening test comprised of 3-domains administered to athletes following a concussion. The three components of the test are: athlete demographics, neuropsychological tests, and a post-concussion symptom scale (Iverson, Lovell, & Collins, 2003; Schatz & Sandel, 2013). The data from this test is kept in a database for comparison (should the same athlete sustain a subsequent concussion). Baseline-testing using the ImPACT test is recommended by the authors of the test for use in varsity athletes prior to the start of competition as it gives a foundation for comparison (Iverson et al., 2003; Schatz et al., 2006). However, the most recent Consensus Statement on Sports Concussions from Berlin negates the necessity of concussion baseline testing (McCrory et al., 2017).

The neuropsychological component of the ImPACT is comprised of six different tests designed to test the cognitive processes of attention, memory, processing speed, and reaction time. If the athlete has no prior testing their scores may be compared to age and sex matched controls (Iverson et al., 2003). The symptom scale used in the ImPACT test to evaluate symptoms is very similar to the SCAT3 symptom checklist and the Post-Concussion Symptom Scale (PCSS). The ImPACT test symptom scale uses a 6-point likert scale to evaluate the severity of 22 common concussion symptoms (Iverson et al., 2003). However, the same limitations for the SCAT3 exist for the ImPACT test symptom scale in that very limited psychometric properties have been published for the symptom scale alone (Alla et al., 2009; Valovich McLeod, Barr, McCrea, & Guskiewicz, 2006). The sensitivity and specificity of the ImPACT test is published for the test as a whole, which includes the neuropsychological tests and the symptom scale. The sensitivity, or probability that the test will be positive if a concussion is present, of the entire ImPACT test is 81.9%. The specificity, the probability that the test will be negative if no concussion is present, is 89.4% (Table 2.0). While these values show relatively good sensitivity and specificity, the ImPACT test is not without its limitations. The ImPACT test has no sideline utility, as it is a computer, subscription-based test. Therefore, administration of the test must occur well after the injury takes place as it requires the use of the internet and a quiet, distraction free environment. This has the potential to increase the acute symptoms of concussion, as the current recovery guidelines stipulate a 24-48 hour period of cognitive and physical rest (McCrory et al., 2017). Moreover, administration of the test is costly, and as a result, the use of the ImPACT test may not be economical for large university programs with hundreds of athletes. Consequently, the use of the ImPACT test has been known to enhance a physician diagnosis in combination with symptom evaluation and a clinical examination (McCrory et al., 2017).

Concussion Recovery and Return-to-Play

The foundation of concussion injury management has been complete rest from any type of mental or physical exertion until symptoms resolve (McCrory et al., 2013). The most recent 2017 Berlin Consensus Statement recommended a period of rest for only the first 24-48 hours following the injury (McCrory et al., 2017). Subsequently, the CISG recommends athletes begin to resume daily activities provided that they remain within their symptom exacerbation threshold. Therefore, non-contact low risk activity is permitted provided that acute symptoms do not worsen (McCrory et al., 2017). Once concussion symptoms have resolved, athletes may begin a graded exertion return-to-play protocol (McCrory et al., 2017). The standard of care is for all athletes to receive physician clearance after sustaining a concussion prior to returning to contact or competition (McCrory et al., 2017, 2013). There is significant debate surrounding the proper management of concussion injuries in athletes and how much rest is the most appropriate course of action. There is limited evidence that examines the exact amount of rest required immediately post-injury. As a result, this calls for further exploration into the quantity of absolute rest that is required before returning to activity (McCrory et al., 2017).

The graduated return-to-play protocol involves six steps; graduation from each stage requires the athlete to remain asymptomatic for the 24-hours following completion of that stage. If the athlete experiences a return or worsening of concussion symptoms, they must return to rest until they are symptom-free prior to reattempting that stage of the program. The six stages of the return-to-play protocol following concussions are as follows (McCrory et al., 2017):

1. Symptom limited activity – the main objective is to reintroduce athletes into regular school or work activities.
    - Athletes are limited by their symptoms at this stage. Physical and cognitive exertion must be within the limits of worsening symptoms. Typically, athletes will spend the most amount of time at this stage, as progression to step 2 is conditional on being asymptomatic.
2. Light-aerobic exercise – the main objective is to increase the athlete’s heart rate (HR).
    - Athletes may use the stationary bike or walk at a moderate pace. HR should be less than 60% of their maximum.

3. Sport-specific activities – increase multi-planar and more complex movement.
    - Introduction to running or skating at this stage but no activities involving head-impact.
4. Non-contact training drills – An increase in physical intensity, cognitive demand and coordination.
    - May attempt full non-contact practice and begin progressive resistance training. Athletes are still unable to perform contact drills.
5. Full-contact practice – Reintroduction into contact to assess technical skills with respect to impact and restore confidence.
    - Once given medical clearance athletes are allowed to complete full practice and training requirements.
6. Return to competition.

An uninterrupted return-to-play (RTP) schedule takes approximately five to seven days to complete once an athlete's symptoms have resolved, however, 10-15% of college athletes take more than 14 days to return to an asymptomatic state and ultimately longer to RTP (McCrea et al., 2003). The school of thought of absolute rest in concussion management is currently being challenged in the literature. The increased energy demands in the cerebral environment immediate following concussion necessitate cognitive and physical rest. However, literature in athletes following acute injury demonstrates removal from physical activity participation increases athlete reports of anxiety and depression (Leddy, Lambert, & Ogles, 1994). The literature on early introduction to activity prior to symptom resolution is very limited. One study of student-athletes demonstrated that those who engaged in moderate physical activity prior to symptom resolution performed better on a post-injury neurocognitive assessment than those who participated in absolute rest and vigorous asymptomatic physical activity (Majerske et al., 2008). This study retrospectively asked athletes to self-report their physical activity in the 30 days following concussion. The timing of when activity was introduced post-injury was not stated for these athletes. A scoping review by Leddy and colleagues reported that aerobic exercise prior to symptom recovery has shown to be effective but is also limited by the study design (Leddy, Baker, & Willer, 2016). These results must be interpreted with caution but provide justification for further exploration into physical and cognitive activity following concussion using a more rigorous methodology like a randomized control trial.

Concussion Prevention and the Link to Neck Strength

The mounting incidence of concussions and the growing concerns of the possible consequences of concussion injuries have demonstrated the need for appropriate concussion prevention strategies. To date, the majority of the prevention literature has examined prevention in three areas: protective equipment, education, and legislation and rule regulation (Harmon et al., 2013; Scopaz & Hatzenbuehler, 2013). A substantial amount of research has gone into examining helmet, headgear, and mouth guard use and design in the reduction of concussion risk. A systematic review of the literature indicated that the use of helmets in sports like cycling, skiing, and snowboarding decreased head injuries, however the effect helmets had on concussion-inducing rotational forces was inconclusive (Lewis et al., 2001;Benson, Hamilton, Meeuwisse, McCrory, & Dvorak, 2009). A second systematic review identified two studies that demonstrated a protective effect of helmets in ski and snowboard athletes, along with a protective effect in a comparison between football and rugby athletes (Emery et al., 2017). Additionally, two cohort studies presented evidence to suggest that greater padding over the zygoma and mandibular area in football helmets and proper fit had a protective effect against concussions (Collins, Lovell, Iverson, Ide, & Maroon, 2006; Greenhill et al., 2016). However, the lack of biomechanical studies and use of appropriate control groups indicates further research is necessary to determine the effectiveness of helmet fit and design on concussion risk reduction (Collins, Lovell, Iverson, G.L., et al., 2006; Greenhill, Navo, Zhao, et al., 2016; Emery et al., 2017). Similarly, a reduction in concussion risk was identified with the use of mouth guards, however, none of these conclusions were statistically significant (Emery et al., 2017). Studies exploring the protective effect of mouth guards have several limitations, including a lack of rigorous study methodology, inadequately powered studies from small sample sizes.

Rule changes to certain contact sports has been suggested as a way to prevent concussions, however, changes to rules and their effectiveness on reducing concussion risk may be questionable as rules of sport can always be broken and may not always be strictly enforced. Even so, the elimination of body checking in youth hockey has shown to be effective in reducing the risk of concussion by 20%-90% (Black et al., 2016, Cusimano et al., 2011, Emery et al., 2017). A 67% concussion reduction was reported when a no-body checking policy was enforced. This rule change, however, is only seen in youth hockey (Emery et al., 2017). Indeed, higher-level athletes and professional hockey players are all still exposed to body checking. Therefore, the effectiveness of limiting body checking in college athletes is unknown, as they have not adopted this policy.

The 2010-2011 National Hockey League (NHL) season introduced a new rule on strict penalty enforcement on hits to the head from the athlete’s blind-spot (NHL, 2010). This rule was then improved upon in the following season to include all hits to the head (NHL, 2011). A 2013 study that examined the effectiveness of the NHL’s new policy indicated that there was no reduction in the incidence of concussions between the 2009-2010 season with the 2010 and 2011 seasons (Donaldson, Asbridge, & Cusimano, 2013). Therefore, stricter policies for elite contact sport athletes may not be effective enough on their own to reduce concussion risk.

A review published in 2013 indicated further research must be conducted on physical training and neck strength as a potential predictive factor or prevention mechanism in concussions (Harmon et al., 2013; Williams et al., 2015). A 2014 study by Collins et al. examined the association between neck strength and the rate of concussion in an adolescent athlete population. This prospective cohort study evaluated the neck strength of over 6,000 high school athletes from 51 high schools across the United States. Measurements of neck strength were evaluated by a certified athletic therapist using a hand-held tension scale - a modification to hand-held dynamometry (Collins et al., 2014). The results of this study showed that individuals with lesser neck strength (younger athletes and females) had a higher incidence of concussion than their stronger counterparts (Collins et al., 2014). The findings of this study suggest that stronger necks have a potentially protective effect against concussion. Subsequently, in 2013, a series of studies were published examining the neck strength of highly trained, elite rugby athletes. These studies found that there was a significant difference in neck strength between athletes of different positions suggesting there to be variability in neck strength amongst athletes (Geary, Green, & Delahunt, 2013, 2014).

Confounding factors.

1. Effect of Neck Strength on Head Stabilization

Recent studies have examined how the anticipatory responses of the neck musculature, in response to an impact to the head, plays a role in concussion prevention. These studies indicate that greater strength and anticipatory activation of the neck muscles were able to reduce the head's kinematic response to spontaneous loads in both males and females (Angelica & Fong, 2008; Eckner et al., 2014). The study of anticipatory action indicates that an athlete who is able to brace him or herself upon impact is less likely to sustain a concussion. This suggests that athletes with greater overall neck strength may be at a biomechanical advantage to resist or absorb potentially concussive impacts, thus decreasing their risk of concussion. At this point, no published data exists on the exploration of neck strength and its protective ability against concussion injuries in university athletes. Moreover, there is yet to be any published evidence comparing differences in neck strength and concussion risk between genders and across different ages within a varsity athlete population.

In 2005, Tierney et al. aimed to determine whether gender differences existed in kinematic and dynamic stabilization variable responses to an external force applied to the head. They examined 40 active (30 minutes of intentional exercise 5x/week) females and males and performed anthropometric, neck strength, and head-neck segment stiffness assessments on all participants. Participants were then required to sit within an external force applicator and were fitted with headgear that was attached to a pulley system. The results showed that females exhibited 49% less isometric neck strength than males. There were also significantly greater differences in head-neck segment dynamic stabilization during head acceleration in response to external force application between male and female athletes (Tierney et al., 2005). This suggests that those with weaker necks have less ability to stabilize the head in response to the external biomechanical forces that cause concussion.

With respect to the athlete population, there is less information regarding the effects of strength on head stabilization. However, in their 2008 cross-sectional study, Tierney et al.

assessed the effect of sex and headgear on head impact kinematics and dynamic stabilization of the head in college soccer players. They measured linear head accelerations in athletes while heading the ball using a custom mouth-piece fit with triaxial accelerometer. The accelerometer measured the resultant linear head accelerations in athletes while heading the soccer ball. Women were found to have significantly weaker strength in the neck (50% less ISO neck flexor strength and 53% less ISO extensor strength) and exhibited greater head accelerations than men when heading the ball ($p= <0.001$)(Tierney et al., 2008b). While this study shows support for an increase in concussion risk in females due to their decreased ability to stabilize the head upon impact, this study is not without its limitations. The assessment of head stabilization and accelerations was for a header from a straight on standing posture, which does not replicate the unpredictable nature of an athletic environment. Furthermore, this study is the first of its kind to use the mouthpiece accelerometer and while this instrument has been shown to be valid in assessing head accelerations it is only able to pick up linear acceleration (Tierney et al., 2008b). It has been hypothesized that angular accelerations contribute more greatly to concussion incidence than linear accelerations (Holbourn, 1943). Further study must be done to examine the amount of angular acceleration to the head during concussion and how to measure stabilization techniques in response to these forces.

2. Differences in Neck Strength in an Athletic Population

In 1987, one of the first studies that looked at neck strength in athletes examined peak isometric neck flexion, extension, and left and right lateral flexion in college football players. The aim of the study was to identify weaknesses in neck muscle strength and note any relationship between neck strength and c-spine stability (Franco & Herzog, 1987). The study examined two groups: linemen and running backs. They found significant differences in neck muscle strength between the two groups of athletes and noted that both groups were significantly weaker between their right and left sides due to the nature of the hitting position in Football. The results suggest that athletes, who have strength imbalances bilaterally in the neck musculature, are placing the cervical vertebrae in a less stable position at the time of impact. This imbalance makes the athlete vulnerable to possible brachial plexus injury, vertebral fracture, and concussion as a result of less stability and muscular control (Franco & Herzog, 1987). Thus, neck strength imbalance is a further confounding factor.

Olivier and DuToit (2008) looked at senior elite rugby union athletes and measured peak isokinetic torque produced by the neck muscles in flexion, extension, and lateral flexion. They found that front row forward players had significantly greater peak torque in extension when compared to back row forwards and backline athletes. Overall, the backline athletes had significantly weaker neck peak torque values through all ranges of motion. This study shows differences in neck strength within athletes of the same age group and training level and suggests that there is a correlation between build and position and suggests a potential higher risk for concussion in athletes of the same sport but with different skill sets and body morphology. A study of the incidence of concussion in the English rugby union identified more concussions to athletes who played in the backs, over the course of three seasons (Kemp, Hudson, Brooks, Fuller, 2008). While the difference in incidence of concussion among forwards and backs was not statistically significant a greater proportion of backs sustained concussions and recovered for a longer period of time. Athletes who are in the backs are leaner and smaller than that of the forward players who are in contact in the scrum spend more overall time in contact (Kemp, Hudson, Brooks, Fuller, 2008). This suggests that neck strength may be relevant even in high-level athletes when neck strength variability may be less than in an adolescent athlete population.

Since 2012, other studies have looked similarly at adult rugby union athletes. While all of the studies looked at peak isometric strength in flexion and extension, only some look at lateral flexion. It is important to note, however, that all studies found similar differences in rugby athletes who play forward and backline positions. All three studies showed that forwards had significantly greater strength in flexion and extension (Hidenbrand & Vasavada, 2013; Konranth & Appleby, 2013; Hamilton et al. 2014; Hamilton & Gatherer, 2014). Strength differences between certain positions, especially in sports where each position is body type specific, suggests that these athletes may have different characteristics that predispose them to an increased concussion risk. While the direct link between position, type of sport, and concussion risk has not been studied, the variance in neck strength between athletes of the same sport suggests a possible link between certain positions being at greater risk for concussion than others based on their individual anthropometric profile and exposure to contact in a game.

There are very few studies that look at specific strength differences in female athletes. Despite the scarcity of literature examining neck strength differences amongst female athletes, several studies show a higher incidence of concussion in females (Abrahams, Mc Fie, Patricios, Posthumus, & September, 2014; Scopaz & Hatzenbuehler, 2013). Biologically women have less strength than men, thus it is possible this reduction in strength, compared to men, predisposes females to an increased risk of concussion. An evaluation of neck strength differences amongst female athletes across various sports would provide a greater understanding for the mechanism behind an elevated incidence of concussion and give support for the development of strengthening interventions as a possible treatment for injury prevention.

Theoretical Framework

The theoretical framework used to ground the methodology of this thesis looks to explain how concussive impacts cause injury to the brain tissue and how mechanically, the musculature of the neck is responsible for absorbing possibly injurious impacts. The definition of concussion stipulates that the injuries are “induced by biomechanical forces to the head” (McCrory et al., 2013, p.84). A review of the current literature on concussions has proposed that concussions are a result of rotational acceleration to the head (Hrysomallis, 2016). As such, the study of head injury mechanics can be used to help predict the nature of the pathology and symptoms following a head injury. To date, the concussion literature that references relevant theoretical framework is limited and specific theories on concussion in sport have yet to be developed. As concussion has such a complex etiology, grounding the research in theory can allow for greater understanding of such a complicated issue. A combination of muscle physiology and injury theories and Newton’s Laws of motion help to guide the development of the research questions for this thesis.

Rotational shear-stress theory.

Rotational shear-stress theory (RST) was developed by Holbourn in 1943 to explain how impacts to the head damage the brain and to also determine the location of the injury after impact. This theory can be used to help explain concussive injuries as well as better understand symptomology and possible cognitive and neurological deficits as a result of injury.

RST proposes a way to determine injury inside the brain upon impact and explains how concussions occur as a result of angular accelerations to the brain. However, concussions are much more complex than just an impact to the head and other factors that contribute to concussion in sport must be considered. Current literature examines several variables that may contribute to the likelihood of an individual sustaining a concussion. These factors include, but are not limited to, the strength of the athlete, the force of impact, use of protective equipment, reaction or anticipatory response to impact, and mechanism of injury (Harmon et al., 2013).

The work put forth by Holbourn, as the primary mechanism for brain injury, is some of the earliest work published on head injury mechanics and subsequent effects on the brain. In its simplest form, RST aims to explain that brain injuries result from angular accelerations to the head and is based on several assumptions of the physical properties of the brain in conjunction with Newton's Laws of Motion (Holbourn, 1943). Holbourn proposed two distinct causes for brain injuries: (1) injury due to deformation of the cranium, (2) injury due to impact, regardless of skull deformation.

According to Holbourn (1943), the brain is governed by the following physical properties:

- The tissues of the brain (including the vasculature and nervous tissue) have approximately uniform density,
- Brain tissue is relatively unaffected by compressive forces (i.e. highly resistant to changes in size, also known as extreme incompressibility),
- Conversely, the brain has low resistance to changes in shape (i.e. can easily be deformed, also known as low rigidity),
- The skull, in contrast, is extremely rigid and acts as the primary protective mechanism to the brain,
- Lastly, the shape of both brain and cranium are critical to determining the location of injury.

RST states that, given the physical properties of the brain and skull, particularly its rigidity and incompressibility, injuries to the brain are most likely to occur due to shear strain or slide deformation, and not compression strain (Holbourn, 1943). Grundfest’s work supports this notion, through a demonstration of how nerves were still capable of conducting impulses despite being subjected to significant compressive forces (10,000 lbs. per square inch) (Grundfest, 1936). Grundfest’s proposition is important when considering injuries that occur without skull deformation~~,~~ as these injury types are most likely to be the result of angular acceleration and ultimately rotational shear stress on the tissues of the brain. These injuries are reportedly caused by the changes in accelerations of the head that result from the force of the impact. Accelerations can either be linear or angular in nature. According to Holbourn (1967), the amount of shear-strain that occurs from linear accelerations is nearly negligible. Therefore, the main assumption of RST is that brain injuries occur through angular accelerations to the head, which result in movement of the brain within the skull as it floats in the cerebral spinal fluid and contra coup as the brain slams against the skull. This ultimately results in shear stress to the brain which, in turn, leads to axonal damage. Understanding Newton’s Laws of Motion, muscle physiology, and Holbourn’s RST as the mechanism of concussion injuries allows for the development of possible prevention strategies. This theory was used to guide the research questions of this thesis, which examines how neck musculature may be able to limit the concussion-causing accelerations to the brain.

Newton’s Laws – the foundation of classical mechanics.

Newton’s laws of motion explain the relationship between a body and the external forces acting up on and the way in which the body responds to these forces. In brief Newton’s Laws of Motion are:

1) A body at rest stays at rest and a body in motion stays in motion unless acted upon by an external force.

2) Force is equal to mass times acceleration

3) When one body exerts a force upon another, the second body exerts the same magnitude of force to the first body in the opposite direction (Browne, 2013).

With respect to concussion, these laws provide a framework for understanding how the human body will react to potentially injurious impacts. Specifically, Newton's second law indicates F=ma, where F is the vector sum of the forces of an object and is equal to the mass of the object multiplied by the acceleration vector of the object (Browne, 2013). Therefore, acceleration of an object is inversely proportional to its mass. Since a concussion is a result of head acceleration and rotation, this law can be applied to identify those at risk for concussion in sport. An athlete with less mass (in their head and neck) is going to experience greater head acceleration than an athlete who has more mass to their head and neck. Furthermore, Newton's third law provides the foundation for explaining how the body must respond to the external forces applied to it during a concussion (Browne, 2013). Several muscle physiology theories can explain the mechanism by which the musculature of the neck will respond to impact.

Skeletal muscle stretch reflex.

Skeletal muscle acts on the skeleton to produce movement at a joint. A skeletal muscle is made up of several muscle fibers. Within each of these muscle fibers there are several repeats of contractile units called a sarcomere. The molecules within the sarcomere, called actin and myosin filaments bind with one another to form cross-bridges that will eventually cause the sarcomere to shorten and the muscle to contract (Koeppen & Stanton, 2017). Muscle contraction can happen voluntarily however certain reflexes exist to elicit contractions in response to the muscle being stretched in order to prevent injury.

Skeletal muscle contains mechanoreceptors called muscle spindles that evaluate the degree of stretch of a muscle. When as muscle is stretched quickly, as is the case during some concussive impacts, there is an increase of action potentials sent to the sensory neurons of the muscle spindle. The activation of these sensory neurons trigger the motor neurons within the stretched muscle to generate a muscle contraction. This reflex arc acts as a way to protect against injury from over stretching(Koeppen & Stanton, 2017). According to Newton, in response to a concussive impact the neck musculature will generate a force in the opposite direction of the impact. However, to prevent injury, the musculature of the neck must generate force great enough to absorb the impact in order to prevent concussion. In some high-risk sports fatigue may play a part in the athlete's inability to brace against potentially injurious impacts.

Over-exertion theory of musculoskeletal injury causation.

In 2001, Kumar presented several theories that comprise an over-arching theory of musculoskeletal injury causation. One of the sub theories presented is the over-exertion theory. This theory states excessive physical effort will result in over-exertion where the biological system or the components of the system exceed their tolerance limit. Each action, whether it is in sport or everyday life, requires the generation of force from one position to another over a certain period of time. Therefore, over-exertion is a function of force, motion, position, and duration. As the demands on the system increase through any of the aforementioned dimensions of this theory, the muscles start to fatigue, ultimately resulting in injury (Kumar, 2001).

With respect to concussion, the muscles of the neck work in the same way. They must be able to generate enough force to counteract the external forces applied to the head. Repetitive impacts to the head will also eventually result in overexertion of the neck musculature, increasing the magnitude of accelerations to the head, possibly resulting in concussion. By increasing neck strength prior to competition, the musculature of the neck, theoretically, has a higher threshold to better resist against force, range of motion, and repetition during competition.

Research Questions and Hypotheses

This thesis aims explore the relationship between neck strength and concussion risk. In order to evaluate this, the following questions were formulated:

1. Is isometric neck strength associated with the likelihood of sustaining a concussion in a university-level varsity athlete population, aged 18-25?

2. Is there a difference in the incidence of concussion between male and female university-level varsity athletes?

3. Is there a relationship between the incidence of concussion and the sport played by university-level varsity athletes?

4. Is there a correlation between neck endurance strength, SCAT 3 symptom scores and the amount of time it takes an athlete to return to play following a concussion injury.

It is hypothesized that varsity athletes with greater neck strength, and greater neck circumference will be the least likely to sustain a concussion throughout the course of an athletic season. Furthermore, female and contact sport athletes are hypothesized to be at considerably greater risk for concussion than other athletes playing “at-risk for concussion” sports.

It is the goal of this study’s findings to add to the existing body of knowledge about neck strength as a potential factor in concussive injury and, ultimately, its prevention

The current literature focuses on management and assessment of concussions, yet there are minimal solutions addressing prevention. Examining which athletes may be at greater risk for concussion will help to narrow the focus of future concussion prevention research.

The study design implemented for this project was a prospective cohort study. This project was granted ethics approval through the Hamilton Integrated Research Ethics Board (HiREB # 1924). The results of this study are presented in the following two chapters. Chapter 2 examines the relationship of cervical muscle endurance and the rate of concussion in a varsity athlete population. Chapter 3 explores the relationship between SCAT3 symptom scores, neck strength, and the amount of time an athlete takes to return to competition as a way to examine injury severity and predict concussion recovery time. Chapter 4 presents a summary and discussion of the findings of this study as well as addresses the clinical implications of the results and provides suggestions for future research.

References

Abrahams, S., Mc Fie, S., Patricios, J., Posthumus, M., & September, A. V. (2014). Risk factors for sports concussion: an evidence-based systematic review. *British Journal of Sports Medicine*, *48*(2), 91–97. https://doi.org/10.1136/bjsports-2013-092734

Alla, S., Sullivan, S. J., Hale, L., & McCrory, P. (2009). Self-report scales/checklists for the measurement of concussion symptoms: a systematic review. *British Journal of Sports Medicine*, *43 Suppl 1*, i3–i12. https://doi.org/10.1136/bjsm.2009.058339

Angelica, M. D., & Fong, Y. (2008). Effect of Neck Strength and Anticipatory Activation in Response to Head Impulsive Loads. *American Journal of Public Health*, *141*(4), 520–529. https://doi.org/10.1016/j.surg.2006.10.010.Use

Association, T. N. C. A. (2013). *NCAA sports medicine handbook, Guideline 21: Sports-related concussion*. Idianapolis, IN. https://doi.org/10.1136/bjsm.34.3.230-a

Bakhos, L. L., Lockhart, G. R., Myers, R., & Linakis, J. G. (2010). Emergency Department Visits for Concussion in Young Child Athletes. *Pediatrics*, *126*(3), e550–e556. https://doi.org/10.1542/peds.2009-3101

Barr, W. B., & McCrea, M. (2001). Sensitivity and specificity of standardized neurocognitive testing immediately following sports concussion.[Erratum appears in J Int Neuropsychol Soc 2002 Mar;8(3):481]. *Journal of the International Neuropsychological Society*, *7*(6), 693–702.

Bazarian, J. J., Zhong, J., Blyth, B., Zhu, T., Kavcic, V., & Peterson, D. (2007). Diffusion Tensor Imaging Detects Clinically Important Axonal Damage after Mild Traumatic Brain Injury: A Pilot Study. *Journal of Neurotrauma*, *24*(9), 1447–1459. https://doi.org/10.1089/neu.2007.0241

Bell, David R. Guskiewicz, Kevin M. Clark, Michael A. Padua, D. A. (2011). Systematic Review of the Balance Error Scoring System. *Athletic Training*, *3*(3), 287–295. https://doi.org/10.1177/1941738111403122

Benson, B. W., Hamilton, G. M., Meeuwisse, W. H., McCrory, P., & Dvorak, J. (2009). Is protective equipment useful in preventing concussion? A systematic review of the literature. *British Journal of Sports Medicine*, *43*(Suppl_1), i56–i67. https://doi.org/10.1136/bjsm.2009.058271

Benson, B. W., McIntosh, A. S., Maddocks, D., Herring, S. A., Raftery, M., & Dvorak, J. (2013). What are the most effective risk-reduction strategies in sport concussion? *Br J Sports Med*, *47*(5), 321–326. https://doi.org/10.1136/bjsports-2013-092216\r47/5/321 [pii]

Benson, B. W., McIntosh, A. S., Maddocks, D., Herring, S. A., Raftery, M., & Dvořák, J. (2013). What are the most effective risk-reduction strategies in sport concussion? *British Journal of Sports Medicine*, *47*(5), 321–326. https://doi.org/10.1136/bjsports-2013-092216

Black, A. M., Sergio, L. E., & Macpherson, A. K. (2017). The Epidemiology of Concussions: Number and nature of concussions and time to recovery among female and male canadian varsity athletes 2008 to 2011. *Clinical Journal of Sport Medicine*, *27*, 52–56. Retrieved from http://www.cjsportmed.com/%0Ahttp://ovidsp.ovid.com/ovidweb.cgi?T=JS&PAGE=reference&D=emed18b&NEWS=N&AN=608297429

Bleiberg, J., Cernich, A. N., Cameron, K., Sun, W., Peck, K., Ecklund, J., … Bailes, J. E. (2004). Duration of Cognitive Impairment after Sports Concussion. *Neurosurgery*, *54*(5), 1073–1080. https://doi.org/10.1227/01.NEU.0000155093.00745.B4

Bloom, G. A., Loughead, T. M., Shapcott, E. J. B., Johnston, K. M., & Delaney, J. S. (2008). The prevalence and recovery of concussed male and female collegiate athletes. *European Journal of Sport Science*, *8*(5), 295–303. https://doi.org/10.1080/17461390802251836

Borich, M. R., Cheung, K. L., Jones, P., Khramova, V., Gavrailoff, L., Boyd, L. A., & Virji-Babul, N. (2013). Concussion: Current Concepts in Diagnosis in Management. *Journal of Neurologic Physical Therapy*, *37*(3), 133–139. https://doi.org/10.1097/NPT.0b013e31829f7460

Broglio, S. P., Ferrara, M. S., Sopiarz, K., & Kelly, M. S. (2008). Reliable change of the sensory organization test. *Clinical Journal of Sport Medicine*, *18*(2), 148–154. https://doi.org/10.1097/JSM.0b013e318164f42a

Broglio, S. P., Macciocchi, S. N., & Ferrara, M. S. (2007). Sensitivity of the concussion assessment battery. *Neurosurgery*, *60*(6), 1050–1057. https://doi.org/10.1227/01.NEU.0000255479.90999.C0

Broglio, S. P., Sosnoff, J. J., Shin, S., He, X., Alcaraz, C., & Zimmerman, J. (2009). Head Impacts During High School Football: A Biomechanical Assessment, *44*(4), 342–349.

Center for Disease Control, Gilchrist, J., Thomas, K. E., Xu, L., McGuire, L. C., & Coronado, V. (2011). Nonfatal traumatic brain injuries related to sports and recreation activities among persons aged ≤19 years--United States, 2001-2009. *MMWR. Morbidity and Mortality Weekly Report*, *60*(39), 1337–1342. https://doi.org/mm6039a1 [pii]

Collie, A. (2006). Cognition in the days following concussion: comparison of symptomatic versus asymptomatic athletes. *Journal of Neurology, Neurosurgery & Psychiatry*, *77*(2), 241–245. https://doi.org/10.1136/jnnp.2005.073155

Collins, C. L., Fletcher, E. N., Fields, S. K., Kluchurosky, L., Rohrkemper, M. K., Comstock, R. D., & Cantu, R. C. (2014a). Neck Strength: A Protective Factor Reducing Risk for Concussion in High School Sports. *Journal of Primary Prevention*, *35*(5), 309–319. https://doi.org/10.1007/s10935-014-0355-2

Collins, C. L., Fletcher, E. N., Fields, S. K., Kluchurosky, L., Rohrkemper, M. K., Comstock, R. D., & Cantu, R. C. (2014b). Neck Strength: A Protective Factor Reducing Risk for Concussion in High School Sports. *Journal of Primary Prevention*, *35*(5), 309–319. https://doi.org/10.1007/s10935-014-0355-2

Collins, M., Lovell, M. R., Iverson, G. L., Ide, T., & Maroon, J. (2006). Examining concussion rates and return to play in high school football players wearing newer helmet technology: A three-year prospective cohort study. *Neurosurgery*, *58*(2), 275–284. https://doi.org/10.1227/01.NEU.0000200441.92742.46

Concussion, S., Tool, A., & Assessment, S. (2013). SCAT3, 259–263.

Covassin, T., Swanik, C. B., & Sachs, M. L. (2003). Sex differences and the incidence of concussions among collegiate athletes. *Journal of Athletic Training (National Athletic Trainers' Association)*, *38*(3), 238–244. Retrieved from http://spot.lib.auburn.edu/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=cin20&AN=2004046415&site=ehost-live

Covassin, T., Swanik, C. B., & Sachs, M. L. (2003). Sex Differences and the Incidence of Concussions Among Collegiate Athletes. *Journal of Athletic Training (National Athletic Trainers' Association)*, *38*(3), 238. Retrieved from http://search.ebscohost.com.lib-proxy.fullerton.edu/login.aspx?direct=true&db=s3h&AN=11720753&site=ehost-live&scope=site

Cramer, C. R. (1999). A Reconditioning Program to Lower the Recurrence Rate of Brachial

Plexus Neurapraxia in Collegiate Football Players. *Journal of Athletic Training*, *34*(4), 390–396.

Daneshvar, D. H., Nowinski, C. J., Mckee, A. C., & Cantu, R. C. (2011). The Epidemiology of Sport-Related Concussion. *Clinics in Sports Medicine*, *30*(1), 1–17. https://doi.org/10.1016/j.csm.2010.08.006

de Koning, C. H. P., van den Heuvel, S. P., Staal, J. B., Smits-Engelsman, B. C. M., & Hendriks, E. J. M. (2008). Clinimetric evaluation of methods to measure muscle functioning in patients with non-specific neck pain: a systematic review. *BMC Musculoskeletal Disorders*, *9*, 142. https://doi.org/10.1186/1471-2474-9-142

Dvorak, J., Mccrory, P., Kirkendall, D. T., & Klinik, S. (2007). Head injuries in the female football player: incidence, mechanisms, risk factors and management. *Br J Sports Med*, *41*, 44–46. https://doi.org/10.1136/bjsm.2007.037960

Eckner, J. T., Oh, Y. K., Joshi, M. S., Richardson, J. K., & Ashton-Miller, J. A. (2014). Effect of neck muscle strength and anticipatory cervical muscle activation on the kinematic response of the head to impulsive loads. *The American Journal of Sports Medicine*, *42*(3), 566–576. https://doi.org/10.1177/0363546513517869

Emery, C. A., Black, A. M., Kolstad, A., Martinez, G., Nettel-Aguirre, A., Engebretsen, L., … Schneider, K. (2017a). What strategies can be used to effectively reduce the risk of concussion in sport? *British Journal of Sports Medicine*, bjsports-2016-097452. https://doi.org/10.1136/bjsports-2016-097452

Franco, J. L., & Herzog, W. (1987). A comparative assessment of neck muscle strength and vertebral stability. *The Journal of Orthopaedic and Sports Physical Therapy*, *8*(7), 351–356. https://doi.org/10.2519/jospt.1987.8.7.351

Gardner, A., Kay-Lambkin, F., Stanwell, P., Donnelly, J., Williams, W. H., Hiles, A., … Jones, D. K. (2012). A Systematic Review of Diffusion Tensor Imaging Findings in Sports-Related Concussion. *Journal of Neurotrauma*, *29*(16), 2521–2538. https://doi.org/10.1089/neu.2012.2628

Geary, K., Green, B. S., & Delahunt, E. (2013). Intrarater reliability of neck strength measurement of rugby union players using a handheld dynamometer. *Journal of Manipulative and Physiological Therapeutics*, *36*(7), 444–449. https://doi.org/10.1016/j.jmpt.2013.05.026

Geary, K., Green, B. S., & Delahunt, E. (2014). Effects of Neck Strength Training on Isometric Neck Strength in Rugby Union Players. *Clin J Sport Med*, *6*(24), 502–508. https://doi.org/10.1097/JSM.0000000000000071

Gessel, L. M., Fields, S. K., Collins, C. L., Dick, R. W., & Comstock, R. D. (2007). Concussions among United States high school and collegiate athletes. *Journal of Athletic Training (National Athletic Trainers' Association)*, *42*(4), 495–503. Retrieved from http://spot.lib.auburn.edu/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=cin20&AN=2009759920&site=ehost-live

Giza, C. C. (2014). The New Metabolic Cascade of Concussion, *75*(0 4), S24–S33. https://doi.org/10.1227/NEU.0000000000000505.The

Giza, C. C., & Hovda, D. A. (2001). The Neurometabolic Cascade of Concussion. *Journal of Athletic Training*, *36*(3), 228–235. https://doi.org/10.1227/NEU.0000000000000505

Greenhill, D. A., Navo, P., Zhao, H., Torg, J., Comstock, R. D., & Boden, B. P. (2016). Inadequate Helmet Fit Increases Concussion Severity in American High School Football Players. *Sports Health*, *8*(3), 238–243. https://doi.org/10.1177/1941738116639027

Guskiewicz, K. M. (2011). Balance Assessment in the Management of Sport-Related Concussion. *Clinics in Sports Medicine*, *30*(1), 89–102. https://doi.org/10.1016/j.csm.2010.09.004

Guskiewicz, K. M., Weaver, N. L., Padua, D. A., Garrett, W. E., Hill, C., & Carolina, N. (2000). Epidemiology of Concussion in Collegiate and High School Football Players, *28*(5).

Guskiewicz, K., Mccrea, M., Marshall, S. W., Cantu, R. C., Randolph, C., Barr, W., … Kelly, J. P. (2003a). The NCAA Concussion Study. *Journal of the American Medical Association*, *290*(19), 2549–2555.

Guskiewicz, K., Mccrea, M., Marshall, S. W., Cantu, R. C., Randolph, C., Barr, W., … Kelly, J. P. (2003b). The NCAA Concussion Study. *Journal of the American Medical Association*, *290*(19), 2549–2555.

Halstead, M. E., & Walter, K. D. (2010). Sport-Related Concussion in Children and Adolescents. *Pediatrics*, *126*(3), 597–615. https://doi.org/10.1542/peds.2010-2005

Hamilton, D. F., Gatherer, D., Maclean, J. G. B., Hutchison, J. D., Nutton, R. W., & Simpson, A. H. R. W. (2012). Age-related differences in the neck strength of adolescent rugby players A CROSS-SECTIONAL COHORT STUDY OF SCOTTISH SCHOOLCHILDREN. *Bone Joint Res*, *1*(7), 152–157.

Harmon, K. G., Drezner, J. A., Gammons, M., Guskiewicz, K. M., Halstead, M., Herring, S. A., … Roberts, W. O. (2013). American Medical Society for Sports Medicine position statement: concussion in sport. *British Journal of Sports Medicine*, *47*(1), 15–26. https://doi.org/10.1136/bjsports-2012-091941

Harmon, K. G., Drezner, J. A., Gammons, M., Guskiewicz, K. M., Halstead, M., Herring, S. A., … Roberts, W. O. (2013). American Medical Society for Sports Medicine position statement: concussion in sport. *Br.J Sports Med*, *47*(1), 15–26. https://doi.org/10.1136/bjsports-2012-091941

Harris, K. D., Heer, D. M., Roy, T. C., Santos, D. M., Whitman, J. M., & Wainner, R. S. (2005). Reliability of a measurement of neck flexor muscle endurance. *Physical Therapy*, *85*(12), 1349–1355.

Harvey, K. P., Hall, E. E., Patel, K., Barnes, K. P., & Ketcham, C. J. (2017). Potential factors influencing recovery from concussion in collegiate student-athletes. *Journal of Concussion*, *1*, 205970021770708. https://doi.org/10.1177/2059700217707084

Henry, L. C., Elbin, R. J., Collins, M. W., Marchetti, G., & Kontos, A. P. (2016). Examining recovery trajectories after sport-related concussion with a multimodal clinical assessment approach. *Neurosurgery*, *78*(2), 232–240. https://doi.org/10.1227/NEU.0000000000001041

Holbourn, A. H. S. (1943). Mechanics of head injuries. *Lancet*, *242*(6267), 438–441. https://doi.org/10.1016/S0140-6736(00)87453-X

Hrysomallis, C. (2016). Neck Muscular Strength, Training, Performance and Sport Injury Risk: A Review. *Sports Medicine*. https://doi.org/10.1007/s40279-016-0490-4

Iverson, G. L., Gardner, A. J., Terry, D. P., Ponsford, J. L., Sills, A. K., Broshek, D. K., & Solomon, G. S. (2017). Predictors of clinical recovery from concussion: A systematic review. *British Journal of Sports Medicine*, *51*(12), 941–948. https://doi.org/10.1136/bjsports-2017-097729

Iverson, G. L., Lovell, M. R., & Collins, M. W. (2003). Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT) Normative Data.

Iverson, G. L., Silverberg, N. D., Mannix, R., Maxwell, B. a., Atkins, J. E., Zafonte, R., & Berkner, P. D. (2015). Factors Associated With Concussion-like Symptom Reporting in

High School Athletes. *JAMA Pediatrics*, *169*(10), 1–9. https://doi.org/10.1001/jamapediatrics.2015.2374

Johnston, K. M., McCrory, P., Mohtadi, N. G., & Meeuwisse, W. (2001). Evidence-based review of sport-related concussion: clinical science. *Clinical Journal of Sport Medicine*, *11*, 150–159. https://doi.org/10.1097/00042752-200107000-00005

Jull, G. A., O'Leary, S. P., & Falla, D. L. (2008). Clinical Assessment of the Deep Cervical Flexor Muscles: The Craniocervical Flexion Test. *Journal of Manipulative and Physiological Therapeutics*, *31*(7), 525–533. https://doi.org/10.1016/j.jmpt.2008.08.003

Kemp, S., Hudson, Z., Brooks, J., Fuller, C. (2008). The Epidemiology of Head Injuries in English Professional Rugby Union. *Clinical Journal of Sport Medicine*, *18*(3). https://doi.org/10.1177/0363546507300691

Khong, E., Odenwald, N., Hashim, E., & Cusimano, M. D. (2016). Diffusion tensor imaging findings in post-concussion syndrome patients after mild traumatic brain injury: A systematic review. *Frontiers in Neurology*, *7*(SEP), 1–8. https://doi.org/10.3389/fneur.2016.00156

King, A., Yang, K., & Zhang, L. (2003). Is head injury caused by linear or angular acceleration. *IRCOBI Conference*, (September), 1–12. Retrieved from http://snell-helmets.org/docs/articles/hic/King_IRCOBI_2003.pdf

Koeppen & Stanton. (2017). *Berne and Levy Physiology*. St. Louis: Elsevier Health Sciences. Retrieved from https://www-clinicalkey-com.libaccess.lib.mcmaster.ca/#!/browse/book/3-s2.0-C20110061689

Koerte, I. K., Ertl-Wagner, B., Reiser, M., Zafonte, R., & Shenton, M. E. (2012). White matter integrity in the brains of professional soccer players without a symptomatic concussion. *Journal of the American Medical Association*, *308*(18).

Kroshus, E., Daneshvar, D. H., Baugh, C. M., Nowinski, C. J., & Cantu, R. C. (2014). NCAA concussion education in ice hockey : an ineffective mandate. *British Journal of Sports Medicine*, *48*((2)), 135–140. https://doi.org/10.1136/bjsports-2013-092498

Kutcher, J. S., & Eckner, J. T. (2010). At-risk populations in sports-related concussion. *Current Sports Medicine Reports*, *9*(1), 16–20. https://doi.org/http://dx.doi.org/10.1249/JSR.0b013e3181caa89d

Lavallee, A. V., Ching, R. P., & Nuckley, D. J. (2013). Developmental biomechanics of neck musculature. *Journal of Biomechanics*, *46*(3), 527–534. https://doi.org/10.1016/j.jbiomech.2012.09.029

Leddy, J. J., Baker, J. G., & Willer, B. (2016). Active Rehabilitation of Concussion and Post-concussion Syndrome. *Physical Medicine and Rehabilitation Clinics of North America*, *27*(2), 437–454. https://doi.org/10.1016/j.pmr.2015.12.003

Leddy, M. H., Lambert, M. J., & Ogles, B. M. (1994). Psychological consequences of athletic injury among high-level competitors. *Research Quarterly for Exercise and Sport*, *65*(4), 347–354. https://doi.org/10.1080/02701367.1994.10607639

Lindstrøm, R., Schomacher, J., Farina, D., Rechter, L., & Falla, D. (2011). Association between neck muscle coactivation , pain , and strength in women with neck pain. *Manual Therapy*, *16*(1), 80–86. https://doi.org/10.1016/j.math.2010.07.006

Littleton, A., & Guskiewicz, K. (2013). Current concepts in sport concussion management: A multifaceted approach. *Journal of Sport and Health Science*, *2*(4), 227–235. https://doi.org/10.1016/j.jshs.2013.04.003

Llewellyn, T., Burdette, G. T., Joyner, a B., & Buckley, T. a. (2014). Concussion reporting rates at the conclusion of an intercollegiate athletic career. *Clinical Journal of Sport Medicine : Official Journal of the Canadian Academy of Sport Medicine*, *24*(1), 76–79. https://doi.org/10.1097/01.jsm.0000432853.77520.3d

Longhi, L., Saatman, K. E., Fujimoto, S., Raghupathi, R., Meaney, D. F., Davis, J., … McIntosh, T. K. (2005). Temporal window of vulnerability to repetitive experimental concussive brain injury. *Neurosurgery*, *56*(2), 364–373. https://doi.org/10.1227/01.NEU.0000149008.73513.44

Lourenço, A. S., Lameiras, C., & Silva, A. G. (2016). Neck Flexor and Extensor Muscle Endurance in Subclinical Neck Pain: Intrarater Reliability, Standard Error of Measurement, Minimal Detectable Change, and Comparison With Asymptomatic Participants in a University Student Population. *Journal of Manipulative and Physiological Therapeutics*, *39*(6), 427–433. https://doi.org/10.1016/j.jmpt.2016.05.005

Majerske, C. W., Mihalik, J. P., Ren, D., Collins, M. W., Reddy, C. C., Lovell, M. R., & Wagner, A. K. (2008). Concussion in sports: Postconcussive activity levels, symptoms, and neurocognitive performance. *Journal of Athletic Training*, *43*(3), 265–274. https://doi.org/10.4085/1062-6050-43.3.265

Manley, G. T., Gardner, A. J., Schneider, K. J., Guskiewicz, K. M., Bailes, J., Cantu, R. C., … Iverson, G. L. (2017). A systematic review of potential long-term effects of sport-related concussion, 1–10. https://doi.org/10.1136/bjsports-2017-097791

Marshall, S. W., Guskiewicz, K. M., Shankar, V., McCrea, M., & Cantu, R. C. (2015). Epidemiology of sports-related concussion in seven US high school and collegiate sports. *Injury Epidemiology*, *2*(1). https://doi.org/10.1186/s40621-015-0045-4

Marshall, S. W., Waller, A. E., Dick, R. W., Pugh, C. B., Loomis, D. P., & Chalmers, D. J. (2002). An ecologic study of protective equipment and injury in two contact sports. *International Journal of Epidemiology*, *31*(3), 587–592. https://doi.org/10.1093/ije/31.3.587

McCrea, H. J., Perrine, K., Niogi, S., & Hartl, R. (2012). Cuncussion in sports. *Sports Health: A Multidisciplinary Approach*, *5*(2), 160–164. https://doi.org/10.1177/1941738112462203

McCrea, M., Guskiewicz, K. M., Marshall, S. W., Barr, W., Randolph, C., Cantu, R. C., … Kelly, J. P. (2003a). Acute Effects and Recovery Time Following. *The Journal of the American Medical Association*, *290*(19), 2556–2563. https://doi.org/10.1001/jama.290.19.2556

McCrea, M., Guskiewicz, K. M., Marshall, S. W., Barr, W., Randolph, C., Cantu, R. C., … Kelly, J. P. (2003b). Acute Effects and Recovery Time Following Concussion in Collegiate Football Players. *The Journal of the American Medical Association*, *290*(19), 2556–2563. https://doi.org/10.1001/jama.290.19.2556

Mccrea, M., Guskiewicz, K., Randolph, C., Barr, W. B., Hammeke, T. A., Marshall, S. W., … Kelly, J. P. (2016). Incidence, Clinical Course, and Predictors of Prolonged Recovery Time Following Sport-Related Concussion in High School and College Athletes. *Journal of the International Neuropsychological Society Copyright E INS*, *19*, 22–33. https://doi.org/10.1017/S1355617712000872

McCrea, M., Hammeke, T., Olsen, G., Leo, P., & Guskiewicz, K. (2004). Unreported concussion in high school football players: implications for prevention. *Clin J Sport Med*, *14*(1), 13–17. https://doi.org/10.1097/00042752-200401000-00003

McCrea, M., Kelly, J. P., Randolph, C., Kluge, J., Bartolic, E., Finn, G., & Baxter, B. (1998). Standardized Assessment of Concussion (SAC): On-Site Mental Status Evaluation of the Athlete. *Journal of Head Trauma Rehabilitation*. https://doi.org/10.1097/00001199-

199804000-00005

McCrory, P., Meeuwisse, W., Dvorak, J., Aubry, M., Bailes, J., Broglio, S., … Vos, P. E. (2017). Consensus statement on concussion in sport — the 5 th international conference on concussion in sport held in Berlin , October 2016. *British Journal of Sports Medicine*, 1–10. https://doi.org/10.1136/bjsports-2017-097699

Mccrory, P., Meeuwisse, W., Dvořák, J., Aubry, M., Bailes, J., Broglio, S., … Vos, P. E. (2017). Consensus statement on concussion in sport—the 5 th international conference on concussion in sport held in Berlin, October 2016. *Br J Sports Med*, *51*, 838–847. https://doi.org/10.1136/bjsports-2017-097699

McCrory, P., Meeuwisse, W. H., Aubry, M., Cantu, R. C., Dvorák, J., Echemendia, R. J., … Turner, M. (2013). Consensus Statement on Concussion in Sport-The 4th International Conference on Concussion in Sport Held in Zurich, November 2012. *PM and R*, *5*(4), 255–279. https://doi.org/10.1016/j.pmrj.2013.02.012

McLeod, T. C. V., & Leach, C. (2012). Psychometric properties of self-report concussion scales and checklists. *Journal of Athletic Training*, *47*(2), 221–223. https://doi.org/10.4085/1062-6050-47.2.221

Meehan, William P. Mannix, Rebekah C. Stracciolini, Andrea Elbin, R.J. Collins, M. W. (2013). Symptom severity predicts prolonged recovery after sport-related concussion: Age and amnesia do not. *Journal of Pediatrics*, *163*(3), 721–725. https://doi.org/10.1016/j.jpeds.2013.03.012.Symptom

Meeuwisse, W. H., Hagel, B. E., Mohtadi, N. G. H., Butterwick, D. J., & Fick, G. H. (2000). The Distribution of Injuries in Men's Canada West University Football: A 5-year Analysis. *The American Journal of Sports Medicine*, *28*(4), 516–523. https://doi.org/10.1177/03635465000280041201

Misra, J. C., & Chakravarty, S. (1984). A study on rotational brain injury. *Journal of Biomechanics*, *17*(7), 459–466. https://doi.org/10.1016/0021-9290(84)90014-9

Omalu, B. I., DeKosky, S. T., Minster, R. L., Kamboh, M. I., Hamilton, R. L., & Wecht, C. H. (2005). Chronic traumatic encephalopathy in a National Football League player. *Neurosurgery*, *57*(1), 128–133. https://doi.org/10.1227/01.NEU.0000163407.92769.ED

Pagano, Marcello; Gauvreau, K. (2000). *Principles of Biostatistics* (2nd Editio). Belmont,CA: Brooks/Cole.

Parazza, S., Vanti, C., O'Reilly, C., Villafañe, J. H., Tricás Moreno, J. M., & Estébanez De Miguel, E. (2014). The relationship between cervical flexor endurance, cervical extensor endurance, VAS, and disability in subjects with neck pain. *Chiropractic & Manual Therapies*, *22*(1), 10. https://doi.org/10.1186/2045-709X-22-10

Peduzzi, P., Concato, J., Kemper, E., Holford, T.R., Feinstein, A. R. (1996). A Simulation Study of the Number of Events per Variable in Logistic Regression Analysis. *Journal of Clinical Epidemiology*, *49*(12), 1373–1379.

Powell, J. W., & Barber-foss, K. D. (1999). Traumatic Brain Injury in High School Athletes. *JAMA*, *282*(10), 959–963.

Prins, M. L., Alexander, D., Giza, C. C., & Hovda, D. A. (2013). Repeated Mild Traumatic Brain Injury: Mechanisms of Cerebral Vulnerability. *Journal of Neurotrauma*, *30*(1), 30–38. https://doi.org/10.1089/neu.2012.2399

Putukian, M., Echemendia, R., Dettwiler-Danspeckgruber, A., Duliba, T., Bruce, J., Furtado, J. L., & Murugavel, M. (2015). Prospective clinical assessment using sideline concussion assessment tool-2 testing in the evaluation of sport-related concussion in college athletes.

Clinical Journal of Sport Medicine, *25*(1), 36–42. https://doi.org/10.1097/JSM.0000000000000102

Rishiraj, N., Lorenz, T., Niven, B., & Michel, M. (2009). University men ' s ice hockey : rates and risk of injuries over 6-years. *Sports Medicine*.

Rose, S. C., Fischer, A. N., & Heyer, G. L. (2015). How long is too long ? The lack of consensus regarding the post-concussion syndrome diagnosis, *9052*, 798–803. https://doi.org/10.3109/02699052.2015.1004756

Safinia, C., Bershad, E. M., Clark, H. B., Santacruz, K., Alakbarova, N., Suarez, J. I., & Divani, A. A. (2016). Chronic Traumatic Encephalopathy in Athletes Involved with High- impact Sports. *Journal of Vascular and Interventional Neurology*, *9*(2), 34–48.

Sandel, N. N. K., Lovell, M. R. M., Kegel, N. N. E., Collins, M. W., & Kontos, A. P. (2013). The Relationship of Symptoms and Neurocognitive Performance to Perceived Recovery From Sports-Related Concussion Among Adolescent Athletes. *Applied Neuropsychology: …*, *2*(1), 64–69. https://doi.org/10.1080/21622965.2012.670580

Schatz, P., Pardini, J. E., Lovell, M. R., Collins, M. W., & Podell, K. (2006). Sensitivity and specificity of the ImPACT Test Battery for concussion in athletes. *Archives of Clinical Neuropsychology*, *21*(1), 91–99. https://doi.org/10.1016/j.acn.2005.08.001

Schatz, P., & Sandel, N. (2013). Sensitivity and specificity of the online version of ImPACT in high school and collegiate athletes. *Am J Sports Med*, *41*(2), 321–326. https://doi.org/10.1177/0363546512466038

Schneider, K., Emery, C., Kang, J., Schneider, G., & Meeuwisse, W. (2011). Are pre-season reports of neck pain, dizziness and/or headaches risk factors for concussion in male youth ice hockey players? *British Journal of Sports Medicine*, *45*(4), 319–320. https://doi.org/10.1136/bjsm.2011.084038.28

Schulz, M. R., Marshall, S. W., Mueller, F. O., Yang, J., Weaver, N. L., Kalsbeek, W. D., & Bowling, J. M. (2004). Incidence and risk factors for concussion in high school athletes, North Carolina, 1996-1999. *American Journal of Epidemiology*, *160*(10), 937–944. https://doi.org/10.1093/aje/kwh304

Scopaz, K., & Hatzenbuehler, J. (2013). Risk modifiers for concussion and prolonged recovery. *Sports Health*, *5*(6), 537–541. https://doi.org/10.1177/1941738112473059

Sebastian, D., Chovvath, R., & Malladi, R. (2015). Cervical extensor endurance test: Areliability study. *Journal of Bodywork and Movement Therapies*, *19*(2), 213–216. https://doi.org/10.1016/j.jbmt.2014.04.014

Seifert, T., & Shipman, V. (2015). The Pathophysiology of Sports Concussion. *Current Pain and Headache Reports*, *19*(8), 1–9. https://doi.org/10.1007/s11916-015-0513-0

Shehata, N., Wiley, J. P., Richea, S., Benson, B. W., Duits, L., & Meeuwisse, W. H. (2009). Sport concussion assessment tool: baseline values for varsity collision sport athletes. *Br J Sports Med*, *43*(10), 730–734. https://doi.org/10.1136/bjsm.2009.059832

Stazyk, K. (2015). *Depression in Children Recovering from Concussion: Correlates and Predictors*.

Stern, R. A., Riley, D. O., Daneshvar, D. H., Nowinski, C. J., Cantu, R. C., & McKee, A. C. (2011). Long-term Consequences of Repetitive Brain Trauma: Chronic Traumatic Encephalopathy. *PM and R*, *3*(10 SUPPL. 2), 460–467. https://doi.org/10.1016/j.pmrj.2011.08.008

Sullivan, J. C., Tavassoli, T., Armstrong, K., Baron-Cohen, S., & Humphrey, A. (2014). Reliability of self, parental, and researcher measurements of head circumference. *Molecular*

Autism, *5*(1), 2–5. https://doi.org/10.1186/2040-2392-5-2

Tavazzi, B., Vagnozzi, R., Signoretti, S., Amorini, A. M., Finocchiaro, A., Cimatti, M., … Lazzarino, G. (2007). Temporal window of metabolic brain vulnerability to concussions: Oxidative and nitrosative stresses - Part II. *Neurosurgery*, *61*(2), 390–396. https://doi.org/10.1227/01.NEU.0000255525.34956.3F

The Physical Activity Council. (2016). 2016 participation report: The physical activity council's annual study tracking sports, fitness, and recreation participaton in the US, 26.

Tierney, R. T., Higgins, M., Caswell, S. V., Brady, J., McHardy, K., Driban, J. B., & Darvish, K. (2008a). Sex differences in head acceleration during heading while wearing soccer headgear. *Journal of Athletic Training*, *43*(6), 578–584. https://doi.org/http://dx.doi.org/10.4085/1062-6050-43.6.578

Tierney, R. T., Higgins, M., Caswell, S. V, Brady, J., McHardy, K., Driban, J. B., & Darvish, K. (2008b). Sex Differences in Head Acceleration During Heading While Wearing Soccer Headgear. *Journal of Athletic Training*, *43*(6), 578–584. https://doi.org/10.4085/1062-6050-43.6.578

Tierney, R. T., Sitler, M. R., Swanik, C. B., Swanik, K. A., Higgins, M., & Torg, J. (2005). Gender differences in head-neck segmnet dynamic stabilization during head accelaration. *Medicine and Science in Sports and Exercise*, *37*(2), 272–279. https://doi.org/10.1249/01.MSS.0000152734.47516.AA

Tsushima, W. T., Siu, A. M., Ahn, H. J., Chang, B. L., & Murata, N. M. (2018). Incidence and Risk of Concussions in Youth Athletes: Comparisons of Age, Sex, Concussion History, Sport, and Football Position. *Archives of Clinical Neuropsychology*, (May). https://doi.org/10.1093/arclin/acy019

USports. (2017). USPORTS Student-Athlete User Guide.

Vagnozzi, R. et al. (2007). Temporal window of metabolic brain vulnerability to concussions: Mitochondrial-related impairment - Part I. Commentary. *Neurosurgery*, *61*(2), 388–389. https://doi.org/10.1227/01.NEU.0000280002.41696.D8

Valovich McLeod, T. C., Barr, W. B., McCrea, M., & Guskiewicz, K. M. (2006). Psychometric and measurement properties of concussion assessment tools in youth sports. *Journal of Athletic Training*, *41*(4), 399–408.

Vasavada, A. N., Danaraj, J., & Siegmund, G. P. (2008). Head and neck anthropometry, vertebral geometry and neck strength in height-matched men and women. *Journal of Biomechanics*, *41*(1), 114–121. https://doi.org/10.1016/j.jbiomech.2007.07.007

Virji-Babul, N., Borich, M. R., Makan, N., Moore, T., Frew, K., Emery, C. A., & Boyd, L. A. (2013). Diffusion Tensor Imaging of Sports-related Concussion in Adolescents. *Pediatric Neurology*, *48*, 24–29.

Williams, R. M., Puetz, T. W., Giza, C. C., & Broglio, S. P. (2015). Concussion Recovery Time Among High School and Collegiate Athletes: A Systematic Review and Meta-Analysis. *Sports Medicine*, *45*(6), 893–903. https://doi.org/10.1007/s40279-015-0325-8

Williamson, R. W., Gerhardstein, D., Cardenas, J., Michael, D. B., Theodore, N., & Rosseauk, N. (2014). Concussion 101: The current state of concussion education programs. *Neurosurgery*, *75*(4), S131–S135. https://doi.org/10.1227/NEU.0000000000000482

World Health Organization (WHO). (2011). ICD-10 Transition. *Family Practice Management*, *18*, 39. https://doi.org/10.1159/000371811

Yengo-kahn, A., Allen, K., & Kerr, Z. Y. (2016). Predictors of postconcussion syndrome in collegiate student-athletes, *40*(April), 1–10. https://doi.org/10.3171/2016.1.FOCUS15593.

Yengo-kahn, A. M., Hale, A. T., Zalneraitis, B. H., Zuckerman, S. L., Sills, A. K., & Solomon, G. S. (2016). Review. *Neurosurgical Focus*, *40*(April). https://doi.org/10.3171/2016.1.FOCUS15611.

Zemek, R. L., Farion, K. J., Sampson, M., & McGahern, C. (2013). Prognosticators of Persistent Symptoms Following Pediatric Concussion. *JAMA Pediatrics*, *167*(3), 259. https://doi.org/10.1001/2013.jamapediatrics.216

Zuckerman, S. L., Kerr, Z. Y., Yengo-Kahn, A., Wasserman, E., Covassin, T., & Solomon, G. S. (2015). Epidemiology of Sports-Related Concussion in NCAA Athletes From 2009-2010 to 2013-2014: Incidence, Recurrence, and Mechanisms. *The American Journal of Sports Medicine*, *43*(11), 2654–2662. https://doi.org/10.1177/0363546515599634

Zuckerman, S. L., Yengo-kahn, A. M., Buckley, T. A., Solomon, G. S., Sills, A. K., & Kerr, Z. Y. (2016). Predictors of postconcussion syndrome in collegiate student-athletes, *40*(April), 1–10. https://doi.org/10.3171/2016.1.FOCUS15593.

Title of Paper: Does neck strength predict concussion risk?

Authors: Erin E. Cole, BSc., Anita Gross, MSc., BScPT, Ira Price, MD., FRCPC, Carol DeMatteo MSc., Dip P & OT, OT Reg (Ont),

To be submitted to: *British Journal of Sports Medicine*

ABSTRACT

Objective: Does isometric neck strength predict concussion risk in university varsity athletes?

Methods: Varsity athletes from high risk sports were recruited to be followed over one complete athletic season. Past-medical history and current health status were assessed prior to starting competition. Anthropometric measures were assessed along with neck flexor and extensor endurance tests to evaluate an athlete's neck strength. Athletes with suspected concussion were evaluated on the sideline and sent for diagnosis by a team physician. Risk of concussion was determined using logistic regression analysis with age, history of past concussion, number of previous concussions, neck pain, depression, height, weight, neck circumference, and strength scores as predictor variables.

Main Results: Two hundred and forty-six athletes, 157 men and 89 women, from five different sports were assessed. Thirty-five athletes (15%) sustained concussion over the course of one athletic season. Four athletes sustained a second concussion. Sixteen percent of male athletes and 11% of female athletes sustained concussions although there was not a statistically significant difference in concussion rate between sexes (p= 0.312). Rugby reported the highest rates of concussion for both men (n=15) and women, (n=5) accounting for 57% of all concussions. Neck pain (p= <0.001), history of past concussion (p= 0.001), were the strongest predictors of concussion risk in varsity athletes.

Conclusion: Neck pain pre-season and past concussion history are significant predictors of concussion. The relationship between neck pain and neck strength in concussions must be explored further. Past medical history and neck pain assessment should be included in pre-season evaluations.

Introduction

Over the past twenty years the incidence of sports-related concussion (SRC) has doubled in college athletes(Zuckerman et al., 2015). In Canada, more than 12,000 students participate in university varsity athletics each year (USports, 2017). Concussions comprised approximately 12% of all sports-related injuries experienced by college athletes over the course of a season (K. Guskiewicz et al., 2003b). Athletes who participate in impact or collision sports, particularly football, soccer, hockey, basketball, rugby, and cheerleading, report the highest incidence of SRC. In 90% of varsity athletes concussion symptoms will resolve spontaneously after seven to ten days (McCrory et al., 2017; Meehan, William P. Mannix, Rebekah C. Stracciolini, Andrea Elbin, R.J. Collins, 2013). Approximately 10% of athletes experience a prolonged recovery course with symptoms persisting greater than two weeks (K. Guskiewicz et al., 2003b). Of those who experience prolonged recovery, ten percent will suffer from symptoms, such as headache, dizziness, trouble sleeping, difficulty concentrating, and impaired cognition, beyond 45 days from the initial injury (Mccrea et al., 2016; Zuckerman et al., 2016). These symptoms impair an athlete's ability to complete simple activities of daily living (Kimberly G Harmon et al., 2013; Sandel et al., 2013), as well as limit their athletic and academic performance due to a decreased tolerance for physical and mental exertion (Littleton & Guskiewicz, 2013; Majerske et al., 2008). Emerging evidence has linked concussions to chronic mental health issues such as Alzheimer's disease, dementia, depression, and chronic traumatic encephalopathy(Manley et al., 2017). The rising incidence and long-term consequences of SRC demonstrate the need for targeted, effective primary prevention strategies. Thus, understanding and identifying the athletes who are most at risk of injury will allow for the development of these strategies.

Limited evidence exists in support of prevention strategies for sports-related concussions.

A 2013 systematic review on the most effective risk-reduction strategies for SRC indicated the majority of concussion prevention literature evaluated 1) the use of protective equipment, such as helmets and mouth guards, 2) rule changes aimed at protecting the athlete, and 3) educational programs for athletes, coaches, and parents (Brian W Benson et al., 2013). They found that concussion prevention required a multi-faceted approach, as no new concrete evidence had emerged to support the aforementioned strategies (Brian W Benson et al., 2013). A more recent systematic review on concussion prevention found the strongest and most consistent strategy to be the elimination of body checking in youth ice hockey athletes (Emery et al., 2017b). This is not a feasible strategy for all levels of play as varsity and professional hockey allow for body checking. Nor is this applicable to other at risk for concussion sports. The authors of this study indicate the need for further exploration of prevention strategies of both intrinsic and extrinsic risk factors using more rigorous prospective study designs (Emery et al., 2017b). Therefore, it is paramount that we explore an alternative primary prevention strategy for SRC.

A concussion is the result of a biomechanical force applied to the head or body, resulting in movement of the brain within the skull (McCrory et al., 2017). Therefore, in order to prevent concussions, we must address how to counteract the injurious momentum transferred to the brain upon impact. Neck strengthening has been proposed, by some, as a worthwhile target for prevention of concussions (Kimberly G Harmon et al., 2013; Hrysomallis, 2016; McCrory et al., 2013). The current literature indicates younger athletes and females are more susceptible to concussions in comparison to their older, male counterparts (Tierney et al., 2005). There is a large body of evidence that demonstrates weaker necks amongst women and children (Eckner et al., 2014; Hamilton et al., 2012; Lavallee, Ching, & Nuckley, 2013). Athletes with stronger neck muscles are able to generate greater absolute force and a greater amount of torque more quickly than their weaker counterparts (Eckner et al., 2014), possibly protecting them from potentially injurious impacts. These studies support the concept of neck strength as a predictive variable for concussion risk and suggest that certain anthropometric variables, including neck girth and relative neck strength, may have a role in determining athletes at greatest risk for SRC.

Collins et al. evaluated to what extent neck strength may be a protective factor for concussion in high school athletes. They found that for every one pound increase in neck strength, concussion risk decreased by 5% (C. L. Collins et al., 2014b). The extent to which this holds true in a trained adult population, such as varsity athletes, has not yet been explored. However, previous studies have established that neck-strengthening protocols in competitive male Rugby Union athletes have been effective at increasing overall neck strength (Geary et al., 2014). Furthermore, a study by Cramer on college football athletes demonstrated a cervical spine and shoulder girdle strengthening protocols can reduce the recurrence of brachial plexus injuries in these athletes (Cramer, 1999) suggesting that certain anthropometric variables may be manipulated in such a way to protect at-risk athletes from concussions.

Handheld dynamometry is the most commonly used tool to assess neck strength (Vasavada, Danaraj, & Siegmund, 2008) however individual units are quite costly and have little significance from a clinical perspective. Evaluation of neck strength in the study by Collins et al. used a tension-scale dynamometer as their primary measurement tool (C. L. Collins et al., 2014b). They attempted to validate the use of the tension scale by comparing measurements with a handheld dynamometer. While the correlation between the tension-scale and the handheld dynamometer was acceptable (C. L. Collins et al., 2014b), there is no doubt question of human error when using the tension scale. The scale requires athletes to pull against the device being held by the assessor (C. L. Collins et al., 2014b) questioning whether the assessor's strength or resistance against the athlete contributes to the results . The tension-scale provides a more economical alternative to a costly handheld dynamometer, nevertheless neither of these tools are readily found in clinics. To evaluate neck strength as a predictor of concussion risk in a clinical setting it is imperative to use a quick, easy, safe, and cost-effective measurement tool. For the purpose of this study we evaluated isometric neck strength using a neck flexor and extensor endurance test. This test has been used in a comparison of university students who reported sub-clinical neck pain and those who did not and was found to have good reliability (ICC= 0.71-0.85) (Lourenço, Lameiras, & Silva, 2016). Furthermore, it requires minimal equipment, and is easy to perform. This test, however, has not yet been used in an athlete population.

The main objective of this study was to determine if neck muscle endurance strength, neck circumference, and neck length are associated with prediction of concussion risk for university athletes. We hypothesized that neck muscle strength, along with the aforementioned anthropometric variables, will have be predictive in determining concussion risk in a group of varsity athletes.

Methods

Participants

Varsity athletes from football, rugby, soccer, hockey, basketball, and cheerleading at McMaster University were followed over the course of one athletic season (August-April). Interested athletes signed informed consent and were taken through the study assessments prior to the first regulation competition game. Eligible participants were athletes who had been declared fit-to-play by their respective team physicians as per university protocol. The Hamilton Integrated Research Ethics Board at McMaster University approved all study procedures.

Procedures

*Past Medical History Assessmen*t – Athletes were asked several questions to evaluate the presence of possible suspected covariates, including number of past concussions, the presence of neck pain, and history of anxiety or depression (Iverson et al., 2017). Data intake forms are found in Appendix C

Neck Strength Measures – For this study an isometric endurance test of the deep neck flexors (DNF) and neck extensors was used. The procedure for the DNF endurance test has been standardized and previously described by Harris et al. (Harris et al., 2005). Prior to the start of the assessment, a cervical range of motion inclinometer (C-ROM) was placed on the athlete's head to evaluate the athlete's head position throughout the test. The use of this tool has been validated to measuring range of motion at the cervical spine(de Koning, van den Heuvel, Staal, Smits-Engelsman, & Hendriks, 2008). Participants were assessed in a supine position. They were instructed to maximally retract their chin and lift their head 2.5 cm off the table. Athletes were instructed to keep their chin tucked and lift their head up as long as possible (Figure 1). The assessor's hand was placed under the athlete's head for the entire duration of the test. The test was complete when an athlete's head touched the assessor's hand for more than one second, or if there was a five-degree change in head position on the CROM (Harris et al., 2005). The time each athlete was able to maintain the lifted head position was recorded in seconds.

Neck extensor endurance was evaluated using the methods previously described by Sebastian et al. (Parazza et al., 2014). Athletes were prone on the plinth, their shoulders in line with the end. Athletes were strapped to the plinth in order to sure minimal activation of the back-extensor muscles (Figure 2). Using the same inclinometer athletes again maximally retracted their chin and lifted the back of the head toward the ceiling. The assessor placed their hand on the athletes back to be able to feel for any activation of the back musculature beneath their hands. Once in position the timer started. A five-degree change in head position signaled the end of the test.


Figure 1 - Demonstration of Neck Flexor Strength Test

Anthropometric Measures – The procedure for all anthropometric measurements are described in Table 1.

<< INSERT TABLE 1.0 HERE >>

Outcome Measures

Primary Outcome Measure

Figure 2 - Demonstration of Neck Extensor Strength Test

The primary outcome measure was the occurrence of SRC as diagnosed by the team physician for that season (August 2016 to April 2017). This is in line with McMaster University Athletics concussion policy. All concussions, whether they occurred in practice or competition, were included in the analysis. Each McMaster varsity team was assigned to a certified Sports Medicine physician, all of whom have extensive experience assessing and managing athletes with concussions. Consequently, all team physicians ruled in a concussion based on the following: 1) Presence of one or more concussion symptoms, 2) mechanism of injury, 3) cognitive impairment, and 4) athlete disposition or abnormal behavior for their character (McCrory et al., 2013). Physician confirmed cases of concussion were documented by the team therapist and reported to the investigator, along with their initial injury assessments which include SCAT3 scores as per the McMaster University concussion protocol.

Statistical Analysis.

Participants were classified into concussed and non-concussed athlete groups. Pearson's chi-square and student t-tests were performed on demographic and strength-related variables to test for differences between the two outcome groups. Where the normality assumption was not met the Wilcoxon Rank Sum test was used to evaluate differences between groups. The significance level was set, *a priori*, to $p \leq 0.05$. Correlations between the presence of concussion and strength and non-strength related variables were examined using Spearman's Rho as much of the data was not normally distributed(Pagano, Marcello; Gauvreau, 2000). Logistic regression analysis was used to model the predictor variables with a binary outcome of concussion (yes=1) or no concussion (no=0). The predictor variables used in the model were selected based on our main research hypotheses, the results from the summary statistics, along with the univariate binary logistic regression analysis. To maintain statistical power, Peduzzi and colleagues suggest 10 or more events per variable in the logistic regression model (Peduzzi, P., Concato, J., Kemper, E., Holford, T.R., Feinstein, 1996). The primary outcome was the presence of concussion and two predictor variables, number of past concussions and neck pain, were used in the final statistical model. The independent variables chosen to be included in the model were subject to linear regression analysis to evaluate for collinearity. Table 4.0 provides an explanation of the regression modelling process for the chosen predictor variables. The selected variables fulfilled the collinearity assumption with variance inflation factors ranging from 1.13 to 2.48 (Pagano, Marcello; Gauvreau, 2000). All analyses were performed using STATA/IC version 14 for mac statistical analysis software.

Results

A total of 246 athletes from football (n = 64), soccer (n = 46), rugby (n = 80), basketball (n = 27), women's hockey (n = 13) and cheerleading (n = 16) were assessed for this study; 89 women and 157 men completed the pre-season assessment. McMaster University does not have a varsity men's hockey team and was therefore these athletes were unavailable for assessment. For continuity, women's hockey (n=13) was removed from any comparison between sports but was included in sex based comparisons. The mean age of the athletes assessed was 19.74 years with standard deviation of 1.70. Thirty-five athletes (14%), 25 men (16% of men) and 10 women (11% of women), sustained concussions over the season. Four male athletes sustained a second concussion within the season. The total number of concussions over the season was 39. Summary statistics for athlete demographics and anthropometric measures by concussion group and sex are presented in Table 2.

<INSERT TABLE 2 HERE>

Non- Strength Related Variables

In a comparison of concussed and non-concussed athletes, there were no significant differences in sex (p = 0.312), age (p= 0.067), or the number of years involved in their respective sport (p = 0.260). However, concussed athletes reported significantly greater depression rates (p=0.011), history of past concussions (p= 0.001), number of past concussions (p= <0.001), and the presence of neck pain (p= < 0.001). There were also significant differences in the rate of concussion between different sports (p= 0.015). Rugby athletes were found to have the highest rate of concussion. Rugby athletes made up 60% (n=15) of concussed males and 50% (n=5) of concussed females. Twenty-eight percent (n=15) of male rugby athletes and 19% (n=5) of female rugby athletes sustained a concussion over the season. Three of the four athletes who experienced repeat concussions were rugby players. Football reported the second highest, overall number of concussions with 13% (n=8) of athletes experiencing a SRC.

Sex-based comparisons of concussed and non-concussed athletes demonstrated significant differences in past concussion history in male athletes (p=<0.001) but not female athletes (p= 0.077). Eighty-eight percent (n=22) of concussed male athletes reported having experienced at least one previous concussion compared to 47% (n=62) of non-concussed males. Seventy percent (n=7) of concussed females reported at least one past concussion compared to 41% (n=32) of females who did not sustain a SRC. Football and rugby athletes reported the greatest number of athletes with past concussion history. One-hundred percent of concussed football athletes (n=8) and 95% of all concussed rugby athletes (n=20, men and women) reported having previous concussion diagnosis. The presence of neck pain was significantly greater in concussed males (p= ≤0.001) but not in concussed females (p= 0.072) females. Thirty-six percent (n=9) of men and 30% of women (n=3) who sustained concussions reported neck pain at the pre-season assessment.

Strength Related Variables

In a comparison of concussed and non-concussed athletes two-tailed students t-tests and the Wilcoxon rank sum test were performed to evaluate the differences in body size and strength in concussed and non-concussed athletes. Males and females were evaluated separately due to the biological differences in size and strength between the sexes. No significant significant differences were found between concussed and non-concussed athletes in both men and women in any of the anthropometric measures evaluated including, height (p = 0.598, p = 0.125), weight

($p = 0.186$, $p = 0.340$), head circumferences ($p = 0.668$, $p = 0.318$), neck circumference ($p = 0.923$, $p = 0.645$), or neck length ($p = 0.059$, $p = 0.969$) Direct strength measures demonstrated significantly greater neck flexor strength in male athletes compared to females ($p= 0.023$), however no differences in neck extensor strength between the sexes ($p= 0.174$). Neither neck flexor nor neck extensor strength was statistically significant between concussion groups for men or women ($p = 0.095$, $p = 0.585$ and $p = 0.663$, $p = 0.577$).

Logistic Regression Analysis

Logistic regression analysis found that the model with the three independent variables past concussion history, the presence of neck pain, and neck flexor strength to be significant ($X^2(3) = 36.52$, $n = 246$, $p < 0.001$). This indicates that the likelihood of an athlete sustaining a concussion in a given season is related to these three variables. Table 4.0 presents the beta coefficients, odds ratios, standard error, Wald statistic, significance and 95% confidence interval for the final regression model. A history of neck pain at the time of the assessment was the strongest predictor of concussion risk with an odds ratio of 7.06 ($p < 0.001$), indicating risk of concussion increases by a factor of 7 when neck pain is indicated. Past concussion history has an odds ratio of 4.6 ($p = 0.002$) indicating five times the risk for concussion in athletes with a past diagnosis of SRC.

Neck extensor strength ($p= 0.498$) and the average of both neck strength tests ($p=0.933$) did not improve the predictive accuracy of the model. Neck flexor strength was the only strength related variable included in the final model ($p= 0.237$). The odds ratio of 0.96 for neck flexor strength indicates neck strength does not protect against concussion in varsity athletes.

< INSERT TABLE 3.0 HERE >

Discussion

In this prospective cohort of university varsity athletes we found the incidence of concussion to be slightly higher than what has been reported in the literature on both Canadian and American university athletes, which indicate approximately 10% of athletes sustain concussions in a given season (Black et al., 2017; K. Guskiewicz et al., 2003b; Zuckerman et al., 2015). Fifteen percent of our athletes sustained a concussion over the course of the season. Neck pain was the greatest predictor of concussion risk (OR= 7.06, p= <0.001), followed by past concussion history (OR= 4.61, p=0.002). Neck strength (OR=0.96, p= 0.237) is not associated with concussion risk. The three predictor variables together, neck pain, past concussion history, and neck flexor strength, account for 18.2% of the variance in concussion outcome.

The current literature indicates that recurrent concussion is indicative of future risk for several chronic mental health issues such as anxiety, depression, and mood disturbances, as well as the suggested primary mechanism of injury for tauopathies like chronic traumatic encephalopathy (Omalu et al., 2005; Prins et al., 2013; Safinia et al., 2016). A history of concussion has also been shown to be a positive predictor of concussion risk (K. Guskiewicz et al., 2003b; Schulz et al., 2004; Tsushima, Siu, Ahn, Chang, & Murata, 2018). A 2018 study found that athletes with a past concussion history had 3 to 5 times greater risk of sustaining a concussion (Tsushima et al., 2018). Our findings reflect what is published in the literature. Fifty percent (n = 123) of our athletes reported history of at least one previous concussion. Additionally, this study found concussed athletes to have significantly higher rates of past concussion (p=<0.001). Eighty-three percent (n = 29) of concussed athletes and 45% (n = 94) of non-concussed athletes reported a history of past concussion prior to the start of the season. The mechanism behind what predisposes athletes with a history of concussion to subsequent concussions is unknown although could be attributed the period of cerebral vulnerability as previously described by Giza (2014) may persist beyond the acute symptomatic time period.

There is a scarcity of literature showing a relationship between neck pain and concussion risk although a 2009 study by Shehata et al. indicated it was the third highest symptom reported on the SCAT3 in pre-season baseline assessments of college varsity athletes (Shehata et al., 2009). However, in this cohort neck pain was the strongest predictor of concussion risk with those reporting neck pain experiencing 7 times the risk for concussion. Thirty-five percent (n=12) of concussed athletes reported neck pain at pre-season evaluation compared to 5% (n=10) in non-concussed athletes. One Canadian study by Schneider et al. demonstrated that the presence of headache and neck pain in male youth hockey players increased the athlete's risk of concussion during the season (Schneider, Emery, Kang, Schneider, & Meeuwisse, 2011). The extent to which neck pain predicts concussion risk has not yet been reported in a varsity athlete cohort. The presence of neck pain may present an increased concussion risk due to an athlete's inability to adequately brace for impact or contract the musculature forcefully enough to limit the forces translating to the head (Lindstrøm, Schomacher, Farina, Rechter, & Falla, 2011).

Neck pain as the greatest predictor of concussion risk calls into question the importance of neck strength in limiting concussion risk. Collins et al. evaluated neck strength in high school athletes and found a significant relationship between stronger necks and a decreased likelihood of concussion (C. L. Collins et al., 2014b). It is known that developmentally, high school athletes have more variability in their body morphology and anthropometric demographics than an older cohort where developmental variation is leveling. Also, the modified dynamometer used to evaluate neck strength in this study possibly introduced high levels of human error at the time of measurement. Fixed apparatus dynamometry is an alternative way to measure neck strength without introducing as much human error however, the use of dynamometers and other fixed-apparatus strength measurement tools are not readily available to clinicians evaluating athletes and are often expensive. For these reasons we chose to use the isometric endurance tests which are economical, easy to administer, and have reported moderate to excellent reliability ($ICC_{2,1}$ = 0.82 to 0.92, $ICC_{3,1}$ = 0.67 to 0.78). Although neck strength was not significantly different between concussed and non-concussed athletes and was not a significant sole predictor of concussion in this group of varsity athletes, we have confidence the measurement of neck strength was valid due to all strength assessments being performed by one single rater. Furthermore, a recent study by Lourenço and colleagues (2016) evaluated the use of these neck flexor and extensor tests in a comparison of university students with subclinical neck pain and those without found the tests to be reliable. The authors also found that there were no significant differences in the neck endurance test scores between those with neck pain and those without (Lourenço et al., 2016). These results mirror what we found in our athlete cohort, particularly as more concussed athletes reported neck pain at the time of assessment.

The overall high rate of concussions in rugby athletes and the significant number of past concussions (up to 9 previous SRC) are of grave concern due to the growing body of literature on the long-term effects of concussion, including increased risk for CTE. As neck strength was not a significant predictor of concussion in this cohort it is imperative to continue an inquiry into effective prevention strategies for SRC.

Limitations

This study is not without its limitations. While 15% of athletes sustaining a concussion is significant, it is possible that 39 concussions is too few to accurately determine the predictive power of neck strength in concussion risk as other variables were more significant and the number of concussions (dependent variable) dictate the number of predictor variables that are able to be included in the logistic regression analysis. This cohort is sampled from a very narrow age range, therefore the variability between weaker and stronger athletes is harder to detect. Furthermore, the use of a quick, easy, and economical measurement tool is imperative for a clinical strength assessment though given the trained nature of the athletes this tool may not have been sensitive enough to determine the variability in strength in these athletes. However, while these strength measures have not been used in a concussed athlete population to date, their primary use is in patients with chronic neck pain which was the most significant predictor of concussion risk. Athletes were followed over the course of one season, thus providing a snapshot of injury risk in a narrow time frame. A study carried out over multiple seasons and generations of athletes would provide a more concrete understanding of concussion risk in a varsity athlete cohort. Lastly, certain teams at McMaster University were more accessible for participation than others (i.e. Men's hockey) therefore some important at-risk athletes were not captured in this study.

Conclusion

Neck strength alone has no effect on predicting concussion risk in university varsity athletes. The presence of neck pain was found to be the greatest of risk factor for concussive injury. An evaluation pre-season health history, including the presence of neck pain and past history of SRC, may be beneficial in determining at-risk athletes. This evaluation would be most beneficial to rugby athletes who are at greatest risk for concussion in a varsity athlete population. Future research should focus on the evaluation of neck strength in a laboratory setting using fixed apparatus dynamometry to eliminate human error and evaluate absolute strength in university athletes. Additionally, future studies should take place across multiple athletic seasons to be able to evaluate neck strength and understand the epidemiology of SRC in Canadian varsity athletes.

References

Abrahams, S., Mc Fie, S., Patricios, J., Posthumus, M., & September, A. V. (2014). Risk factors for sports concussion: an evidence-based systematic review. *British Journal of Sports Medicine*, *48*(2), 91–97. https://doi.org/10.1136/bjsports-2013-092734

Alla, S., Sullivan, S. J., Hale, L., & McCrory, P. (2009). Self-report scales/checklists for the measurement of concussion symptoms: a systematic review. *British Journal of Sports Medicine*, *43 Suppl 1*, i3–i12. https://doi.org/10.1136/bjsm.2009.058339

Angelica, M. D., & Fong, Y. (2008). Effect of Neck Strength and Anticipatory Activation in Response to Head Impulsive Loads. *American Journal of Public Health*, *141*(4), 520–529. https://doi.org/10.1016/j.surg.2006.10.010.Use

Association, T. N. C. A. (2013). *NCAA sports medicine handbook, Guideline 21: Sports-related concussion*. Idianapolis, IN. https://doi.org/10.1136/bjsm.34.3.230-a

Bakhos, L. L., Lockhart, G. R., Myers, R., & Linakis, J. G. (2010). Emergency Department Visits for Concussion in Young Child Athletes. *Pediatrics*, *126*(3), e550–e556. https://doi.org/10.1542/peds.2009-3101

Barr, W. B., & McCrea, M. (2001). Sensitivity and specificity of standardized neurocognitive testing immediately following sports concussion.[Erratum appears in J Int Neuropsychol Soc 2002 Mar;8(3):481]. *Journal of the International Neuropsychological Society*, *7*(6), 693–702.

Bazarian, J. J., Zhong, J., Blyth, B., Zhu, T., Kavcic, V., & Peterson, D. (2007). Diffusion Tensor Imaging Detects Clinically Important Axonal Damage after Mild Traumatic Brain Injury: A Pilot Study. *Journal of Neurotrauma*, *24*(9), 1447–1459. https://doi.org/10.1089/neu.2007.0241

Bell, David R. Guskiewicz, Kevin M. Clark, Michael A. Padua, D. A. (2011). Systematic Review of the Balance Error Scoring System. *Athletic Training*, *3*(3), 287–295. https://doi.org/10.1177/1941738111403122

Benson, B. W., Hamilton, G. M., Meeuwisse, W. H., McCrory, P., & Dvorak, J. (2009). Is protective equipment useful in preventing concussion? A systematic review of the literature. *British Journal of Sports Medicine*, *43*(Suppl_1), i56–i67. https://doi.org/10.1136/bjsm.2009.058271

Benson, B. W., McIntosh, A. S., Maddocks, D., Herring, S. A., Raftery, M., & Dvorak, J. (2013). What are the most effective risk-reduction strategies in sport concussion? *Br J Sports Med*, *47*(5), 321–326. https://doi.org/10.1136/bjsports-2013-092216\r47/5/321 [pii]

Benson, B. W., McIntosh, A. S., Maddocks, D., Herring, S. A., Raftery, M., & Dvořák, J. (2013). What are the most effective risk-reduction strategies in sport concussion? *British Journal of Sports Medicine*, *47*(5), 321–326. https://doi.org/10.1136/bjsports-2013-092216

Black, A. M., Sergio, L. E., & Macpherson, A. K. (2017). The Epidemiology of Concussions: Number and nature of concussions and time to recovery among female and male canadian varsity athletes 2008 to 2011. *Clinical Journal of Sport Medicine*, *27*, 52–56. Retrieved from http://www.cjsportmed.com/%0Ahttp://ovidsp.ovid.com/ovidweb.cgi?T=JS&PAGE=reference&D=emed18b&NEWS=N&AN=608297429

Bleiberg, J., Cernich, A. N., Cameron, K., Sun, W., Peck, K., Ecklund, J., … Bailes, J. E. (2004). Duration of Cognitive Impairment after Sports Concussion. *Neurosurgery*, *54*(5), 1073–1080. https://doi.org/10.1227/01.NEU.0000155093.00745.B4

Bloom, G. A., Loughead, T. M., Shapcott, E. J. B., Johnston, K. M., & Delaney, J. S. (2008). The prevalence and recovery of concussed male and female collegiate athletes. *European Journal of Sport Science*, *8*(5), 295–303. https://doi.org/10.1080/17461390802251836

Borich, M. R., Cheung, K. L., Jones, P., Khramova, V., Gavrailoff, L., Boyd, L. A., & Virji-Babul, N. (2013). Concussion: Current Concepts in Diagnosis in Management. *Journal of Neurologic Physical Therapy*, *37*(3), 133–139. https://doi.org/10.1097/NPT.0b013e31829f7460

Broglio, S. P., Ferrara, M. S., Sopiarz, K., & Kelly, M. S. (2008). Reliable change of the sensory organization test. *Clinical Journal of Sport Medicine*, *18*(2), 148–154. https://doi.org/10.1097/JSM.0b013e318164f42a

Broglio, S. P., Macciocchi, S. N., & Ferrara, M. S. (2007). Sensitivity of the concussion assessment battery. *Neurosurgery*, *60*(6), 1050–1057. https://doi.org/10.1227/01.NEU.0000255479.90999.C0

Broglio, S. P., Sosnoff, J. J., Shin, S., He, X., Alcaraz, C., & Zimmerman, J. (2009). Head Impacts During High School Football: A Biomechanical Assessment, *44*(4), 342–349.

Center for Disease Control, Gilchrist, J., Thomas, K. E., Xu, L., McGuire, L. C., & Coronado, V. (2011). Nonfatal traumatic brain injuries related to sports and recreation activities among persons aged ≤19 years--United States, 2001-2009. *MMWR. Morbidity and Mortality Weekly Report*, *60*(39), 1337–1342. https://doi.org/mm6039a1 [pii]

Collie, A. (2006). Cognition in the days following concussion: comparison of symptomatic versus asymptomatic athletes. *Journal of Neurology, Neurosurgery & Psychiatry*, *77*(2), 241–245. https://doi.org/10.1136/jnnp.2005.073155

Collins, C. L., Fletcher, E. N., Fields, S. K., Kluchurosky, L., Rohrkemper, M. K., Comstock, R. D., & Cantu, R. C. (2014a). Neck Strength: A Protective Factor Reducing Risk for Concussion in High School Sports. *Journal of Primary Prevention*, *35*(5), 309–319. https://doi.org/10.1007/s10935-014-0355-2

Collins, C. L., Fletcher, E. N., Fields, S. K., Kluchurosky, L., Rohrkemper, M. K., Comstock, R. D., & Cantu, R. C. (2014b). Neck Strength: A Protective Factor Reducing Risk for Concussion in High School Sports. *Journal of Primary Prevention*, *35*(5), 309–319. https://doi.org/10.1007/s10935-014-0355-2

Collins, M., Lovell, M. R., Iverson, G. L., Ide, T., & Maroon, J. (2006). Examining concussion rates and return to play in high school football players wearing newer helmet technology: A three-year prospective cohort study. *Neurosurgery*, *58*(2), 275–284. https://doi.org/10.1227/01.NEU.0000200441.92742.46

Concussion, S., Tool, A., & Assessment, S. (2013). SCAT3, 259–263.

Covassin, T., Swanik, C. B., & Sachs, M. L. (2003). Sex differences and the incidence of concussions among collegiate athletes. *Journal of Athletic Training (National Athletic Trainers' Association)*, *38*(3), 238–244. Retrieved from http://spot.lib.auburn.edu/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=cin20&AN=2004046415&site=ehost-live

Covassin, T., Swanik, C. B., & Sachs, M. L. (2003). Sex Differences and the Incidence of Concussions Among Collegiate Athletes. *Journal of Athletic Training (National Athletic Trainers' Association)*, *38*(3), 238. Retrieved from http://search.ebscohost.com.lib-proxy.fullerton.edu/login.aspx?direct=true&db=s3h&AN=11720753&site=ehost-live&scope=site

Cramer, C. R. (1999). A Reconditioning Program to Lower the Recurrence Rate of Brachial

Plexus Neurapraxia in Collegiate Football Players. *Journal of Athletic Training*, *34*(4), 390–396.

Daneshvar, D. H., Nowinski, C. J., Mckee, A. C., & Cantu, R. C. (2011). The Epidemiology of Sport-Related Concussion. *Clinics in Sports Medicine*, *30*(1), 1–17. https://doi.org/10.1016/j.csm.2010.08.006

de Koning, C. H. P., van den Heuvel, S. P., Staal, J. B., Smits-Engelsman, B. C. M., & Hendriks, E. J. M. (2008). Clinimetric evaluation of methods to measure muscle functioning in patients with non-specific neck pain: a systematic review. *BMC Musculoskeletal Disorders*, *9*, 142. https://doi.org/10.1186/1471-2474-9-142

Dvorak, J., Mccrory, P., Kirkendall, D. T., & Klinik, S. (2007). Head injuries in the female football player: incidence, mechanisms, risk factors and management. *Br J Sports Med*, *41*, 44–46. https://doi.org/10.1136/bjsm.2007.037960

Eckner, J. T., Oh, Y. K., Joshi, M. S., Richardson, J. K., & Ashton-Miller, J. A. (2014). Effect of neck muscle strength and anticipatory cervical muscle activation on the kinematic response of the head to impulsive loads. *The American Journal of Sports Medicine*, *42*(3), 566–576. https://doi.org/10.1177/0363546513517869

Emery, C. A., Black, A. M., Kolstad, A., Martinez, G., Nettel-Aguirre, A., Engebretsen, L., … Schneider, K. (2017a). What strategies can be used to effectively reduce the risk of concussion in sport? *British Journal of Sports Medicine*, bjsports-2016-097452. https://doi.org/10.1136/bjsports-2016-097452

Emery, C. A., Black, A. M., Kolstad, A., Martinez, G., Nettel-Aguirre, A., Engebretsen, L., … Schneider, K. (2017b). What strategies can be used to effectively reduce the risk of concussion in sport? *British Journal of Sports Medicine*, bjsports-2016-097452. https://doi.org/10.1136/bjsports-2016-097452

Franco, J. L., & Herzog, W. (1987). A comparative assessment of neck muscle strength and vertebral stability. *The Journal of Orthopaedic and Sports Physical Therapy*, *8*(7), 351–356. https://doi.org/10.2519/jospt.1987.8.7.351

Gardner, A., Kay-Lambkin, F., Stanwell, P., Donnelly, J., Williams, W. H., Hiles, A., … Jones, D. K. (2012). A Systematic Review of Diffusion Tensor Imaging Findings in Sports-Related Concussion. *Journal of Neurotrauma*, *29*(16), 2521–2538. https://doi.org/10.1089/neu.2012.2628

Geary, K., Green, B. S., & Delahunt, E. (2013). Intrarater reliability of neck strength measurement of rugby union players using a handheld dynamometer. *Journal of Manipulative and Physiological Therapeutics*, *36*(7), 444–449. https://doi.org/10.1016/j.jmpt.2013.05.026

Geary, K., Green, B. S., & Delahunt, E. (2014). Effects of Neck Strength Training on Isometric Neck Strength in Rugby Union Players. *Clin J Sport Med*, *6*(24), 502–508. https://doi.org/10.1097/JSM.0000000000000071

Gessel, L. M., Fields, S. K., Collins, C. L., Dick, R. W., & Comstock, R. D. (2007). Concussions among United States high school and collegiate athletes. *Journal of Athletic Training (National Athletic Trainers' Association)*, *42*(4), 495–503. Retrieved from http://spot.lib.auburn.edu/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=cin20&AN=2009759920&site=ehost-live

Giza, C. C. (2014). The New Metabolic Cascade of Concussion, *75*(0 4), S24–S33. https://doi.org/10.1227/NEU.0000000000000505.The

Giza, C. C., & Hovda, D. A. (2001). The Neurometabolic Cascade of Concussion. *Journal of*

Athletic Training, *36*(3), 228–235. https://doi.org/10.1227/NEU.0000000000000505

Greenhill, D. A., Navo, P., Zhao, H., Torg, J., Comstock, R. D., & Boden, B. P. (2016). Inadequate Helmet Fit Increases Concussion Severity in American High School Football Players. *Sports Health*, *8*(3), 238–243. https://doi.org/10.1177/1941738116639027

Guskiewicz, K. M. (2011). Balance Assessment in the Management of Sport-Related Concussion. *Clinics in Sports Medicine*, *30*(1), 89–102. https://doi.org/10.1016/j.csm.2010.09.004

Guskiewicz, K. M., Weaver, N. L., Padua, D. A., Garrett, W. E., Hill, C., & Carolina, N. (2000). Epidemiology of Concussion in Collegiate and High School Football Players, *28*(5).

Guskiewicz, K., Mccrea, M., Marshall, S. W., Cantu, R. C., Randolph, C., Barr, W., … Kelly, J. P. (2003a). The NCAA Concussion Study. *Journal of the American Medical Association*, *290*(19), 2549–2555.

Guskiewicz, K., Mccrea, M., Marshall, S. W., Cantu, R. C., Randolph, C., Barr, W., … Kelly, J. P. (2003b). The NCAA Concussion Study. *Journal of the American Medical Association*, *290*(19), 2549–2555.

Halstead, M. E., & Walter, K. D. (2010). Sport-Related Concussion in Children and Adolescents. *Pediatrics*, *126*(3), 597–615. https://doi.org/10.1542/peds.2010-2005

Hamilton, D. F., Gatherer, D., Maclean, J. G. B., Hutchison, J. D., Nutton, R. W., & Simpson, A. H. R. W. (2012). Age-related differences in the neck strength of adolescent rugby players A CROSS-SECTIONAL COHORT STUDY OF SCOTTISH SCHOOLCHILDREN. *Bone Joint Res*, *1*(7), 152–157.

Harmon, K. G., Drezner, J. A., Gammons, M., Guskiewicz, K. M., Halstead, M., Herring, S. A., … Roberts, W. O. (2013). American Medical Society for Sports Medicine position statement: concussion in sport. *British Journal of Sports Medicine*, *47*(1), 15–26. https://doi.org/10.1136/bjsports-2012-091941

Harmon, K. G., Drezner, J. A., Gammons, M., Guskiewicz, K. M., Halstead, M., Herring, S. A., … Roberts, W. O. (2013). American Medical Society for Sports Medicine position statement: concussion in sport. *Br.J Sports Med*, *47*(1), 15–26. https://doi.org/10.1136/bjsports-2012-091941

Harris, K. D., Heer, D. M., Roy, T. C., Santos, D. M., Whitman, J. M., & Wainner, R. S. (2005). Reliability of a measurement of neck flexor muscle endurance. *Physical Therapy*, *85*(12), 1349–1355.

Harvey, K. P., Hall, E. E., Patel, K., Barnes, K. P., & Ketcham, C. J. (2017). Potential factors influencing recovery from concussion in collegiate student-athletes. *Journal of Concussion*, *1*, 205970021770708. https://doi.org/10.1177/2059700217707084

Henry, L. C., Elbin, R. J., Collins, M. W., Marchetti, G., & Kontos, A. P. (2016). Examining recovery trajectories after sport-related concussion with a multimodal clinical assessment approach. *Neurosurgery*, *78*(2), 232–240. https://doi.org/10.1227/NEU.0000000000001041

Holbourn, A. H. S. (1943). Mechanics of head injuries. *Lancet*, *242*(6267), 438–441. https://doi.org/10.1016/S0140-6736(00)87453-X

Hrysomallis, C. (2016). Neck Muscular Strength, Training, Performance and Sport Injury Risk: A Review. *Sports Medicine*. https://doi.org/10.1007/s40279-016-0490-4

Iverson, G. L., Gardner, A. J., Terry, D. P., Ponsford, J. L., Sills, A. K., Broshek, D. K., & Solomon, G. S. (2017). Predictors of clinical recovery from concussion: A systematic review. *British Journal of Sports Medicine*, *51*(12), 941–948. https://doi.org/10.1136/bjsports-2017-097729

Iverson, G. L., Lovell, M. R., & Collins, M. W. (2003). Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT) Normative Data.

Iverson, G. L., Silverberg, N. D., Mannix, R., Maxwell, B. a., Atkins, J. E., Zafonte, R., & Berkner, P. D. (2015). Factors Associated With Concussion-like Symptom Reporting in High School Athletes. *JAMA Pediatrics*, *169*(10), 1–9. https://doi.org/10.1001/jamapediatrics.2015.2374

Johnston, K. M., McCrory, P., Mohtadi, N. G., & Meeuwisse, W. (2001). Evidence-based review of sport-related concussion: clinical science. *Clinical Journal of Sport Medicine*, *11*, 150–159. https://doi.org/10.1097/00042752-200107000-00005

Jull, G. A., O'Leary, S. P., & Falla, D. L. (2008). Clinical Assessment of the Deep Cervical Flexor Muscles: The Craniocervical Flexion Test. *Journal of Manipulative and Physiological Therapeutics*, *31*(7), 525–533. https://doi.org/10.1016/j.jmpt.2008.08.003

Kemp, S., Hudson, Z., Brooks, J., Fuller, C. (2008). The Epidemiology of Head Injuries in English Professional Rugby Union. *Clinical Journal of Sport Medicine*, *18*(3). https://doi.org/10.1177/0363546507300691

Khong, E., Odenwald, N., Hashim, E., & Cusimano, M. D. (2016). Diffusion tensor imaging findings in post-concussion syndrome patients after mild traumatic brain injury: A systematic review. *Frontiers in Neurology*, *7*(SEP), 1–8. https://doi.org/10.3389/fneur.2016.00156

King, A., Yang, K., & Zhang, L. (2003). Is head injury caused by linear or angular acceleration. *IRCOBI Conference*, (September), 1–12. Retrieved from http://snell-helmets.org/docs/articles/hic/King_IRCOBI_2003.pdf

Koeppen & Stanton. (2017). *Berne and Levy Physiology*. St. Louis: Elsevier Health Sciences. Retrieved from https://www-clinicalkey-com.libaccess.lib.mcmaster.ca/#!/browse/book/3-s2.0-C20110061689

Koerte, I. K., Ertl-Wagner, B., Reiser, M., Zafonte, R., & Shenton, M. E. (2012). White matter integrity in the brains of professional socer players without a symptomatic concussion. *Journal of the American Medical Association*, *308*(18).

Kroshus, E., Daneshvar, D. H., Baugh, C. M., Nowinski, C. J., & Cantu, R. C. (2014). NCAA concussion education in ice hockey : an ineffective mandate. *British Journal of Sports Medicine*, *48*((2)), 135–140. https://doi.org/10.1136/bjsports-2013-092498

Kutcher, J. S., & Eckner, J. T. (2010). At-risk populations in sports-related concussion. *Current Sports Medicine Reports*, *9*(1), 16–20. https://doi.org/http://dx.doi.org/10.1249/JSR.0b013e3181caa89d

Lavallee, A. V., Ching, R. P., & Nuckley, D. J. (2013). Developmental biomechanics of neck musculature. *Journal of Biomechanics*, *46*(3), 527–534. https://doi.org/10.1016/j.jbiomech.2012.09.029

Leddy, J. J., Baker, J. G., & Willer, B. (2016). Active Rehabilitation of Concussion and Post-concussion Syndrome. *Physical Medicine and Rehabilitation Clinics of North America*, *27*(2), 437–454. https://doi.org/10.1016/j.pmr.2015.12.003

Leddy, M. H., Lambert, M. J., & Ogles, B. M. (1994). Psychological consequences of athletic injury among high-level competitors. *Research Quarterly for Exercise and Sport*, *65*(4), 347–354. https://doi.org/10.1080/02701367.1994.10607639

Lindstrøm, R., Schomacher, J., Farina, D., Rechter, L., & Falla, D. (2011). Association between neck muscle coactivation , pain , and strength in women with neck pain. *Manual Therapy*, *16*(1), 80–86. https://doi.org/10.1016/j.math.2010.07.006

Littleton, A., & Guskiewicz, K. (2013). Current concepts in sport concussion management: A multifaceted approach. *Journal of Sport and Health Science*, *2*(4), 227–235. https://doi.org/10.1016/j.jshs.2013.04.003

Llewellyn, T., Burdette, G. T., Joyner, a B., & Buckley, T. a. (2014). Concussion reporting rates at the conclusion of an intercollegiate athletic career. *Clinical Journal of Sport Medicine : Official Journal of the Canadian Academy of Sport Medicine*, *24*(1), 76–79. https://doi.org/10.1097/01.jsm.0000432853.77520.3d

Longhi, L., Saatman, K. E., Fujimoto, S., Raghupathi, R., Meaney, D. F., Davis, J., … McIntosh, T. K. (2005). Temporal window of vulnerability to repetitive experimental concussive brain injury. *Neurosurgery*, *56*(2), 364–373. https://doi.org/10.1227/01.NEU.0000149008.73513.44

Lourenço, A. S., Lameiras, C., & Silva, A. G. (2016). Neck Flexor and Extensor Muscle Endurance in Subclinical Neck Pain: Intrarater Reliability, Standard Error of Measurement, Minimal Detectable Change, and Comparison With Asymptomatic Participants in a University Student Population. *Journal of Manipulative and Physiological Therapeutics*, *39*(6), 427–433. https://doi.org/10.1016/j.jmpt.2016.05.005

Majerske, C. W., Mihalik, J. P., Ren, D., Collins, M. W., Reddy, C. C., Lovell, M. R., & Wagner, A. K. (2008). Concussion in sports: Postconcussive activity levels, symptoms, and neurocognitive performance. *Journal of Athletic Training*, *43*(3), 265–274. https://doi.org/10.4085/1062-6050-43.3.265

Manley, G. T., Gardner, A. J., Schneider, K. J., Guskiewicz, K. M., Bailes, J., Cantu, R. C., … Iverson, G. L. (2017). A systematic review of potential long-term effects of sport-related concussion, 1–10. https://doi.org/10.1136/bjsports-2017-097791

Marshall, S. W., Guskiewicz, K. M., Shankar, V., McCrea, M., & Cantu, R. C. (2015). Epidemiology of sports-related concussion in seven US high school and collegiate sports. *Injury Epidemiology*, *2*(1). https://doi.org/10.1186/s40621-015-0045-4

Marshall, S. W., Waller, A. E., Dick, R. W., Pugh, C. B., Loomis, D. P., & Chalmers, D. J. (2002). An ecologic study of protective equipment and injury in two contact sports. *International Journal of Epidemiology*, *31*(3), 587–592. https://doi.org/10.1093/ije/31.3.587

McCrea, H. J., Perrine, K., Niogi, S., & Hartl, R. (2012). Cuncussion in sports. *Sports Health: A Multidisciplinary Approach*, *5*(2), 160–164. https://doi.org/10.1177/1941738112462203

McCrea, M., Guskiewicz, K. M., Marshall, S. W., Barr, W., Randolph, C., Cantu, R. C., … Kelly, J. P. (2003a). Acute Effects and Recovery Time Following. *The Journal of the American Medical Association*, *290*(19), 2556–2563. https://doi.org/10.1001/jama.290.19.2556

McCrea, M., Guskiewicz, K. M., Marshall, S. W., Barr, W., Randolph, C., Cantu, R. C., … Kelly, J. P. (2003b). Acute Effects and Recovery Time Following Concussion in Collegiate Football Players. *The Journal of the American Medical Association*, *290*(19), 2556–2563. https://doi.org/10.1001/jama.290.19.2556

Mccrea, M., Guskiewicz, K., Randolph, C., Barr, W. B., Hammeke, T. A., Marshall, S. W., … Kelly, J. P. (2016). Incidence, Clinical Course, and Predictors of Prolonged Recovery Time Following Sport-Related Concussion in High School and College Athletes. *Journal of the International Neuropsychological Society Copyright E INS*, *19*, 22–33. https://doi.org/10.1017/S1355617712000872

McCrea, M., Hammeke, T., Olsen, G., Leo, P., & Guskiewicz, K. (2004). Unreported concussion in high school football players: implications for prevention. *Clin J Sport Med*, *14*(1), 13–17.

https://doi.org/10.1097/00042752-200401000-00003

McCrea, M., Kelly, J. P., Randolph, C., Kluge, J., Bartolic, E., Finn, G., & Baxter, B. (1998). Standardized Assessment of Concussion (SAC): On-Site Mental Status Evaluation of the Athlete. *Journal of Head Trauma Rehabilitation*. https://doi.org/10.1097/00001199-199804000-00005

McCrory, P., Meeuwisse, W., Dvorak, J., Aubry, M., Bailes, J., Broglio, S., … Vos, P. E. (2017). Consensus statement on concussion in sport — the 5 th international conference on concussion in sport held in Berlin , October 2016. *British Journal of Sports Medicine*, 1–10. https://doi.org/10.1136/bjsports-2017-097699

Mccrory, P., Meeuwisse, W., Dvořák, J., Aubry, M., Bailes, J., Broglio, S., … Vos, P. E. (2017). Consensus statement on concussion in sport—the 5 th international conference on concussion in sport held in Berlin, October 2016. *Br J Sports Med*, *51*, 838–847. https://doi.org/10.1136/bjsports-2017-097699

McCrory, P., Meeuwisse, W. H., Aubry, M., Cantu, R. C., Dvorák, J., Echemendia, R. J., … Turner, M. (2013). Consensus Statement on Concussion in Sport-The 4th International Conference on Concussion in Sport Held in Zurich, November 2012. *PM and R*, *5*(4), 255–279. https://doi.org/10.1016/j.pmrj.2013.02.012

McLeod, T. C. V., & Leach, C. (2012). Psychometric properties of self-report concussion scales and checklists. *Journal of Athletic Training*, *47*(2), 221–223. https://doi.org/10.4085/1062-6050-47.2.221

Meehan, William P. Mannix, Rebekah C. Stracciolini, Andrea Elbin, R.J. Collins, M. W. (2013). Symptom severity predicts prolonged recovery after sport-related concussion: Age and amnesia do not. *Journal of Pediatrics*, *163*(3), 721–725. https://doi.org/10.1016/j.jpeds.2013.03.012.Symptom

Meeuwisse, W. H., Hagel, B. E., Mohtadi, N. G. H., Butterwick, D. J., & Fick, G. H. (2000). The Distribution of Injuries in Men's Canada West University Football: A 5-year Analysis. *The American Journal of Sports Medicine*, *28*(4), 516–523. https://doi.org/10.1177/03635465000280041201

Misra, J. C., & Chakravarty, S. (1984). A study on rotational brain injury. *Journal of Biomechanics*, *17*(7), 459–466. https://doi.org/10.1016/0021-9290(84)90014-9

Omalu, B. I., DeKosky, S. T., Minster, R. L., Kamboh, M. I., Hamilton, R. L., & Wecht, C. H. (2005). Chronic traumatic encephalopathy in a National Football League player. *Neurosurgery*, *57*(1), 128–133. https://doi.org/10.1227/01.NEU.0000163407.92769.ED

Pagano, Marcello; Gauvreau, K. (2000). *Principles of Biostatistics* (2nd Editio). Belmont,CA: Brooks/Cole.

Parazza, S., Vanti, C., O'Reilly, C., Villafañe, J. H., Tricás Moreno, J. M., & Estébanez De Miguel, E. (2014). The relationship between cervical flexor endurance, cervical extensor endurance, VAS, and disability in subjects with neck pain. *Chiropractic & Manual Therapies*, *22*(1), 10. https://doi.org/10.1186/2045-709X-22-10

Peduzzi, P., Concato, J., Kemper, E., Holford, T.R., Feinstein, A. R. (1996). A Simulation Study of the Number of Events per Variable in Logistic Regression Analysis. *Journal of Clinical Epidemiology*, *49*(12), 1373–1379.

Powell, J. W., & Barber-foss, K. D. (1999). Traumatic Brain Injury in High School Athletes. *JAMA*, *282*(10), 959–963.

Prins, M. L., Alexander, D., Giza, C. C., & Hovda, D. A. (2013). Repeated Mild Traumatic Brain Injury: Mechanisms of Cerebral Vulnerability. *Journal of Neurotrauma*, *30*(1), 30–38.

https://doi.org/10.1089/neu.2012.2399

Putukian, M., Echemendia, R., Dettwiler-Danspeckgruber, A., Duliba, T., Bruce, J., Furtado, J. L., & Murugavel, M. (2015). Prospective clinical assessment using sideline concussion assessment tool-2 testing in the evaluation of sport-related concussion in college athletes. *Clinical Journal of Sport Medicine*, *25*(1), 36–42. https://doi.org/10.1097/JSM.0000000000000102

Rishiraj, N., Lorenz, T., Niven, B., & Michel, M. (2009). University men ' s ice hockey : rates and risk of injuries over 6-years. *Sports Medicine*.

Rose, S. C., Fischer, A. N., & Heyer, G. L. (2015). How long is too long ? The lack of consensus regarding the post-concussion syndrome diagnosis, *9052*, 798–803. https://doi.org/10.3109/02699052.2015.1004756

Safinia, C., Bershad, E. M., Clark, H. B., Santacruz, K., Alakbarova, N., Suarez, J. I., & Divani, A. A. (2016). Chronic Traumatic Encephalopathy in Athletes Involved with High- impact Sports. *Journal of Vascular and Interventional Neurology*, *9*(2), 34–48.

Sandel, N. N. K., Lovell, M. R. M., Kegel, N. N. E., Collins, M. W., & Kontos, A. P. (2013). The Relationship of Symptoms and Neurocognitive Performance to Perceived Recovery From Sports-Related Concussion Among Adolescent Athletes. *Applied Neuropsychology: …*, *2*(1), 64–69. https://doi.org/10.1080/21622965.2012.670580

Schatz, P., Pardini, J. E., Lovell, M. R., Collins, M. W., & Podell, K. (2006). Sensitivity and specificity of the ImPACT Test Battery for concussion in athletes. *Archives of Clinical Neuropsychology*, *21*(1), 91–99. https://doi.org/10.1016/j.acn.2005.08.001

Schatz, P., & Sandel, N. (2013). Sensitivity and specificity of the online version of ImPACT in high school and collegiate athletes. *Am J Sports Med*, *41*(2), 321–326. https://doi.org/10.1177/0363546512466038

Schneider, K., Emery, C., Kang, J., Schneider, G., & Meeuwisse, W. (2011). Are pre-season reports of neck pain, dizziness and/or headaches risk factors for concussion in male youth ice hockey players? *British Journal of Sports Medicine*, *45*(4), 319–320. https://doi.org/10.1136/bjsm.2011.084038.28

Schulz, M. R., Marshall, S. W., Mueller, F. O., Yang, J., Weaver, N. L., Kalsbeek, W. D., & Bowling, J. M. (2004). Incidence and risk factors for concussion in high school athletes, North Carolina, 1996-1999. *American Journal of Epidemiology*, *160*(10), 937–944. https://doi.org/10.1093/aje/kwh304

Scopaz, K., & Hatzenbuehler, J. (2013). Risk modifiers for concussion and prolonged recovery. *Sports Health*, *5*(6), 537–541. https://doi.org/10.1177/1941738112473059

Sebastian, D., Chovvath, R., & Malladi, R. (2015). Cervical extensor endurance test: Areliability study. *Journal of Bodywork and Movement Therapies*, *19*(2), 213–216. https://doi.org/10.1016/j.jbmt.2014.04.014

Seifert, T., & Shipman, V. (2015). The Pathophysiology of Sports Concussion. *Current Pain and Headache Reports*, *19*(8), 1–9. https://doi.org/10.1007/s11916-015-0513-0

Shehata, N., Wiley, J. P., Richea, S., Benson, B. W., Duits, L., & Meeuwisse, W. H. (2009). Sport concussion assessment tool: baseline values for varsity collision sport athletes. *Br J Sports Med*, *43*(10), 730–734. https://doi.org/10.1136/bjsm.2009.059832

Stazyk, K. (2015). *Depression in Children Recovering from Concussion: Correlates and Predictors*.

Stern, R. A., Riley, D. O., Daneshvar, D. H., Nowinski, C. J., Cantu, R. C., & McKee, A. C. (2011). Long-term Consequences of Repetitive Brain Trauma: Chronic Traumatic

Encephalopathy. *PM and R*, *3*(10 SUPPL. 2), 460–467. https://doi.org/10.1016/j.pmrj.2011.08.008

Sullivan, J. C., Tavassoli, T., Armstrong, K., Baron-Cohen, S., & Humphrey, A. (2014). Reliability of self, parental, and researcher measurements of head circumference. *Molecular Autism*, *5*(1), 2–5. https://doi.org/10.1186/2040-2392-5-2

Tavazzi, B., Vagnozzi, R., Signoretti, S., Amorini, A. M., Finocchiaro, A., Cimatti, M., … Lazzarino, G. (2007). Temporal window of metabolic brain vulnerability to concussions: Oxidative and nitrosative stresses - Part II. *Neurosurgery*, *61*(2), 390–396. https://doi.org/10.1227/01.NEU.0000255525.34956.3F

The Physical Activity Council. (2016). 2016 participation report: The physical activity council's annual study tracking sports, fitness, and recreation participaton in the US, 26.

Tierney, R. T., Higgins, M., Caswell, S. V., Brady, J., McHardy, K., Driban, J. B., & Darvish, K. (2008a). Sex differences in head acceleration during heading while wearing soccer headgear. *Journal of Athletic Training*, *43*(6), 578–584. https://doi.org/http://dx.doi.org/10.4085/1062-6050-43.6.578

Tierney, R. T., Higgins, M., Caswell, S. V, Brady, J., McHardy, K., Driban, J. B., & Darvish, K. (2008b). Sex Differences in Head Acceleration During Heading While Wearing Soccer Headgear. *Journal of Athletic Training*, *43*(6), 578–584. https://doi.org/10.4085/1062-6050-43.6.578

Tierney, R. T., Sitler, M. R., Swanik, C. B., Swanik, K. A., Higgins, M., & Torg, J. (2005). Gender differences in head-neck segmnet dynamic stabilization during head accelaration. *Medicine and Science in Sports and Exercise*, *37*(2), 272–279. https://doi.org/10.1249/01.MSS.0000152734.47516.AA

Tsushima, W. T., Siu, A. M., Ahn, H. J., Chang, B. L., & Murata, N. M. (2018). Incidence and Risk of Concussions in Youth Athletes: Comparisons of Age, Sex, Concussion History, Sport, and Football Position. *Archives of Clinical Neuropsychology*, (May). https://doi.org/10.1093/arclin/acy019

USports. (2017). USPORTS Student-Athlete User Guide.

Vagnozzi, R. et al. (2007). Temporal window of metabolic brain vulnerability to concussions: Mitochondrial-related impairment - Part I. Commentary. *Neurosurgery*, *61*(2), 388–389. https://doi.org/10.1227/01.NEU.0000280002.41696.D8

Valovich McLeod, T. C., Barr, W. B., McCrea, M., & Guskiewicz, K. M. (2006). Psychometric and measurement properties of concussion assessment tools in youth sports. *Journal of Athletic Training*, *41*(4), 399–408.

Vasavada, A. N., Danaraj, J., & Siegmund, G. P. (2008). Head and neck anthropometry, vertebral geometry and neck strength in height-matched men and women. *Journal of Biomechanics*, *41*(1), 114–121. https://doi.org/10.1016/j.jbiomech.2007.07.007

Virji-Babul, N., Borich, M. R., Makan, N., Moore, T., Frew, K., Emery, C. A., & Boyd, L. A. (2013). Diffusion Tensor Imaging of Sports-related Concussion in Adolescents. *Pediatric Neurology*, *48*, 24–29.

Williams, R. M., Puetz, T. W., Giza, C. C., & Broglio, S. P. (2015). Concussion Recovery Time Among High School and Collegiate Athletes: A Systematic Review and Meta-Analysis. *Sports Medicine*, *45*(6), 893–903. https://doi.org/10.1007/s40279-015-0325-8

Williamson, R. W., Gerhardstein, D., Cardenas, J., Michael, D. B., Theodore, N., & Rosseauk, N. (2014). Concussion 101: The current state of concussion education programs. *Neurosurgery*, *75*(4), S131–S135. https://doi.org/10.1227/NEU.0000000000000482

World Health Organization (WHO). (2011). ICD-10 Transition. *Family Practice Management*, *18*, 39. https://doi.org/10.1159/000371811

Yengo-kahn, A., Allen, K., & Kerr, Z. Y. (2016). Predictors of postconcussion syndrome in collegiate student-athletes, *40*(April), 1–10. https://doi.org/10.3171/2016.1.FOCUS15593.

Yengo-kahn, A. M., Hale, A. T., Zalneraitis, B. H., Zuckerman, S. L., Sills, A. K., & Solomon, G. S. (2016). Review. *Neurosurgical Focus*, *40*(April). https://doi.org/10.3171/2016.1.FOCUS15611.

Zemek, R. L., Farion, K. J., Sampson, M., & McGahern, C. (2013). Prognosticators of Persistent Symptoms Following Pediatric Concussion. *JAMA Pediatrics*, *167*(3), 259. https://doi.org/10.1001/2013.jamapediatrics.216

Zuckerman, S. L., Kerr, Z. Y., Yengo-Kahn, A., Wasserman, E., Covassin, T., & Solomon, G. S. (2015). Epidemiology of Sports-Related Concussion in NCAA Athletes From 2009-2010 to 2013-2014: Incidence, Recurrence, and Mechanisms. *The American Journal of Sports Medicine*, *43*(11), 2654–2662. https://doi.org/10.1177/0363546515599634

Zuckerman, S. L., Yengo-kahn, A. M., Buckley, T. A., Solomon, G. S., Sills, A. K., & Kerr, Z. Y. (2016). Predictors of postconcussion syndrome in collegiate student-athletes, *40*(April), 1–10. https://doi.org/10.3171/2016.1.FOCUS15593.

Table 1: Procedure overview for anthropometric assessments

Test	Procedure
Height (m)	Height was measured using a measuring tape fixed to a wall. At the time of assessment, it was measured to the nearest centimeter. It was converted to meters for statistical analysis.
Weight (kg)	Weight was measured to the nearest hundredth of a kilogram using a calibrated digital scale. Athletes were dressed in light athletic gear.
Neck Length (cm)	Neck length was measured with the athlete seated, looking straight ahead. A soft tape measure was used to measure from the external occipital protuberance to the middle of the C7 spinous process. All measurements were taken to the nearest tenth of a centimeter.
Head Circumference (cm)	 Head circumference was measured by placing a soft tape measure in the center of the forehead just above the bridge of the eyebrows. The measuring tape wraps around the temporal bone, behind the ears, over top of the external occipital protuberance and around the other side of the head to meet the other end in the center of the forehead. We measured head circumference to the nearest tenth of a centimeter.
Neck Circumference (cm)	 Neck circumference was measured with athletes seated straight in a low back chair, looking straight ahead. A soft tape measure was placed at the midline of the neck between the middle cervical spine and the mid-anterior neck. For men, the measuring tape was placed just below the laryngeal prominence. All measurements were taken to the nearest tenth of a centimeter.

Table 2: Summary statistics with group comparisons for all independent variables by dependent variable outcome (concussion status)

Demographics & anthropometric factors	Concussed Athletes n= 35	Non-Concussed Athletes n= 211	Test Statistic
Age years, mean (sd)	20.26 (1.73)	19.66 (1.69)	z= 2.05, p= 0.050
Sex n (%)			
Male	25 (71.43)	132 (62.56)	χ^2= 1.023, *df*= 1, p= 0.312
Female	10 (28.57)	79 (37.44)	
Sport n (%)			
Football	8 (22.86)	56 (26.54)	
Soccer	3 (8.57)	43 (20.38)	χ^2= 14.82, *df*= 5, p= 0.011
Rugby	20 (57.14)	60 (29.38)	
Basketball	4 (11.43)	23 (10.90)	
Women's Hockey	0 (0.00)	13 (6.16)	
Cheerleading	0 (0.00)	16 (7.58)	
Number of years in sport, mean (sd)	8.37 (4.07)	9.14 (4.43)	z= 1.13, p= 0.260
Past concussion, n (%)			
Yes	29 (82.86)	94 (44.55)	χ^2= 32.18, *df*= 1,
No	6 (17.14)	117 (55.45)	p= < 0.001*
Presence of neck pain, n (%)			
Yes	12 (34.29)	10 (4.74)	χ^2= 28.66, *df*= 1,
No	23 (65.71)	201 (95.26)	p= < 0.001**
Height m, mean (sd)			
Male	1.83 (.079)	1.81 (.076)	$t_{(155)}$= 0.644, p= 0.521
Female	1.72 (.090)	1.68 (.071)	$t_{(87)}$= 1.549, p= 0.125
Weight kg, mean (sd)			
Male	94.45 (17.35)	90.50 (21.27)	z = 1.69, p= 0.092
Female	70 (8.78)	67.60 (11.36)	z = 1.01, p= 0.314
Head circumference cm, mean (sd)			
Male	56.92 (1.84)	54.88 (1.80)	z = 0.102, p= 0.918
Female	54.88 (1.80)	54.27 (1.81)	z = 1.31, p= 0.191
Neck circumference cm, mean (sd)			
Male	43.72 (5.14)	44.21 (3.69)	z= -0.276, p= 0.783
Female	36.69 (3.21)	36.48 (2.50)	z= 0.461, p= 0.645
Neck length cm, mean (sd)			
Male	13.84 (2.01)	13.15 (3.19)	z= 2.05, p= 0.041*
Female	12.23 (1.42)	12.28 (1.52)	z=0.039, p= 0.969
Flexor strength s, mean (sd)			
Male	16.62 (5.62)	19.58 (7.82)	z= -1.51, p= 0.131
Female	15.75 (6.12)	17.39 (7.29)	z= -0.546, p= 0.585

Extensor strength s, mean (sd)			
Male	282.86 (100.31)	279.30 (120.74)	z= 1.67, p= 0.0945
Female	235.99 (118.97)	260.48 (131.58)	z= 0.585, p= 0.553

Key: sd = standard deviation, df = degrees of freedom, * - denotes significance at 0.05 level, ** - denotes significance at 0.01 level

Table 3: Logistic regression predicting the likelihood of concussion in university athletes

Variables	OR	B	SE	Wald	df	Sig.	95% CI	
							Lower	Upper
Past Concussion	4.61	1.53	0.49	3.15	3	0.002*	0.577	2.480
Neck Pain	7.06	1.95	0.51	3.86	3	0.000*	0.962	2.947
Flexor Endurance Test	0.96	-0.039	0.03	-1.18	3	0.237	-0.103	0.0253
Constant	0.09	-2.43	0.71	-3.44	3	0.001*	-3.810	-1.042

Key: OR= odds ratio, B= beta coefficient, SE= standard error, Wald= Wald statistic, df= degrees of freedom, Sig. = p-value, 95% CI = 95% confidence interval. * = significant at the 0.05 significant level (2-tailed)

Table 4.0: Steps in determining predictor variables in logistic regression modelling

Dependent variable: Presence of concussion (0 = no, 1 = yes)

Variables	OR	B	SE	Wald	df	Sig.	Model R^2 (*p-value*)
1. *Demographics*							
Age	1.21	0.190	0.105	1.80	3	0.071	$R^2 = 0.021$ (*p = 0.2300)*
Sex	0.67	-0.406	0.489	-0.83	3	0.407	
Sport	1.00	0.006	0.160	0.04	3	0.972	
Constant	0.004	-5.47	2.17	-2.52	3	0.012	
2. *Demographics + Covariates*							
Age	1.15	0.139	0.120	1.16	4	0.245	$R^2 = 0.1981$ (*p = < 0.001)*
Sport	0.743	-0.297	0.166	-1.78	4	0.075	
Past Concussion	4.60	1.53	0..490	-3.11	4	0.002*	
Neck Pain	10.68	2.368	0.559	-4.24	4	< 0.001*	
Constant	0.006	-5.187	2.466	-2.10	4	0.035	
3. *Anthropomerty and Strength*							
Head circumference	1.05	0.046	0.11	0.43	4	0.670	$R^2 = 0.035$ (*p = 0.1334)*
Neck circumference	1.04	0.034	0.047	0.73	4	0.464	
Flexor Endurance Test	0.93	-0.068	0.032	-2.13	4	0.034*	-
Extensor Endurance Test	1.00	0.001	0.002	0.84	4	0.399	
Constant	-4.99	-4.99	4.97	-1.01	4	0.315	

4. Significant Predictors							
Past Concussion	4.61	1.53	0.49	3.15	3	0.002*	R^2 = 0.1835 (*p = < 0.001*)
Neck Pain	7.06	1.95	0.51	3.86	3	0.000*	
Flexor Endurance Test	0.96	-0.039	0.03	-1.18	3	0.237	-
Constant	0.09	-2.43	0.71	-3.44	3	0.001*	

Key: OR= odds ratio, B= beta coefficient, SE= standard error, Wald= Wald statistic, df= degrees of freedom, Sig. = p-value, 95% Model R^2 = the approximate amount of variability in the dependent variable explained by the chosen predictor variables . * = significant at the 0.05 significant level (2-tailed).

Note: The formation of these regression models was done using forwards and backwards selection. To begin the modelling process, all potential predictors were placed in the model together to determine any possible significant predictors. In doing this only neck pain and past concussion were significant. Variables were then removed, one-by-one, based on the highest p-values. After identifying the strongest possible predictors for each category of independent variables, demographics, covariates, anthropometry, and strength, multiple models (shown above) were evaluated using forwards and backwards selection. The final regression model presented here as “significant predictors” and provided in Table 3.0 best fit the data while ensuring not to invalidate the regression model with too many predictor variables for the number of concussion events.

Chapter Three

Title of Paper: Symptom intensity and neck pain predict the length of concussion recovery in Canadian university athletes.

Authors: Erin E. Cole, BSc., Anita Gross, MSc., BScPT, Ira Price, MD., FRCPC, Carol DeMatteo MSc., Dip P & OT, OT Reg (Ont),

To be submitted to: *British Journal of Sports Medicine*

ABSTRACT

Objective: To explore the predictors of total recovery and time to return to play in university athletes?

Methods: Varsity athletes from high risk sports were recruited to be followed over the course of one athletic season. Prior to beginning competition, athletes completed basic questionnaires of past-medical history and current health status. Anthropometric measures were collected along with neck flexor and extensor endurance tests to assess neck strength. Athletes with suspected concussions were assessed on the sideline using the SCAT3 and evaluated by a team physician for diagnosis. All concussed athletes were monitored during recovery until return-to-play.

Main Results: Thirty-five athletes (15%) experienced a concussion over the athletic season. The average amount of time to return to play was 18 days. Basketball athletes reported the longest time to recovery (mean= 22 days). Strength- and anthropometric-based variables were included in the preliminary predictive model along with total symptom score, history of concussion, neck pain and sport. Symptom scores and the presence of neck pain were the only two significant predictors of time to return to play.

Conclusion: Individual neck strength scores are not predictive of recovery time. Symptom intensity and neck pain are the most significant predictors of length of recovery in varsity

athletes. The relationship between neck strength and neck pain with respect to recovery time should be explored further.

Introduction

1.6 to 3.8 million sports-related concussions (SRC) reportedly take place each year in the United States (Center for Disease Control et al., 2011; Gessel et al., 2007). The majority of SRCs occur in athletes between the ages of 14 and 22. While high school athletes report a greater number of SRC overall, a by-sport comparison of high school and college athletes has demonstrated that college athletes report a higher number of concussions in comparison to their younger counterparts in the same sport. The National Collegiate Athletic Association (NCAA) reports approximately 10% of all varsity athletes sustain a concussion in a year (K. Guskiewicz et al., 2003a). The data on the incidence of concussion in Canadian varsity athletes is scarce. A 2017 study of Canadian university athletes reports findings similar to that of larger American cohort studies (Black et al., 2017). Symptoms of concussion are classified as somatic, cognitive, emotional, and sleep related with headache being the most frequently reported symptom. Most athletes recover spontaneously from concussion within seven to 14 days(Kimberly G Harmon et al., 2013; H. J. McCrea, Perrine, Niogi, & Hartl, 2012). However, about 10% of athletes will experience concussion symptoms persisting longer than the expected two-week period (Mccrea et al., 2016). Prolonged concussion recovery is called post-concussion syndrome (PCS). There is much debate over the criteria for diagnosis of PCS. The World Health Organization defines PCS as the presence of three or more symptoms for more than four weeks (World Health Organization (WHO), 2011). However, a study that surveyed over 500 physicians reported that most doctors diagnose the presence of PCS after an athlete has experienced at least one concussion symptom for at least four weeks (Rose et al., 2015).

Predictors of prolonged concussion recovery have been studied extensively in youth and high school aged athletes. Initial studies, mostly on high school athletes, indicate the strongest predictors of concussion risk to include female sex, past concussion diagnosis, and a history of migraines (Harvey, Hall, Patel, Barnes, & Ketcham, 2017; McCrory et al., 2013). These risk factors are not well supported in the literature on collegiate athletes. A 2017 study by Harvey and colleagues found there to be no significant differences in concussion recovery time for sex, history of concussion, or the past diagnosis of migraines. However, this study included a small sample size and excluded athletes who took longer than 30 days to recover. Additionally, they included athletes from sports that are not considered high risk for concussion as per the current literature, such as tennis and golf (Harvey et al., 2017). Further exploration into the risk factors for PCS within the university athlete population is required.

Acute concussion symptoms seriously impair a student-athlete's ability to fulfill their academic responsibilities, impede their athletic performance, and restrict their ability to carry out simple tasks of daily life. Furthermore, there is much speculation surrounding an increased risk of developing depression and anxiety in athletes with PCS (Stazyk, 2015). There is minimal literature detailing the long-term sequelae associated with PCS however, the symptomology and perpetuation of mental health issues necessitates examination of the risk factors associated with recovery in a university varsity athlete cohort.

Recent literature on concussion risk has presented the possibility that body morphology and muscle strength may be important factors in determining who is at greatest risk for sustaining a concussion. In 2014, Collins published a paper demonstrating there to be significant differences in neck muscle strength of concussed and non-concussed high school athlete (C. L. Collins et al., 2014b). The methods for clinical neck strength testing in an athlete population are not well documented in the literature and the use of a tension-scale in the Collins study may have introduced significant variability in the strength measurements obtained for each athlete.

Nonetheless, variability in strength in highly trained university athletes has been documented. One study examined the variability in neck strength among elite rugby athletes and found there to be significant differences in strength between athletes of different positions (Geary et al., 2014; Tierney et al., 2008a). Furthermore these differences were associated with increased risk for cervical spine injuries in the athletes with weaker neck musculature. A study examining the head kinematics and anticipatory or “bracing” response to external force in female athletes produced similar findings. Female athletes had a decreased anticipatory response to an external load and therefore were unable to resist the impact as well as their male counterparts (Tierney et al., 2005, 2008a). The extent to which body size and muscle strength influence concussion symptom severity or return-to-play time has yet to be examined. Research into this topic could provide valuable insight into concussion management and prevention strategies. The purpose of this study was to examine the relationship of neck muscle strength, concussion symptom scores, and other possible covariates on the length of concussion recovery time between male and female university athletes. The hypothesis being that if neck strength has a protective effect on head movement, it may relate to a less serious injury and thus a shorter recovery period.

Methods

Participants

A convenience sample of male and female varsity athletes from McMaster University in Hamilton, Ontario were recruited to participate in this study. Participating athletes were from “high-risk” concussion sports including basketball, women’s cheerleading, men’s football, women’s hockey, rugby, and soccer. All athletes had to be considered fit to participate in varsity athletics by team physicians in order to be enrolled in the study. The Hamilton Integrated Research Ethics board approved all study procedures (#1924).

Procedures

Pre-season Assessment

After providing informed consent, athletes were assessed at pre-season prior to competition and followed over the course of their athletic season for one academic year (August to April, 2017).

*Past Medical History Assessmen*t – Athletes were asked several questions to evaluate the presence of the potential covariates: 1) a prior history of concussion, 2) neck pain or injury, 3) the presence of anxiety and depression (Iverson et al., 2017) at the time of assessment. Data intake forms are found in Appendix 1.

Neck Strength and Anthropometric Evaluation – Neck strength evaluation was completed using the deep neck flexor endurance (DNF) test and neck extensor endurance test. The DNF endurance test has been used in a healthy adult population and has moderate to excellent reliability (ICC 2,1 = 0.67-0.78, ICC 3,1 = 0.82-0.91) (Harris et al., 2005). The procedures for all strength and anthropometric assessments can be found in Table 1.0

< INSERT TABLE 1.0 HERE>

Concussion Assessment

McMaster university protocol is to remove any athlete with a suspected concussion from the field of play for assessment. At the time of injury SCAT3 was administered to every athlete with suspected concussion for baseline evaluation either by a trained student athletic therapist under direct supervision or the team's head therapist. Following a possible concussion all athletes were seen by the team physician. Team therapists reported concussions for their team to study staff weekly. A copy of each concussed athletes SCAT3 scores were recorded. Athletes who were diagnosed by their team physician as having sustained a concussion, were monitored throughout their recovery.

Outcome Measures

Primary Outcome Measure

The primary outcome measure for this study was the length of time it took the athlete to return to competition following a concussion. Concussed athletes were followed as they completed the McMaster University protocol for concussion recovery. Athletes are restricted to absolute physical and cognitive rest while they are symptomatic. McMaster University obtains baseline Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT) scores for all incoming athletes participating in high-risk for concussion sports to help determine cognitive function of athletes prior to injury. While this information was not considered for this study it is important to note that this information helped to guide diagnosis. Once asymptomatic following a concussion, athletes were required to repeat the ImPACT test. The team physician and lead athletic therapist reviewed the scores of the ImPACT test and the symptoms reported by the athletes to determine if they are fit to begin a graduated return-to-play protocol based on the Zurich and the Berlin consensus statements on concussion in sport (McCrory et al., 2013, 2017). Athletes progress through the five return-to-play stages and are required to remain asymptomatic before advancing. Study partipants were followed over their course of recovery. The combined total amount of time until the athlete was asymptomatic and the time required to complete a graded return-to-play protocol was considered to be the total recovery time.

Statistical Analysis

A multiple regression analysis was conducted to determine the predictive model for time to return-to-play. Summary statistics were carried out on the key variables as means and standard deviations for continuous data and medians and quartiles for categorical data (Table 2.0).

Differences in recovery time between men and women and between sports were evaluated using the Wilcoxon rank sum test and a one-way analysis of variance. Given that the normality assumption was not met we transformed the dependent variable (time to return-to-play) into the natural logarithm of the time to return–to-play. A forward-stepwise regression was conducted to determine the best predictive model.

<<INSERT TABLE 2.0 ABOUT HERE>>

Results

A total of 246 athletes were assessed pre-season. Thirty-five athletes (15%) sustained a concussion over the course of the year. Four athletes (11%) sustained a second concussion in the same season. Descriptive statistics for all independent and dependent variables are reported in Table 2.0. The average total recovery time to return to competition was 17.68 days for all athletes. Male athletes recovered on average 17 days while females took longer, averaging 19 days to recover. There were no significant differences in recovery time between the sexes (p=0.499). The average amount of time an athlete was symptomatic was 11 days. No significant differences in symptom duration were noted between men and women (p=0.279).

Basketball athletes experienced the longest average recovery at 22 days. Rugby athletes reported the second longest recovery time, averaging 18 days however, these athletes had the greatest range in their time to recovery from five to 58 days. Football athletes recovered in an average of 17 days while soccer players recovered the fastest with total recovery time averaging 13 days. However, no significant differences in recovery time was noted between the sports (p= 0.320). With respect to prolonged recovery (longer than 28 days) only two males and two females experienced concussion symptoms beyond four weeks. The mean time to recover for these men and women were 50 and 42 days, respectively.

Eighty-eight percent of male athletes (n=22) and 70% of females (n=7) reported a history of past concussion. Yet, there were no differences in recovery time in athletes with a history of previous concussion (p=0.0503). Depression was scarcely reported in our athlete cohort, 12% of male athletes (n=3) reported a history of depression at pre-season assessment. No females reported a history of any mental health issues. There were no significant differences in recovery time between men who reported a history of depression and those who did not (p= 0.402).

Symptom intensity was measured using the symptom scores on the SCAT3. The mean score for all athletes was 22 (out of a maximum score of 132). There was no difference in symptom intensity between males (mean score =21) and females (mean score = 25.2) (z= -0.402, p= 0.688). Similarly, no differences in symptom intensity were reported between sports (p=0.358). While there were no significant differences in symptom score between males and females or between sport, symptom intensity was a significant predictor of recovery time in athletes.

Thirty-five percent of athletes (n=12) reported the presence of pre-season neck pain. Seventy-five percent of these athletes were males (n=9) however, no significant differences in neck pain was reported between male and female athletes (p=0.357). Neck pain was a significant predictor of recovery time in athletes.

Regression analysis

Symptom intensity and neck pain were the only two variables in our final regression model. Neck flexor strength and neck endurance strength were not individually predictive of recovery time in the final regression model. No anthropometric variables (height, weight, head circumference, neck circumference, and neck length) were significant in the overall regression model of concussion recovery time. Covariates for concussion risk including, past concussion history and depression were not significant predictors of recovery time.

Symptom score was the most significant predictor of concussion recovery (coefficient = 0.024, p=< 0.001). Neck pain was the only other significant predictor of recovery time (coefficient = -0.3089, p=<0.040). The negative coefficient demonstrates that neck pain has an inverse relationship to recovery time. Athletes without neck pain reported longer recovery time (average recovery time = 19.63 days) compared to those with neck pain (average recovery time = 13.45 days), though these differences were not statistically significant (z = 1.477, p= 0.1396).The final regression model for all athletes is $y = 2.276+0.0238x_1-0.3089x_2$, where x_1 is symptom score and x_2 is the presence of neck pain. The model is significant with $p \leq 0.001$, $F_{(2,32)} = 24.98$ and adjusted R-squared value = 0.585.

Discussion

These results provide information on predictors of prolonged concussion recovery in a varsity athlete cohort. Neither sex nor age were predictive of length of recovery. Multiple studies have suggested that younger athletes and female athletes report prolonged concussion recovery and are at greater risk for PCS (Iverson et al., 2017). It is possible that age is not predictive of concussion recovery given the narrow age range of the athlete population assessed. Sex may not be predictive in this cohort given that only ten females sustained a concussion in the season. A longer assessment period over multiple seasons may have provided a more robust examination of concussion recovery in a more balanced sample of concussed males and females.

A 2017 systematic review by Iverson and colleagues demonstrated that athletes who report greater intensity of acute symptoms, as well as pre-injury depression and attention deficit hyper-activity disorder(ADHD) experience longer recovery time (Henry, Elbin, Collins, Marchetti, & Kontos, 2016; Iverson et al., 2017). ADHD diagnosis was not reported by any athletes in our cohort and the presence of depression was not significant in predicting total recovery time. Intensity of symptoms was significant in our final regression model. Athletes who reported more intense symptoms during their acute injury assessment on the SCAT3 took longer to recover. The most common symptom reported on the SCAT3 was headache with 97% of athletes reporting headache (n=34).

A large body of literature reports concussion symptoms spontaneously resolve within a 10-day period(Mccrea et al., 2016). Women have been reported to experience more intense acute symptoms and are at a greater risk of an extended recovery period (Scopaz & Hatzenbuehler, 2013). The results of this study are similar to the findings in the literature as male athletes reported being symptomatic for an average of 10 days while women were symptomatic for an average of 13 days. Despite women being symptomatic for longer than men, both sexes symptoms resolved within what is considered in the literature as a normal recovery period. A study on the incidence and clinical course of concussion recovery in high school and college athletes reported that that only a 10% will experience symptoms beyond the expected two-week recovery period (Mccrea et al., 2016). Our results report similar findings as 11% experienced concussion beyond four weeks (n=4). There were no differences in this extended recovery time between males and females (p=0.227).

It is well documented in the literature that athletes who participate in contact or collision sports are at greater risk for concussions (Abrahams et al., 2014). Athletes from football, soccer, rugby, and basketball sustained concussions during the athletic season with the majority of concussed athletes participating in rugby (57% of concussions). Sport was not significant in determining recovery time. Basketball athletes reported the longest recovery time. A 2016 looking at the physiology of prolonged concussion demonstrated prolonged symptoms were more common in ice hockey athletes(Mccrea et al., 2016). Similarly, a review of the risk modifiers for prolonged concussion reported males in contact sports such as hockey and football and female soccer are at greater risk for prolonged recovery than other athletes. We discovered similar findings in our smaller cohort of concussed athletes 57% were athletes from contact sports (n=28). No female hockey players sustained a concussion and men's hockey athletes were unavailable for assessment these results exclude an important athlete population. As such future studies examining predictors of prolonged recovery should be sure to include hockey athletes.

Limitations

This study is not without limitations. We acknowledge that the overall number of concussion injuries (n=35), while representing 15% of our athlete population, is small in absolute terms due to the short observation period and therefore a predictive model may be harder to validate than if the study captured concussions and recovery time over several seasons. Furthermore, the predictive variables considered in the model were those considered to have the most influence as confounding factors or covariates based on the current literature in addition to the strength and anthropometric variables considered in our research objectives. The inclusion of other confounding variables to recovery such as amount of screen time, time spent studying, alcohol consumption, and number of hours of sleep per night could also be considered important in determining recovery time in university athletes, but these were not available.

Conclusion

Symptom intensity and neck pain are the most significant predictors of length of recovery in varsity athletes. Neck pain was inversely related to length of recovery time. Individual neck strength scores are not predictive of recovery time. A longer recovery surveillance and more thorough evaluation of the differences in recovery between sports and gender should be considered.

References

Abrahams, S., Mc Fie, S., Patricios, J., Posthumus, M., & September, A. V. (2014). Risk factors for sports concussion: an evidence-based systematic review. *British Journal of Sports Medicine*, *48*(2), 91–97. https://doi.org/10.1136/bjsports-2013-092734

Alla, S., Sullivan, S. J., Hale, L., & McCrory, P. (2009). Self-report scales/checklists for the measurement of concussion symptoms: a systematic review. *British Journal of Sports Medicine*, *43 Suppl 1*, i3–i12. https://doi.org/10.1136/bjsm.2009.058339

Angelica, M. D., & Fong, Y. (2008). Effect of Neck Strength and Anticipatory Activation in Response to Head Impulsive Loads. *American Journal of Public Health*, *141*(4), 520–529. https://doi.org/10.1016/j.surg.2006.10.010.Use

Association, T. N. C. A. (2013). *NCAA sports medicine handbook, Guideline 21: Sports-related concussion*. Idianapolis, IN. https://doi.org/10.1136/bjsm.34.3.230-a

Bakhos, L. L., Lockhart, G. R., Myers, R., & Linakis, J. G. (2010). Emergency Department Visits for Concussion in Young Child Athletes. *Pediatrics*, *126*(3), e550–e556. https://doi.org/10.1542/peds.2009-3101

Barr, W. B., & McCrea, M. (2001). Sensitivity and specificity of standardized neurocognitive testing immediately following sports concussion.[Erratum appears in J Int Neuropsychol Soc 2002 Mar;8(3):481]. *Journal of the International Neuropsychological Society*, *7*(6), 693–702.

Bazarian, J. J., Zhong, J., Blyth, B., Zhu, T., Kavcic, V., & Peterson, D. (2007). Diffusion Tensor Imaging Detects Clinically Important Axonal Damage after Mild Traumatic Brain Injury: A Pilot Study. *Journal of Neurotrauma*, *24*(9), 1447–1459. https://doi.org/10.1089/neu.2007.0241

Bell, David R. Guskiewicz, Kevin M. Clark, Michael A. Padua, D. A. (2011). Systematic Review of the Balance Error Scoring System. *Athletic Training*, *3*(3), 287–295. https://doi.org/10.1177/1941738111403122

Benson, B. W., Hamilton, G. M., Meeuwisse, W. H., McCrory, P., & Dvorak, J. (2009). Is protective equipment useful in preventing concussion? A systematic review of the literature. *British Journal of Sports Medicine*, *43*(Suppl_1), i56–i67. https://doi.org/10.1136/bjsm.2009.058271

Benson, B. W., McIntosh, A. S., Maddocks, D., Herring, S. A., Raftery, M., & Dvorak, J. (2013). What are the most effective risk-reduction strategies in sport concussion? *Br J Sports Med*, *47*(5), 321–326. https://doi.org/10.1136/bjsports-2013-092216\r47/5/321 [pii]

Benson, B. W., McIntosh, A. S., Maddocks, D., Herring, S. A., Raftery, M., & Dvořák, J. (2013). What are the most effective risk-reduction strategies in sport concussion? *British Journal of Sports Medicine*, *47*(5), 321–326. https://doi.org/10.1136/bjsports-2013-092216

Black, A. M., Sergio, L. E., & Macpherson, A. K. (2017). The Epidemiology of Concussions: Number and nature of concussions and time to recovery among female and male canadian varsity athletes 2008 to 2011. *Clinical Journal of Sport Medicine*, *27*, 52–56. Retrieved from http://www.cjsportmed.com/%0Ahttp://ovidsp.ovid.com/ovidweb.cgi?T=JS&PAGE=reference&D=emed18b&NEWS=N&AN=608297429

Bleiberg, J., Cernich, A. N., Cameron, K., Sun, W., Peck, K., Ecklund, J., … Bailes, J. E. (2004). Duration of Cognitive Impairment after Sports Concussion. *Neurosurgery*, *54*(5), 1073–1080. https://doi.org/10.1227/01.NEU.0000155093.00745.B4

Bloom, G. A., Loughead, T. M., Shapcott, E. J. B., Johnston, K. M., & Delaney, J. S. (2008).

The prevalence and recovery of concussed male and female collegiate athletes. *European Journal of Sport Science*, *8*(5), 295–303. https://doi.org/10.1080/17461390802251836

Borich, M. R., Cheung, K. L., Jones, P., Khramova, V., Gavrailoff, L., Boyd, L. A., & Virji-Babul, N. (2013). Concussion: Current Concepts in Diagnosis in Management. *Journal of Neurologic Physical Therapy*, *37*(3), 133–139. https://doi.org/10.1097/NPT.0b013e31829f7460

Broglio, S. P., Ferrara, M. S., Sopiarz, K., & Kelly, M. S. (2008). Reliable change of the sensory organization test. *Clinical Journal of Sport Medicine*, *18*(2), 148–154. https://doi.org/10.1097/JSM.0b013e318164f42a

Broglio, S. P., Macciocchi, S. N., & Ferrara, M. S. (2007). Sensitivity of the concussion assessment battery. *Neurosurgery*, *60*(6), 1050–1057. https://doi.org/10.1227/01.NEU.0000255479.90999.C0

Broglio, S. P., Sosnoff, J. J., Shin, S., He, X., Alcaraz, C., & Zimmerman, J. (2009). Head Impacts During High School Football: A Biomechanical Assessment, *44*(4), 342–349.

Center for Disease Control, Gilchrist, J., Thomas, K. E., Xu, L., McGuire, L. C., & Coronado, V. (2011). Nonfatal traumatic brain injuries related to sports and recreation activities among persons aged ≤19 years--United States, 2001-2009. *MMWR. Morbidity and Mortality Weekly Report*, *60*(39), 1337–1342. https://doi.org/mm6039a1 [pii]

Collie, A. (2006). Cognition in the days following concussion: comparison of symptomatic versus asymptomatic athletes. *Journal of Neurology, Neurosurgery & Psychiatry*, *77*(2), 241–245. https://doi.org/10.1136/jnnp.2005.073155

Collins, C. L., Fletcher, E. N., Fields, S. K., Kluchurosky, L., Rohrkemper, M. K., Comstock, R. D., & Cantu, R. C. (2014a). Neck Strength: A Protective Factor Reducing Risk for Concussion in High School Sports. *Journal of Primary Prevention*, *35*(5), 309–319. https://doi.org/10.1007/s10935-014-0355-2

Collins, C. L., Fletcher, E. N., Fields, S. K., Kluchurosky, L., Rohrkemper, M. K., Comstock, R. D., & Cantu, R. C. (2014b). Neck Strength: A Protective Factor Reducing Risk for Concussion in High School Sports. *Journal of Primary Prevention*, *35*(5), 309–319. https://doi.org/10.1007/s10935-014-0355-2

Collins, M., Lovell, M. R., Iverson, G. L., Ide, T., & Maroon, J. (2006). Examining concussion rates and return to play in high school football players wearing newer helmet technology: A three-year prospective cohort study. *Neurosurgery*, *58*(2), 275–284. https://doi.org/10.1227/01.NEU.0000200441.92742.46

Concussion, S., Tool, A., & Assessment, S. (2013). SCAT3, 259–263.

Covassin, T., Swanik, C. B., & Sachs, M. L. (2003). Sex differences and the incidence of concussions among collegiate athletes. *Journal of Athletic Training (National Athletic Trainers' Association)*, *38*(3), 238–244. Retrieved from http://spot.lib.auburn.edu/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=cin20&AN=2004046415&site=ehost-live

Covassin, T., Swanik, C. B., & Sachs, M. L. (2003). Sex Differences and the Incidence of Concussions Among Collegiate Athletes. *Journal of Athletic Training (National Athletic Trainers' Association)*, *38*(3), 238. Retrieved from http://search.ebscohost.com.lib-proxy.fullerton.edu/login.aspx?direct=true&db=s3h&AN=11720753&site=ehost-live&scope=site

Cramer, C. R. (1999). A Reconditioning Program to Lower the Recurrence Rate of Brachial Plexus Neurapraxia in Collegiate Football Players. *Journal of Athletic Training*, *34*(4), 390–

396.

Daneshvar, D. H., Nowinski, C. J., Mckee, A. C., & Cantu, R. C. (2011). The Epidemiology of Sport-Related Concussion. *Clinics in Sports Medicine*, *30*(1), 1–17. https://doi.org/10.1016/j.csm.2010.08.006

de Koning, C. H. P., van den Heuvel, S. P., Staal, J. B., Smits-Engelsman, B. C. M., & Hendriks, E. J. M. (2008). Clinimetric evaluation of methods to measure muscle functioning in patients with non-specific neck pain: a systematic review. *BMC Musculoskeletal Disorders*, *9*, 142. https://doi.org/10.1186/1471-2474-9-142

Dvorak, J., Mccrory, P., Kirkendall, D. T., & Klinik, S. (2007). Head injuries in the female football player: incidence, mechanisms, risk factors and management. *Br J Sports Med*, *41*, 44–46. https://doi.org/10.1136/bjsm.2007.037960

Eckner, J. T., Oh, Y. K., Joshi, M. S., Richardson, J. K., & Ashton-Miller, J. A. (2014). Effect of neck muscle strength and anticipatory cervical muscle activation on the kinematic response of the head to impulsive loads. *The American Journal of Sports Medicine*, *42*(3), 566–576. https://doi.org/10.1177/0363546513517869

Emery, C. A., Black, A. M., Kolstad, A., Martinez, G., Nettel-Aguirre, A., Engebretsen, L., … Schneider, K. (2017a). What strategies can be used to effectively reduce the risk of concussion in sport? *British Journal of Sports Medicine*, bjsports-2016-097452. https://doi.org/10.1136/bjsports-2016-097452

Emery, C. A., Black, A. M., Kolstad, A., Martinez, G., Nettel-Aguirre, A., Engebretsen, L., … Schneider, K. (2017b). What strategies can be used to effectively reduce the risk of concussion in sport? *British Journal of Sports Medicine*, bjsports-2016-097452. https://doi.org/10.1136/bjsports-2016-097452

Franco, J. L., & Herzog, W. (1987). A comparative assessment of neck muscle strength and vertebral stability. *The Journal of Orthopaedic and Sports Physical Therapy*, *8*(7), 351–356. https://doi.org/10.2519/jospt.1987.8.7.351

Gardner, A., Kay-Lambkin, F., Stanwell, P., Donnelly, J., Williams, W. H., Hiles, A., … Jones, D. K. (2012). A Systematic Review of Diffusion Tensor Imaging Findings in Sports-Related Concussion. *Journal of Neurotrauma*, *29*(16), 2521–2538. https://doi.org/10.1089/neu.2012.2628

Geary, K., Green, B. S., & Delahunt, E. (2013). Intrarater reliability of neck strength measurement of rugby union players using a handheld dynamometer. *Journal of Manipulative and Physiological Therapeutics*, *36*(7), 444–449. https://doi.org/10.1016/j.jmpt.2013.05.026

Geary, K., Green, B. S., & Delahunt, E. (2014). Effects of Neck Strength Training on Isometric Neck Strength in Rugby Union Players. *Clin J Sport Med*, *6*(24), 502–508. https://doi.org/10.1097/JSM.0000000000000071

Gessel, L. M., Fields, S. K., Collins, C. L., Dick, R. W., & Comstock, R. D. (2007). Concussions among United States high school and collegiate athletes. *Journal of Athletic Training (National Athletic Trainers' Association)*, *42*(4), 495–503. Retrieved from http://spot.lib.auburn.edu/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=cin20&AN=2009759920&site=ehost-live

Giza, C. C. (2014). The New Metabolic Cascade of Concussion, *75*(0 4), S24–S33. https://doi.org/10.1227/NEU.0000000000000505.The

Giza, C. C., & Hovda, D. A. (2001). The Neurometabolic Cascade of Concussion. *Journal of Athletic Training*, *36*(3), 228–235. https://doi.org/10.1227/NEU.0000000000000505

Greenhill, D. A., Navo, P., Zhao, H., Torg, J., Comstock, R. D., & Boden, B. P. (2016). Inadequate Helmet Fit Increases Concussion Severity in American High School Football Players. *Sports Health*, *8*(3), 238–243. https://doi.org/10.1177/1941738116639027

Guskiewicz, K. M. (2011). Balance Assessment in the Management of Sport-Related Concussion. *Clinics in Sports Medicine*, *30*(1), 89–102. https://doi.org/10.1016/j.csm.2010.09.004

Guskiewicz, K. M., Weaver, N. L., Padua, D. A., Garrett, W. E., Hill, C., & Carolina, N. (2000). Epidemiology of Concussion in Collegiate and High School Football Players, *28*(5).

Guskiewicz, K., Mccrea, M., Marshall, S. W., Cantu, R. C., Randolph, C., Barr, W., … Kelly, J. P. (2003a). The NCAA Concussion Study. *Journal of the American Medical Association*, *290*(19), 2549–2555.

Guskiewicz, K., Mccrea, M., Marshall, S. W., Cantu, R. C., Randolph, C., Barr, W., … Kelly, J. P. (2003b). The NCAA Concussion Study. *Journal of the American Medical Association*, *290*(19), 2549–2555.

Halstead, M. E., & Walter, K. D. (2010). Sport-Related Concussion in Children and Adolescents. *Pediatrics*, *126*(3), 597–615. https://doi.org/10.1542/peds.2010-2005

Hamilton, D. F., Gatherer, D., Maclean, J. G. B., Hutchison, J. D., Nutton, R. W., & Simpson, A. H. R. W. (2012). Age-related differences in the neck strength of adolescent rugby players A CROSS-SECTIONAL COHORT STUDY OF SCOTTISH SCHOOLCHILDREN. *Bone Joint Res*, *1*(7), 152–157.

Harmon, K. G., Drezner, J. A., Gammons, M., Guskiewicz, K. M., Halstead, M., Herring, S. A., … Roberts, W. O. (2013). American Medical Society for Sports Medicine position statement: concussion in sport. *British Journal of Sports Medicine*, *47*(1), 15–26. https://doi.org/10.1136/bjsports-2012-091941

Harmon, K. G., Drezner, J. A., Gammons, M., Guskiewicz, K. M., Halstead, M., Herring, S. A., … Roberts, W. O. (2013). American Medical Society for Sports Medicine position statement: concussion in sport. *Br.J Sports Med*, *47*(1), 15–26. https://doi.org/10.1136/bjsports-2012-091941

Harris, K. D., Heer, D. M., Roy, T. C., Santos, D. M., Whitman, J. M., & Wainner, R. S. (2005). Reliability of a measurement of neck flexor muscle endurance. *Physical Therapy*, *85*(12), 1349–1355.

Harvey, K. P., Hall, E. E., Patel, K., Barnes, K. P., & Ketcham, C. J. (2017). Potential factors influencing recovery from concussion in collegiate student-athletes. *Journal of Concussion*, *1*, 205970021770708. https://doi.org/10.1177/2059700217707084

Henry, L. C., Elbin, R. J., Collins, M. W., Marchetti, G., & Kontos, A. P. (2016). Examining recovery trajectories after sport-related concussion with a multimodal clinical assessment approach. *Neurosurgery*, *78*(2), 232–240. https://doi.org/10.1227/NEU.0000000000001041

Holbourn, A. H. S. (1943). Mechanics of head injuries. *Lancet*, *242*(6267), 438–441. https://doi.org/10.1016/S0140-6736(00)87453-X

Hrysomallis, C. (2016). Neck Muscular Strength, Training, Performance and Sport Injury Risk: A Review. *Sports Medicine*. https://doi.org/10.1007/s40279-016-0490-4

Iverson, G. L., Gardner, A. J., Terry, D. P., Ponsford, J. L., Sills, A. K., Broshek, D. K., & Solomon, G. S. (2017). Predictors of clinical recovery from concussion: A systematic review. *British Journal of Sports Medicine*, *51*(12), 941–948. https://doi.org/10.1136/bjsports-2017-097729

Iverson, G. L., Lovell, M. R., & Collins, M. W. (2003). Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT) Normative Data.

Iverson, G. L., Silverberg, N. D., Mannix, R., Maxwell, B. a., Atkins, J. E., Zafonte, R., & Berkner, P. D. (2015). Factors Associated With Concussion-like Symptom Reporting in High School Athletes. *JAMA Pediatrics*, *169*(10), 1–9. https://doi.org/10.1001/jamapediatrics.2015.2374

Johnston, K. M., McCrory, P., Mohtadi, N. G., & Meeuwisse, W. (2001). Evidence-based review of sport-related concussion: clinical science. *Clinical Journal of Sport Medicine*, *11*, 150–159. https://doi.org/10.1097/00042752-200107000-00005

Jull, G. A., O'Leary, S. P., & Falla, D. L. (2008). Clinical Assessment of the Deep Cervical Flexor Muscles: The Craniocervical Flexion Test. *Journal of Manipulative and Physiological Therapeutics*, *31*(7), 525–533. https://doi.org/10.1016/j.jmpt.2008.08.003

Kemp, S., Hudson, Z., Brooks, J., Fuller, C. (2008). The Epidemiology of Head Injuries in English Professional Rugby Union. *Clinical Journal of Sport Medicine*, *18*(3). https://doi.org/10.1177/0363546507300691

Khong, E., Odenwald, N., Hashim, E., & Cusimano, M. D. (2016). Diffusion tensor imaging findings in post-concussion syndrome patients after mild traumatic brain injury: A systematic review. *Frontiers in Neurology*, *7*(SEP), 1–8. https://doi.org/10.3389/fneur.2016.00156

King, A., Yang, K., & Zhang, L. (2003). Is head injury caused by linear or angular acceleration. *IRCOBI Conference*, (September), 1–12. Retrieved from http://snell-helmets.org/docs/articles/hic/King_IRCOBI_2003.pdf

Koeppen & Stanton. (2017). *Berne and Levy Physiology*. St. Louis: Elsevier Health Sciences. Retrieved from https://www-clinicalkey-com.libaccess.lib.mcmaster.ca/#!/browse/book/3-s2.0-C20110061689

Koerte, I. K., Ertl-Wagner, B., Reiser, M., Zafonte, R., & Shenton, M. E. (2012). White matter integrity in the brains of professional soccer players without a symptomatic concussion. *Journal of the American Medical Association*, *308*(18).

Kroshus, E., Daneshvar, D. H., Baugh, C. M., Nowinski, C. J., & Cantu, R. C. (2014). NCAA concussion education in ice hockey : an ineffective mandate. *British Journal of Sports Medicine*, *48*((2)), 135–140. https://doi.org/10.1136/bjsports-2013-092498

Kutcher, J. S., & Eckner, J. T. (2010). At-risk populations in sports-related concussion. *Current Sports Medicine Reports*, *9*(1), 16–20. https://doi.org/http://dx.doi.org/10.1249/JSR.0b013e3181caa89d

Lavallee, A. V., Ching, R. P., & Nuckley, D. J. (2013). Developmental biomechanics of neck musculature. *Journal of Biomechanics*, *46*(3), 527–534. https://doi.org/10.1016/j.jbiomech.2012.09.029

Leddy, J. J., Baker, J. G., & Willer, B. (2016). Active Rehabilitation of Concussion and Post-concussion Syndrome. *Physical Medicine and Rehabilitation Clinics of North America*, *27*(2), 437–454. https://doi.org/10.1016/j.pmr.2015.12.003

Leddy, M. H., Lambert, M. J., & Ogles, B. M. (1994). Psychological consequences of athletic injury among high-level competitors. *Research Quarterly for Exercise and Sport*, *65*(4), 347–354. https://doi.org/10.1080/02701367.1994.10607639

Lindstrøm, R., Schomacher, J., Farina, D., Rechter, L., & Falla, D. (2011). Association between neck muscle coactivation , pain , and strength in women with neck pain. *Manual Therapy*, *16*(1), 80–86. https://doi.org/10.1016/j.math.2010.07.006

Littleton, A., & Guskiewicz, K. (2013). Current concepts in sport concussion management: A multifaceted approach. *Journal of Sport and Health Science*, *2*(4), 227–235. https://doi.org/10.1016/j.jshs.2013.04.003

Llewellyn, T., Burdette, G. T., Joyner, a B., & Buckley, T. a. (2014). Concussion reporting rates at the conclusion of an intercollegiate athletic career. *Clinical Journal of Sport Medicine : Official Journal of the Canadian Academy of Sport Medicine*, *24*(1), 76–79. https://doi.org/10.1097/01.jsm.0000432853.77520.3d

Longhi, L., Saatman, K. E., Fujimoto, S., Raghupathi, R., Meaney, D. F., Davis, J., … McIntosh, T. K. (2005). Temporal window of vulnerability to repetitive experimental concussive brain injury. *Neurosurgery*, *56*(2), 364–373. https://doi.org/10.1227/01.NEU.0000149008.73513.44

Lourenço, A. S., Lameiras, C., & Silva, A. G. (2016). Neck Flexor and Extensor Muscle Endurance in Subclinical Neck Pain: Intrarater Reliability, Standard Error of Measurement, Minimal Detectable Change, and Comparison With Asymptomatic Participants in a University Student Population. *Journal of Manipulative and Physiological Therapeutics*, *39*(6), 427–433. https://doi.org/10.1016/j.jmpt.2016.05.005

Majerske, C. W., Mihalik, J. P., Ren, D., Collins, M. W., Reddy, C. C., Lovell, M. R., & Wagner, A. K. (2008). Concussion in sports: Postconcussive activity levels, symptoms, and neurocognitive performance. *Journal of Athletic Training*, *43*(3), 265–274. https://doi.org/10.4085/1062-6050-43.3.265

Manley, G. T., Gardner, A. J., Schneider, K. J., Guskiewicz, K. M., Bailes, J., Cantu, R. C., … Iverson, G. L. (2017). A systematic review of potential long-term effects of sport-related concussion, 1–10. https://doi.org/10.1136/bjsports-2017-097791

Marshall, S. W., Guskiewicz, K. M., Shankar, V., McCrea, M., & Cantu, R. C. (2015). Epidemiology of sports-related concussion in seven US high school and collegiate sports. *Injury Epidemiology*, *2*(1). https://doi.org/10.1186/s40621-015-0045-4

Marshall, S. W., Waller, A. E., Dick, R. W., Pugh, C. B., Loomis, D. P., & Chalmers, D. J. (2002). An ecologic study of protective equipment and injury in two contact sports. *International Journal of Epidemiology*, *31*(3), 587–592. https://doi.org/10.1093/ije/31.3.587

McCrea, H. J., Perrine, K., Niogi, S., & Hartl, R. (2012). Cuncussion in sports. *Sports Health: A Multidisciplinary Approach*, *5*(2), 160–164. https://doi.org/10.1177/1941738112462203

McCrea, M., Guskiewicz, K. M., Marshall, S. W., Barr, W., Randolph, C., Cantu, R. C., … Kelly, J. P. (2003a). Acute Effects and Recovery Time Following. *The Journal of the American Medical Association*, *290*(19), 2556–2563. https://doi.org/10.1001/jama.290.19.2556

McCrea, M., Guskiewicz, K. M., Marshall, S. W., Barr, W., Randolph, C., Cantu, R. C., … Kelly, J. P. (2003b). Acute Effects and Recovery Time Following Concussion in Collegiate Football Players. *The Journal of the American Medical Association*, *290*(19), 2556–2563. https://doi.org/10.1001/jama.290.19.2556

Mccrea, M., Guskiewicz, K., Randolph, C., Barr, W. B., Hammeke, T. A., Marshall, S. W., … Kelly, J. P. (2016). Incidence, Clinical Course, and Predictors of Prolonged Recovery Time Following Sport-Related Concussion in High School and College Athletes. *Journal of the International Neuropsychological Society Copyright E INS*, *19*, 22–33. https://doi.org/10.1017/S1355617712000872

McCrea, M., Hammeke, T., Olsen, G., Leo, P., & Guskiewicz, K. (2004). Unreported concussion in high school football players: implications for prevention. *Clin J Sport Med*, *14*(1), 13–17. https://doi.org/10.1097/00042752-200401000-00003

McCrea, M., Kelly, J. P., Randolph, C., Kluge, J., Bartolic, E., Finn, G., & Baxter, B. (1998). Standardized Assessment of Concussion (SAC): On-Site Mental Status Evaluation of the Athlete. *Journal of Head Trauma Rehabilitation*. https://doi.org/10.1097/00001199-199804000-00005

McCrory, P., Meeuwisse, W., Dvorak, J., Aubry, M., Bailes, J., Broglio, S., … Vos, P. E. (2017). Consensus statement on concussion in sport — the 5 th international conference on concussion in sport held in Berlin , October 2016. *British Journal of Sports Medicine*, 1–10. https://doi.org/10.1136/bjsports-2017-097699

Mccrory, P., Meeuwisse, W., Dvořák, J., Aubry, M., Bailes, J., Broglio, S., … Vos, P. E. (2017). Consensus statement on concussion in sport—the 5 th international conference on concussion in sport held in Berlin, October 2016. *Br J Sports Med*, *51*, 838–847. https://doi.org/10.1136/bjsports-2017-097699

McCrory, P., Meeuwisse, W. H., Aubry, M., Cantu, R. C., Dvorák, J., Echemendia, R. J., … Turner, M. (2013). Consensus Statement on Concussion in Sport-The 4th International Conference on Concussion in Sport Held in Zurich, November 2012. *PM and R*, *5*(4), 255–279. https://doi.org/10.1016/j.pmrj.2013.02.012

McLeod, T. C. V., & Leach, C. (2012). Psychometric properties of self-report concussion scales and checklists. *Journal of Athletic Training*, *47*(2), 221–223. https://doi.org/10.4085/1062-6050-47.2.221

Meehan, William P. Mannix, Rebekah C. Stracciolini, Andrea Elbin, R.J. Collins, M. W. (2013). Symptom severity predicts prolonged recovery after sport-related concussion: Age and amnesia do not. *Journal of Pediatrics*, *163*(3), 721–725. https://doi.org/10.1016/j.jpeds.2013.03.012.Symptom

Meeuwisse, W. H., Hagel, B. E., Mohtadi, N. G. H., Butterwick, D. J., & Fick, G. H. (2000). The Distribution of Injuries in Men's Canada West University Football: A 5-year Analysis. *The American Journal of Sports Medicine*, *28*(4), 516–523. https://doi.org/10.1177/03635465000280041201

Misra, J. C., & Chakravarty, S. (1984). A study on rotational brain injury. *Journal of Biomechanics*, *17*(7), 459–466. https://doi.org/10.1016/0021-9290(84)90014-9

Omalu, B. I., DeKosky, S. T., Minster, R. L., Kamboh, M. I., Hamilton, R. L., & Wecht, C. H. (2005). Chronic traumatic encephalopathy in a National Football League player. *Neurosurgery*, *57*(1), 128–133. https://doi.org/10.1227/01.NEU.0000163407.92769.ED

Pagano, Marcello; Gauvreau, K. (2000). *Principles of Biostatistics* (2nd Editio). Belmont,CA: Brooks/Cole.

Parazza, S., Vanti, C., O'Reilly, C., Villafañe, J. H., Tricás Moreno, J. M., & Estébanez De Miguel, E. (2014). The relationship between cervical flexor endurance, cervical extensor endurance, VAS, and disability in subjects with neck pain. *Chiropractic & Manual Therapies*, *22*(1), 10. https://doi.org/10.1186/2045-709X-22-10

Peduzzi, P., Concato, J., Kemper, E., Holford, T.R., Feinstein, A. R. (1996). A Simulation Study of the Number of Events per Variable in Logistic Regression Analysis. *Journal of Clinical Epidemiology*, *49*(12), 1373–1379.

Powell, J. W., & Barber-foss, K. D. (1999). Traumatic Brain Injury in High School Athletes. *JAMA*, *282*(10), 959–963.

Prins, M. L., Alexander, D., Giza, C. C., & Hovda, D. A. (2013). Repeated Mild Traumatic Brain Injury: Mechanisms of Cerebral Vulnerability. *Journal of Neurotrauma*, *30*(1), 30–38. https://doi.org/10.1089/neu.2012.2399

Putukian, M., Echemendia, R., Dettwiler-Danspeckgruber, A., Duliba, T., Bruce, J., Furtado, J. L., & Murugavel, M. (2015). Prospective clinical assessment using sideline concussion assessment tool-2 testing in the evaluation of sport-related concussion in college athletes. *Clinical Journal of Sport Medicine*, *25*(1), 36–42. https://doi.org/10.1097/JSM.0000000000000102

Rishiraj, N., Lorenz, T., Niven, B., & Michel, M. (2009). University men ' s ice hockey : rates and risk of injuries over 6-years. *Sports Medicine*.

Rose, S. C., Fischer, A. N., & Heyer, G. L. (2015). How long is too long ? The lack of consensus regarding the post-concussion syndrome diagnosis, *9052*, 798–803. https://doi.org/10.3109/02699052.2015.1004756

Safinia, C., Bershad, E. M., Clark, H. B., Santacruz, K., Alakbarova, N., Suarez, J. I., & Divani, A. A. (2016). Chronic Traumatic Encephalopathy in Athletes Involved with High- impact Sports. *Journal of Vascular and Interventional Neurology*, *9*(2), 34–48.

Sandel, N. N. K., Lovell, M. R. M., Kegel, N. N. E., Collins, M. W., & Kontos, A. P. (2013). The Relationship of Symptoms and Neurocognitive Performance to Perceived Recovery From Sports-Related Concussion Among Adolescent Athletes. *Applied Neuropsychology: …*, *2*(1), 64–69. https://doi.org/10.1080/21622965.2012.670580

Schatz, P., Pardini, J. E., Lovell, M. R., Collins, M. W., & Podell, K. (2006). Sensitivity and specificity of the ImPACT Test Battery for concussion in athletes. *Archives of Clinical Neuropsychology*, *21*(1), 91–99. https://doi.org/10.1016/j.acn.2005.08.001

Schatz, P., & Sandel, N. (2013). Sensitivity and specificity of the online version of ImPACT in high school and collegiate athletes. *Am J Sports Med*, *41*(2), 321–326. https://doi.org/10.1177/0363546512466038

Schneider, K., Emery, C., Kang, J., Schneider, G., & Meeuwisse, W. (2011). Are pre-season reports of neck pain, dizziness and/or headaches risk factors for concussion in male youth ice hockey players? *British Journal of Sports Medicine*, *45*(4), 319–320. https://doi.org/10.1136/bjsm.2011.084038.28

Schulz, M. R., Marshall, S. W., Mueller, F. O., Yang, J., Weaver, N. L., Kalsbeek, W. D., & Bowling, J. M. (2004). Incidence and risk factors for concussion in high school athletes, North Carolina, 1996-1999. *American Journal of Epidemiology*, *160*(10), 937–944. https://doi.org/10.1093/aje/kwh304

Scopaz, K., & Hatzenbuehler, J. (2013). Risk modifiers for concussion and prolonged recovery. *Sports Health*, *5*(6), 537–541. https://doi.org/10.1177/1941738112473059

Sebastian, D., Chovvath, R., & Malladi, R. (2015). Cervical extensor endurance test: Areliability study. *Journal of Bodywork and Movement Therapies*, *19*(2), 213–216. https://doi.org/10.1016/j.jbmt.2014.04.014

Seifert, T., & Shipman, V. (2015). The Pathophysiology of Sports Concussion. *Current Pain and Headache Reports*, *19*(8), 1–9. https://doi.org/10.1007/s11916-015-0513-0

Shehata, N., Wiley, J. P., Richea, S., Benson, B. W., Duits, L., & Meeuwisse, W. H. (2009). Sport concussion assessment tool: baseline values for varsity collision sport athletes. *Br J Sports Med*, *43*(10), 730–734. https://doi.org/10.1136/bjsm.2009.059832

Stazyk, K. (2015). *Depression in Children Recovering from Concussion: Correlates and Predictors*.

Stern, R. A., Riley, D. O., Daneshvar, D. H., Nowinski, C. J., Cantu, R. C., & McKee, A. C. (2011). Long-term Consequences of Repetitive Brain Trauma: Chronic Traumatic Encephalopathy. *PM and R*, *3*(10 SUPPL. 2), 460–467.

https://doi.org/10.1016/j.pmrj.2011.08.008

Sullivan, J. C., Tavassoli, T., Armstrong, K., Baron-Cohen, S., & Humphrey, A. (2014). Reliability of self, parental, and researcher measurements of head circumference. *Molecular Autism*, *5*(1), 2–5. https://doi.org/10.1186/2040-2392-5-2

Tavazzi, B., Vagnozzi, R., Signoretti, S., Amorini, A. M., Finocchiaro, A., Cimatti, M., … Lazzarino, G. (2007). Temporal window of metabolic brain vulnerability to concussions: Oxidative and nitrosative stresses - Part II. *Neurosurgery*, *61*(2), 390–396. https://doi.org/10.1227/01.NEU.0000255525.34956.3F

The Physical Activity Council. (2016). 2016 participation report: The physical activity council's annual study tracking sports, fitness, and recreation participaton in the US, 26.

Tierney, R. T., Higgins, M., Caswell, S. V., Brady, J., McHardy, K., Driban, J. B., & Darvish, K. (2008a). Sex differences in head acceleration during heading while wearing soccer headgear. *Journal of Athletic Training*, *43*(6), 578–584. https://doi.org/http://dx.doi.org/10.4085/1062-6050-43.6.578

Tierney, R. T., Higgins, M., Caswell, S. V, Brady, J., McHardy, K., Driban, J. B., & Darvish, K. (2008b). Sex Differences in Head Acceleration During Heading While Wearing Soccer Headgear. *Journal of Athletic Training*, *43*(6), 578–584. https://doi.org/10.4085/1062-6050-43.6.578

Tierney, R. T., Sitler, M. R., Swanik, C. B., Swanik, K. A., Higgins, M., & Torg, J. (2005). Gender differences in head-neck segmnet dynamic stabilization during head accelaration. *Medicine and Science in Sports and Exercise*, *37*(2), 272–279. https://doi.org/10.1249/01.MSS.0000152734.47516.AA

Tsushima, W. T., Siu, A. M., Ahn, H. J., Chang, B. L., & Murata, N. M. (2018). Incidence and Risk of Concussions in Youth Athletes: Comparisons of Age, Sex, Concussion History, Sport, and Football Position. *Archives of Clinical Neuropsychology*, (May). https://doi.org/10.1093/arclin/acy019

USports. (2017). USPORTS Student-Athlete User Guide.

Vagnozzi, R. et al. (2007). Temporal window of metabolic brain vulnerability to concussions: Mitochondrial-related impairment - Part I. Commentary. *Neurosurgery*, *61*(2), 388–389. https://doi.org/10.1227/01.NEU.0000280002.41696.D8

Valovich McLeod, T. C., Barr, W. B., McCrea, M., & Guskiewicz, K. M. (2006). Psychometric and measurement properties of concussion assessment tools in youth sports. *Journal of Athletic Training*, *41*(4), 399–408.

Vasavada, A. N., Danaraj, J., & Siegmund, G. P. (2008). Head and neck anthropometry, vertebral geometry and neck strength in height-matched men and women. *Journal of Biomechanics*, *41*(1), 114–121. https://doi.org/10.1016/j.jbiomech.2007.07.007

Virji-Babul, N., Borich, M. R., Makan, N., Moore, T., Frew, K., Emery, C. A., & Boyd, L. A. (2013). Diffusion Tensor Imaging of Sports-related Concussion in Adolescents. *Pediatric Neurology*, *48*, 24–29.

Williams, R. M., Puetz, T. W., Giza, C. C., & Broglio, S. P. (2015). Concussion Recovery Time Among High School and Collegiate Athletes: A Systematic Review and Meta-Analysis. *Sports Medicine*, *45*(6), 893–903. https://doi.org/10.1007/s40279-015-0325-8

Williamson, R. W., Gerhardstein, D., Cardenas, J., Michael, D. B., Theodore, N., & Rosseauk, N. (2014). Concussion 101: The current state of concussion education programs. *Neurosurgery*, *75*(4), S131–S135. https://doi.org/10.1227/NEU.0000000000000482

World Health Organization (WHO). (2011). ICD-10 Transition. *Family Practice Management*, *18*, 39. https://doi.org/10.1159/000371811

Yengo-kahn, A., Allen, K., & Kerr, Z. Y. (2016). Predictors of postconcussion syndrome in collegiate student-athletes, *40*(April), 1–10. https://doi.org/10.3171/2016.1.FOCUS15593.

Yengo-kahn, A. M., Hale, A. T., Zalneraitis, B. H., Zuckerman, S. L., Sills, A. K., & Solomon, G. S. (2016). Review. *Neurosurgical Focus*, *40*(April). https://doi.org/10.3171/2016.1.FOCUS15611.

Zemek, R. L., Farion, K. J., Sampson, M., & McGahern, C. (2013). Prognosticators of Persistent Symptoms Following Pediatric Concussion. *JAMA Pediatrics*, *167*(3), 259. https://doi.org/10.1001/2013.jamapediatrics.216

Zuckerman, S. L., Kerr, Z. Y., Yengo-Kahn, A., Wasserman, E., Covassin, T., & Solomon, G. S. (2015). Epidemiology of Sports-Related Concussion in NCAA Athletes From 2009-2010 to 2013-2014: Incidence, Recurrence, and Mechanisms. *The American Journal of Sports Medicine*, *43*(11), 2654–2662. https://doi.org/10.1177/0363546515599634

Zuckerman, S. L., Yengo-kahn, A. M., Buckley, T. A., Solomon, G. S., Sills, A. K., & Kerr, Z. Y. (2016). Predictors of postconcussion syndrome in collegiate student-athletes, *40*(April), 1–10. https://doi.org/10.3171/2016.1.FOCUS15593.

Table 1.0 – Procedures and psychometric properties for anthropometric and strength assessments.

1.DNF Endurance Test

Psychometric Properties(Jull, O'Leary, & Falla, 2008; Lourenço et al., 2016):

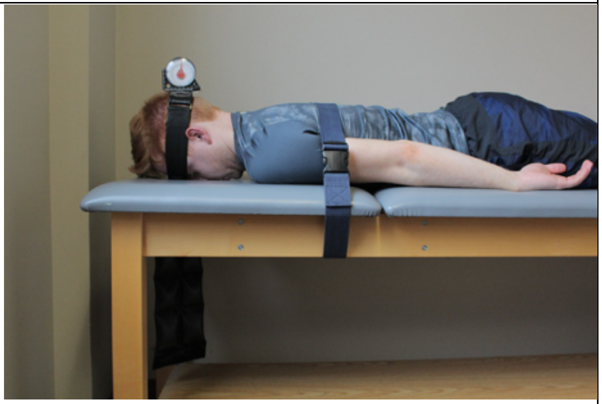
$ICC_{(2,1)}$= 0.71-0.85(CITE)

SEM (s): 6.91-9.84

MDC (s): 19.51-27.26

Construct validity – comparison of EMG and DNF endurance test has down the test to be a valid tool to evaluate the deep neck flexors.

Procedure: A cervical range of motion (CROM) inclinometer was placed on the athlete's head to determine the position of their head in space. The use of this tool has been validated as an appropriate method to measuring range of motion at the cervical spine. Participants were assessed in a supine position with their knees bent and feet flat on the plinth. They were asked to maximally retract their chin prior to beginning the test. Athletes were instructed to keep their chin tucked and lift their head up just an inch. Athletes were given one trial test. Once their head was lifted the assessor placed their hand under the athletes' head as the timer was started. The test was complete when an athlete's head touched the assessor's hand for more than one second, or if there was a five-degree change in head position. The time each athlete was able to maintain the lifted head position was recorded in seconds. The test was stopped if the athlete was able to maintain the head position for greater than 90 seconds.



2. Neck Extensor Endurance Test

Psychometric Properties(Lourenço et al., 2016; Sebastian, Chovvath, & Malladi, 2015)***:***

$ICC_{(2,1)}$= 0.52-0.73(CITE)

SEM (min): 0.74-0.84

MDC (min): 2.05-2.34

Validity – No published validity in comparison to gold standard.

Procedures:

Athletes laid prone on the plinth, their shoulders in line with the end. Athletes were strapped to the plinth in order to sure minimal activation of the back-extensor muscles. Using the same inclinometer athletes once again maximally retracted their chin and lifted the back of the head toward the ceiling. The assessor placed their hand on the athletes back to be able to feel for any activation of the back musculature beneath their hands. Once in position the timer started. A five-degree change in head position signaled the end of the test.

3.Head Circumference

Psychometric Properties(Sullivan, Tavassoli, Armstrong, Baron-Cohen, & Humphrey, 2014)***:***

$ICC_{(2,1)}$= 0.98

$ICC_{(1,k)}=0.84$

Procedures:

Head circumference was measured by placing a soft tape measure in the center of the forehead just above the bridge of the eyebrows. The measuring tape wraps around the temporal bone, behind the ears, over top of the external occipital protuberance and around the other side of the head to meet the other end in the center of the forehead.

Head circumference was measured to the nearest tenth of a centimeter.

4.Neck Circumference

Psychometric Properties (Laberge et al. 2007):

$ICC_{(2,1)}$= 0.76-0.95

$ICC_{(1,k)}$= 0.95-0.99

Procedures: Neck circumference was measured with athletes seated straight in a low back chair, looking straight ahead. A soft tape measure was placed at the midline of the neck between the middle cervical spine and the mid-anterior neck. For men, the measuring tape was placed just below the laryngeal prominence. All measurements were taken to the nearest tenth of a centimeter.

5.Height and Weight

Height- Height was measured using a measuring tape fixed to a wall. At the time of assessment, it was measured to the nearest centimeter. It was converted to meters for statistical analysis.

Weight- Weight was measured to the nearest hundredth of a kilogram using a calibrated digital scale. Athletes were dressed in light athletic gear.

Table 2.0 – Summary statistics for independent and dependent variables

Variable	**Male Athletes n= 24**	**Female Athletes n= 10**	**Test statistic**
Age in years mean (sd)	20.28 (1.77)	20.10(1.66)	$t_{(33)}$=0.276, p=0.784
Sport n (%)			
Football	8 (32.00)	---	
Soccer	1 (4.00)	2 (20.00)	
Rugby	14 (60.00)	5 (50.00)	
Basketball	1 (4.00)	3 (30.00)	
Women's Hockey	----	0 (0.00)	
Cheerleading	----	0 (0.00)	
Past concussion n (%)			
Yes	22(88.00)	8 (80.00)	χ^2=0.373, *df*=1, p=0.541
No	3 (12.00)	2 (20.00)	
Number of past concussions mean (sd)	3 (2.06)	2.1 (1.73)	$t_{(33)}$=1.217, p=0.232
Presence of Neck Pain n (%)			
Yes	9 (36.00)	2 (20.00)	χ^2= .849, *df*=1 p=0.357
No	16 (64.00)	8 (80.00)	
Height mean (sd), m	1.82 (.078)	1.72 (.0902)	$t_{(33)}$=3.37, p=<0.005*
Weight mean (sd), kg	93.416 (17.761=)	70.00 (8.79)	$t_{(33)}$= 3.95, p=<0.001*
Head circumference mean (sd)	56.84 (1.85)	54.88 (1.80)	$t_{(33)}$=2.848, p=0.007*
Neck circumference, cm	44.284 (5.77)	36.69 (3.21)	$t_{(33)}$=3.906, p=<0.005*
Neck Length, cm	13.79 (1.99)	12.23 (1.42)	$t_{(33)}$=2.212, p=0.034*
Flexor Strength, s	16.505 (5.53)	15.752 (6.122)	$t_{(33)}$=0.353, p=0.726
Extensor Strength, s	289.28 (103.31)	235.995(118.97)	$t_{(155)}$=1.32, p=0.196
Composite Strength Score, mean (sd)	152.89 (52.63)	131.91 (55.25)	$t_{(33}$=1.05, p=0.301
Number of Symptoms on SCAT3 mean (sd)	8.5 (5.3313)	9.1 (6.10)	$t_{(33)}$=-.260, p=0.796
Total Symptom Score on SCAT mean (sd)	20.16 (17.361)	25.2 (20.874)	$t_{(33)}$=-.733, p=0.469
Days Symptomatic mean (sd)	9.36 (8.16)	12.9 (9.024)	$t_{(33)}$=-1.13, p=0.267
Days to on RTP Protocol mean (sd)	7.76 (4.71)	6.2 (2.201)	$t_{(33)}$=.998, p=0.326

Total Days to Recovery mean (sd)	17.12(11.93)	19.1 (10.92)	$t_{(33)}$=-.454, p=0.653

Key: * - denotes significance at the 0.05 level

Table 3.0: Linear regression model predicting recovery time in Canadian university athletes

VARIABLES	B	S.E.	t	Sig.	95% C.I.	
					Lower	Upper
Neck pain	-0.309	0.144	-2.15	0.040	-0.602	0.016
Symptom Score	0.024	0.004	6.41	<0.001	0.016	0.031
Constant	2.276	0.117	19.39	<0.001	2.036	2.515

Key: B = beta coefficient, S.E = standard error, t = test satistic for testing if B =0, Sig = p=value, 95% C.I = 95% confidence interval,

CHAPTER 4: DISCUSSION & CLINICAL IMPLICATIONS

Summary of Main Results

Concussion prevention strategies have been limited to the use of protective equipment such as helmets and mouth guards, educational programs for coaches, players and parents, and rule or legislation changes. The effectiveness of these strategies is limited in university athletes. Neck strengthening has been proposed as a possible prevention strategy for sports-related concussion(Hrysomallis, 2016) due to their ability to attenuate the biomechanical forces experienced during sport. However, the extent to which neck strength is associated with concussion risk in varsity athletes remains unknown. This study explored the relationship between neck strength, concussion symptom scores other variable list with concussion risk and recovery time in university athletes. This chapter summarizes findings from a sample of 246 varsity athletes at McMaster University. The key points generated from these results provide Information relevant to:

1) concussion risk factors in varsity athletes,
2) the role of neck strength in concussion risk,
3) concussion recovery time in varsity athletes, and
4) the relationship between neck strength, concussion symptom scores and overall recovery time.

In addition to discussing the aforementioned findings and their respective limitations, this chapter explores the relationship of the findings to the theories used to support the research question, as well as recommendations for clinical practice, future research, and policy with respect to sports-related concussion (SRC.)

Overall Completeness and Applicability of this Study

Concussion Risk in Varsity Athletes

The research presented in Chapter Two examined the risk of concussion in varsity athletes with respect to neck strength and anthropometric variables. This study also evaluated other possible covariates for SRC including: age, sex, sport, history of anxiety or depression, past concussion diagnoses, and neck pain at the time of pre-season assessment.

Effect of age on concussion risk.

There is strong evidence in the literature that states athletes between the ages of 14 and 22 are most vulnerable to SRC (Collins et al., 2014b; Gessel et al., 2007). This study evaluates a narrow age range of athletes, 95% being between 17 and 22. The mean age of athletes who sustained a concussion was 20.23 years compared to 19.68 in the non-concussed group. There were no significant differences in age between the two concussion groups and age was not a significant predictor of concussion risk. This is likely due to the narrow age range of varsity athletes but could also be related to other possible risk factors that are more strongly related to concussion risk, such as past concussion history.

Effect of sex on concussion risk.

Several studies have demonstrated that women report higher rates of concussion than men in the same sport. These findings may be misleading as it is known that females are more likely to seek medical attention and report injury than males (Iverson et al., 2015). Nonetheless, the past literature on varsity athletes confirm these findings (Covassin, Swanik, and Sachs 2003; Zuckerman et al. 2015). In our study a greater percentage of males (16%, n = 25) sustained a concussion than females (11%, n = 10) however, there were no significant differences in the rate of concussion between the sexes. These results contradict what has been previously suggested in the literature. No differences in SRC between male and female athletes could be due to maturation of this age group. A varsity athlete cohort is older and stronger than an adolescent cohort which may explain these findings. Additionally, a larger sample of concussed athletes with a more equal representation of male and females may show a different trend in concussion risk.

Effect of sport on concussion risk.

Daneshvar and colleagues examined the epidemiology of SRC and found contact and collision sports to report the highest rates of concussion (Daneshvar et al., 2011). Football, rugby, soccer, basketball, hockey, cheerleading, and lacrosse are among the sports with the highest incidence of concussion. (Daneshvar et al., 2011). For this study, men's hockey and lacrosse were unavailable for assessment. Concussion risk was explored for football, men's and women's basketball, rugby and soccer, as well as women's hockey and cheerleading. There were significant differences in concussion rates between sports. Rugby reported the highest rate of concussion. Thirty percent of all rugby athletes experienced a concussion over the course of one season compared to the 13% of football athletes, 15% of basketball athletes, and 7 % of soccer athletes diagnosed with SRC. Women's hockey and cheerleading had no concussed athletes during this season.

One ecological study comparing injury rates of football and rugby athletes demonstrated that football players report an overall injury rate that is one-third of the rate in rugby athletes(Marshall et al., 2002). They also found that areas of the body with greater protective equipment in football players had lower rates of injury than in rugby athletes who do not wear protective equipment, particularly the head (Marshall et al., 2002). Despite these results, a recent systematic review of concussion prevention strategies indicates that protective equipment like helmets, mouth guards, and head gear have questionable effectiveness (Emery et al., 2017b).

Other possible factors that could explain the higher rate of SRC in rugby athletes include the nature of the game, rule regulation, or other confounding factors like past concussion history or the presence of neck pain in these athletes. Concussion rates are reportedly highest in female soccer athletes (Covassin et al., 2003; Dvorak, Mccrory, Kirkendall, & Klinik, 2007; Zuckerman et al., 2015) however, our findings indicated the highest rate of concussion for females was in rugby athletes (50%, n=5) followed by basketball (30%, n=3). These differences are possibly due to limited data on female rugby athletes and a small sample of females with a concussion in one season. Similarly, 28% of men's rugby athletes reported concussions; twice the number of SRCs as men's football and more than four times the number of concussions for both men's soccer and men's basketball athletes.

Effect of past-concussion history on concussion risk.

Several studies have determined that a history of previous concussion is one of the most significant predictors of future concussion (Marshall, Guskiewicz, Shankar, McCrea, & Cantu, 2015; Schulz et al., 2004; Tsushima et al., 2018). An epidemiological evaluation of high school and collegiate athletes found that athletes who have experienced a SRC within the last two years experienced double the rate of concussion than athletes who had never sustained any concussion at all(Marshall et al., 2015). Athletes who reported two or more concussions experienced concussion rates five times higher than those who had never sustained an injury (Marshall et al., 2015). Our findings support these results as history of past concussion was one of the strongest predictors of risk in varsity athletes, irrespective of gender or sport. A past concussion diagnosis indicated nearly 5 times the risk of concussion compared to athletes who had never sustained a SRC.

The reason why past concussion is significant in determining concussion risk could be for a variety of factors. For example, nature of the sport. Rugby, a contact sport, played at high speed with no protective equipment, may subject athletes to higher intensity impacts than other athletes (Marshall et al., 2015). We found that ninety-one percent of concussed athletes with a history of previous concussion also experienced neck pain which may decrease an athlete's ability to brace against impacts. Additional speculation has been made surrounding a decreased threshold for withstanding impacts in athletes with previous concussion. A decrease in the neurotransmitter activity following SRC could possible cause an increase an athletes vulnerability to subsequent injuries (Giza & Hovda, 2001; Marshall et al., 2015).

Effect of neck pain on concussion risk.

In the present study, the most significant predictor of concussion risk was the presence of neck pain at the time of evaluation. Athletes who reported neck pain were seven times more likely to sustain a concussion than those who did not. Furthermore, athletes who reported the presence of neck pain had significantly weaker neck flexor endurance scores than those who did not, regardless of concussion diagnosis ($p = 0.04$). The presence of neck pain has been shown to result in muscular coactivation of the splenius capitus muscle, responsible for neck extension, and the sternocleidomastoid muscle, responsible for neck flexion (Lindstrøm et al., 2011). Coactivation (simultaneous contraction) of the muscles may result in fatigue and has been cited as a risk factor for concussion in athletes (Abrahams et al., 2014; Lindstrøm et al., 2011), as it has also been shown to cause a reduction in neck strength. A study examining the relationship between neck pain, strength, and muscular coactivation described an average total reduction in neck strength of about 30% in women who reported neck pain. Women are more likely to report neck pain and have less overall neck strength than men (Vasavada et al., 2008). We found there to be a significant difference in neck strength between male and female athletes overall.

However, when separated into groups by sex there were only significant differences in the presence of neck pain between concussed and non-concussed males, not females ($p \leq 0.001$ and $p = 0.066$, respectively). This is possibly due to the sample being predominantly male (63%), as well as men experiencing a larger proportion of the concussions reported in this cohort (70%).

The Effect of Neck Strength in Concussion

Neck flexor and extensor endurance tests were used to measure isometric strength in the athletes. Both the flexor and extensor values were averaged together to produce a strength composite score and then risk was evaluated using both individual strength test scores and the composite score to determine best predictive model. Male athletes had significantly greater neck strength for both the flexor and extensor tests, as well as composite strength score. AS expected, males were found to have significantly larger neck circumference and neck length compared to female athletes. There is a significant body of literature that demonstrates females and children have less neck strength than their male and adult counterparts (Eckner et al., 2014; Hamilton et al., 2012; Lavallee et al., 2013). Stronger muscles are able to generate more tensile stiffness in response to potentially injurious impacts (Eckner et al., 2014). Stronger athletes are also able to generate a more substantial amount of torque more quickly (Eckner et al., 2014) to counteract the angular accelerations thought to cause concussion (Holbourn, 1943; King, Yang, & Zhang, 2003; Misra & Chakravarty, 1984). A study examining sex differences in kinematic and dynamic head stabilization in response to external loads found women exhibit greater angular acceleration and displacement in than men despite initiating muscle contraction for bracing earlier. Additionally, the authors discovered women had overall lower isometric strength and neck girth than men (Tierney et al., 2005). These findings were also reflected in a similar study on soccer athletes and head accelerations experienced during heading exercises suggesting females might be at greater risk for concussion due to less strength and smaller body size(Tierney et al., 2008a).

The epidemiological assessment of SRC reports higher rates of concussion in both women and children (Kutcher & Eckner, 2010; McCrory et al., 2017). While in our cohort more males (15%) sustained concussion than females (11%), our findings indicate men did not report significantly greater concussion rates compared to women. The differences in neck strength between males and females, and the smaller proportion of females in our sample population (36%), provides sufficient basis to encourage further exploration in to the relationship between neck strength and neck pain as modifiable risk factors in concussion prevention.

Neck flexor strength was significantly greater in male athletes than in female athletes however between concussion groups there were no significant differences in men or women. There are a limited number of studies examining neck strength differences between concussed and non-concussed varsity athletes. A study by Collins and colleagues published 2014 evaluated neck strength in high school basketball, soccer, and lacrosse athletes. They found that for every one pound increase in strength the likelihood of sustaining a concussion decreased by 5% (Collins et al., 2014a). The differences in findings between our study and the Collins study could be in part due to the variability in strength across adolescent youth is greater than that in varsity athletes. In a comparison of high school and varsity football athletes, Broglio et al. found there was greater head accelerations in the younger, high school cohort than in the varsity athletes. He attributed these differences to greater strength in older athletes due to physical maturation and the inevitable differences that occur at higher levels of competition (Broglio et al., 2009; Eckner et al., 2014). The variability in strength between a freshman high school athlete and a freshman university athlete was significant. Whereas the variability between trained varsity athletes was not as extensive as in their high school counterparts.

The strength measurement used in the present study was a simple, timed endurance test of the deep neck flexors and neck extensors. Past studies evaluating neck strength have used hand held dynamometers to assess strength (Geary et al., 2013, 2014). While the psychometric properties for these devices showed moderate to excellent inter-rater reliability, they were quite costly and not readily available in most clinical settings (Geary et al., 2013). The endurance measures used in our cohort were chosen because they were economical, safe to administer to athletes prior to competition, required minimal equipment and are clinically relevant. However, may not have been sensitive enough to detect variability within this more uniform population. Furthermore, our study and the majority of published studies examining neck strength in athletes measure isometric strength. Yet, concussion injuries often take place through a range of motion. Evaluation of neck strength using a dynamic tool may provide further clarification on the relevance of neck strength in a varsity athlete population.

The extent to which neck strength influences risk is still uncertain as neck pain factored significantly in the prediction of concussion and strength did not in the present study. A more in-depth exploration of the presence of neck pain and its influence on neck muscle strength and in particular its influence on the mechanisms of sustaining a concussive injury in athletes. Perhaps the presence of neck pain prior to competition is a major indicator of concussion risk and these athletes should be more closely monitored or targeted specifically for prevention strategies before being able to participate in competition.

Concussion Recovery in Varsity Athletes

In Chapter three, we examined if greater neck strength was indicative of a faster recovery time in athletes who do sustain as concussion as these athletes would arguably experience impacts at a lesser magnitude. We explored the relationship between recovery time, neck strength, and concussion symptoms intensity based on the SCAT 3 symptom scale (modified Post Concussive Symptom Scale) to determine if greater strength decreases the severity of concussion in injured athletes.

Time to return to competition (full recovery) was our primary outcome. Using a stepwise regression model, this study found the presence of neck pain and symptom intensity as measured by SCAT3- symptom score to be the strongest predictors of recovery time in varsity athletes. Overall, this model accounted for 59% of the variance in concussion recovery time. Concussed athletes typically recover spontaneously within two-weeks from the time of injury (Iverson et al., 2017; McCrea et al., 2003b; Williams et al., 2015). However, a smaller subset of these athletes (approximately 10%) will go on to have symptoms that persist longer than 2 weeks. The results of this thesis echo what is found in the literature with respect to symptom resolution. The primary outcome was total recovery time through to being cleared to return to competition which was an average of 18 days. The amount of time acute concussion symptoms were present was an average of 11 days. We found only 11% of all athletes (n=4) to have symptoms that persisted beyond 28 days.

Unexpectedly, female sex and past concussion history were not significant in the predictor model for prolonged recovery. The flexor and extensor test values used to determine neck strength of the athletes were not significant in predicting recovery time. Neck pain was a significant predictor of recovery time or risk of concussion. However, the coefficient for neck pain in our model was negative. Indicating that reporting neck pain is indicative of shorter time to recover. This finding is likely due to the fact that a minority of concussed athletes reported neck pain at pre-season (35%). No differences in neck strength between those with neck pain and those without was noted. While neck pain was negative in the regression model for total concussion recovery, athletes who reported neck pain pre-season spent a greater number of days with acute concussion symptoms but took less time to be cleared for return to competition.

The findings of this study reinforce the main findings of the current literature on concussion recovery. Intensity of acute concussion symptoms are the strongest predictor of the length of recovery in athletes across all levels of competition (Meehan, Mannix, Stracciolini, Elbin, Collins, 2013). An evaluation of the characteristics of athletes who report greater symptom intensity should be further explored to better understand who is most susceptible to persistent symptoms post injury.

Implications for practice

Several of our findings reflected what was shown in the literature to date. However, the most significant finding was how the presence of neck pain influenced concussion risk and recovery in varsity athletes. The presence of neck pain likely inhibits the function of the neck musculature in response to impact whether through coactivation of the muscles responsible for neck flexion and extension or another mechanism. This decrease in muscle function with the presence of neck pain may put athletes at an increased risk for concussion and a prolonged concussion recovery. Clinically this information is important in helping us guide our pre-season assessments for athletes. Several universities subject their athletes to concussion screening prior to the start of the competitive season. These results suggest athletes should be evaluated for neck pain at the time of assessment and followed more closely due to heightened risk for concussion and extended recovery if injured.

Concussion history is a well-documented risk factor for future concussions. In our study athletes who reported a past concussion were 5 times more likely to sustain a concussion than those who had never had a previous SRC. Given that the evidence shows a dose-response relationship between the number of past concussions with the rate of future concussion, a thorough examination of an athlete's past medical history may be warranted. The results in this thesis report the greatest number of concussions in rugby athletes. Ninety-five percent of concussed rugby athletes (n=19) reported a history of previous concussion. In light of the concerns of the long-term implications of repeated concussions and the development of CTE, these injuries and risk for future injury should be taken extremely seriously and encourage thorough evaluation of athletes pre-season. Evaluating an athlete's past concussion history for the number of previous concussion may help to identify athletes who are at the greatest risk of injury. The risks of repeated concussion should be explained in detail to the athletes as to sufficiently educate them on the risks of participation, particularly those who play high-risk sports like rugby. Future research into the association between past number of concussion and future risk is necessary to identify a cut-off for determining when risk is too high for participation due to an athlete's past concussion history.

Implications for Research

The findings in our study help to guide the future research questions with respect to concussion prevention. In particular these findings demonstrate the need for further exploration into certain risk factors like the effect of neck pain and its effect on muscle strength and activation in an athlete population. We found neck pain to be one of the greatest predictors of concussion risk. However, our study used a simple binary outcome of yes or no in response to the question of neck pain. A more in-depth clinical assessment of neck pain in athletes, its relationship to past-concussion history and how it relates to concussion risk is necessary to fully understand its predictive power.

Future research with respect to neck strength, concussion, and neck pain is necessary to understand the effect that neck pain (and its underlying cause) has on absolute strength and how that translates to concussion risk. Furthermore, this study is limited in its design based on the time frame for evaluation. A study that follows athletes over a longer period of time, or follows a generation of athletes over the course of their athletic career would be able to tell a more comprehensive story of concussion risk in a cohort of varsity athletes. Additionally, a longer follow up would allow for a greater number of concussion events to be included in the analysis.

Implications for Policy

In the spring of 2018 Ontario passed Rowan's law, the only safety legislation with respect to concussions in Canada. This legislation stipulates that all coaches, athletes, and parents of minors provide evidence that they have reviewed concussion awareness resources prior to engaging in sport. While this is a significant first step in protecting athletes from concussions, further policy changes should be considered with respect to an evaluation of fitness for athletes who participate in high-risk concussion sports. Rugby athletes have been shown to be at significantly greater risk for concussion than other high-risk athletes. The emerging literature implicating severe consequences to concussions, including depression, anxiety, mood disorders, Alzheimer's disease and the development of CTE indicate the need for legislation that protects athletes who participate in high-risk sports. Implementing policy that enforces these athletes to be evaluated by a certified therapist or physician for determinants of concussion risk prior to participation may be useful. A study on collegiate athletes concussion education program indicated athletes desired the participation of coaches and physicians in the dissemination of concussion education resources (Llewellyn, Burdette, Joyner, & Buckley, 2014). More stringent evaluation on an athlete's, coaches, and parents' knowledge of concussion injuries may be warranted to prove a comprehensive understanding of the risks and the consequences of SRC. Enforcing more coherent physical examinations and structured education sessions for those most at risk may help with concussion prevention in these athletes.

Contributions to theoretical framework

Several theories were used to ground this research and guide the development of the primary research questions for this thesis. Rotational Shear Stress theory (RST) and Newton's Laws were used to explain the mechanisms by which concussions occur and the principles of mechanics that describe how neck musculature could play an important role in attenuating injurious forces in SRC (Browne, 2013; Holburn, 1943). The over-exertion theory of musculoskeletal injury causation informed this research by providing a framework that explains how the neck musculature has a finite capacity to counteract the external forces applied to the body that cause concussions. Once muscles reach their maximum force exertion they are unable to continue to attenuate external forces as effectively, possibly leading to injury (Kumar, 2001). While the results of this thesis do not contribute to informing RST or Newton's Laws, the findings of chapters two and three can help to inform over-exertion theory.

Pre-season neck pain was the strongest predictor of concussion risk in university athletes. In healthy female university students the presence of subclinical neck pain is associated with over active sternocleidomastoid and splenius capitus muscles as a mechanism to protect the neck (Lindstrom et al., 2011). Overactivation of these two main stabilizer muscles requires a constant generation of force, therefore limiting the capacity for adequate contraction against external loads when in an athletic environment. Furthermore, regardless of the etiology of the neck pain present in the athletes studied in this thesis, these findings demonstrate the existence of a muscular pathology at the time of pre-season assessment that likely limits their ability to withstand external loads and has substantial implications for risk of concussion during the season. As such, these findings help to elaborate on over-exertion theory indicating that over-exertion of the neck musculature results not only in neck pain or some sort of neck muscle pathology but can also result in concussion injuries.

Limitations

As with all studies this project is not without its respective limitations. The pre-season assessment used binary outcomes for most assessments of medical history. For example, the presence of neck pain and if athletes had sustained a previous concussion were answered with simple ‘yes/no’ responses. While this made data collection easier and coding simpler, it introduced potential recall bias with respect to athlete’s responses. To eliminate this bias, one could corroborate the self-reported questionnaire with the athlete’s medical record.

The overall sample size was able to provide a good picture of the concussion risk factors present within a varsity athlete population, however the study was conducted over one single season. This resulted in only 35 athletes who sustained a concussion. This smaller sample of concussed athletes presents some challenges with respect to statistical analysis as a certain number of events (i.e. concussion) is required per predictive variable included in a logistic regression analysis. Additionally, this study targeted athletes who were considered at risk for concussion. In order to assess the incidence of concussion in a global varsity athlete population assessment could be expanded across all varsity sports.

Finally, there are very few neck strength assessment tools that are applicable in a clinical setting. We found there to be no difference in neck strength or neck circumference (which be indirectly related to strength) between concussion groups. The neck flexor and extensor endurance tests have not yet been used in an athlete population. Exploration of neck strength in a laboratory setting and how it relates to real-world concussion risk may provide a more thorough understanding of the relationship between neck strength and concussion in a varsity athlete cohort.

Conclusion

Athletes with concussion reported the presence of neck pain more so than their non-concussed counterparts at the time of pre-season assessment. Similarly, neck pain is also a significant predictor of total recovery time in this cohort. While the neck strength values used in these studies were not found to be significant predictors of concussion risk or recovery time, it is possible that the neck musculature play a significant role in concussion risk in varsity athletes. To that end, neck strength should be evaluated using a more sensitive test within the varsity athlete population where variability in strength is not as vast as in younger athletes. Furthermore, evaluation of strength and neck pain in relation to the incidence of concussion should be examined across multiple athletic seasons in order to have a larger sample of concussed athletes for comparison. Rate of concussion in varsity athletes are the same amongst males and females and are not dependent on the age of the athlete at this level of competition. Rates of concussion are significantly different among sports. Contact sports, particularly rugby, report the highest rates of concussion and as such should be evaluated more closely at the time of pre-season assessment as these athletes also reported the highest rates of other covariates, including past concussion history and neck pain.

Funding and Conflict of Interest Statement

This study was funded solely through scholarship funding to Erin Cole, the principal investigator, by the McMaster University School of Rehabilitation Science. There are no conflicts of interest to report for this study.

References

Abrahams, S., Mc Fie, S., Patricios, J., Posthumus, M., & September, A. V. (2014). Risk factors for sports concussion: an evidence-based systematic review. *British Journal of Sports Medicine*, *48*(2), 91–97. https://doi.org/10.1136/bjsports-2013-092734

Alla, S., Sullivan, S. J., Hale, L., & McCrory, P. (2009). Self-report scales/checklists for the measurement of concussion symptoms: a systematic review. *British Journal of Sports Medicine*, *43 Suppl 1*, i3–i12. https://doi.org/10.1136/bjsm.2009.058339

Angelica, M. D., & Fong, Y. (2008). Effect of Neck Strength and Anticipatory Activation in Response to Head Impulsive Loads. *American Journal of Public Health*, *141*(4), 520–529. https://doi.org/10.1016/j.surg.2006.10.010.Use

Bakhos, L. L., Lockhart, G. R., Myers, R., & Linakis, J. G. (2010). Emergency Department Visits for Concussion in Young Child Athletes. *Pediatrics*, *126*(3), e550–e556. https://doi.org/10.1542/peds.2009-3101

Barr, W. B., & McCrea, M. (2001). Sensitivity and specificity of standardized neurocognitive testing immediately following sports concussion.[Erratum appears in J Int Neuropsychol Soc 2002 Mar;8(3):481]. *Journal of the International Neuropsychological Society*, *7*(6), 693–702.

Bazarian, J. J., Zhong, J., Blyth, B., Zhu, T., Kavcic, V., & Peterson, D. (2007). Diffusion Tensor Imaging Detects Clinically Important Axonal Damage after Mild Traumatic Brain Injury: A Pilot Study. *Journal of Neurotrauma*, *24*(9), 1447–1459. https://doi.org/10.1089/neu.2007.0241

Bell, David R. Guskiewicz, Kevin M. Clark, Michael A. Padua, D. A. (2011). Systematic Review of the Balance Error Scoring System. *Athletic Training*, *3*(3), 287–295. https://doi.org/10.1177/1941738111403122

Benson, B. W., Hamilton, G. M., Meeuwisse, W. H., McCrory, P., & Dvorak, J. (2009). Is protective equipment useful in preventing concussion? A systematic review of the literature. *British Journal of Sports Medicine*, *43*(Suppl_1), i56–i67. https://doi.org/10.1136/bjsm.2009.058271

Benson, B. W., McIntosh, A. S., Maddocks, D., Herring, S. A., Raftery, M., & Dvorak, J. (2013). What are the most effective risk-reduction strategies in sport concussion? *Br J Sports Med*, *47*(5), 321–326. https://doi.org/10.1136/bjsports-2013-092216\r47/5/321 [pii]

Black, A. M., Sergio, L. E., & Macpherson, A. K. (2017). The Epidemiology of Concussions: Number and nature of concussions and time to recovery among female and male canadian varsity athletes 2008 to 2011. *Clinical Journal of Sport Medicine*, *27*, 52–56. Retrieved from http://www.cjsportmed.com/%0Ahttp://ovidsp.ovid.com/ovidweb.cgi?T=JS&PAGE=reference&D=emed18b&NEWS=N&AN=608297429

Bleiberg, J., Cernich, A. N., Cameron, K., Sun, W., Peck, K., Ecklund, J., … Bailes, J. E. (2004). Duration of Cognitive Impairment after Sports Concussion. *Neurosurgery*, *54*(5), 1073–1080. https://doi.org/10.1227/01.NEU.0000155093.00745.B4

Bloom, G. A., Loughead, T. M., Shapcott, E. J. B., Johnston, K. M., & Delaney, J. S. (2008). The prevalence and recovery of concussed male and female collegiate athletes. *European Journal of Sport Science*, *8*(5), 295–303. https://doi.org/10.1080/17461390802251836

Borich, M. R., Cheung, K. L., Jones, P., Khramova, V., Gavrailoff, L., Boyd, L. A., & Virji-Babul, N. (2013). Concussion: Current Concepts in Diagnosis in Management. *Journal of*

Neurologic Physical Therapy, *37*(3), 133–139. https://doi.org/10.1097/NPT.0b013e31829f7460

Broglio, S. P., Ferrara, M. S., Sopiarz, K., & Kelly, M. S. (2008). Reliable change of the sensory organization test. *Clinical Journal of Sport Medicine*, *18*(2), 148–154. https://doi.org/10.1097/JSM.0b013e318164f42a

Broglio, S. P., Macciocchi, S. N., & Ferrara, M. S. (2007). Sensitivity of the concussion assessment battery. *Neurosurgery*, *60*(6), 1050–1057. https://doi.org/10.1227/01.NEU.0000255479.90999.C0

Broglio, S. P., Sosnoff, J. J., Shin, S., He, X., Alcaraz, C., & Zimmerman, J. (2009). Head Impacts During High School Football: A Biomechanical Assessment, *44*(4), 342–349.

Center for Disease Control, Gilchrist, J., Thomas, K. E., Xu, L., McGuire, L. C., & Coronado, V. (2011). Nonfatal traumatic brain injuries related to sports and recreation activities among persons aged ≤19 years--United States, 2001-2009. *MMWR. Morbidity and Mortality Weekly Report*, *60*(39), 1337–1342. https://doi.org/mm6039a1 [pii]

Collie, A. (2006). Cognition in the days following concussion: comparison of symptomatic versus asymptomatic athletes. *Journal of Neurology, Neurosurgery & Psychiatry*, *77*(2), 241–245. https://doi.org/10.1136/jnnp.2005.073155

Collins, C. L., Fletcher, E. N., Fields, S. K., Kluchurosky, L., Rohrkemper, M. K., Comstock, R. D., & Cantu, R. C. (2014a). Neck Strength: A Protective Factor Reducing Risk for Concussion in High School Sports. *Journal of Primary Prevention*, *35*(5), 309–319. https://doi.org/10.1007/s10935-014-0355-2

Collins, M., Lovell, M. R., Iverson, G. L., Ide, T., & Maroon, J. (2006). Examining concussion rates and return to play in high school football players wearing newer helmet technology: A three-year prospective cohort study. *Neurosurgery*, *58*(2), 275–284. https://doi.org/10.1227/01.NEU.0000200441.92742.46

Concussion In Sport Group. (2013). SCAT3, 259–263.

Covassin, T., Swanik, C. B., & Sachs, M. L. (2003). Sex Differences and the Incidence of Concussions Among Collegiate Athletes. *Journal of Athletic Training (National Athletic Trainers' Association)*, *38*(3), 238. Retrieved from http://search.ebscohost.com.lib-proxy.fullerton.edu/login.aspx?direct=true&db=s3h&AN=11720753&site=ehost-live&scope=site

Cramer, C. R. (1999). A Reconditioning Program to Lower the Recurrence Rate of Brachial Plexus Neurapraxia in Collegiate Football Players. *Journal of Athletic Training*, *34*(4), 390–396.

Daneshvar, D. H., Nowinski, C. J., Mckee, A. C., & Cantu, R. C. (2011). The Epidemiology of Sport-Related Concussion. *Clinics in Sports Medicine*, *30*(1), 1–17. https://doi.org/10.1016/j.csm.2010.08.006

de Koning, C. H. P., van den Heuvel, S. P., Staal, J. B., Smits-Engelsman, B. C. M., & Hendriks, E. J. M. (2008). Clinimetric evaluation of methods to measure muscle functioning in patients with non-specific neck pain: a systematic review. *BMC Musculoskeletal Disorders*, *9*, 142. https://doi.org/10.1186/1471-2474-9-142

Dvorak, J., Mccrory, P., Kirkendall, D. T., & Klinik, S. (2007). Head injuries in the female football player: incidence, mechanisms, risk factors and management. *Br J Sports Med*, *41*, 44–46. https://doi.org/10.1136/bjsm.2007.037960

Eckner, J. T., Oh, Y. K., Joshi, M. S., Richardson, J. K., & Ashton-Miller, J. A. (2014). Effect of neck muscle strength and anticipatory cervical muscle activation on the kinematic response of the head to impulsive loads. *The American Journal of Sports Medicine*, *42*(3), 566–576. https://doi.org/10.1177/0363546513517869

Emery, C. A., Black, A. M., Kolstad, A., Martinez, G., Nettel-Aguirre, A., Engebretsen, L., … Schneider, K. (2017a). What strategies can be used to effectively reduce the risk of concussion in sport? *British Journal of Sports Medicine*, bjsports-2016-097452. https://doi.org/10.1136/bjsports-2016-097452

Franco, J. L., & Herzog, W. (1987). A comparative assessment of neck muscle strength and vertebral stability. *The Journal of Orthopaedic and Sports Physical Therapy*, *8*(7), 351–356. https://doi.org/10.2519/jospt.1987.8.7.351

Gardner, A., Kay-Lambkin, F., Stanwell, P., Donnelly, J., Williams, W. H., Hiles, A., … Jones, D. K. (2012). A Systematic Review of Diffusion Tensor Imaging Findings in Sports-Related Concussion. *Journal of Neurotrauma*, *29*(16), 2521–2538. https://doi.org/10.1089/neu.2012.2628

Geary, K., Green, B. S., & Delahunt, E. (2013). Intrarater reliability of neck strength measurement of rugby union players using a handheld dynamometer. *Journal of Manipulative and Physiological Therapeutics*, *36*(7), 444–449. https://doi.org/10.1016/j.jmpt.2013.05.026

Geary, K., Green, B. S., & Delahunt, E. (2014). Effects of Neck Strength Training on Isometric Neck Strength in Rugby Union Players. *Clin J Sport Med*, *6*(24), 502–508. https://doi.org/10.1097/JSM.0000000000000071

Gessel, L. M., Fields, S. K., Collins, C. L., Dick, R. W., & Comstock, R. D. (2007). Concussions among United States high school and collegiate athletes. *Journal of Athletic Training (National Athletic Trainers' Association)*, *42*(4), 495–503. Retrieved from http://spot.lib.auburn.edu/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=cin20&AN=2009759920&site=ehost-live

Giza, C. C. (2014). The New Metabolic Cascade of Concussion, *75*(0 4), S24–S33. https://doi.org/10.1227/NEU.0000000000000505.The

Giza, C. C., & Hovda, D. A. (2001). The Neurometabolic Cascade of Concussion. *Journal of Athletic Training*, *36*(3), 228–235. https://doi.org/10.1227/NEU.0000000000000505

Greenhill, D. A., Navo, P., Zhao, H., Torg, J., Comstock, R. D., & Boden, B. P. (2016). Inadequate Helmet Fit Increases Concussion Severity in American High School Football Players. *Sports Health*, *8*(3), 238–243. https://doi.org/10.1177/1941738116639027

Guskiewicz, K. M. (2011). Balance Assessment in the Management of Sport-Related Concussion. *Clinics in Sports Medicine*, *30*(1), 89–102. https://doi.org/10.1016/j.csm.2010.09.004

Guskiewicz, K. M., Weaver, N. L., Padua, D. A., Garrett, W. E., Hill, C., & Carolina, N. (2000). Epidemiology of Concussion in Collegiate and High School Football Players, *28*(5).

Guskiewicz, K., Mccrea, M., Marshall, S. W., Cantu, R. C., Randolph, C., Barr, W., … Kelly, J. P. (2003b). The NCAA Concussion Study. *Journal of the American Medical Association*, *290*(19), 2549–2555.

Halstead, M. E., & Walter, K. D. (2010). Sport-Related Concussion in Children and Adolescents. *Pediatrics*, *126*(3), 597–615. https://doi.org/10.1542/peds.2010-2005

Hamilton, D. F., Gatherer, D., Maclean, J. G. B., Hutchison, J. D., Nutton, R. W., & Simpson, A. H. R. W. (2012). Age-related differences in the neck strength of adolescent rugby players: A cross-sectional cohort study of Scottish schoolchildren. *Bone Joint Res*, *1*(7), 152–157.

Harmon, K. G., Drezner, J. A., Gammons, M., Guskiewicz, K. M., Halstead, M., Herring, S. A.,

… Roberts, W. O. (2013). American Medical Society for Sports Medicine position statement: concussion in sport. *British Journal of Sports Medicine*, *47*(1), 15–26. https://doi.org/10.1136/bjsports-2012-091941

Harris, K. D., Heer, D. M., Roy, T. C., Santos, D. M., Whitman, J. M., & Wainner, R. S. (2005). Reliability of a measurement of neck flexor muscle endurance. *Physical Therapy*, *85*(12), 1349–1355.

Harvey, K. P., Hall, E. E., Patel, K., Barnes, K. P., & Ketcham, C. J. (2017). Potential factors influencing recovery from concussion in collegiate student-athletes. *Journal of Concussion*, *1*, 205970021770708. https://doi.org/10.1177/2059700217707084

Henry, L. C., Elbin, R. J., Collins, M. W., Marchetti, G., & Kontos, A. P. (2016). Examining recovery trajectories after sport-related concussion with a multimodal clinical assessment approach. *Neurosurgery*, *78*(2), 232–240. https://doi.org/10.1227/NEU.0000000000001041

Holbourn, A. H. S. (1943). Mechanics of head injuries. *Lancet*, *242*(6267), 438–441. https://doi.org/10.1016/S0140-6736(00)87453-X

Hrysomallis, C. (2016). Neck Muscular Strength, Training, Performance and Sport Injury Risk: A Review. *Sports Medicine*. https://doi.org/10.1007/s40279-016-0490-4

Iverson, G. L., Gardner, A. J., Terry, D. P., Ponsford, J. L., Sills, A. K., Broshek, D. K., & Solomon, G. S. (2017). Predictors of clinical recovery from concussion: A systematic review. *British Journal of Sports Medicine*, *51*(12), 941–948. https://doi.org/10.1136/bjsports-2017-097729

Iverson, G. L., Lovell, M. R., & Collins, M. W. (2003). Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT) Normative Data.

Iverson, G. L., Silverberg, N. D., Mannix, R., Maxwell, B. a., Atkins, J. E., Zafonte, R., & Berkner, P. D. (2015). Factors Associated With Concussion-like Symptom Reporting in High School Athletes. *JAMA Pediatrics*, *169*(10), 1–9. https://doi.org/10.1001/jamapediatrics.2015.2374

Johnston, K. M., McCrory, P., Mohtadi, N. G., & Meeuwisse, W. (2001). Evidence-based review of sport-related concussion: clinical science. *Clinical Journal of Sport Medicine*, *11*, 150–159. https://doi.org/10.1097/00042752-200107000-00005

Jull, G. A., O'Leary, S. P., & Falla, D. L. (2008). Clinical Assessment of the Deep Cervical Flexor Muscles: The Craniocervical Flexion Test. *Journal of Manipulative and Physiological Therapeutics*, *31*(7), 525–533. https://doi.org/10.1016/j.jmpt.2008.08.003

Kemp, S., Hudson, Z., Brooks, J., Fuller, C. (2008). The Epidemiology of Head Injuries in English Professional Rugby Union. *Clinical Journal of Sport Medicine*, *18*(3). https://doi.org/10.1177/0363546507300691

Khong, E., Odenwald, N., Hashim, E., & Cusimano, M. D. (2016). Diffusion tensor imaging findings in post-concussion syndrome patients after mild traumatic brain injury: A systematic review. *Frontiers in Neurology*, *7*(SEP), 1–8. https://doi.org/10.3389/fneur.2016.00156

King, A., Yang, K., & Zhang, L. (2003). Is head injury caused by linear or angular acceleration. *IRCOBI Conference*, (September), 1–12. Retrieved from http://snell-helmets.org/docs/articles/hic/King_IRCOBI_2003.pdf

Koeppen & Stanton. (2017). *Berne and Levy Physiology*. St. Louis: Elsevier Health Sciences. Retrieved from https://www-clinicalkey-com.libaccess.lib.mcmaster.ca/#!/browse/book/3-s2.0-C20110061689

Koerte, I. K., Ertl-Wagner, B., Reiser, M., Zafonte, R., & Shenton, M. E. (2012). White matter integrity in the brains of professional socer players without a symptomatic concussion. *Journal of the American Medical Association*, *308*(18).

Kroshus, E., Daneshvar, D. H., Baugh, C. M., Nowinski, C. J., & Cantu, R. C. (2014). NCAA concussion education in ice hockey : an ineffective mandate. *British Journal of Sports Medicine*, *48*((2)), 135–140. https://doi.org/10.1136/bjsports-2013-092498

Kutcher, J. S., & Eckner, J. T. (2010). At-risk populations in sports-related concussion. *Current Sports Medicine Reports*, *9*(1), 16–20. https://doi.org/http://dx.doi.org/10.1249/JSR.0b013e3181caa89d

Lavallee, A. V., Ching, R. P., & Nuckley, D. J. (2013). Developmental biomechanics of neck musculature. *Journal of Biomechanics*, *46*(3), 527–534. https://doi.org/10.1016/j.jbiomech.2012.09.029

Leddy, J. J., Baker, J. G., & Willer, B. (2016). Active Rehabilitation of Concussion and Post-concussion Syndrome. *Physical Medicine and Rehabilitation Clinics of North America*, *27*(2), 437–454. https://doi.org/10.1016/j.pmr.2015.12.003

Leddy, M. H., Lambert, M. J., & Ogles, B. M. (1994). Psychological consequences of athletic injury among high-level competitors. *Research Quarterly for Exercise and Sport*, *65*(4), 347–354. https://doi.org/10.1080/02701367.1994.10607639

Lindstrøm, R., Schomacher, J., Farina, D., Rechter, L., & Falla, D. (2011). Association between neck muscle coactivation , pain , and strength in women with neck pain. *Manual Therapy*, *16*(1), 80–86. https://doi.org/10.1016/j.math.2010.07.006

Littleton, A., & Guskiewicz, K. (2013). Current concepts in sport concussion management: A multifaceted approach. *Journal of Sport and Health Science*, *2*(4), 227–235. https://doi.org/10.1016/j.jshs.2013.04.003

Llewellyn, T., Burdette, G. T., Joyner, a B., & Buckley, T. a. (2014). Concussion reporting rates at the conclusion of an intercollegiate athletic career. *Clinical Journal of Sport Medicine : Official Journal of the Canadian Academy of Sport Medicine*, *24*(1), 76–79. https://doi.org/10.1097/01.jsm.0000432853.77520.3d

Longhi, L., Saatman, K. E., Fujimoto, S., Raghupathi, R., Meaney, D. F., Davis, J., … McIntosh, T. K. (2005). Temporal window of vulnerability to repetitive experimental concussive brain injury. *Neurosurgery*, *56*(2), 364–373. https://doi.org/10.1227/01.NEU.0000149008.73513.44

Lourenço, A. S., Lameiras, C., & Silva, A. G. (2016). Neck Flexor and Extensor Muscle Endurance in Subclinical Neck Pain: Intrarater Reliability, Standard Error of Measurement, Minimal Detectable Change, and Comparison With Asymptomatic Participants in a University Student Population. *Journal of Manipulative and Physiological Therapeutics*, *39*(6), 427–433. https://doi.org/10.1016/j.jmpt.2016.05.005

Majerske, C. W., Mihalik, J. P., Ren, D., Collins, M. W., Reddy, C. C., Lovell, M. R., & Wagner, A. K. (2008). Concussion in sports: Postconcussive activity levels, symptoms, and neurocognitive performance. *Journal of Athletic Training*, *43*(3), 265–274. https://doi.org/10.4085/1062-6050-43.3.265

Manley, G. T., Gardner, A. J., Schneider, K. J., Guskiewicz, K. M., Bailes, J., Cantu, R. C., … Iverson, G. L. (2017). A systematic review of potential long-term effects of sport-related concussion, 1–10. https://doi.org/10.1136/bjsports-2017-097791

Marshall, S. W., Guskiewicz, K. M., Shankar, V., McCrea, M., & Cantu, R. C. (2015). Epidemiology of sports-related concussion in seven US high school and collegiate sports. *Injury Epidemiology*, *2*(1). https://doi.org/10.1186/s40621-015-0045-4

Marshall, S. W., Waller, A. E., Dick, R. W., Pugh, C. B., Loomis, D. P., & Chalmers, D. J. (2002). An ecologic study of protective equipment and injury in two contact sports. *International Journal of Epidemiology*, *31*(3), 587–592. https://doi.org/10.1093/ije/31.3.587

McCrea, H. J., Perrine, K., Niogi, S., & Hartl, R. (2012). Cuncussion in sports. *Sports Health: A Multidisciplinary Approach*, *5*(2), 160–164. https://doi.org/10.1177/1941738112462203

McCrea, M., Guskiewicz, K. M., Marshall, S. W., Barr, W., Randolph, C., Cantu, R. C., … Kelly, J. P. (2003a). Acute effects and recovery time following. *The Journal of the American Medical Association*, *290*(19), 2556–2563. https://doi.org/10.1001/jama.290.19.2556

McCrea, M., Guskiewicz, K., Randolph, C., Barr, W. B., Hammeke, T. A., Marshall, S. W., … Kelly, J. P. (2016). Incidence, clinical course, and predictors of prolonged recovery time following sport-related concussion in high school and college athletes. *Journal of the International Neuropsychological Society Copyright E INS*, *19*, 22–33. https://doi.org/10.1017/S1355617712000872

McCrea, M., Hammeke, T., Olsen, G., Leo, P., & Guskiewicz, K. (2004). Unreported concussion in high school football players: implications for prevention. *Clin J Sport Med*, *14*(1), 13–17. https://doi.org/10.1097/00042752-200401000-00003

McCrea, M., Kelly, J. P., Randolph, C., Kluge, J., Bartolic, E., Finn, G., & Baxter, B. (1998). Standardized assessment of concussion (SAC): On-site mental status evaluation of the athlete. *Journal of Head Trauma Rehabilitation*. https://doi.org/10.1097/00001199-199804000-00005

McCrory, P., Meeuwisse, W., Dvorak, J., Aubry, M., Bailes, J., Broglio, S., … Vos, P. E. (2017). Consensus statement on concussion in sport — the 5 th international conference on concussion in sport held in Berlin , October 2016. *British Journal of Sports Medicine*, 1–10. https://doi.org/10.1136/bjsports-2017-097699

McCrory, P., Meeuwisse, W. H., Aubry, M., Cantu, R. C., Dvorák, J., Echemendia, R. J., … Turner, M. (2013). Consensus Statement on Concussion in Sport-The 4th International Conference on Concussion in Sport Held in Zurich, November 2012. *PM and R*, *5*(4), 255–279. https://doi.org/10.1016/j.pmrj.2013.02.012

McLeod, T. C. V., & Leach, C. (2012). Psychometric properties of self-report concussion scales and checklists. *Journal of Athletic Training*, *47*(2), 221–223. https://doi.org/10.4085/1062-6050-47.2.221

Meehan, William P. Mannix, Rebekah C. Stracciolini, Andrea Elbin, R.J. Collins, M. W. (2013). Symptom severity predicts prolonged recovery after sport-related concussion: Age and amnesia do not. *Journal of Pediatrics*, *163*(3), 721–725. https://doi.org/10.1016/j.jpeds.2013.03.012.Symptom

Meeuwisse, W. H., Hagel, B. E., Mohtadi, N. G. H., Butterwick, D. J., & Fick, G. H. (2000). The Distribution of injuries in men's Canada West university football: A 5-year analysis. *The American Journal of Sports Medicine*, *28*(4), 516–523. https://doi.org/10.1177/03635465000280041201

Misra, J. C., & Chakravarty, S. (1984). A study on rotational brain injury. *Journal of Biomechanics*, *17*(7), 459–466. https://doi.org/10.1016/0021-9290(84)90014-9

NCAA. (2013). *NCAA sports medicine handbook, Guideline 21: Sports-related concussion*. Idianapolis, IN. https://doi.org/10.1136/bjsm.34.3.230-a

Omalu, B. I., DeKosky, S. T., Minster, R. L., Kamboh, M. I., Hamilton, R. L., & Wecht, C. H. (2005). Chronic traumatic encephalopathy in a National Football League player.

Neurosurgery, *57*(1), 128–133. https://doi.org/10.1227/01.NEU.0000163407.92769.ED

Pagano, Marcello; Gauvreau, K. (2000). *Principles of Biostatistics* (2nd Editio). Belmont,CA: Brooks/Cole.

Parazza, S., Vanti, C., O'Reilly, C., Villafañe, J. H., Tricás Moreno, J. M., & Estébanez De Miguel, E. (2014). The relationship between cervical flexor endurance, cervical extensor endurance, VAS, and disability in subjects with neck pain. *Chiropractic & Manual Therapies*, *22*(1), 10. https://doi.org/10.1186/2045-709X-22-10

Peduzzi, P., Concato, J., Kemper, E., Holford, T.R., Feinstein, A. R. (1996). A simulation study of the number of events per variable in logistic regression analysis. *Journal of Clinical Epidemiology*, *49*(12), 1373–1379.

Powell, J. W., & Barber-foss, K. D. (1999). Traumatic brain injury in high school athletes. *JAMA*, *282*(10), 959–963.

Prins, M. L., Alexander, D., Giza, C. C., & Hovda, D. A. (2013). Repeated mild traumatic brain injury: mechanisms of cerebral vulnerability. *Journal of Neurotrauma*, *30*(1), 30–38. https://doi.org/10.1089/neu.2012.2399

Putukian, M., Echemendia, R., Dettwiler-Danspeckgruber, A., Duliba, T., Bruce, J., Furtado, J. L., & Murugavel, M. (2015). Prospective clinical assessment using sideline concussion assessment tool-2 testing in the evaluation of sport-related concussion in college athletes. *Clinical Journal of Sport Medicine*, *25*(1), 36–42. https://doi.org/10.1097/JSM.0000000000000102

Rishiraj, N., Lorenz, T., Niven, B., & Michel, M. (2009). University men ' s ice hockey : rates and risk of injuries over 6-years. *Sports Medicine*.

Rose, S. C., Fischer, A. N., & Heyer, G. L. (2015). How long is too long ? The lack of consensus regarding the post-concussion syndrome diagnosis, *9052*, 798–803. https://doi.org/10.3109/02699052.2015.1004756

Safinia, C., Bershad, E. M., Clark, H. B., Santacruz, K., Alakbarova, N., Suarez, J. I., & Divani, A. A. (2016). Chronic Traumatic Encephalopathy in Athletes Involved with High- impact Sports. *Journal of Vascular and Interventional Neurology*, *9*(2), 34–48.

Sandel, N. N. K., Lovell, M. R. M., Kegel, N. N. E., Collins, M. W., & Kontos, A. P. (2013). The Relationship of Symptoms and Neurocognitive Performance to Perceived Recovery From Sports-Related Concussion Among Adolescent Athletes. *Applied Neuropsychology: ...*, *2*(1), 64–69. https://doi.org/10.1080/21622965.2012.670580

Schatz, P., Pardini, J. E., Lovell, M. R., Collins, M. W., & Podell, K. (2006). Sensitivity and specificity of the ImPACT Test Battery for concussion in athletes. *Archives of Clinical Neuropsychology*, *21*(1), 91–99. https://doi.org/10.1016/j.acn.2005.08.001

Schatz, P., & Sandel, N. (2013). Sensitivity and specificity of the online version of ImPACT in high school and collegiate athletes. *Am J Sports Med*, *41*(2), 321–326. https://doi.org/10.1177/0363546512466038

Schneider, K., Emery, C., Kang, J., Schneider, G., & Meeuwisse, W. (2011). Are pre-season reports of neck pain, dizziness and/or headaches risk factors for concussion in male youth ice hockey players? *British Journal of Sports Medicine*, *45*(4), 319–320. https://doi.org/10.1136/bjsm.2011.084038.28

Schulz, M. R., Marshall, S. W., Mueller, F. O., Yang, J., Weaver, N. L., Kalsbeek, W. D., & Bowling, J. M. (2004). Incidence and risk factors for concussion in high school athletes, North Carolina, 1996-1999. *American Journal of Epidemiology*, *160*(10), 937–944. https://doi.org/10.1093/aje/kwh304

Scopaz, K., & Hatzenbuehler, J. (2013). Risk modifiers for concussion and prolonged recovery. *Sports Health*, *5*(6), 537–541. https://doi.org/10.1177/1941738112473059

Sebastian, D., Chovvath, R., & Malladi, R. (2015). Cervical extensor endurance test: Areliability study. *Journal of Bodywork and Movement Therapies*, *19*(2), 213–216. https://doi.org/10.1016/j.jbmt.2014.04.014

Seifert, T., & Shipman, V. (2015). The Pathophysiology of Sports Concussion. *Current Pain and Headache Reports*, *19*(8), 1–9. https://doi.org/10.1007/s11916-015-0513-0

Shehata, N., Wiley, J. P., Richea, S., Benson, B. W., Duits, L., & Meeuwisse, W. H. (2009). Sport concussion assessment tool: baseline values for varsity collision sport athletes. *Br J Sports Med*, *43*(10), 730–734. https://doi.org/10.1136/bjsm.2009.059832

Stazyk, K. (2015). *Depression in Children Recovering from Concussion: Correlates and Predictors*.

Stern, R. A., Riley, D. O., Daneshvar, D. H., Nowinski, C. J., Cantu, R. C., & McKee, A. C. (2011). Long-term Consequences of Repetitive Brain Trauma: Chronic Traumatic Encephalopathy. *PM and R*, *3*(10 SUPPL. 2), 460–467. https://doi.org/10.1016/j.pmrj.2011.08.008

Sullivan, J. C., Tavassoli, T., Armstrong, K., Baron-Cohen, S., & Humphrey, A. (2014). Reliability of self, parental, and researcher measurements of head circumference. *Molecular Autism*, *5*(1), 2–5. https://doi.org/10.1186/2040-2392-5-2

Tavazzi, B., Vagnozzi, R., Signoretti, S., Amorini, A. M., Finocchiaro, A., Cimatti, M., … Lazzarino, G. (2007). Temporal window of metabolic brain vulnerability to concussions: Oxidative and nitrosative stresses - Part II. *Neurosurgery*, *61*(2), 390–396. https://doi.org/10.1227/01.NEU.0000255525.34956.3F

The Physical Activity Council. (2016). 2016 participation report: The physical activity council's annual study tracking sports, fitness, and recreation participaton in the US, 26.

Tierney, R. T., Higgins, M., Caswell, S. V., Brady, J., McHardy, K., Driban, J. B., & Darvish, K. (2008a). Sex differences in head acceleration during heading while wearing soccer headgear. *Journal of Athletic Training*, *43*(6), 578–584. https://doi.org/http://dx.doi.org/10.4085/1062-6050-43.6.578

Tierney, R. T., Higgins, M., Caswell, S. V, Brady, J., McHardy, K., Driban, J. B., & Darvish, K. (2008b). Sex Differences in Head Acceleration During Heading While Wearing Soccer Headgear. *Journal of Athletic Training*, *43*(6), 578–584. https://doi.org/10.4085/1062-6050-43.6.578

Tierney, R. T., Sitler, M. R., Swanik, C. B., Swanik, K. A., Higgins, M., & Torg, J. (2005). Gender differences in head-neck segmnet dynamic stabilization during head accelaration. *Medicine and Science in Sports and Exercise*, *37*(2), 272–279. https://doi.org/10.1249/01.MSS.0000152734.47516.AA

Tsushima, W. T., Siu, A. M., Ahn, H. J., Chang, B. L., & Murata, N. M. (2018). Incidence and Risk of Concussions in Youth Athletes: Comparisons of Age, Sex, Concussion History, Sport, and Football Position. *Archives of Clinical Neuropsychology*, (May). https://doi.org/10.1093/arclin/acy019

USports. (2017). USPORTS Student-Athlete User Guide.

Vagnozzi, R. et al. (2007). Temporal window of metabolic brain vulnerability to concussions: Mitochondrial-related impairment - Part I. Commentary. *Neurosurgery*, *61*(2), 388–389. https://doi.org/10.1227/01.NEU.0000280002.41696.D8

Valovich McLeod, T. C., Barr, W. B., McCrea, M., & Guskiewicz, K. M. (2006). Psychometric and measurement properties of concussion assessment tools in youth sports. *Journal of Athletic Training*, *41*(4), 399–408.

Vasavada, A. N., Danaraj, J., & Siegmund, G. P. (2008). Head and neck anthropometry, vertebral geometry and neck strength in height-matched men and women. *Journal of Biomechanics*, *41*(1), 114–121. https://doi.org/10.1016/j.jbiomech.2007.07.007

Virji-Babul, N., Borich, M. R., Makan, N., Moore, T., Frew, K., Emery, C. A., & Boyd, L. A. (2013). Diffusion Tensor Imaging of Sports-related Concussion in Adolescents. *Pediatric Neurology*, *48*, 24–29.

Williams, R. M., Puetz, T. W., Giza, C. C., & Broglio, S. P. (2015). Concussion Recovery Time Among High School and Collegiate Athletes: A Systematic Review and Meta-Analysis. *Sports Medicine*, *45*(6), 893–903. https://doi.org/10.1007/s40279-015-0325-8

Williamson, R. W., Gerhardstein, D., Cardenas, J., Michael, D. B., Theodore, N., & Rosseauk, N. (2014). Concussion 101: The current state of concussion education programs. *Neurosurgery*, *75*(4), S131–S135. https://doi.org/10.1227/NEU.0000000000000482

World Health Organization (WHO). (2011). ICD-10 Transition. *Family Practice Management*, *18*, 39. https://doi.org/10.1159/000371811

Yengo-kahn, A., Allen, K., & Kerr, Z. Y. (2016). Predictors of postconcussion syndrome in collegiate student-athletes, *40*(April), 1–10. https://doi.org/10.3171/2016.1.FOCUS15593.

Yengo-kahn, A. M., Hale, A. T., Zalneraitis, B. H., Zuckerman, S. L., Sills, A. K., & Solomon, G. S. (2016). Review. *Neurosurgical Focus*, *40*(April). https://doi.org/10.3171/2016.1.FOCUS15611.

Zemek, R. L., Farion, K. J., Sampson, M., & McGahern, C. (2013). Prognosticators of Persistent Symptoms Following Pediatric Concussion. *JAMA Pediatrics*, *167*(3), 259. https://doi.org/10.1001/2013.jamapediatrics.216

Zuckerman, S. L., Kerr, Z. Y., Yengo-Kahn, A., Wasserman, E., Covassin, T., & Solomon, G. S. (2015). Epidemiology of Sports-Related Concussion in NCAA Athletes From 2009-2010 to 2013-2014: Incidence, Recurrence, and Mechanisms. *The American Journal of Sports Medicine*, *43*(11), 2654–2662. https://doi.org/10.1177/0363546515599634

Zuckerman, S. L., Yengo-kahn, A. M., Buckley, T. A., Solomon, G. S., Sills, A. K., & Kerr, Z. Y. (2016). Predictors of postconcussion syndrome in collegiate student-athletes, *40*(April), 1–10. https://doi.org/10.3171/2016.1.FOCUS15593.

Appendix A – Hamilton Integrated Research Ethics Board Approval Letter

HiREB
Hamilton Integrated Research Ethics Board

27 July 2016

Project Number: 1924

Project Title: Examination of the Role of Neck Strength on the Incidence of Concussion in a Varsity Athlete Population.

Student Principal Investigator: Miss. Erin Cole

Local Principal Investigator: Ms. Carol DeMatteo

We have completed our review of your study and are please to issue our final approval. You may now begin your study.

The following documents have been approved on both ethical and scientific grounds:

Document Name	Document Date	Document Version
CONSENT_V2.0_July12_CLEAN	12/Jul/2016	2.0
Data Intake Form_Version1_JULY12	12/Jul/2016	2.0
EC_ThesisEthicsProtocol_V2JULY12_CLEAN	12/Jul/2016	2.0

Any changes to this study must be submitted with an Amendment Request Form before they can be implemented.

This approval is effective for 12 months from the date of this letter. Upon completion of your study please submit a **Study Completion Form**.
If you require more time to complete your study, you must request an extension in writing before this approval expires. Please submit an **Annual Review Form** with your request.

PLEASE QUOTE THE ABOVE REFERENCED PROJECT NUMBER ON ALL FUTURE CORRESPONDENCE

Good luck with your research,

Kristina Trim, PhD, RSW
Chair, HiREB Student Research Committee
McMaster University

The Hamilton Integrated Research Ethics Board operates in compliance with and is constituted in accordance with the requirements of: The Tri-Council Policy Statement on Ethical Conduct of Research Involving Humans; The International Conference on Harmonization of Good Clinical Practices; Part C Division 5 of the Food and Drug Regulations of Health Canada, and the provisions of the Ontario Personal Health Information Protection Act 2004 and its applicable Regulations;for studies conducted at St. Joseph's Hospital, HIREB complies with the health ethics guide of the Catholic Alliance of Canada

Appendix B – Consent Form

INFORMATION SHEET FOR PARTICIPANTS

Examining the Role of Neck Strength in the Incidence of Concussion in McMaster University Athletes.

Principal Investigator:
Erin Cole, BSc.
Master's Candidate, The School of Rehabilitation Science

Local PI:
Carol DeMatteo, MSc Dip P&OT

Associate Professor, The School of Rehabilitation Science**You are being invited to participate in a research study conducted by Erin Cole, a Master's student, within the Faculty of Health Sciences. As a competitive athlete it is almost certain that you have been affected, either personally or through a teammate, by a concussion. In this research study we are looking to determine if there are any factors that are able to predict who are the athletes with a greater risk for concussion.**

In order to decide whether or not you want to be a part of this research study, you should understand what is involved and the potential risks and benefits. This form gives detailed information about the research study, which will be discussed with you. Once you understand the study, you will be asked to sign this form if you wish to participate.

There is no conflict of interest that exists in relation to this study, and there is no potential benefit to the investigator(s) beyond the professional benefit from academic achievement or presentation of the results.WHY IS THIS RESEARCH BEING DONE?

The known risks of concussions in sport have become more and more severe within the last 20 years. However, there is still very little known about concussions, how we may prevent them and who is at risk of suffering from this injury. This study will attempt to assess some of the potential variables that contribute to an increased likelihood of sustaining a concussion as a varsity athlete.

WHAT IS THE PURPOSE OF THIS STUDY?

To determine if neck strength, sex, or type of sport indicate any increased risk for sustaining a concussion as a varsity athlete.

WHAT WILL MY RESPONSIBILITIES BE IF I TAKE PART IN THE STUDY?

If you volunteer to participate in this study, we will ask you to do the following things:

Complete a medical history questionnaire.
This brief survey will capture more information on your current health status and past injuries that may play a role in increased risk for concussion. We will collect information on the number of past concussions you have experienced, if you currently are suffering from any other head, neck or back injuries or any mental health issues you may be experiencing or have experienced previously. All of this data will be kept confidential by removing any participant identifiers and replacing them with a participant study code. All of this information will be stored in a secure location that is only accessible to authorized study personnel.

Complete neck strength measurement tests.
During your regular season, university-mandated baseline concussion assessments you will perform two endurance tests. In these tests you will be required to hold your head in a certain position off of a treatment table for as long as possible. You may ask to stop these tests at any time.

Provide anthropometric measurements.
In addition to the data collected in the medical survey, you will be asked if we may take height and weight measurements, as well as measurements of your head and neck circumferences, and the length of your neck. These measures will help to examine athlete characteristics at the time of data analysis.

WHAT WILL HAPPEN DURING THE STUDY?

If you consent to participate in this study, the following things will take place:

1) Medical History Questionnaire
- You will be given a paper and pen survey to complete that will ask questions about past concussions or neck injuries that may influence the findings of the study.

2) Anthropometric Measurements

- A soft tape measure will be used to measure the circumference of your head around the forehead.
- Neck circumference will be measured using the tape measure around the mid-neck (below the Adam's apple). The length of the neck will also be measured.
- A meter-stick will be used to measure your height and a scale will measure your weight.

3) Strength Measurements

- To measure the strength of the muscles on the front side of the neck (flexors) you will lay on your back on a treatment bed.
- You will tuck your chin as much is possible and a line will be drawn on the side of the neck to be able to determine any variability from your starting position.
- You will hold your head off the table with your chin tucked for as long as possible.
- The assessor will tell you when the test is over.
- For the muscles on the back of the neck (extensors) the neck strength the procedure is almost the same, however you will be positioned lying on your stomach.
- Additionally, there will be a small weight attached to your head using an adjustable strap.
- You will tuck your chin and hold your head horizontally until the assessor informs you the test is over.
- You may stop these tests at any time due to fatigue or pain.

The whole procedure should take between 5-10 minutes.

WHAT ARE THE POSSIBLE RISKS AND DISCOMFORTS?

There are no risks to participation in this study. The methods used to measure neck strength are safe and isometric(non-moving) in nature which allows us to ensure no potential injury or extreme muscle fatigue. However, there may be some very slight discomfort due to the Velcro strap used for one of the strength tests.

HOW MANY PEOPLE WILL BE IN THIS STUDY?

We will recruit as many varsity athletes as possible to be in this study.

WHAT ARE THE POSSIBLE BENEFITS FOR ME AND/OR FOR SOCIETY?

You will receive no direct benefit from participation in this study. However, the results will be made available to you upon completion of the study. Pending the finding of this study we may be able to determine which individuals are more at risk for concussion and focus our future research on preventative strategies.

WHAT INFORMATION WILL BE KEPT PRIVATE?

Your data will not be shared with anyone except with your consent. All personal information including your name, age, and sex will be removed from the database and replaced with a generic participant ID number. The list identifying the ID number to the individual participant will be stored in a password protected on a locked computer. This document will be stored on a server that is separate from the database itself.. The data, with identifying information removed, will be securely stored in a locked office in the School of Rehabilitation Science.

For the purposes of ensuring the proper monitoring of the research study, it is possible that a member of the Hamilton Integrated Research Ethics Board may consult your research data. However, no records which identify you by name or initials will be allowed to leave the data storage location in the Institute for Applied Health Sciences. By signing this consent form, you (or your legally acceptable representative) authorize such access.

If the results of the study are published, your name will not be used and no information that discloses your identity will be released or published without your specific consent to the disclosure. However, it is important to note that this original signed consent form and the data that follows may be included in your health record.

CAN PARTICIPATION IN THE STUDY END EARLY?

If you volunteer to be in this study, you may withdraw at any time and this will in no way affect any other involvement you have with the University or related athletic or rehabilitation facilities/services. You have the option of removing your data from the study. You may also refuse to answer any questions you don't want to answer and still remain in the study. The investigator may withdraw you from this research if circumstances arise which warrant doing so

WILL I BE PAID TO PARTICIPATE IN THIS STUDY?

There is no reimbursement for participation in this study

WILL THERE BE ANY COSTS?

Your participation in this research project will not involve any additional costs to you or your health care insurer.

.

IF I HAVE ANY QUESTIONS OR PROBLEMS, WHOM CAN I CALL?

If you have any questions about the research now or later, or if you think you have a research-related injury, please contact:
Carol DeMatteo, McMaster University 905-525-9140 ext. 27805

CONSENT STATEMENT

Participant:

I have read the preceding information thoroughly. I have had an opportunity to ask questions and all of my questions have been answered to my satisfaction. I agree to participate in this study. I understand that I will receive a signed copy of this form.

Name	Signature of patient	Date

Person obtaining consent:

I have discussed this study in detail with the participant. I believe the participant understands what is involved in this study.

Name, Role in Study	Signature	Date

Witness: *(required if participants are unable to read, or if translation is necessary)*

I was present when the information in this form was explained and discussed with the participant. I believe the participant understands what is involved in this study.

Name	Signature	Date

This study has been reviewed by the Hamilton Integrated Research Ethics Board (HIREB). The REB is responsible for ensuring that participants are informed of the risks associated with the research, and that participants are free to decide if participation is right for them. If you have any questions about your rights as a research participant, please call The Office of the Chair, HIREB at 905-521-2100 ext. 42013.

Appendix C – Baseline Assessment Intake Form

1. Demographics & Medical History (to be completed by the athlete)			
Name:	**Sex:**	**Sport:**	**Age:**
Have you had any previous concussions? **0-2☐ 3-5 ☐ 6-8 ☐ 9+☐**		**When was your last concussion?** **In the last 3 mos.☐ 6 mos.☐ 1 yr.☐ 2+ yrs.☐**	
Do you have any neck pain currently? **YES ☐ NO ☐**	**Do you have any of the following at present:** **Neck injury ☐ Back injury☐ Shoulder injury ☐** **Neuropathy☐ Anxiety☐ Depression☐ Other: ______________**		
If you have history of mental health issues are these on going? **YES ☐ NO ☐**		**How many years have you played this sport? ______** **What position do you play?**	

2. Anthropometric Data (to be completed by the assessor)		
Height (cm):	**Weight (kg):**	**BMI:**
Head Circumference (cm):	**Neck Circumference (cm):**	**Neck Length (cm):**
Neck- Head circumference ratio:	**Neck length – head circumference ratio:**	

3. Strength Measurements (to be completed by the assessor)	
Deep Flexor Endurance Test:	**Extensor Endurance Test:**

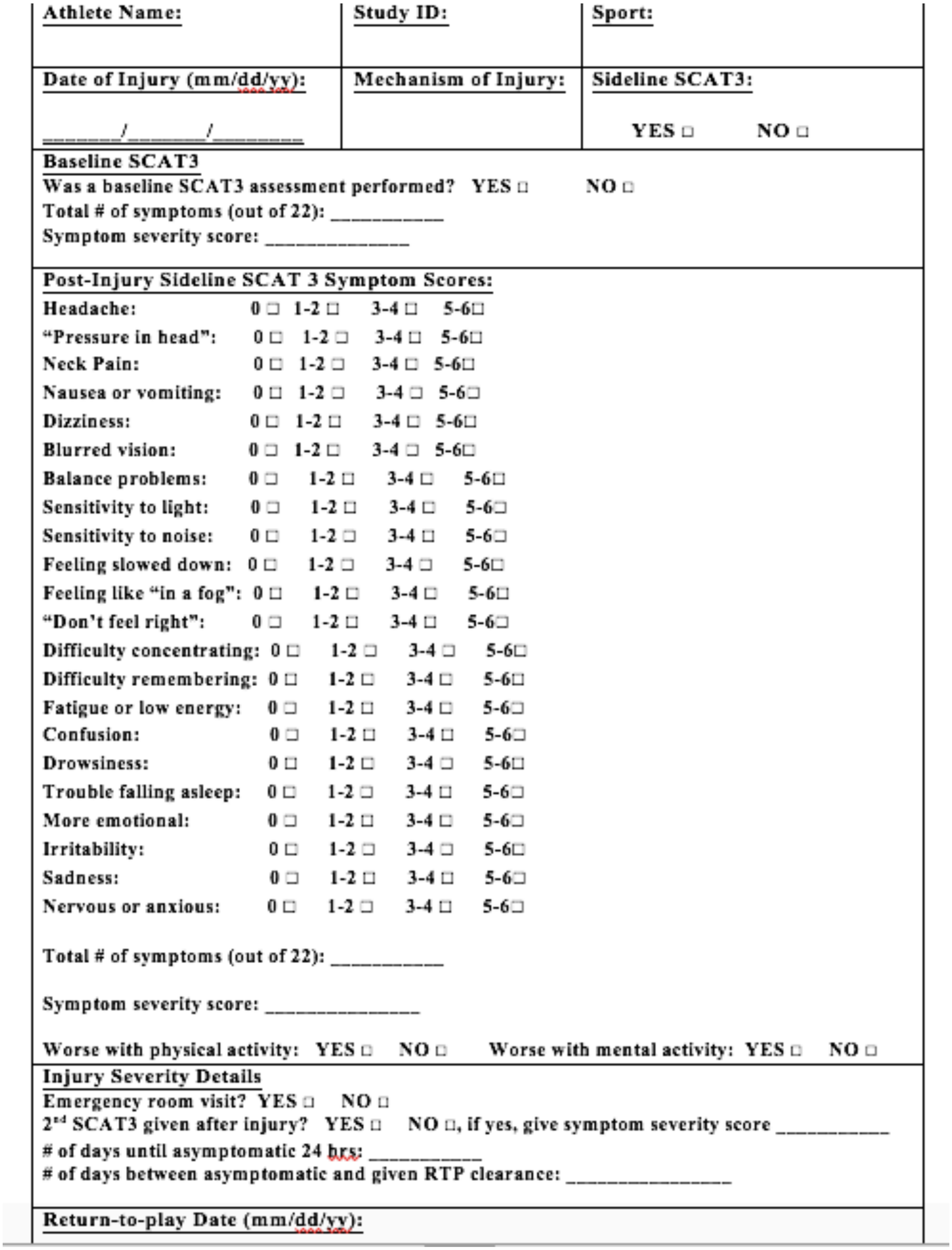
Comments:____

____

____

____

Appendix D – Concussion Injury Intake Form



Athlete Name:	**Study ID:**	**Sport:**
Date of Injury (mm/dd/yy): _______/_______/________	**Mechanism of Injury:**	**Sideline SCAT3:** YES ☐ NO ☐

Baseline SCAT3
Was a baseline SCAT3 assessment performed? YES ☐ NO ☐
Total # of symptoms (out of 22): ___________
Symptom severity score: ______________

Post-Injury Sideline SCAT 3 Symptom Scores:

Headache:	0 ☐	1-2 ☐	3-4 ☐	5-6☐
"Pressure in head":	0 ☐	1-2 ☐	3-4 ☐	5-6☐
Neck Pain:	0 ☐	1-2 ☐	3-4 ☐	5-6☐
Nausea or vomiting:	0 ☐	1-2 ☐	3-4 ☐	5-6☐
Dizziness:	0 ☐	1-2 ☐	3-4 ☐	5-6☐
Blurred vision:	0 ☐	1-2 ☐	3-4 ☐	5-6☐
Balance problems:	0 ☐	1-2 ☐	3-4 ☐	5-6☐
Sensitivity to light:	0 ☐	1-2 ☐	3-4 ☐	5-6☐
Sensitivity to noise:	0 ☐	1-2 ☐	3-4 ☐	5-6☐
Feeling slowed down:	0 ☐	1-2 ☐	3-4 ☐	5-6☐
Feeling like "in a fog":	0 ☐	1-2 ☐	3-4 ☐	5-6☐
"Don't feel right":	0 ☐	1-2 ☐	3-4 ☐	5-6☐
Difficulty concentrating:	0 ☐	1-2 ☐	3-4 ☐	5-6☐
Difficulty remembering:	0 ☐	1-2 ☐	3-4 ☐	5-6☐
Fatigue or low energy:	0 ☐	1-2 ☐	3-4 ☐	5-6☐
Confusion:	0 ☐	1-2 ☐	3-4 ☐	5-6☐
Drowsiness:	0 ☐	1-2 ☐	3-4 ☐	5-6☐
Trouble falling asleep:	0 ☐	1-2 ☐	3-4 ☐	5-6☐
More emotional:	0 ☐	1-2 ☐	3-4 ☐	5-6☐
Irritability:	0 ☐	1-2 ☐	3-4 ☐	5-6☐
Sadness:	0 ☐	1-2 ☐	3-4 ☐	5-6☐
Nervous or anxious:	0 ☐	1-2 ☐	3-4 ☐	5-6☐

Total # of symptoms (out of 22): ___________

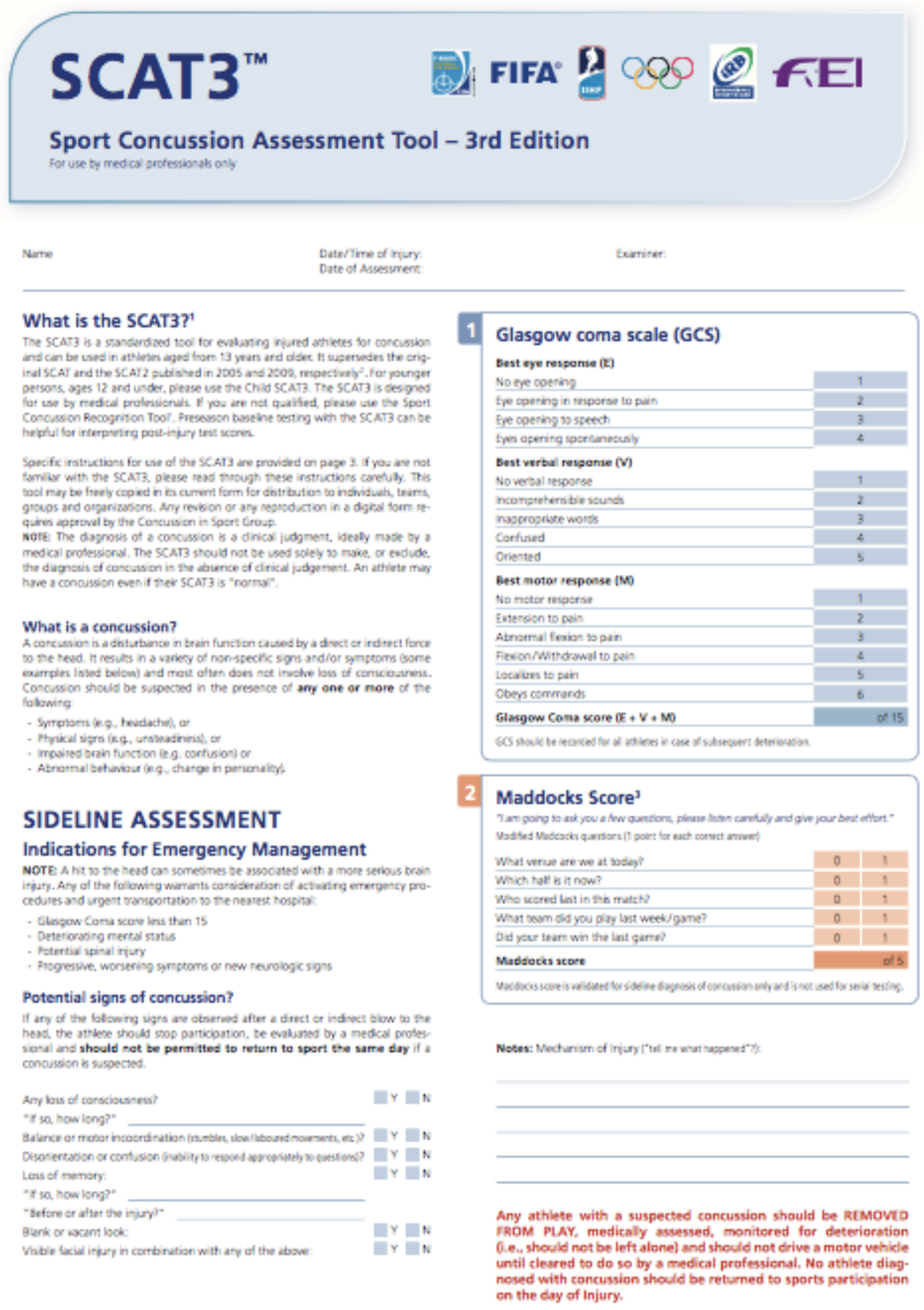
Symptom severity score: _______________

Worse with physical activity: YES ☐ NO ☐ Worse with mental activity: YES ☐ NO ☐

Injury Severity Details
Emergency room visit? YES ☐ NO ☐
2nd SCAT3 given after injury? YES ☐ NO ☐, if yes, give symptom severity score ___________
# of days until asymptomatic 24 hrs: ___________
# of days between asymptomatic and given RTP clearance: ________________

Return-to-play Date (mm/dd/yy):

Appendix E – Sport Concussion Assessment Tool, 3rd edition



SCAT3™

Sport Concussion Assessment Tool – 3rd Edition

For use by medical professionals only

Name

Date/Time of Injury:
Date of Assessment:

Examiner:

What is the SCAT3?[1]

The SCAT3 is a standardized tool for evaluating injured athletes for concussion and can be used in athletes aged from 13 years and older. It supersedes the original SCAT and the SCAT2 published in 2005 and 2009, respectively[2]. For younger persons, ages 12 and under, please use the Child SCAT3. The SCAT3 is designed for use by medical professionals. If you are not qualified, please use the Sport Concussion Recognition Tool[1]. Preseason baseline testing with the SCAT3 can be helpful for interpreting post-injury test scores.

Specific instructions for use of the SCAT3 are provided on page 3. If you are not familiar with the SCAT3, please read through these instructions carefully. This tool may be freely copied in its current form for distribution to individuals, teams, groups and organizations. Any revision or any reproduction in a digital form requires approval by the Concussion in Sport Group.

NOTE: The diagnosis of a concussion is a clinical judgment, ideally made by a medical professional. The SCAT3 should not be used solely to make, or exclude, the diagnosis of concussion in the absence of clinical judgement. An athlete may have a concussion even if their SCAT3 is "normal".

What is a concussion?

A concussion is a disturbance in brain function caused by a direct or indirect force to the head. It results in a variety of non-specific signs and/or symptoms (some examples listed below) and most often does not involve loss of consciousness. Concussion should be suspected in the presence of **any one or more** of the following:

- Symptoms (e.g., headache), or
- Physical signs (e.g., unsteadiness), or
- Impaired brain function (e.g. confusion) or
- Abnormal behaviour (e.g., change in personality).

SIDELINE ASSESSMENT

Indications for Emergency Management

NOTE: A hit to the head can sometimes be associated with a more serious brain injury. Any of the following warrants consideration of activating emergency procedures and urgent transportation to the nearest hospital:

- Glasgow Coma score less than 15
- Deteriorating mental status
- Potential spinal injury
- Progressive, worsening symptoms or new neurologic signs

Potential signs of concussion?

If any of the following signs are observed after a direct or indirect blow to the head, the athlete should stop participation, be evaluated by a medical professional and **should not be permitted to return to sport the same day** if a concussion is suspected.

Any loss of consciousness? ☐ Y ☐ N
"If so, how long?" ______
Balance or motor incoordination (stumbles, slow/laboured movements, etc.)? ☐ Y ☐ N
Disorientation or confusion (inability to respond appropriately to questions)? ☐ Y ☐ N
Loss of memory: ☐ Y ☐ N
"If so, how long?" ______
"Before or after the injury?" ______
Blank or vacant look: ☐ Y ☐ N
Visible facial injury in combination with any of the above: ☐ Y ☐ N

1 Glasgow coma scale (GCS)

Best eye response (E)	
No eye opening	1
Eye opening in response to pain	2
Eye opening to speech	3
Eyes opening spontaneously	4
Best verbal response (V)	
No verbal response	1
Incomprehensible sounds	2
Inappropriate words	3
Confused	4
Oriented	5
Best motor response (M)	
No motor response	1
Extension to pain	2
Abnormal flexion to pain	3
Flexion/Withdrawal to pain	4
Localizes to pain	5
Obeys commands	6
Glasgow Coma score (E + V + M)	of 15

GCS should be recorded for all athletes in case of subsequent deterioration.

2 Maddocks Score[3]

"I am going to ask you a few questions, please listen carefully and give your best effort."

Modified Maddocks questions (1 point for each correct answer)

What venue are we at today?	0	1
Which half is it now?	0	1
Who scored last in this match?	0	1
What team did you play last week/game?	0	1
Did your team win the last game?	0	1
Maddocks score		of 5

Maddocks score is validated for sideline diagnosis of concussion only and is not used for serial testing.

Notes: Mechanism of Injury ("tell me what happened"?):

Any athlete with a suspected concussion should be REMOVED FROM PLAY, medically assessed, monitored for deterioration (i.e., should not be left alone) and should not drive a motor vehicle until cleared to do so by a medical professional. No athlete diagnosed with concussion should be returned to sports participation on the day of Injury.

BACKGROUND

Name: ____________ Date: ____________
Examiner: ____________
Sport/team/school: ____________ Date/time of injury: ____________
Age: ____________ Gender: ☐ M ☐ F
Years of education completed: ____________
Dominant hand: ☐ right ☐ left ☐ neither
How many concussions do you think you have had in the past? ____________
When was the most recent concussion? ____________
How long was your recovery from the most recent concussion? ____________
Have you ever been hospitalized or had medical imaging done for a head injury? ☐ Y ☐ N
Have you ever been diagnosed with headaches or migraines? ☐ Y ☐ N
Do you have a learning disability, dyslexia, ADD/ADHD? ☐ Y ☐ N
Have you ever been diagnosed with depression, anxiety or other psychiatric disorder? ☐ Y ☐ N
Has anyone in your family ever been diagnosed with any of these problems? ☐ Y ☐ N
Are you on any medications? If yes, please list: ☐ Y ☐ N

SCAT3 to be done in resting state. Best done 10 or more minutes post excercise.

SYMPTOM EVALUATION

3 How do you feel?

"You should score yourself on the following symptoms, based on how you feel now".

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

Total number of symptoms (Maximum possible 22)
Symptom severity score (Maximum possible 132)

Do the symptoms get worse with physical activity? ☐ Y ☐ N
Do the symptoms get worse with mental activity? ☐ Y ☐ N

☐ self rated
☐ clinician interview
☐ self rated and clinician monitored
☐ self rated with parent input

Overall rating: If you know the athlete well prior to the injury, how different is the athlete acting compared to his/her usual self?

Please circle one response:

no different	very different	unsure	N/A

Scoring on the SCAT3 should not be used as a stand-alone method to diagnose concussion, measure recovery or make decisions about an athlete's readiness to return to competition after concussion. Since signs and symptoms may evolve over time, it is important to consider repeat evaluation in the acute assessment of concussion.

COGNITIVE & PHYSICAL EVALUATION

4 Cognitive assessment

Standardized Assessment of Concussion (SAC)[4]

Orientation (1 point for each correct answer)

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

Immediate memory

List	Trial 1		Trial 2		Trial 3		Alternative word list		
elbow	0	1	0	1	0	1	candle	baby	finger
apple	0	1	0	1	0	1	paper	monkey	penny
carpet	0	1	0	1	0	1	sugar	perfume	blanket
saddle	0	1	0	1	0	1	sandwich	sunset	lemon
bubble	0	1	0	1	0	1	wagon	iron	insect
Total									

Immediate memory score total of 15

Concentration: Digits Backward

List	Trial 1		Alternative digit list		
4-9-3	0	1	6-2-9	5-2-6	4-1-5
3-8-1-4	0	1	3-2-7-9	1-7-9-5	4-9-6-8
6-2-9-7-1	0	1	1-5-2-8-6	3-8-5-2-7	6-1-8-4-3
7-1-8-4-6-2	0	1	5-3-9-1-4-8	8-3-1-9-6-4	7-2-4-8-5-6
Total of 4					

Concentration: Month in Reverse Order (1 pt. for entire sequence correct)

Dec-Nov-Oct-Sept-Aug-Jul-Jun-May-Apr-Mar-Feb-Jan	0	1
Concentration score		of 5

5 Neck Examination:

Range of motion Tenderness Upper and lower limb sensation & strength
Findings: ____________

6 Balance examination

Do one or both of the following tests.
Footwear (shoes, barefoot, braces, tape, etc.) ____________

Modified Balance Error Scoring System (BESS) testing[5]
Which foot was tested (i.e. which is the **non-dominant** foot) ☐ Left ☐ Right
Testing surface (hard floor, field, etc.) ____________

Condition

Double leg stance:	Errors
Single leg stance (non-dominant foot):	Errors
Tandem stance (non-dominant foot at back):	Errors

And/Or

Tandem gait[6,7]
Time (best of 4 trials): ________ seconds

7 Coordination examination

Upper limb coordination
Which arm was tested: ☐ Left ☐ Right
Coordination score of 1

8 SAC Delayed Recall[4]

Delayed recall score of 5

INSTRUCTIONS

Words in *Italics* throughout the SCAT3 are the instructions given to the athlete by the tester.

Symptom Scale

"You should score yourself on the following symptoms, based on how you feel now".

To be completed by the athlete. In situations where the symptom scale is being completed after exercise, it should still be done in a resting state, at least 10 minutes post exercise.
For total number of symptoms, maximum possible is 22.
For Symptom severity score, add all scores in table, maximum possible is 22 x 6 = 132.

SAC[4]

Immediate Memory

"I am going to test your memory. I will read you a list of words and when I am done, repeat back as many words as you can remember, in any order."

Trials 2 & 3:

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

Complete all 3 trials regardless of score on trial 1 & 2. Read the words at a rate of one per second. **Score 1 pt. for each correct response.** Total score equals sum across all 3 trials. Do not inform the athlete that delayed recall will be tested.

Concentration

Digits backward

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

If correct, go to next string length. If incorrect, read trial 2. **One point possible for each string length.** Stop after incorrect on both trials. The digits should be read at the rate of one per second.

Months in reverse order

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

1 pt. for entire sequence correct

Delayed Recall

The delayed recall should be performed after completion of the Balance and Coordination Examination.

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

Score 1 pt. for each correct response

Balance Examination

Modified Balance Error Scoring System (BESS) testing[5]

This balance testing is based on a modified version of the Balance Error Scoring System (BESS)[5]. A stopwatch or watch with a second hand is required for this testing.

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

(a) Double leg stance:

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

(b) Single leg stance:

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

(c) Tandem stance:

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

Balance testing – types of errors

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

Each of the 20-second trials is scored by counting the errors, or deviations from the proper stance, accumulated by the athlete. The examiner will begin counting errors only after the individual has assumed the proper start position. **The modified BESS is calculated by adding one error point for each error during the three 20-second tests. The maximum total number of errors for any single condition is 10**. If a athlete commits multiple errors simultaneously, only one error is recorded but the athlete should quickly return to the testing position, and counting should resume once subject is set. Subjects that are unable to maintain the testing procedure for a minimum of **five seconds** at the start are assigned the highest possible score, ten, for that testing condition.

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

Tandem Gait[6,7]

Participants are instructed to stand with their feet together behind a starting line (the test is best done with footwear removed). Then, they walk in a forward direction as quickly and as accurately as possible along a 38mm wide (sports tape), 3 meter line with an alternate foot heel-to-toe gait ensuring that they approximate their heel and toe on each step. Once they cross the end of the 3m line, they turn 180 degrees and return to the starting point using the same gait. A total of 4 trials are done and the best time is retained. Athletes should complete the test in 14 seconds. Athletes fail the test if they step off the line, have a separation between their heel and toe, or if they touch or grab the examiner or an object. In this case, the time is not recorded and the trial repeated, if appropriate.

Coordination Examination

Upper limb coordination

Finger-to-nose (FTN) task:

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

Scoring: 5 correct repetitions in < 4 seconds = 1
Note for testers: Athletes fail the test if they do not touch their nose, do not fully extend their elbow or do not perform five repetitions. **Failure should be scored as 0.**

References & Footnotes

1. This tool has been developed by a group of international experts at the 4th International Consensus meeting on Concussion in Sport held in Zurich, Switzerland in November 2012. The full details of the conference outcomes and the authors of the tool are published in The BJSM Injury Prevention and Health Protection, 2013, Volume 47, Issue 5. The outcome paper will also be simultaneously co-published in other leading biomedical journals with the copyright held by the Concussion in Sport Group, to allow unrestricted distribution, providing no alterations are made.

2. McCrory P et al., Consensus Statement on Concussion in Sport – the 3rd International Conference on Concussion in Sport held in Zurich, November 2008. British Journal of Sports Medicine 2009; 43: i76-89.

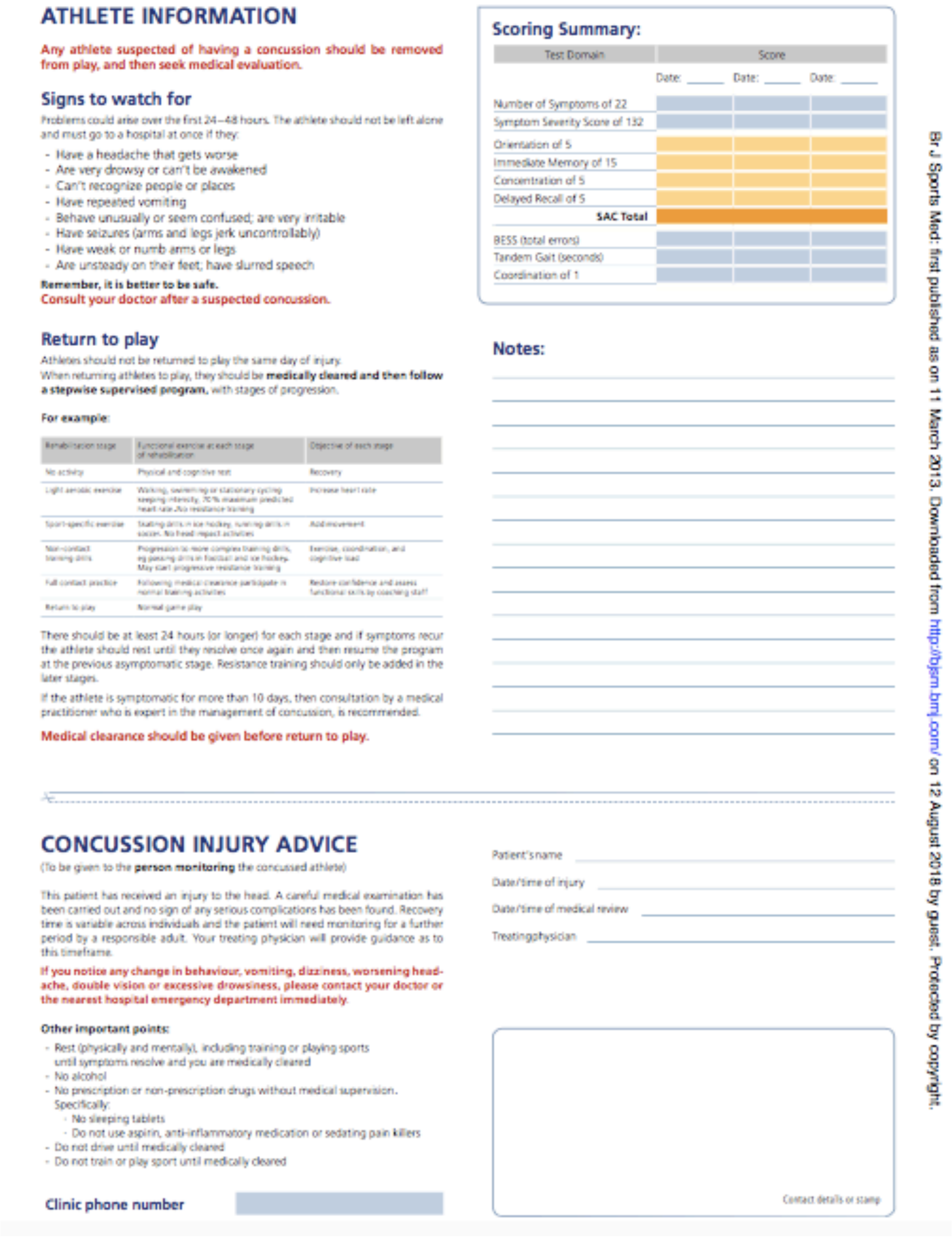
3. Maddocks, DL; Dicker, GD; Saling, MM. The assessment of orientation following concussion in athletes. Clinical Journal of Sport Medicine. 1995; 5(1): 32–3.

4. McCrea M. Standardized mental status testing of acute concussion. Clinical Journal of Sport Medicine. 2001; 11: 176–181.

5. Guskiewicz KM. Assessment of postural stability following sport-related concussion. Current Sports Medicine Reports. 2003; 2: 24–30.

6. Schneiders, A.G., Sullivan, S.J., Gray, A., Hammond-Tooke, G.& McCrory, P. Normative values for 16-37 year old subjects for three clinical measures of motor performance used in the assessment of sports concussions. Journal of Science and Medicine in Sport. 2010; 13(2): 196–201.

7. Schneiders, A.G., Sullivan, S.J., Kvarnstrom, J.K., Olsson, M., Yden, T. & Marshall, S.W. The effect of footwear and sports-surface on dynamic neurological screening in sport-related concussion. Journal of Science and Medicine in Sport. 2010; 13(4): 382–386



ATHLETE INFORMATION

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

Signs to watch for

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

- Have a headache that gets worse
- Are very drowsy or can't be awakened
- Can't recognize people or places
- Have repeated vomiting
- Behave unusually or seem confused; are very irritable
- Have seizures (arms and legs jerk uncontrollably)
- Have weak or numb arms or legs
- Are unsteady on their feet; have slurred speech

Remember, it is better to be safe.

Consult your doctor after a suspected concussion.

Return to play

Athletes should not be returned to play the same day of injury.
When returning athletes to play, they should be **medically cleared and then follow a stepwise supervised program,** with stages of progression.

For example:

Rehabilitation stage	Functional exercise at each stage of rehabilitation	Objective of each stage
No activity	Physical and cognitive rest	Recovery
Light aerobic exercise	Walking, swimming or stationary cycling keeping intensity, 70 % maximum predicted heart rate. No resistance training	Increase heart rate
Sport-specific exercise	Skating drills in ice hockey, running drills in soccer. No head impact activities	Add movement
Non-contact training drills	Progression to more complex training drills, eg passing drills in football and ice hockey. May start progressive resistance training	Exercise, coordination, and cognitive load
Full contact practice	Following medical clearance participate in normal training activities	Restore confidence and assess functional skills by coaching staff
Return to play	Normal game play	

There should be at least 24 hours (or longer) for each stage and if symptoms recur the athlete should rest until they resolve once again and then resume the program at the previous asymptomatic stage. Resistance training should only be added in the later stages.

If the athlete is symptomatic for more than 10 days, then consultation by a medical practitioner who is expert in the management of concussion, is recommended.

Medical clearance should be given before return to play.

Scoring Summary:

Test Domain	Score		
	Date: ______	Date: ______	Date: ______
Number of Symptoms of 22			
Symptom Severity Score of 132			
Orientation of 5			
Immediate Memory of 15			
Concentration of 5			
Delayed Recall of 5			
SAC Total			
BESS (total errors)			
Tandem Gait (seconds)			
Coordination of 1			

Notes:

CONCUSSION INJURY ADVICE

(To be given to the **person monitoring** the concussed athlete)

This patient has received an injury to the head. A careful medical examination has been carried out and no sign of any serious complications has been found. Recovery time is variable across individuals and the patient will need monitoring for a further period by a responsible adult. Your treating physician will provide guidance as to this timeframe.

If you notice any change in behaviour, vomiting, dizziness, worsening headache, double vision or excessive drowsiness, please contact your doctor or the nearest hospital emergency department immediately.

Other important points:

- Rest (physically and mentally), including training or playing sports until symptoms resolve and you are medically cleared
- No alcohol
- No prescription or non-prescription drugs without medical supervision. Specifically:
  - No sleeping tablets
  - Do not use aspirin, anti-inflammatory medication or sedating pain killers
- Do not drive until medically cleared
- Do not train or play sport until medically cleared

Clinic phone number

Patient's name ______

Date/time of injury ______

Date/time of medical review ______

Treating physician ______

Contact details or stamp