NEUROPSYCHOLOGICAL ASSESSMENT OF CONCUSSION IN COLLEGIATE STUDENT-ATHLETES

A Dissertation

by

LINDSEY JORDAN CARNES

Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Chair of Committee,	Cynthia A. Riccio
Committee Members,	J. Timothy Lightfoot
	Krystal Simmons
	Victor L. Willson
Head of Department,	Shanna Hagan-Burke

August 2019

Major Subject: School Psychology

ABSTRACT

Due to the importance of neuropsychological assessment in the sports concussion management process, the purpose of this study was to investigate a newer assessment (C3Logix), comparing it to the well-established ImPACT concussion system. Additionally, this investigation contributed to the limited literature regarding concussion recovery in young adults, with a focus on sex differences in the recovery process. Both baseline and post-injury assessment data (i.e., C3Logix and ImPACT) were utilized from young adult student-athletes ($n = 42$) attending a large, southern university who experienced a concussion over the course of one academic year.

Results indicated acceptable convergent validity between C3Logix and ImPACT. Across the assessment systems, there were correlations between measures of symptom severity, memory, visual motor speed, reaction time, and processing speed. Impulse Control (ImPACT) and Visual Acuity (C3Logix) demonstrated little to no association with any other domains. A significant multivariate effect was revealed for sex on performance at baseline for C3Logix and ImPACT, with female athletes performing better than males on C3Logix SAC, Trails A, Trails B, and Processing Speed modules, and the ImPACT Verbal Memory and Visual Motor Speed composites. It was hypothesized that female athletes would report more symptoms on the graded symptom checklists, yet surprisingly there were no significant differences in symptom severity scores between the sexes. Finally, the initial injury Symptom Severity score on C3Logix and the athlete's sex significantly predicted the number of follow-up assessments completed during recovery.

DEDICATION

This dissertation is dedicated in memory of my grandfather,

Hal Robert Pettigrew

who funded my education, encouraged me to take action and make my dreams a reality, and who used his brain for the ultimate good: to make this world a better place for children and families.

Grandpa, I'm still working on becoming better at long division, but I hope this will do in the meantime.

ACKNOWLEDGEMENTS

I would like to thank my chair, advisor, and “academic mama,” Dr. Riccio, for all of her wisdom, patience, and perseverance with me during my graduate training and the dissertation process. I am also very thankful for my graduate professors and supervisors, Dr. Simmons, Dr. Rae, Dr. Blake, and Dr. Clemens, for their dedication, passion, and for giving me the tools I need to succeed. Additionally, I would like to thank my committee members, Dr. Willson and Dr. Lightfoot, for their guidance throughout the course of this research. A big “Thanks and Gig ’Em” goes out to David Weir and the Texas A&M Athletic Department for their partnership.

To Ashley, Emily, Danielle, Laura, Morgan, Nikki, and Stephanie, I don’t think I’ve ever lucked out more than the day y’all became my cohort. I would not be here today without your compassion, loyalty, and hilarious sense of humor. It is such a privilege to call you not only my colleagues, but also lifelong friends.

I would also like to thank my big, loving, and animated family for their unwavering support and for helping me to keep things in perspective. I would especially like to thank both of my grandmothers. As Rita Pierson said, “Every child deserves a champion—an adult who will never give up on them, who understands the power of connection, and insists that they become the best that they can possibly be.” Grandma and Nanny, thank you for being my champions.

To my friends back home: thank you for keeping life fun, for being my cheerleaders, and my prayer warriors. A special thank you to my two “kindred spirits” who have helped me to survive in different ways: Becca (my personal editor) and Miranda (my personal physician).

Most importantly, I give joyful thanks to my Lord and Savior, Jesus Christ, who has called me and equipped me, and provides a peace and hope that “surpasses all understanding.” To God be the glory!

CONTRIBUTORS AND FUNDING SOURCES

This work was supported by a dissertation committee consisting of Dr. Riccio, chair, Dr. Simmons, and Dr. Willson, Professor Emeritus, of the Department of Education and Human Development, and Dr. Lightfoot from the Department of Health and Kinesiology. The data gathered for this dissertation was aided by David Weir, LAT, ATC, Senior Associate Athletic Trainer and Concussion Management Coordinator for the Texas A&M Athletics Department. All other work conducted for the dissertation was completed by the student independently. No outside funding was received for the research and compilation of this document.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER I

INTRODUCTION

Concussions have been thrust into the limelight in recent years. A topic that has been largely misunderstood historically was suddenly at the center of a national controversy with the increase in violence, mental health disorders, and death in high-profile athletes, and the discovery of a disease associated with repeated head trauma called Chronic Traumatic Encephalopathy (CTE; Guay et al., 2016). With an approximated 1.6 to 3.8 million sport-related concussions occurring annually (Langlois, Rutland-Brown, & Wald, 2006), the media coverage surrounding concussive injuries has left many in the public with questions and concerns about long-term risks, particularly in regard to what these findings mean for children and young adults who play sports. This has resulted in an increase of fear, anxiety, and even "hysteria" associated with the topic (Adelson, 2017a, p. 1; Lyall, 2015).

Response to the Problem

The increase in information about the consequences of concussion has caused some people to question the benefits of contact sports altogether (Dallas Morning News, 2016; Gregory, 2014; Mahaffey, 2012). Conversely, there are an exorbitant number of athletes who are on their fourth or fifth concussion, yet it is extremely difficult for them (and their families) to stop their participation in these sports, even though they clearly are putting themselves at great risk by continuing to play.

There are many aspects that contribute to the complexity of this issue. For one, there are a multitude of positive results from participating in sports, including psychosocial, physical/health, and educational benefits (Merkel, 2013). Additionally, one must have some understanding of sports as a cultural entity. McKee (2014) described sports as "a 'culture', a way of life…and in many instances…a source of pride and identity" (p. 1). The success of these athletes often extends far beyond their accomplishments on the field, court, and so on. For many of them, their involvement in these sports is much more than just playing a game—it plays a huge part in shaping who they are as individuals. Therefore, asking athletes to stop playing sports is equivalent to asking them to give up a piece of their identity.

Furthermore, there is a discrepancy between the increased exposure on the topic and actual research to back up the concerns. In other words, "Headlines travel fast. Science takes time" (Adelson, 2017b, p. 1); however, researchers are working hard to catch up, and literature in this area has increased significantly in the last two decades (Guskiewicz, 2016). Additionally, Return-to-Play (RTP) and Return-to-Learn (RTL) guidelines have been established, and major sports organizations have revised many of their standards and policies in regard to the prevention and management of concussion (McCrory et al., 2017).

Neuropsychological assessment has emerged as an important piece of the concussion management and the recovery process. Neuropsychological assessments are sensitive to detecting subtle cognitive impairments that are often present in concussion (Harmon et al., 2013). Because of this, neuropsychological assessment can be very beneficial in tracking the recovery of concussion and aid in making RTP and RTL decisions. In the past decade, these assessments have shifted from a comprehensive, paper-and-pencil format to a more efficient, computerized approach (Echemendia, & Bauer, 2015). There has been an upsurge in the number of these computerized neurocognitive tests on the market and adopted into clinical practice since 2005 (Resch, McCrea, & Cullum, 2013); however, these new assessments do not always have a large amount of research evidence in the literature. Consequently, this means that practitioners are making important decisions about an athlete's concussion care based off these assessment results, without truly knowing if the product is reliable or valid.

Purpose of the Study

The purpose of this study is to add to what is known about concussion recovery, management, and assessment in a sports context, and to address gaps in the empirical literature. Much of the current research has been conducted with adults, and there is still little known about the effect of concussions on developing brains (i.e., young adults, adolescents, children). Additionally, a large portion of the research that has been conducted so far has focused on male athletes, and little is known about sex differences in the recovery process. Finally, due to the importance of neuropsychological assessment in the concussion management process, this study aims to investigate the utility of a new assessment called C3Logix.

Research Questions

1) What is the level of agreement between module scores on the C3Logix assessment battery at baseline?
    - Because the modules on C3Logix measure the areas most commonly affected by concussion (e.g., reaction time, memory, processing speed), it is hypothesized that the module scores will be significantly correlated with each other.
2) What is the level of agreement between composite scores on the Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT) battery at baseline?
    - Because the modules on ImPACT also measure the areas most commonly affected by concussion (e.g., reaction time, memory, processing speed), it is hypothesized that the composite scores will be significantly correlated with each other.

3) What is the level of agreement in the scores obtained with C3Logix and ImPACT at baseline?
    - Because many of the tasks on both ImPACT and C3Logix were developed based on long-standing traditional neurocognitive tests, it is hypothesized that C3Logix module scores will be significantly and directly associated with ImPACT composite scores.
4) Are there sex differences at baseline for C3Logix modules and ImPACT composite scores?
    - Based on previous research, it is hypothesized that female athletes will report more symptoms on the graded symptom checklists and will perform higher on tests of verbal memory and processing speed as compared to males.
    - It is hypothesized that male athletes will perform higher in visual memory and reaction time activities compared to females.
5) Are there sex differences in the C3Logix baseline and immediate post-injury Symptom Severity?
    - It is hypothesized that females will demonstrate greater differences overall between baseline and post-injury Symptom Severity scores compared to males.
6) What is the average number of days it takes for an athlete to recover back to baseline with C3Logix?
    - Based on past results and consensus, it is hypothesized that overall, student-athletes will be back to baseline within 3-10 days.
    - It is hypothesized that it will take females a greater number of days on average to recover to baseline compared to males.

7) What is the average number of follow-up C3Logix assessments until an athlete recovers to baseline?
    - It is hypothesized that overall most student-athletes will undergo approximately 3-10 follow-up assessments before he or she recovers back to baseline, based on the previous literature.
    - It is hypothesized that females will exhibit a greater average number of follow-up assessments after a concussive injury compared to males.
8) Does the C3Logix immediate post-injury Symptom Severity score and/or sex predict the number of follow-up assessments and recovery time?
    - It is hypothesized that a higher Symptom Severity score at the time of concussion will predict more follow-up assessments over a longer time period.

Definition of Terms

Concussion: A mild traumatic brain injury (mTBI), better known as a concussion, is caused by a bump, blow, or jolt to the head or by a hit to the body that causes the head and brain to move rapidly back and forth. This sudden movement can cause the brain to bounce around or twist in the skull, stretching and damaging the brain cells and creating chemical changes in the brain. Though the term concussion is often interchangeable with mTBI, the term concussion will be used for the purposes of the current discussion.

CHAPTER II

REVIEW OF LITERATURE

Concussion

A concussion is a subset of traumatic brain injury (TBI; McCrory et al., 2013). The Center for Disease Control and Prevention (CDC; 2015) defines a concussion as an injury that changes how the brain functions. It is:

> caused by a bump, blow, or jolt to the head or by a hit to the body that causes the head and brain to move rapidly back and forth. This sudden movement can cause the brain to bounce around or twist in the skull, stretching and damaging the brain cells and creating chemical changes in the brain. (p. 1)

The word concussion comes from the Latin word "concutere," which means "to shake violently" (Maroon et al., 2000, p. 660). This shaking results in the altered alertness of the individual. Concussions can happen in a variety of ways, from random mishaps (e.g., walking into a door), to being involved in a car accident, and of course, playing sports. Any time an athlete slams into an object (e.g., ball, pole, ground) or another person, there is the potential for a concussion. A common misconception is that a person's head has to be hit in order to become concussed (Kelly & Rosenberg, 1997). Concussions may occur as a result of an indirect impact as well. When a person's body is suddenly jolted, resulting in the head and shoulders aggressively changing speed and/or direction, the ensuing whiplash frequently results in concussion (Cantu & Hyman, 2012).

Biomechanics. Damage sustained to the brain during a concussion is caused by two different types of physical forces: linear and rotational (Guskiewicz & Mihalik, 2011). Linear forces, or straight-on accelerations that snap the head, often occur during car accidents. For example, if a car was to hit a tree, the driver's brain often makes contact with the front of the skull, and then it moves backward, hitting the back of the skull. This second point of contact is called second impact. In rotational accelerations, the brain rotates or spins inside the skull. This type of force is often more damaging than linear because blood vessels and brain tissue are often damaged or sheared. This type of injury can occur, for example, when an offensive football player is running towards the end zone and suddenly is tackled from the side by a defensive player (Guskiewicz & Mihalik, 2011).

Neurometabolic Cascade. The biomechanical forces experienced during a concussion also affect the brain on a cellular level. The brain is made up of billions of neurons—individual nerve cells that act as a chain to carry electrical signals from the brain to the body (Wilberger, Ortega, & Slobounov, 2006). Each individual neuron acts as a link in the chain transporting messages through the use of chemicals called neurotransmitters. Calcium (Ca^{2+}) and potassium (K^+) ions also play an important part in the functioning of the neuron (Wilberger, Ortega, & Slobounov, 2006).

During a concussion, injury to the function of these cells can occur, setting off a neurometabolic cascade of events that may include ionic shifts, bioenergetic challenges, cytoskeletal and axonal alterations, impairments in neurotransmission, and vulnerability to delayed cell death and chronic dysfunction (Giza & Hovda, 2001; Giza & Hovda, 2014). The acceleration of the brain tissue in the skull during a concussion causes neurons to stretch, allowing K^+ to rush out of the cell and Ca^{2+} to rush in, which harms the neuron's structure. The neuron's function becomes impaired because the membrane pumps are forced into overdrive in an attempt to restore homeostasis of the ions (i.e., pull K^+ back into the cell, and push Ca^{2+} back out). The over-activity of the membrane pumps depletes the neuron of energy. This decreased energy, in addition to the damaged structure as a result of increased Ca^{2+}, weakens the cell's ability to transmit signals to other neurons (Giza & Hovda, 2001; Giza & Hovda, 2014).

While the cell is recovering, it is left vulnerable to further injury. If another concussive impact is experienced while neurons are still healing, symptoms can be exacerbated and recovery time may lengthen; however, if adequate recovery time is allowed, ion levels should eventually balance out and the cell should return to normal functioning (Giza & Hovda, 2001; Giza & Hovda, 2014). For a visual presentation of the biological processes that occur in the neuron as a result of a concussion, please see the figure in Giza & Hovda (2014).

Table 1

Major Categories of Concussion Symptoms

Concussion Symptoms			
Physical	**Emotional**	**Cognitive**	**Sleep Disturbance**
• Headache • Nausea • Vomiting • Dizziness • Balance Problems • Visual Problems (e.g. blurred or fuzzy vision) • Sensitivity to Light • Sensitivity to Noise • Feeling Dazed or Stunned • Fatigue	• Irritability • Sadness • More Emotional than Usual • Nervousness or Anxiety	• Feeling Mentally "Foggy" • Feeling Slowed Down • Difficulty Concentrating • Difficulty Remembering • Forgetful of Recent Information • Confusion • Answers Questions Slowly • Repeats Questions	• Drowsiness • Sleeping More than Usual • Sleeping Less than Usual • Difficulty Falling Asleep

Symptoms. There are a variety of symptoms that may be reported by the individual or observed by a second party at some point after a "bump, blow, or jolt to the head or body" (CDC, 2015, p. 1). There are four main classifications for concussion symptoms: physical, emotional, sleep disturbance, and cognitive (Harmon et al., 2013). These are presented above in Table 1. Somatic symptoms often include complaints of sensitivity to light and noise, nausea, vomiting, headaches, visual issues, and balance problems. Changes in the individual's emotional state also may occur. For example, they may appear moody or anxious, and even may become depressed. The athlete may complain of feeling sluggish or groggy and may experience sleep disturbances (i.e., sleeping too much or too little). Finally, a person with a concussion can experience a variety of cognitive problems, such as confusion, attention issues, slowed responding, memory problems, and lowered impulse control (CDC, 2015; Harmon et al., 2013).

Severity. The term concussion is often interchangeable with mild traumatic brain injury (mTBI), particularly in literature from the United States. This overlap has led to some confusion and controversy (Moscote-Salazar & Satyarthee, 2016). TBIs are classified into three different categories: mild, moderate, and severe. The severity of a TBI is based on a number of factors.

The Glasgow Coma Scale (GCS; Teasdale & Jennett, 1974) is one of the most common tools used when assessing a TBI (Finfer & Cohen, 2001). With the GCS, individuals are rated on their verbal responses, motor movements, and ability to open their eyes. The ratings in each category are added together for an overall GCS score. Any alteration of consciousness (AOC) or mental state, such as disorientation or feelings of confusion, is taken into account. Post-Traumatic Amnesia (PTA), or the amount of time it takes for an individual to demonstrate conscious memory of what is going on around them, is another indicator. Loss of consciousness (LOC) has been a particularly contentious consideration. Historically, health care providers did not typically diagnose a TBI, of any level of severity, if the person did not lose consciousness (Ruff & Jamora, 2009); however, the presence of LOC is not needed for a TBI to occur. If LOC does occur, the amount of time the individual is unconscious is an important factor in determining severity.

Severe TBIs are the most life threatening and usually are a result of a crushing blow to the head in which there is often an open (i.e. penetrating) head injury where the skull has been fractured or pierced; however, closed head injuries (i.e. non-penetrating) can also receive a severe classification (Bešenski, 2002). TBIs receive a severe classification if the individual has a GCS score of 3-8, has experienced AOC for over 24 hours, LOC for 24 hours or longer, and PTA for seven days or longer (Baalen et al., 2003). Severe TBIs account for about ten percent of all head injuries (Dennis, 2009).

Moderate TBIs occur with a GSC score of 9-12, AOC for over 24 hours, LOC for more than 30 minutes but less than 24 hours, and PTA over 24 hours but less than seven days (Baalen et al., 2003). About ten percent of TBIs are considered moderate (Dennis, 2009). These injuries are typically the result of a non-penetrating blow to the head (Maas, Stocchetti, & Bullock, 2008).

Mild TBIs (mTBI) represent 80-90% of closed head traumas (McCrory et al., 2013). These brain injuries are the least severe, but they are brain injuries nonetheless. According to the American Congress of Rehabilitation Medicine (1993), mTBIs are defined by *any* of the following: a GSC score of 13-15, LOC of 30 minutes or less, PTA that does not exceed 24 hours, or the presence of AOC.

As discussed above, concussions are a subset of TBIs, on the milder end of the brain injury spectrum. The terms concussion and mTBI are frequently used synonymously; however, while all concussions are mTBIs, not all mTBIs are concussions (Harmon et al., 2013). Concussions are generally distinctive from other, more severe TBIs in the duration and resolution of symptoms (McCrory et al., 2013). For the purposes of the current discussion, the term concussion will be used for the remainder of this paper.

Concussion Grading Scales. There are a variety of grading systems developed for determining the severity of a concussion. The two most common are from the American Academy of Neurology (AAN) and Cantu's system (Cantu, 2001; Quality Standards Subcommittee of the American Academy of Neurology, 1997). The two sets of guidelines are very similar, both focusing on the key symptoms associated with concussion. LOC continues to be a contentious point, even when diagnosing brain injuries on the milder end of the spectrum. Again, there is often a misconception that a person has to experience LOC in order to have sustained a concussion (Kelly, 2001). LOC only happens in about 10% of concussions, however (McCrory et al., 2013). While the AAN system focuses more on the presence of LOC to assigning a severity grade at the time of injury, Cantu places more weight on the persistence of post-concussion symptoms, assigning a grade after the athlete is symptom free (Erlanger et al., 2003).

Both systems classify concussions as Grade I (mild), Grade II (moderate), or Grade III (severe). Generally speaking, for both systems, Grade I concussions involve symptoms that last no longer than 15-30 minutes in length, with no LOC. In Grade II, symptoms last over 15-30 minutes, but less than one week. The athlete may experience some PTA, but for no longer than 24 hours in duration. Additionally, Cantu's Grade II concussions may involve some LOC but for less than one minute. The most obvious indicator of a Grade III concussion is any LOC lasting longer than one minute. Symptoms also persist for more than one week, and the individual may experience PTA lasting longer than 24 hours (Erlanger et al., 2003). Figure 1 indicates where concussions fall on the TBI spectrum.

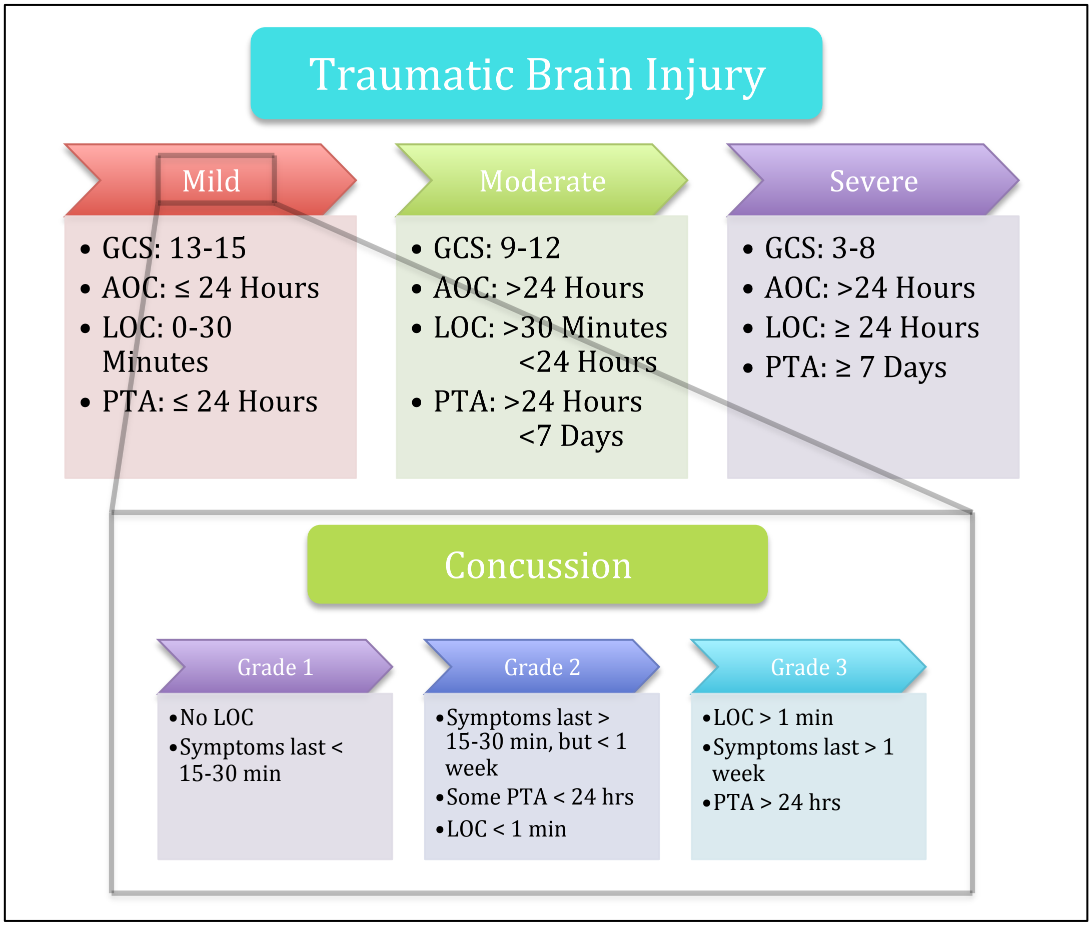

Figure 1. Spectrum of traumatic brain injury.

Recovery. Recovering from a concussion is a complex process that is unique for each individual. *If* medical attention is sought after a concussion, the individual often undergoes a computed tomography (CT) scan to confirm there are no hematomas and/or fractures—the images are rarely abnormal in concussion cases (Bazarian, Blyth, & Cimpello, 2006). After his or her symptoms have been extensively reviewed and any other life threatening conditions ruled out, the individual is typically discharged with over-the-counter medication (e.g. Tylenol) and physical and mental rest prescribed (Thomas, 2012).

The matter of rest is an area of particular significance. As mentioned previously, people often experience headaches, nausea, and fatigue after sustaining a concussion. Rest can help to ease discomfort and minimize these symptoms. It also can aid in the overall recovery process by reducing cognitive energy demands, thereby decreasing the activation of injured brain cells (Leddy, Baker, & Willer, 2016).

Historically, doctors recommended that the concussed individual be kept awake or woken up every one to two hours (Thomas, 2012); however, these recommendations were developed before the invention of neuroimaging and are no longer necessary. In fact, sleep is an essential part of the brain's recovery process, and therefore it is important that the person receive as much undisturbed rest as possible, though it may be appropriate that someone check on them once during the night (Thomas, 2012).

There is much debate on the amount of rest needed for optimal outcomes, though 24-48 hours is a general recommendation (McCrory et al., 2013). After this initial phase, the individual who sustained a concussion may attempt to progressively become more active, in a graduated step-wise fashion, while staying below his or her symptom threshold. If symptoms do return during activity, he or she should immediately stop that activity and rest until the symptoms improve (McCrory et al., 2017).

As discussed above, rest is also important because the brain's neurons are still recovering, leaving the brain vulnerable to further injury. In fact, people who suffer one concussion are three to six times more at risk to sustain a second concussion (Delaney, Lacroix, Leclerc, & Johnston, 2002; Guskiewicz et al., 2003; Kelly & Rosenberg, 1997). Additionally, those who have experienced multiple concussions experience more severe symptoms for a prolonged period of time (De Beaumont, Lassonde, Leclerc, & Théoret, 2007; Noble & Hesdorffer, 2013).

There has been much consideration in the literature regarding the average length of time it takes to recover from a concussion. Many of the studies published before 2005 suggest that 80-90% of individuals recover from their symptoms within 7-10 days after injury (McCrory et al., 2017). This generally appears to be true, with cognitive and vestibular deficits improving rapidly during the first two weeks post-injury; however, more recently, authors have suggested that recovery from a concussion more realistically takes about a month for the majority of individuals (McCrory et al., 2017). This is greatly variable, however, especially within certain populations.

Post-Concussion Syndrome. About 10% of people who sustain a concussion experience Post-Concussion Syndrome (PCS; Jotwani & Harmon, 2013; Willer & Leddy, 2006). PCS is a term used to describe a constellation of prolonged post-concussive symptoms beyond the generally accepted time frame, sometimes months and even years after the injury (Leddy et al., 2016). Iverson and Lange (2011) found that most clinicians make a diagnosis of PCS using criteria from the *International Classification of Diseases, Tenth Edition* (ICD-10; World Health Organization, 2004) or *Diagnostic and Statistical Manual of Mental Disorders, Fourth Edition* (DSM-IV; American Psychiatric Association, 2000).

According to the ICD-10, a person meets the criteria for PCS if he or she experiences at least 3 or more symptoms after a significant head trauma. These symptoms include headache, dizziness, fatigue, irritability, insomnia, concentration difficulty, memory difficulty, and reduced tolerance to stress, emotional excitement, and alcohol. In contrast, the DSM-IV (American

Psychiatric Association, 2000) presents PCS as a construct for further study and takes a much more conservative approach to the diagnosis. PCS is defined by the DSM-IV as 1) objective evidence of cognitive deficits in attention or memory, and 2) subjective reports of at least three or more of the following symptoms: fatigue, sleep disturbance, headache, dizziness, irritability/aggression, affective disturbance, apathy, and/or personality change. These criteria must be present for at least three months (American Psychiatric Association, 2000).

The fifth edition of the DSM (DSM-5; American Psychiatric Association, 2013) does not specifically mention PCS by name, but clinicians (who are expected to use the most recent edition of the manual) often diagnose individuals displaying PCS symptoms with either Major or Mild Neurocognitive Disorder (NCD) due to TBI (Wortzel & Arciniegas, 2014). In order to meet criteria for NCD, the individual must have experienced a TBI and show evidence of cognitive decline in one or more of the following domains: complex attention, executive function, learning and memory, language, perceptual-motor, or social cognition. These declines must impact the individual's daily activities to either a mild or major degree. The symptoms must present themselves immediately after injury and persist past the acute post-injury period (American Psychiatric Association, 2013).

One of the major difficulties for practitioners in diagnosing PCS is discerning whether these lingering symptoms are associated with prolonged concussion pathophysiology (discussed above) or if they are an expression of a secondary process such as a cervical injury, premorbid clinical depression, or migraine headaches (Leddy, Sandhu, Sodhi, Baker, & Willer, 2012). In addition to these, the differential diagnosis of PCS includes vestibular dysfunction, somatization, chronic fatigue, chronic pain, ocular dysfunction, or some combination of these conditions (Leddy et al., 2016). If the symptoms were experienced relatively early after the concussion, get worse with exertion, and get better with rest, then the pathophysiology of the concussion is most likely the cause of the PCS symptoms. If symptoms are worsened even by minimal activity and no longer respond to rest, this may represent a secondary process (Leddy et al., 2012). It is very important that the clinician obtain a detailed history of the individual's premorbid functioning. If the individual suffered from migraines, depression, anxiety, ADHD, or any learning disabilities before the injury, concussions can exacerbate these conditions, and those conditions in turn can be responsible for ongoing symptoms (Leddy et al., 2016).

Children and Adolescents. One major population that exhibits a unique recovery from concussion is youth. There has been a rapid increase in research with regard to the impacts and management of concussions in adults; however, little information is available in pediatric literature. This discrepancy is concerning as there are a multitude of physiological, cognitive, and behavioral differences between adults and children that are important to consider. For example, it takes a longer amount of time for a child's brain to recover from a concussion than it does for an adult's brain (Karlin, 2011; Purcell, Harvey, & Seabrook, 2016). This gives children a larger window of vulnerability for repeated concussion (Davis & Purcell, 2014). Notably, more damage has to be done (i.e., approximately two to three fold greater impact force) for symptoms to be observable in children (McCrory, Collie, Anderson, & Davis, 2004). Therefore, when comparing an adult and a child with the exact same post-concussive symptoms, it can be assumed that the child experienced a greater impact force than the adult.

There are some anatomical and physiological differences between children and adults. For example, a child's central nervous system is still developing, and this immaturity serves as a risk factor in concussion (Karlin, 2011). This extends to myelination. Myelin is the protective substance that insulates the brain's axons of the neuron. The development of myelin continues to occur through adolescence (Luna, 2009). Should a child experience a concussion before the myelination process is complete, this incomplete myelination, along with the elasticity of the skull vault, puts the developing brain at more risk for Diffuse Axonal Injury (DAI; Cook, Schweer, Shebesta, Hartjes, & Falcone Jr., 2006; Kieslich, Fiedler, Heller, Kreuz, & Jacobi, 2002; Ommaya, Goldsmith, & Thibault, 2002). With DAI, shearing of the brain tissue occurs, stretching many axons and inducing trauma or separation of the axons from the cell bodies. This, in turn, disrupts communication across a diffused area of the brain (Smith, Meaney, & Shull, 2003).

Moreover, a child's head to body ratio is disproportionate relative to that of an adult (Buzzini & Guskiewicz, 2006). Their head is much larger than the rest of the body, leaving the neck (supporting the brain and head) much weaker. This is especially true from the time a child is five to eight years old. Around the age of fourteen, the adolescent's skull is approximately 90% as large as an adult (Cantu & Hyman, 2012). Additionally, as children and adolescents undergo sporadic growth spurts, weight and mass increase. As a result, force and momentum increase during collisions; however, this does not always occur in tandem with the development of neck and shoulder muscles. This can impair the dissipation of energy from the head's impact to the rest of the body (Buzzini & Guskiewicz, 2006). This weaker neck strength also influences the way a child braces before a hit, making the impact of force transferred to the head more severe (Cantu & Hyman, 2012).

While cognitive and social impairments are difficult when experienced at any point in life, these deficits associated with concussion are especially detrimental for children and adolescents, as they are going through a sensitive period of development in these areas (McCrory et al., 2004). The brain is cognitively maturing at a rapid pace during this period of time. Even the slightest changes in children's abilities to attend and process information can have a large impact on their ability to cope with the social and educational demands placed upon them. After a concussion, some children may not exhibit any cognitive deficits in regards to assessment results, testing within the normal neuropsychological range after a concussion, yet they may undergo many behavioral and personality changes (McCrory et al., 2004).

Sex Differences. Research also has identified different recovery outcomes from concussion based on sex. Females appear to not only experience more concussions than their male counterparts when compared across equivalent sports (Kostyun & Hafeez, 2015), but they also tend to exhibit poorer and more prolonged outcomes (Broshek et al., 2005). In general, females tend to perform better neurocognitively on tasks of verbal memory, information processing speed, and perceptual motor speed, whereas males typically perform better in visuospatial and visual memory activities (Covassin & Elbin, 2011). After a concussion, however, females exhibit more significant cognitive changes in regards to neuropsychological assessment results, particularly in slowed reaction time and impaired visual memory (Covassin, Elbin, Harris, Parker, & Kontos, 2012; Lax et al., 2015). While there are only a few empirical studies in this area, especially in human-subject literature, there are many theories to explain why females appear to be at greater risk for concussion.

For one, compared to males, females have decreased neck strength and neck girth (Covassin & Elbin, 2011). Females also have less head-neck segment mass, and as a result, they may experience greater angular acceleration to the head after impact (Tierney et al., 2005). Females also have longer cervical spine segments, which could have an influence on transmitting the force from their heads to their torsos after a concussive impact (Barth, Freeman, Broshek, & Varney, 2001). The primary female hormone, estrogen, may play a role in the recovery process for concussion as well (Covassin et al., 2012). Animal models using rodents found that estrogen treatment served as a protective factor for males, but exacerbated the effects of the injury in females (Emerson, Headrick, & Vink, 1993). Though much debate surrounds the role of hormones in concussion, limited research has been published.

Another factor that may contribute to the differences between males and females with concussion is symptom reporting. Some argue that females are more forthcoming and report more symptoms than males (Broshek et al., 2005; Zuckerman et al., 2014). This may be due to societal and cultural influences within male sport environments. Males are often under more pressure to show their masculinity by "toughing it out" when injured (Covassin & Elbin, 2011, p. 127). As a result, they are less likely to report symptoms, even if they are experiencing them. Females, on the other hand, have proven to be more concerned about future consequences, including health factors, than males (Granito, 2002). Females also report more symptoms at baseline, even before a concussive injury has occurred, compared to males (Covassin et al., 2012; Zuckerman et al., 2014).

Sport-Related Concussion

Concussions can happen to anyone, so why is it important to focus on athletes? Athletes are a unique population to study in this area, as their participation in sports continually puts them at risk for sustaining a concussion. Some individuals may experience a concussion as the result of a fall or car accident, but in general, the average person typically attempts to keep their heads out of harm's way. Due to their circumstances, athletes are repeatedly in positions where there is greater potential for their heads to be hit. Further, often athletes return to play soon, if not almost immediately, after sustaining a concussion (Halstead & Walter, 2010). Therefore, it is common for an individual to sustain multiple concussions over the course of his or her athletic career. This puts the individual at risk for a number of undesirable outcomes (Moser et al., 2007).

Athletes are also a unique population with regard to the cultural and social-emotional considerations discussed earlier. Clinically treating an athlete with a concussion (or multiple concussions) often elicits various ethical dilemmas. Two key ethical considerations for practitioners are beneficence, or “all forms of action intended to benefit or promote the good of other persons,” and nonmaleficence, or “do no harm” (Echemendia & Bauer, 2015, p. 291). Return-to-play decisions are filled with tension between promoting good (e.g., preventing an athlete from returning to play too soon) and doing no harm (e.g., recognizing the importance of playing to the athlete). Ultimately, making these decisions involves a process of cost/benefit analyses, which should be done in a collaborative manner in order to respect the autonomy of the athlete (Echemendia & Bauer, 2015).

For instance, when recommending a professional athlete retire from play due to the number of concussions he or she has sustained, one must take into consideration the financial repercussions for that individual and his or her family as a result of losing his or her livelihood not to mention the lack of preparation for other activities and loss of purpose that the athlete may experience (Echemendia, 2016). On a college level, recommending retirement often means a loss of scholarship and educational opportunities. When working with youth, retirement usually results in removal from peer groups and loss of a physical outlet, as well as an altered identity and decreased self-esteem. All of these issues can be remedied through appropriate avenues, but they are essential considerations nonetheless (Echemendia, 2016).

Epidemiology. About 38 million youth participate in organized sports in the United States each year (National Council of Youth Sports, 2008). Furthermore, 170 million adults participate in physical activities, including sports (Daneshvar, Nowinski, McKee, & Cantu, 2011). Overall, researchers estimate that at least 10 million TBIs are sustained annually, with around 1.7 million of those being Americans (Faul, Xu, Wald, & Coronado, 2010). Of these, it is approximated that 1.6 to 3.8 million are sport-related TBIs, estimating for those in which no medical care is sought (Langlois et al., 2006). Much of this variance is because original estimates surrounding sport-related concussions included only those head injuries involving LOC (Halstead & Walter, 2010). Still, these figures are most likely a massive underestimate of the total TBI burden, as many individuals suffering from mild or moderate TBI do not seek out medical care, especially when in relation to sports (Daneshvar et al., 2011).

Underreporting. One of the major problems with researching the identification, treatment, and outcome of concussions in sports is the underreporting of concussion symptoms (Langlois et al., 2006). This underreporting is the result of a variety of issues. Despite the recent headway made in this area, athletes, parents, and coaches often lack the education needed to identify and address concussions. Additionally, there is still much confusion in the general public regarding the definition of a concussion. Many people believe that "seeing stars" or getting "dinged" is just a normal part of the game—they are unaware of the damage that is being done (Halstead & Walter, 2010). Even more disturbing, sometimes these athletes, parents, or coaches can see that something is wrong, yet concussion symptoms are ignored because they do not want the athlete pulled from the game. These players are worried about appearing weak, letting the team down, or losing the opportunity to compete if they tell anyone about their symptoms (McCrea, Hammeke, Olsen, Leo, & Guskiewicz, 2004).

Meehan, Mannix, O'Brien, and Collins (2013) investigated the prevalence of undiagnosed concussions with athletes from two sports concussion clinics, highlighting the importance of consensus on the definition of concussion. Using the definition of concussion proposed by the 2008 Zurich conference on concussion in sport (McCrory et al., 2013), the authors asked their current athletes if they had ever experienced a blow to the head that matched that definition but was not diagnosed. They found that nearly one third of athletes seen in their clinics had sustained previously undiagnosed concussions, defined according to the Zurich conference guidelines and followed by signs and symptoms on the Post-Concussion Symptom Scale (PCSS). Additionally, these athletes with previously undiagnosed concussions were more likely to have LOC and a higher mean PCSS score with their current injury than athletes without previously undiagnosed concussions (Meehan et al., 2013).

Echlin et al. (2010) recently looked at underreporting in youth ice hockey. He and his colleagues tracked the number of concussions reported among the players on two teams. They collected data by placing physicians in the stands watching the players. Anytime the physicians observed a player displaying concussion symptoms during a game, they made note of it and then examined that player between periods. For every one concussion reported by a player or a coach, the physician observer reported seven concussions, with a rate of 21.5 concussions occurring per 1,000 man-games (Echlin et al., 2010).

Findings such as these highlight the difficulty with concussion epidemiology due to underreporting and the lack of widespread use of an injury surveillance system (McCrea et al., 2004). With better awareness and recognition of the injury, the number of diagnosed concussions likely will increase (Halstead & Walter, 2010). Because of the large numbers of participants in youth and high school sports, concussions in these populations account for the majority of sport-related concussions.

***Youth prevalence*.** While there have been many studies investigating incidence and characteristics of concussion on the professional, college, and high school levels, data is significantly lacking with regard to grade school and middle school athletes. Through a retrospective review of the National Electronic Injury Surveillance System (NEIJSS), Bakhos, Lockhart, Myers, and Linakis (2010) found that younger children, aged 8 to 13 years old, represented about 40% of all emergency room visits for sport-related concussions (SRCs) from the years 2001 to 2005. They also discovered that SRCs seem even more problematic for certain sports. The largest number of emergency room visits among younger athletes was seen in football and basketball, most likely a result of the higher level of participation in these sports (Bakhos et al., 2010). Figure 2 illustrates the estimated percentages of emergency room visits for younger youth by sport.

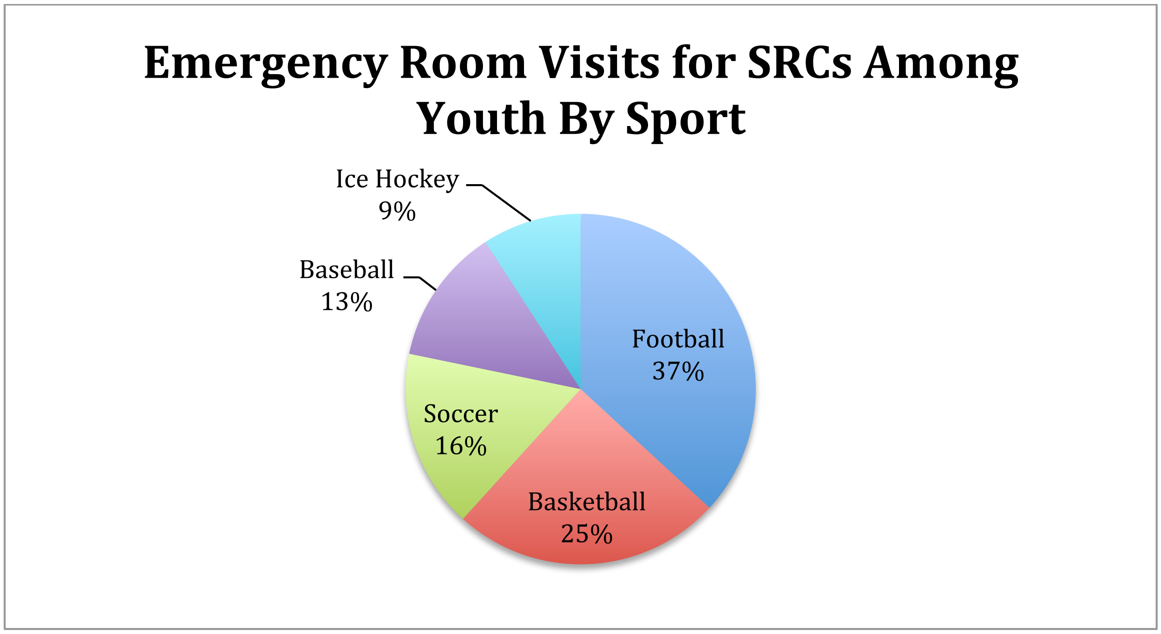

Figure 2. Estimated emergency room visits for SRCs among youth age 8-13 years old from 2001-2005. Data from Bakhos et al., 2010.

High school prevalence. It has been estimated that concussions represent about 8.9% of all high school athletic injuries (Gessel, Fields, Collins, Dick, & Comstock, 2007). Through the use of the National High School Sports-Related Injury Surveillance System (NHSSRISS), Marar, McIlvain, Fields, and Comstock (2012) were able to investigate the epidemiology of concussions in a broad spectrum of high school sports from 2008-2010. It appears that football and soccer represented the majority of concussions among adolescents. Additionally, they found that the overall rate of concussion was higher in competition than in practice, and in all sex-comparable sports studied, girls had higher concussion rates than boys (Marar et al., 2012). Figure 3 shows the estimated percentages of concussion rates for high school students by sport.

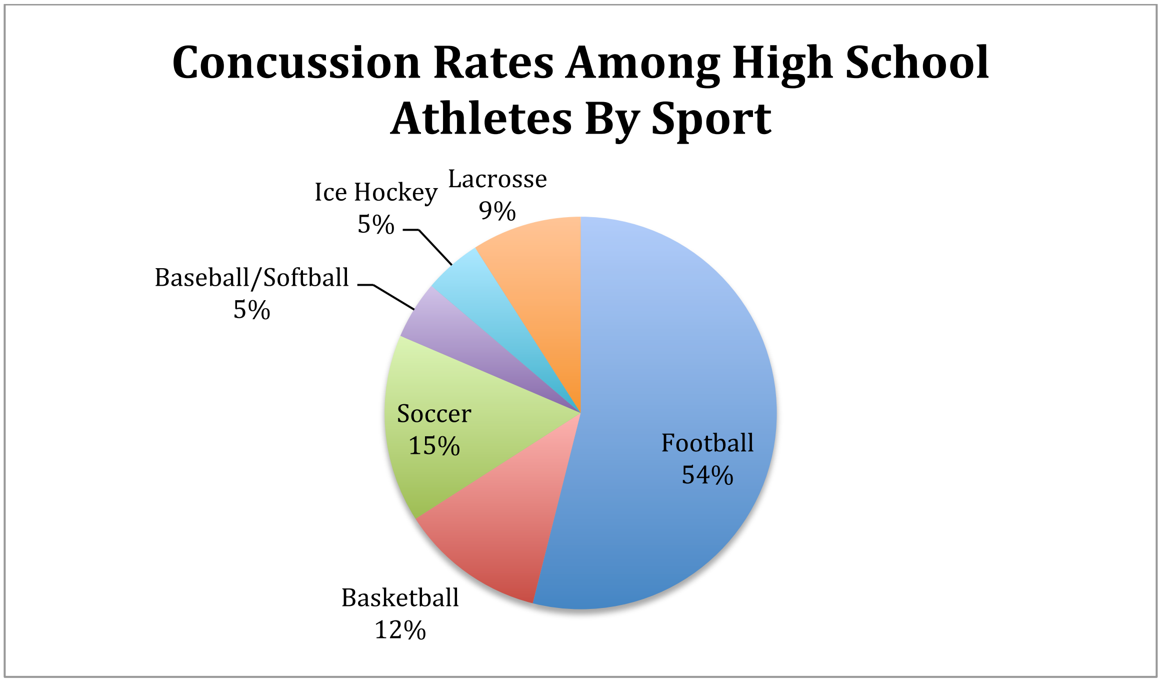

Figure 3. Estimated percentages of concussion rates for high school athletes from 2008-2010. Data from Marar et al. (2012).

Collegiate prevalence. Due to demand and feasibility, many studies have looked at the incidence of concussions across college athletic programs. Over the past twenty years, the rate of reported concussion has been increasing steadily within this research (Daneshvar et al., 2011). This trend is likely due to improvement in the detection of concussion at this level, but also may reflect an increase in the true number of concussive impacts occurring. As athletes get bigger, stronger, and faster, it is logical that the forces associated with their collisions also would increase in magnitude (Daneshvar et al., 2011).

Through a review of 16 years (1988-2004) of National Collegiate Athletic Association (NCAA) injury surveillance data, Hootman, Dick, and Agel (2007) were able to examine the incidence of a variety of injuries across collegiate sports and identify potential modifiable risk factors to target for injury prevention initiatives. In their study, concussions are presented as injury rate per 1000 athletic-exposures. In this case, ice hockey accounted for the majority of concussive injuries followed by football and soccer. As with high school athletes, it was found again that college athletes tend to have a higher risk of concussion in competition as compared to practice. Additionally, collegiate females once again were reported to have a higher rate of concussion than males in similar sports (Hootman et al., 2007). Figure 4 demonstrates the estimated concussion injury rates for collegiate students by sport.

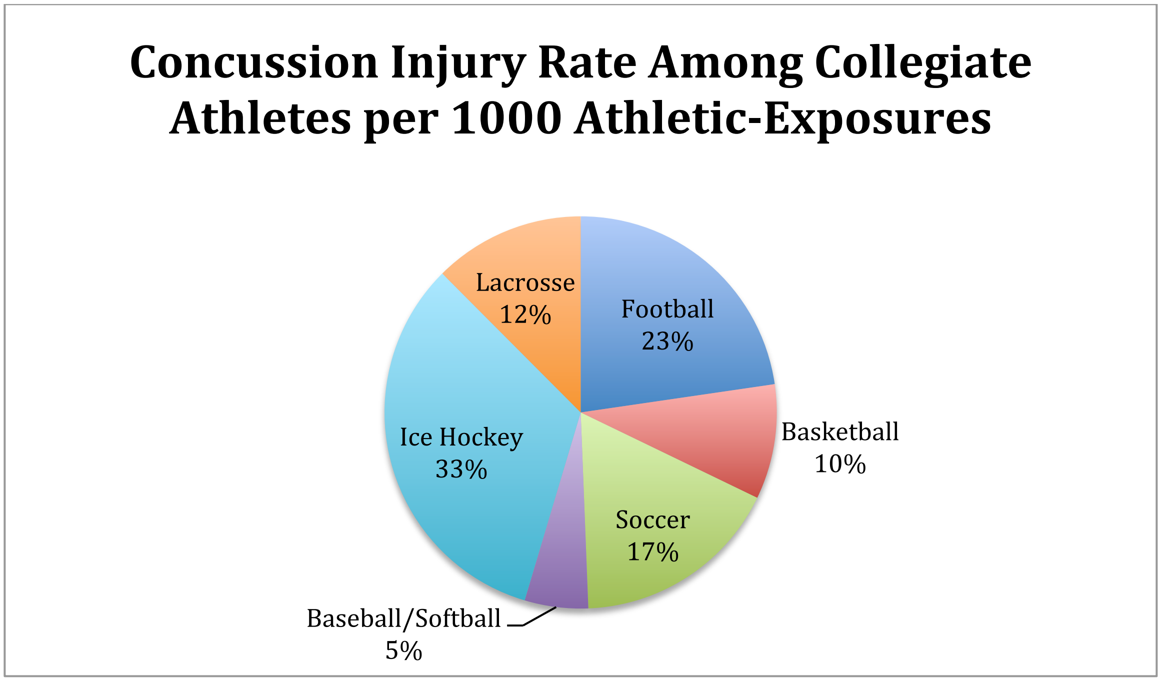

Figure 4. Estimated percentages of concussion injury rates for collegiate athletes per 100 athletic-exposures from 1988-2004. Data from Hootman, Dick, and Agel (2007).

History of Concerns with Concussion in Sports

Sport-related head trauma has become a hot-button topic in the recent media. An increase in violence, suicide, mental health disorders, and early onset dementia in professional athletes has led to growing concern over the last few decades (Nowinski, 2013). Lives of athletes, such as Andre Waters, Junior Seau, and Derek Boogaard, have been lost, and professional sports organizations such as the National Football League (NFL) and National Hockey League (NHL) have experienced major lawsuits for mishandling traumatic brain injuries of athletes. The growing concern has resulted in a larger spotlight on the issue, as well as an increase in research surrounding topics such as Chronic Traumatic Encephalopathy (CTE) and Second Impact Syndrome (SIS).

Chronic Traumatic Encephalopathy (CTE). CTE is a progressive neurodegenerative disease that is associated with trauma from repeated concussions or sub-concussive blows (Omalu, 2014). The disease is often found in athletes, military veterans, and victims of domestic violence. CTE is characterized by a specific pattern of brain shrinkage due to toxic neurofibrillary tangles made up of tau protein (McKee et al., 2009). CTE involves a combination of psychological, cognitive, physiological, and behavioral symptoms, such as explosive or aggressive behaviors, memory loss, suicidal thoughts, mood swings, trouble walking and/or speaking, and depression (Yi, Padalino, Chin, Montenegro, & Cantu, 2013). Unfortunately, no treatments currently exist for CTE, and it can only be diagnosed through autopsy after the individual has passed away. The brain bank at Boston University has found the disease in a variety of individuals, ranging from an 18-year-old high school athlete to an 80-year-old NFL veteran whose brain was the size of a one-year-old child at death. The disease often progresses long after an athlete has retired (McKee, 2014).

Nevertheless, this is an area that is fraught with disagreement and dissention. Though the research on this topic has exploded in the last decade, there are still many questions surrounding the diagnosis, as well as limited scientific evidence regarding the etiology and criteria (Asken et al., 2016). Many of the clinical features found in CTE also are found in other neurodegenerative, neurological, and psychiatric disorders (Iverson, Gardner, McCrory, Zafonte, & Castellani, 2015). This makes the differential diagnoses for CTE very challenging. Additionally, millions of people participate in contact sports and sustain multiple concussions across their lifetimes, but not all develop CTE. In fact, very little information is available on the epidemiology of CTE, and the strength of association remains unknown and unquantified (Barr, 2016). Across research labs, different neuropathological criteria are used for diagnosis, and no consensus has been reached on clinical features of the disease (Iverson et al., 2015). CTE has been reported in a wide range of individuals, from adolescents, who have only played sports for a short time, to older professional retirees. This highlights the need for a dose-response relationship between repetitive brain injury, neuropathology, and clinical symptoms in CTE, which has not yet been established (Barr, 2016). Furthermore, the current data may be biased by the fact that the families of athletes who are not experiencing the symptoms of CTE are less likely to request an autopsy and/or donate his or her brain to research centers.

Second Impact Syndrome (SIS). First coined by Saunders and Harbaugh (1984), the term SIS describes when an athlete is exhibiting post-concussive symptoms after an initial head injury and then experiences a second head injury during this recovery period. As a result, cerebral vascular congestion, catastrophic brain swelling, transtentorial brainstem herniation, and death can occur (Bey & Ostick, 2009). These devastating injuries appear to occur most frequently in children and adolescents, with the developmental status of the brain thought to increase the risk (Cantu, 1998).

Although the incidence of SIS is extremely rare (McCrory, Davis, & Makdissi, 2012), news coverage over tragedies, such as the death of 17-year-old Chad Stover, has brought SIS to the public's attention (Gregory, 2014). In October of 2013, Chad was playing defensive end for his high school football team. During the first quarter of a Friday night playoff game, he collided helmet to helmet with an opponent. His coaches checked on him, but Chad assured them he was okay, and he returned to play. Later, during the fourth quarter, Chad experienced a much smaller hit to the head, grazing another player's leg with his helmet. When the play ended, Chad stood, and as the teams lined up once again, he collapsed unconscious on the field and didn't get back up. He was rushed to the hospital, and after two weeks on life support, passed away. Though the official cause of death was blunt-force injury to the cranium, many believe that Chad's death is another occurrence of SIS (Gregory, 2014).

Though stories like Chad's continue to appear in the media and medical literature, SIS is a very controversial topic within the sports research community. Many believe that there is a lack of empirical evidence for its existence (Bey & Ostick, 2009; Byard & Vink, 2009; McCrory et al., 2012; Randolph, 2011); however, the threat of SIS drives many policies and return-to-play guidelines for athletes with concussions (McCrory et al., 2012). The main point of contention lies in the question of whether a second blow to the head is required for SIS or if the brain swelling is the result of a single injury. McCrory and colleagues (1998, 2001, 2012) argue that the whole notion of SIS is mostly dependent upon circumstantial case reports, many of which did not actually involve a second impact. They feel the terminology is misleading and that SIS is more likely a condition representing "diffuse cerebral swelling" (McCrory & Berkovic, 1998; McCrory, 2001; McCrory et al., 2012).

Responses to Research Findings

As a result of the concerns above, a large amount of research has been conducted with respect to this topic. In fact, a PubMed search revealed that the literature on this subject has increased from only a handful of studies prior to 1980, around 100 studies in the 1990s, about 600 in the 2000s, to an impressive 1,400 studies from 2010-2015, and these figures only continue to grow with each passing year (Guskiewicz, 2016). In response to all of these research findings, major sports organizations, such as the Concussion in Sport Group (CISG) and National Collegiate Athletic Association (NCAA), have hosted various collaborative meetings and revised many of their policies in regard to the prevention, assessment, and management of concussion in a sport context.

Changes to Sport (Education, Prevention, & Reform). In light of all the information discussed above, some individuals are attempting to come up with ways to make sports safer. One way of doing this is by educating players, their parents, and coaches (Covassin, Elbin, & Sarmiento, 2012). Education is also an essential component of the first R of concussion management: Recognize (McCrory et al., 2017). The CDC (2015) developed an education initiative entitled "Heads Up: Concussion in Youth Sports" to do just that. The program provides materials regarding recognition, response, and prevention in SRC. It is primarily implemented through use of a multimedia educational toolkit sent to coaches who order it. There are three goals for the "Heads Up" program. The first goal is to raise awareness and educate coaches about concussion. The second goal is to help coaches educate others about concussion. The final goal is to improve coaches' ability to prevent, recognize, and manage concussions in their young athletes. Within three months of the program's launch, over 20,000 toolkits were distributed (CDC, 2015).

Sarmiento, Mitchko, Klein, and Wong (2010) evaluated the impact and sustainability of "Heads Up." Overall, evaluation of the "Heads Up" program revealed positive changes in high school coaches' knowledge, attitudes, behavior, and skills related to concussion prevention and management. One third of the coaches reported that they learned something new about concussions from the toolkit. Fifty percent of coaches noted that the toolkit made them view and approach concussions more seriously. A follow-up study found that 77% of youth coaches reported being better able to identify athletes who may have a concussion (Covassin, Elbin, & Sarmiento, 2012). Coaches did, however, report that they face many barriers in preventing and addressing concussions, one of the most prevalent being that athletes and their parents discount the severity of concussions. They also reported difficulties with concussion-specific injury policies (Sarmiento, Mitchko, Klein, & Wong, 2010).

Others are focusing their efforts on prevention through reform and rule changes in the most prevalent sports. For example, many state legislatures have passed bills (e.g. Texas House Bill 2038, or Natasha's Law) that establish Return-to-Play (RTP) guidelines for school-aged athletes with concussions (Tomei, Doe, Prestigiacomo, & Gandhi, 2012). Additionally, the governing bodies of many major sports organizations have implemented rule changes. Because of the high-speed collisions associated with kickoff returns, the NFL moved kickoff from the 30- to 35-yard line in 2011 (Battista, 2016). In 2013, the NCAA implemented a new targeting rule for football, in which players would be ejected and suspended and the team would receive a 15-yard penalty should a helmet-to-helmet collision occur (Johnson, 2013). Furthermore, the Sports Legacy Institute has suggested a program for football similar to the pitch count system used in baseball (Nowinski, 2013). The goal of this Hit Count Initiative is simply to reduce the number of times a player is hit per day. In high school football, a player can take approximately 700 hits to the head per season, with most of these hits occurring during practice. With this system, once a player has been hit a specific number of times in a day, they are pulled from the contact elements of practice (Nowinski, 2013).

Some of the most effective changes with regard to policy reform are related to intentional physical contact in youth hockey (McCrory et al., 2017). USA Hockey and Hockey Canada, the major governing bodies for youth hockey in North America, have recently changed their rules associated with body checking. Currently, the organizations have banned body checking for any players under the age of 13 (Korioth, 2014). Most injuries in hockey occur due to intentional contact; concussions, more severe TBIs, and spine injuries related to the sport are most common in children under 14 (Polites et al., 2014). These types of injuries start to decrease with athletes 15 years and older, presumably because players grow physically and become more developed, and the size discrepancy between players begins to level out (Korioth, 2014). A recent review by Cusimano, Nastis, and Zuccaro (2013) found that the stricter body checking rules has resulted in injury rates that are anywhere from three to twelve times lower than previous seasons in which these rules were not enforced.

There have been calls for rule changes in other sports as well. As discussed previously, soccer is one of the sports with the highest rates of concussion, especially in female athletes (Cantu, Nowinski, Robbins, & Sports Legacy Institute, 2015). Currently, US Soccer regulations suggest introducing heading around the age of ten years old. In order to reduce the amount of concussions in the sport, a new campaign called “Safer Soccer” proposes eliminating the heading element of soccer until the age of fourteen. Many former professional players, such as Brandi Chastain, Cindy Parlow Cone, and Joy Fawcett, are rallying behind the idea. The campaign has even made a large impact on social media through the hashtag #NoHeaderNoBrainer. Supporters post pictures of themselves wearing their jerseys backwards to represent guidelines that should be reversed with regard to heading (Cantu, Nowinski, Robbins, & Sports Legacy Institute, 2015).

National Collegiate Athletic Association (NCAA). Another organization that has worked to contribute to the research on SRC and take great strides toward protecting and supporting their student athletes is the NCAA. This is pertinent for several reasons, as there is greater risk involved at this level of play. For one, there are a greater number of people at risk, as there are many more players participating at a collegiate level than at a professional level, and as discussed previously, it is more difficult on younger brains to recover from concussions.

Interestingly enough, the NCAA was established in 1906 as a result of President Theodore Roosevelt's concerns over head injuries in college football (Zillmer, Hong, Weidensaul, & Westerfer, 2011), and since its induction, the NCAA has played an important role in the SRC world.

One major step taken by the NCAA was the passing of the Concussion Safety Protocol Legislation in January 2015 (NCAA, 2015). During this meeting, five of the Division I conferences (i.e., Atlantic Coast Conference [ACC], Big 12 Conference, Big Ten Conference, Pac-12 Conference, and Southeastern Conference [SEC]) established a Concussion Safety Protocol Committee, and they agreed upon regulations that require each of the 65 schools involved to submit a concussion safety protocol to the committee for review. Each school's protocols must be consistent with the InterAssociation Consensus Guidelines (NCAA, 2015).

According to these guidelines, each school must address specific components of their concussion management plan (NCAA Sport Science Institute, 2017). To start, they must describe how they plan to provide concussion education to all relevant parties involved (e.g., student-athletes, coaches, athletic trainers, team physicians, athletic directors). There also must be a signed acknowledgement after education has been received that they understand all aspects of their institution's concussion management plan. Each school must explain their pre-season baseline evaluation procedures (e.g., concussion history, symptom evaluation, cognitive assessment, balance evaluation). Additionally, they have to describe their approach to concussion recognition and diagnosis, as well as post-concussion assessment (i.e., acute treatment and follow-up evaluations). Finally, each institution must provide a stepwise progression for Return-to-Learn (RTL) and RTP (NCAA Sport Science Institute, 2017).

The NCAA acknowledges that SRC management and prevention is an evolving science, and there are many knowledge gaps within clinical practice (Hainline, 2017). In order to guide best practice and contribute to the existing literature, the NCAA has backed various research initiatives. In 2014, they launched a $30 million landmark clinical study on concussion in alliance with the U.S. Department of Defense (DoD). This project is managed by the Concussion Assessment Research and Education (CARE) Consortium. The study will enroll an estimated 37,000 student-athletes from 26 different universities, including four military academies. In addition, the NCAA and DoD alliance includes the Mind Matters Challenge, which seeks submissions for innovative education and research approaches to help change the culture of concussion reporting and management, as well as guide best practices (Hainline, 2017).

Sports Concussion Management. The management of concussion recovery within the sports setting is unique for many reasons. Sport concussion management often involves a larger, multidisciplinary group of specialists who collaborate on the care of the injured athlete (Ellis, Leddy, & Willer, 2016). This group may include (but is not limited to) coaches, parents, physicians, school nurses, school administration, athletic trainers, and neuropsychologists. As discussed previously, athletes are more frequently put into positions where there is greater potential to receive a concussion; once they sustain a concussion, they are more vulnerable to receive another one. This multidisciplinary team must take great care to lessen the risk of the athlete sustaining another concussion by making the decision to return the athlete to physical and cognitive activity at the appropriate time (Echemendia, 2006). This is important because, within the sports context, there is often an added pressure to return these athletes to play as quickly as possible. Additionally, in higher levels of play where games are televised (i.e., collegiate and professional), the athlete's injury frequently becomes public knowledge (Pardini, Johnson, & Lovell, 2011). Therefore, it is even more essential that the multidisciplinary team maintain the confidentiality of the injured athlete.

Many of these collaborative management teams refer to the consensus statements released by CISG when making critical concussion care decisions. The CISG is a group of the world's leading authorities on concussion management (McCrory et al., 2017). About every four years (2001, 2004, 2008, 2012, 2016), the CISG holds an international conference to review and discuss the most current issues and evidence-based research in concussion. Using a consensus-based approach, the CISG publishes a set of guidelines regarding concussion management after each meeting (McCrory et al., 2017).

As a result of the most recent meeting, the CISG developed the "11 'R's of sport-related concussion management" (McCrory et al., 2017, p. 1-2). These include Recognize, Remove, Re-evaluate, Rest, Rehabilitation, Refer, Recover, Return to Sport, Reconsider, Residual Effects and Sequelae, and Risk Reduction. These 11 Rs not only provide a stepwise set of general guidelines to use for those involved in concussion care, but they also highlight some of the most important considerations within concussion management. At the same time, it is important to note that there is not a one-size-fits-all approach to concussion care. What may work for one player may not be helpful for another. Therefore, the CISG emphasizes the individualization of each athlete's care, taking into account all the variables at play for that specific person (McCrory et al., 2017).

In order to successfully manage a concussion in an athlete, one must be able to recognize when a concussion has occurred (the first 'R'; McCrory et al., 2017). This can be difficult, however, in the chaos of a game or practice. One tool that can make this process easier is the use of sideline evaluations (e.g., Sports Concussion Assessment Tool version 5 [SCAT5], Standardized Assessment of Concussion [SAC]). Whenever a concussion is suspected (i.e., the player's head was hit, it hit something else, or underwent rapid acceleration-deceleration), that player should immediately be removed from play and be evaluated by a licensed health care provider (e.g., athletic trainer, team physician). A sideline evaluation is a brief screener that can detect cognitive and mental status changes related to the acute phase of concussion, in addition to common signs and symptoms (McKeever & Schatz, 2003). It is important to note that this screener is not intended to replace a more comprehensive evaluation and should only be used as one tool in the concussion management process (McCrory et al., 2017).

During this acute time, it is also very important to rule out suspected medical emergencies such as cervical injury, intracranial bleeding, skull fractures, and so on (Kirkwood et al., 2008; McCrory et al., 2017). If a player's performance on the sideline evaluation further supports the presence of a concussion, that athlete should immediately be removed from the sporting event and proceed to a more diagnostic evaluation (e.g., emergency room, doctor's office). The player should be monitored closely for hours after the suspected concussive event, as concussions are an evolving injury and some signs and symptoms are not apparent right away. Once a concussion is officially diagnosed, physical and cognitive rest are vital in order to help balance out the "metabolic mismatch" the brain is experiencing after a concussion (Grady, Master, & Gioia, 2012, p. 380; McCrory et al., 2017).

Return-to-Play. One of the most pressing concerns for everyone involved when dealing with SRC is when the athlete will be able to return to his or her respective sport. Most of the time, the athlete, family, and coaches are very eager for the athlete to get back, but because of the concerns associated with repeated concussion, SIS, and PCS, it is vital not to RTP prematurely

(Echemendia, 2006). A great amount of research has been conducted with regard to the timing and strategies involved in RTP after a concussion. Historically, RTP decisions were made based on the concussion grade (discussed above), but now concussions are often classified as simple or complex (McCrory et al., 2005). The CISG group has addressed the issues involved with RTP and suggested guidelines for RTP since their induction (Aubry et al., 2002).

According to the most recent consensus statement by the CISG (McCrory et al., 2017), it is recommended that the athlete undergo a period of both physical and cognitive rest for 24-48 hours before any RTP protocols are initiated. Table 2 presents all the recommended stages for RTP. At least 24 hours (frequently longer) should be dedicated to each stage of the process. Should symptoms become exacerbated during any point in time, the athlete should drop back down to the previous step for an additional 24 hours.

After the initial rest period, the individual may begin to participate in daily activities that do not trigger symptoms in the first RTP stage. Step two includes the introduction of light aerobic exercise that will increase the heart rate (e.g., walking, cycling). The next step involves adding more movement into the exercises with sport-specific drills that involve a low-risk for head impact. From there, individuals may increase difficulty through training drills that intensify coordination and thinking in step four. During step five, the athlete should be assessed by a healthcare professional in order to receive medical clearance to return to his or her sport. Once clearance has been given, the athlete may participate in normal practice activities. This helps the coaching staff assess the current functioning of the injured player, and serves to restore the confidence of the athlete and those involved in his or her care. Once the individual has met the criteria for each stage of the RTP protocol (a weeklong process at minimum), he or she can then enter the sixth and final stage, a full return-to-sport and game play (McCrory et al., 2017).

Table 2

Graduated Stepwise Return-To-Play Rehabilitation

Return-to-Play Strategy		
Stage	**Rehabilitation Objective**	**Exercise**
1	Symptom-limited activity	Gradual reintroduction of daily activities that do not provoke symptoms.
2	Light aerobic exercise	Walking or stationary cycling at slow to medium pace. No resistance training yet.
3	Sport-specific exercise	Running or skating drills. No head impact activities.
4	Non-contact training drills	Harder training drills (e.g., passing drills). May begin progressive resistance training.
5	Full contact practice	Following medical clearance, participate in normal training activities.
6	Return to sport	Normal game play.

According to the CISG, should symptoms persist (i.e., longer than two weeks for adults and one month for children) and the athlete experience difficulty progressing through the RTP process, the individual should be referred to a medical professional with expertise in concussion management in order to assess for PCS and receive more intensive rehabilitation exercises (McCrory et al., 2017). Many physicians utilize Leddy and colleagues' (Leddy et al., 2010) sub-symptom threshold exercise training program to address persistent symptoms by restoring autonomic balance and improving cerebral autoregulation.

Return-to-Learn. It has been well established that not only do physical activities exacerbate and prolong concussion symptoms, but cognitive activities can as well (Gioia, 2016; Rose, McNally, & Heyer, 2016; Sady, Vaughan, & Gioia, 2011). This makes recovery for younger athletes, who must attend school, more complicated. RTP has been the most pressing concern since the visibility on SRC has increased, and there is a plethora of research on getting the athlete back to his or her respective sport, but there has been very limited literature published on getting athletes back in school (i.e., RTL), and hardly any studies using an empirical approach have been conducted in this area. This is serious because, for student education, RTL is more important than RTP (Master, Gioia, Leddy, & Grady, 2012).

Younger athletes with a concussion may experience impairments in the same functional domains as adults, but the negative effects these impairments can have on his or her educational development make concussions a more serious issue with the younger populations (Karlin, 2011). Due to the issues with concentration, processing speed, and memory, schoolwork often suffers as a result of a concussion. Students often complain of worsened symptoms when they are in class or working on homework. Sometimes students must miss school as a result of their symptoms, but this can lead to additional consequences. Perhaps most obviously, when the student misses school, he or she misses out on learning important information. Consequently, school districts have policies on the number of days of absences before a student must repeat the course (Karlin, 2011). Obviously, there are similar concerns with regard to collegiate athletes.

Moreover, for children and adolescents, absence from school can have a negative impact on psychosocial development. In addition to the way concussion symptoms can impact a person’s ability to interact socially, students may perceive changes in their school relationships and reduced social acceptance as a result of prolonged absences. Home isolation can lead to feelings of depression and anxiety. Likewise, the thought of accumulating make-up work is also very stressful for students, as well as the fact that they must pass their classes in order to play (Karlin, 2011).

Concerns such as these highlight the importance of RTL protocols. Fortunately, at their most recent meeting, the CISG developed guidelines for a graduated RTL strategy (McCrory et al., 2017). Similar to the RTP protocol, the RTL suggestions focus on a sensible approach with gradual return to activity that does not result in the exacerbation of symptoms. Management should be handled conservatively, with the emphasis placed on RTL before RTP. As is the case with the RTP protocol, the student should undergo a period of both cognitive and physical rest before the RTL process is started. Table 3 presents all the recommended stages for RTL.

Table 3

Graduated Stepwise Return-To-Learn Rehabilitation

Return-to-Learn Strategy		
Stage	**Rehabilitation Objective**	**Exercise**
1	Symptom-limited activities	Typical activities of the child during the day as long as they do not increase symptoms (e.g., reading, texting, screen time).
2	School activities	Homework, reading or other cognitive activities outside of the classroom
3	Return to school part-time	Gradual introduction of schoolwork. May need to start with a partial school day or with increased breaks during the day
4	Return to school full time	Gradually progress school activities until a full day can be tolerated

In stage one, the athlete begins to attempt typical daily activities at home, starting with 5-15 minutes of engagement, and then gradually building up from there. Next, the student may attempt to complete school-based activities (e.g., homework, reading) in the home setting, with the goal of increasing tolerance to cognitive work. In stage three, the student-athlete returns to school part time with the gradual re-introduction of classwork and increased academic activities. This might involve a partial school day or increased breaks. Once the student is tolerating this step successfully, he or she can continue to gradually progress school activities until he or she can handle a full academic day. At this point the student should focus on catching up on missed work. Finally, only after the student-athlete has successfully advanced through all four stages of the RTL protocol, he or she can begin the RTP process. Should the student experience difficulty progressing through the RTL process, school activities may need to be modified or additional accommodations (e.g. shortened assignments, extended time, breaks, sunglasses, earplugs, printed copies of notes) put in place to help the student succeed.

The CISG group also recommends that schools have an SRC policy in place to help with the accommodation process. Policies should include concussion education and management information for coaches, trainers, nurses, teachers, staff, and administration (McCrory et al., 2017). This helps the appropriate individuals be able to recognize and respond appropriately to a student's concussion symptoms. Then, once the child returns to the classroom, teachers and school staff are more prepared for the cognitive setbacks a student may experience as a result of a concussion. This is important as many concussions happen during school-sanctioned sporting events.

Neuropsychological Assessment

An emerging and important piece of concussion management and the recovery process is neuropsychological evaluation. Neuropsychologists have in-depth training in brain-behavior relationships, as well as an extensive understanding of how medical injuries and neurological disorders, concussion included, impact cognition, emotion, social, and daily functioning (McCrory et al., 2017). Compared to clinical exams, neuropsychological assessments are more sensitive to detecting subtle cognitive impairments that are often present in concussion (Harmon et al., 2013).

Neuropsychological assessment has been used in the evaluation of brain injury since World War II (Echemendia, 2006), but it was not used in the sports setting until Barth and colleagues (1989) pioneered the Sports as a Laboratory Assessment Model (SLAM). In this seminal, large-scale study, athletes received neurocognitive testing before they began the sports season (i.e., baseline testing), and then underwent recurrent post-concussive evaluations. This approach was innovative for its time as no one else before this had utilized neuropsychological assessment pre-injury with athletes. Barth found that neurocognitive deficits were apparent, compared to the athlete's preseason baseline, at 24 hours post-injury and 5 days post-injury. There appeared to be a gradual recovery over a period of 10 days for most of the athletes (Barth et al., 1989). Since then, there has been a massive increase in the literature regarding the validity, reliability, and utility of neuropsychological assessment with athletes, and the SLAM model has served as a foundation for concussion management practices (Pardini et al., 2011).

Considering that athletes with concussions often experience deficits in reaction time, memory, attention, impulse control, and processing speed, among other cognitive domains (Ellis, Leddy, & Willer, 2016; Purcell, 2014), neuropsychological assessment can be very beneficial in tracking the recovery of concussion and aid in making RTP and RTL decisions. Following the example of the SLAM model, this process often begins with baseline assessment, conducted before the start of the season (Guay et al., 2016). This baseline testing allows for a comparison of post-injury cognitive functioning with pre-injury scores. Previously, neuropsychological assessments (including baseline) were conducted using a comprehensive, paper-and-pencil format (Kontos, Collins, & Russo, 2004). In the past decade, though, there has been a shift to a more efficient, computerized approach to baseline testing (Guay et al., 2016). This allows athletic departments to screen a large number of athletes quickly, focusing on the most influential cognitive domains that are affected by concussion (e.g., memory, processing speed, and so on; Moser et al., 2007). From there, if an athlete sustains a concussion, he or she is most likely given a sideline assessment, as well as recurrent post-injury follow-up assessments to establish the point at which the athlete has recovered or clinical symptoms are no longer present

(Moser et al., 2007). This comparison of pre- and post-injury scores not only informs a multidisciplinary concussion team of how much a concussion has impacted the functioning of an athlete, but also aids the process of making critical concussion care decisions.

Measurement issues. The increased exposure to the effects of concussion also has led to an increase in proposed solutions to the various issues associated with concussions (Guskiewicz, 2016). From improvements to protective equipment (e.g., helmets) to new concussion-based pharmaceuticals, many companies have developed (and profited from) new products aimed at solving problems in concussion management process. This has extended to the neuropsychological assessment realm as well. There has been an upsurge in the number of computerized neurocognitive tests on the market and adopted into clinical practice since 2005 (Echemendia, & Bauer, 2015; Resch, McCrea, & Cullum, 2013). The problem is that the number of clinical studies published on these new assessments has not followed the same trajectory. This means that practitioners are utilizing these measures, and making important decisions about an athlete's concussion care, without truly knowing if the product is reliable or valid.

Without well-established psychometrics, it is difficult to know if a decline in performance means an athlete's brain is impaired by a concussion, or if it is the result of a different confounding factor (e.g., fatigue, anxiety; Bailey, 2017). Yet, many of the new assessments do not include a manual, or the manual only provides administration instructions without providing information on the reliability, validity, operating characteristics, expected levels of performance, and so on—leaving professionals at a disadvantage when interpreting the results (Echemendia, & Bauer, 2015). Additionally, these new assessments often are marketed before full information is available regarding how cultural, educational, and other pre-injury factors affect test performance. While many of these newer assessments are essentially computerized versions of traditional tests, the technological components (i.e., human-machine interface) result in a very different testing experience, and therefore these measures require their own validation efforts (Echemendia, & Bauer, 2015).

The few studies that are published on the topic have found great variability in test-retest reliability of many of these newer assessments (Bailey, 2017). Additionally, it has been determined that contextual factors play an important role in the validity of assessment results. Many athletes do not understand the importance of baseline evaluation at the time of testing, so they do not always give their full effort; however, after they have sustained a concussion, and RTP is on the line, his or her motivation level changes, and results may be impacted. Furthermore, athletes may purposely underperform during baseline, so in the event that they do experience a concussion, his or her results will not display as large of a discrepancy, and he or she will not appear concussed (Schatz, Moser, Solomon, Ott, & Karpf, 2012). Finally, in the event of a concussion, repeated, serial administration of these measures is often used in order to track recovery. As a result, practice effects may occur, causing inflated scores that imitate improvement if alternate test forms are not available and/or utilized (Resch, McCrea, & Cullum, 2013).

CHAPTER III

METHODS

Due to the importance of neuropsychological assessment in the concussion management process, the purpose of this study was to investigate a newer assessment (C3Logix), as well as to contribute to the limited literature regarding concussion recovery in young adults, with a focus on sex differences in the recovery process.

Participants

The present study utilized de-identified assessment data from student-athletes at a large southern university who sustained a concussion either on or off the field (*n* = 42). This involved both male and female athletes from a wide range of university sports. To be included in the study, participants must have sustained a concussion during the 2016-2017 academic year. They also must have undergone baseline and post-injury assessment through the University Athletic Department. No other exclusion criteria were used. Because of the high profile nature of athletics and in an effort to maintain the confidentiality of the student athletes, each participant's assessment data was de-identified by the University Athletics Department prior to being distributed to the investigator. Data did not include the sport or other information that could lead to identification of the student-athlete.

For this sample of concussed athletes, 64.3% were male (*n* = 27) and 35.7% were female (*n* = 15). The mean age for participants was 19.17 years overall. The mean age for male athletes was 19.74 (SD = 1.23); the mean age for female athletes was 18.13 (SD = 0.83). Available demographic characteristics for the sample are presented in Table 4. Neither race/ethnicity nor socioeconomic status was collected.

Table 4

Participant Demographic Characteristics

Athlete Demographics			
Variable	**N**	**%**	**Age M (SD)**
All	42		19.17 (1.34)
Sex			
Males	27	64.3	19.74 (1.23)
Females	15	35.7	18.13 (0.83)

Procedures

The University Athletics Department manages over 650 student athletes across 20 varsity sports. Upon arrival at the university, each new student-athlete (i.e., freshman or transfer) provided a detailed medical history, including an extensive account of previous head injuries. Each new student-athlete also underwent a baseline neuropsychological and balance assessment through the use of the Comprehensive Concussion Care (C3) Logix system (Neurologix Technology, Inc., Cleveland, OH, USA, 2013) and, until the 2017-2018 season, the Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT; ImPACT Applications Inc., Pittsburgh, Pennsylvania, USA, 2007) system.

Should a student-athlete exhibit any signs, symptoms, or behaviors consistent with a concussion while engaged in sport, the athlete was removed from practice or competition, and evaluated by a member of the Sports Medicine staff. An assessment of symptoms was performed at the time of the injury and then serially thereafter (i.e., 2-3 hours post-injury, 24 hours, 48 hours, and so on). When the concussion occurred outside of sport (e.g., motor vehicle accident), the same follow-up occurred. Once the athlete demonstrated a significant decrease in symptoms, a follow-up post-injury C3Logix assessment was administered to evaluate their level of functioning. If scores were within at least 90% of baseline scores, and the athlete remained asymptomatic for 24 additional hours after the post-injury follow-up assessment, a five-step graduated exertional RTP protocol was begun, with symptoms being reassessed immediately following the exertional activities. In previous years, an ImPACT follow-up assessment was only conducted upon physician request.

IRB approval for this study was obtained from Texas A&M University, as well as from the Athletics Department Research Review Team. Research questions were investigated through the use of the C3Logix and ImPACT assessment data collected by the Athletics Department at baseline and following concussion. Through use of the Athletics Department database, the Concussion Management Coordinator gathered the baseline and post-injury assessment data for each student-athlete who sustained a concussion during the 2016-2017 academic year. The Coordinator then removed the name and sport from each assessment printout in order to maintain confidentiality. An identification number was assigned to the corresponding C3Logix and ImPACT printouts.

Measures

The following instruments were administered by the Athletics Department in the 2016-2017 academic year with each new student-athlete before the beginning of the season, and then again if the athlete sustained a concussion. The data from these measures were utilized for the purposes of this study.

ImPACT. ImPACT is a neurocognitive assessment administered on a desktop or laptop computer. It evaluates the effects of concussion through modules measuring sequencing, attention, word memory, visual memory, and reaction time. ImPACT can be administered with individuals ranging in age from 12- to 60-years-old. Participants complete a post-concussion symptom inventory and six different modules (Word Memory, Design Memory, X's and O's, Symbol Match, Color Match, & Three Letters), which are generally completed within a 20-25 minute time frame. The Total Symptom Score is calculated based off a 22-item graded symptom checklist, in which participants endorse symptoms on a seven-point Likert scale (0 to 6). The higher the score indicated, the more severe the symptom. The questions in this module are modeled after the Post-Concussion Symptom Scale (Lovell & Collins, 1998).

An overview of the ImPACT modules and constructs measured are presented in Table 5. Each module has a set of scores that are unique to that specific task, reflecting speed of performance and/or accuracy. Additionally six composite scores (Verbal Memory, Visual Memory, Visual Motor Speed, Reaction Time, Impulse Control, Total Symptom), validity, a Cognitive Efficiency Index, and a Reliable Change Index score are all calculated.

ImPACT has been researched widely and has substantial support in the literature related to validity and reliability. Nakayama and colleagues (2014) found that ImPACT yielded reliable results across modules with college students at 45 and 50 days after baseline. Intra-class correlation coefficients (ICCs) were as follows: Verbal Memory = .69, Visual Memory = .69, Visual Motor Speed = .88, and Reaction Time = .81. Moreover, studies have shown that ImPACT results have good construct, concurrent, and discriminant validity with significant correlations found between traditional pencil-and-paper neuropsychological testing domains and ImPACT composites (Iverson, Lovell, & Collins, 2005; Maerlender et al., 2010; Schatz & Putz, 2006).

Table 5

Overview of Constructs Measured by ImPACT

ImPACT Assessment Overview	
Module	**Construct Measured**
Post Concussion Symptom Inventory	• Concussion Severity
Word Memory	• Attentional Processes • Verbal Recognition Memory
Design Memory	• Attentional Processes • Visual Recognition Memory
X's and O's	• Visual Working Memory • Visual Processing/Visual Motor Speed
Symbol Match	• Visual Processing Speed • Learning • Memory
Color Match	• Choice Reaction Time • Impulse Control/Response Inhibition
Three Letters	• Working Memory • Visual-Motor Response Speed

Note. Adapted from ImPACT Applications Inc. (2007)

C3Logix. C3Logix is a comprehensive mobile assessment of multiple neurologic domains administered on an iPad. It evaluates not only the cognitive effects of concussion, but the physical (i.e., motor and vestibular) components as well. C3Logix assesses such domains as reaction time, working memory, processing speed, postural stability, vision, and the vestibulo-ocularmotor reflex. Participants complete a post-concussion symptom inventory and six different modules (Standard Assessment of Concussion [SAC] Memory, Balance Error Scoring System [BESS], Visual Acuity, Processing Speed, Reaction Time [Simple and Choice], and Trails A & B), which are generally completed in about 17 minutes. The Symptom Severity score is calculated based off a 27-item graded symptom checklist, in which participants endorse symptoms on a seven-point Likert scale (0 to 6). The higher the score indicated, the more severe the symptom. The questions in this module are modeled after the Sport Concussion Assessment Tool (SCAT5; CISG, 2017). An overview of the C3Logix modules and constructs measured are presented in Table 6.

Table 6

Overview of Constructs Measured by C3Logix

C3Logix Assessment Overview	
Module	**Construct Measured**
Symptom Severity	• Concussion Severity
Standard Assessment of Concussion (SAC) Memory	• Orientation • Concentration • Immediate Memory • Delayed Memory
Balance Error Scoring System (BESS)	• Vestibular Function • Postural Stability
Visual Acuity	• Static Vision • Dynamic Vision • Vestibulo-Oculomotor Reflex
Processing Speed	• Cognitive Efficiency • Visual-Spatial Scanning
Simple & Choice Reaction Time	• Visual-Motor Response Speed • Impulse Control/Response Inhibition
Trails A & B	• Set Shifting • Psychomotor Speed • Visual Attention • Visual-Spatial Scanning

Note. Adapted from Neurologix Technology, Inc. (2013)

C3Logix produces nine raw scores from the various modules. The system aggregates an individual athlete's data over time to create score comparisons. The data is presented in a polygon shaped figure on the assessment summary printout, comparing an individual's baseline performance to each post-concussive follow-up. This visualization helps to clearly demonstrate the areas of impairment and aid practitioners in making well-informed decisions more efficiently. While the purpose of C3Logix is to compare an individual's performance to themselves at different time points, 50th percentile norms are provided as a reference. The tasks utilized in C3Logix are based on long standing traditional paper-and-pencil measures (e.g., Trail Making Test, Single Digit Modalities, SAC, BESS) that have been transformed into electronic form for ease and mobility (Alberts & Linder, 2015).

Research on the C3Logix system is limited; there have only been a few published studies so far investigating the reliability and validity of the measure. Utilizing both C3Logix and paper-and-pencil measures, Simon and colleagues (2017) studied the Balance module with the BESS system by looking at the within-session reliability after one week. Additionally, they examined the neurocognitive one-week concurrent validity and test–retest reliability of Processing Speed, Trails A, and Trails B. Results indicated acceptable concurrent validity for these neurocognitive measures with the corresponding paper-and pencil measures. Intra-class correlation coefficients (ICCs) were as follows: Trails A = .52, Trails B = .72, and Processing Speed = .88. Moreover, the Balance module demonstrated strong one-week reliability (Simon et al., 2017).

Bernstein, Calamia, Pratt, and Mullenix (2018) conducted an exploratory study to determine whether the C3Logix system is sensitive to the effects of concussion. Here, college students (n = 54) completed C3Logix at baseline and then again within a couple of days following a suspected concussion. After a concussion injury, participants reported significantly greater Symptom Severity ($p < .001$) and performed more poorly on measures of Reaction Time (Simple Reaction Time [SRT] $p < .001$; Choice Reaction Time [CRT] $p = .02$) and Balance ($p = .05$; Bernstein, Calamia, Pratt, & Mullenix, 2018). Oliver et al. (2015) and Borges, Raab, and

Lininger (2017) have also conducted preliminary and pilot studies that utilized aspects of the C3Logix system.

Makwana and Xu (2019) sought to investigate whether or not athletes perform better on C3Logix measures compared to nonathletes due to their higher levels of physical activity. Using university undergraduate students (95 athletes and 92 nonathletes), the researchers found that athletes outperformed nonathletes on reaction time tasks: SRT ($F(1,184) = 5.447$, $p = .01$) and CRT ($F(1,184) = 5.013$, $p = .01$). There were no significant differences found on the other domains. Additionally, it should be noted that with this sample, sex demonstrated a significant effect on SAC, SRT, and CRT (Makwana & Xu, 2019).

Variables. As indicated in the descriptions of the two measures, both the ImPACT and C3Logix batteries yield a score for symptom severity. ImPACT yields this score based off a 22-item Likert scale, and C3Logix calculates the score based off a 27-item Likert scale of symptoms. Many of the items on both assessments are exactly the same or are very similar in phrasing. In some instances, the measures will examine different issues within the same symptom cluster (e.g., C3Logix asks about blurred vision where ImPACT looks at visual problems in general). C3Logix probes further into physical symptoms by asking about issues like neck pain, ringing in the ears, and pressure in the head.

ImPACT and C3Logix also overlap in other areas, generating scores measuring memory, processing speed, reaction time (RT), and impulse control. C3Logix presents results as raw module scores, and ImPACT uses the raw module scores to calculate specific composite scores. The similarities between these tasks hypothetically should result in scores that are significantly correlated. The specific scores generated for each construct in both batteries are presented in Table 7.

Table 7

Overview of the Variables Measured in the Current Study

Study Variables		
Construct	**ImPACT**	**C3Logix**
Symptom Severity	• Total Symptom Score	• Symptom Severity Module Score
Memory	• Verbal Memory Composite • Visual Memory Composite	• Standard Assessment of Concussion Memory Combined Score
Processing Speed	• Visual Motor Speed Composite • Cognitive Efficiency Index Score	• Processing Speed Module Score • Trails A Module Score • Trails B Module Score
Reaction Time (RT)	• Reaction Time Composite • Visual Motor Speed Composite	• Simple RT Module Score • Choice RT Module Score
Impulse Control	• Impulse Control Composite	• Trails A Module Score • Trails B Module Score • Simple RT Module Score • Choice RT Module Score

Planned Analyses

Once IRB and Athletics Department approval were obtained and the de-identified dataset was received, descriptive statistics were examined for all variables (i.e., sex, C3Logix composite scores, ImPACT composite scores, time of assessment [baseline or post-injury]). Variables were evaluated for normality with the Shapiro-Wilk test statistic, *W*, in SPSS (Shapiro & Wilk, 1965). Additional information on normality was provided through evaluation of the skewness and kurtosis of the data distribution. In the event that the data was non-parametic, Spearman's *rho* was used instead of Pearson's *r*. To address research questions, correlational analysis, analysis of variance, and regression were conducted. All analyses were investigated using SPSS 26 with an alpha of .05.

CHAPTER IV

RESULTS

Initial activity included identifying those athletes who had both C3Logix and ImPACT baseline data (*n* = 38). The Athletics Department prefers the C3Logix system to ImPACT, and therefore prioritizes that assessment and uses it for follow-up evaluations, unless otherwise requested by a physician. Four athletes did not have ImPACT baseline assessments; however, 19 athletes had follow-up ImPACT data post-injury. Forty-one athletes had both baseline and follow-up C3Logix assessments. These scores were included in the analyses.

Data Inspection

Fifteen athletes experienced multiple concussive events while at Texas A&M with follow-up data within the 2016-2017 academic year. For the purposes of these analyses, only the most recent baseline and scores associated with the most recent concussive incident were included. Follow-up data from prior concussive events were graphed separately and the recovery trajectory was observed anecdotally.

Data were tested for normality by examining the skewness and kurtosis of the data distribution, as well as the Shapiro-Wilk test of normality. Variables met assumptions of normality based on skewness and kurtosis with values between -1 and +1. For ImPACT, all composite variables met assumptions of normality, except for Total Symptom Score ($p = < .001$) and Visual Motor Speed ($p = < .001$). Impulse Control did not meet assumptions with Shapiro-Wilk ($p = < .002$), although skewness and kurtosis were within the acceptable range. Results are presented in Table 8.

Table 8

Normality Evaluation for the ImPACT Assessment

ImPACT Normality Results				
ImPACT Composite	**Skewness**	**Kurtosis**	**Shapiro-Wilk Statistic**	***P***
Verbal Memory	-.91	.75	.93	.03
Visual Memory	-.10	-.90	.98	.54
Visual Motor Speed	-1.07	1.91	.92	.009
Reaction Time	.49	.36	.97	.30
Impulse Control	.82	-.37	.89	.002
Total Symptoms	1.89	2.69	.62	<.001
Cognitive Efficiency Index	-.15	-.63	.98	.68

Similar analysis was conducted for C3Logix. On C3Logix, continuous variables that were not normally distributed included Symptom Severity (*p* = < .001), Standard Assessment of Concussion Memory (SAC; *p* = < .001), Balance (*p* = .002), and Trails B (*p* = < .001). Results are presented in Table 9.

Table 9

Normality Evaluation for the C3Logix Assessment

C3Logix Normality Results				
ImPACT Composite	**Skewness**	**Kurtosis**	**Shapiro-Wilk Statistic**	***P***
Symptom Severity	2.06	3.57	.68	<.001
SAC	-1.20	.71	.85	<.001
Balance	1.35	2.24	.90	.002
Trails A	.98	1.30	.93	.02
Trails B	2.19	7.37	.83	<.001
Processing Speed	.78	.35	.94	.02
Simple Reaction Time	.86	1.05	.95	.10
Choice Reaction Time	.61	-.08	.97	.26
Visual Acuity	.14	-.53	.95	.05

Note. SAC = Standard Assessment of Concussion Memory

Based on this information, the decision was made to use Spearman's *rho* to run correlational analyses rather than to transform the data. The characteristics of this population are important (e.g., all having had sustained at least one concussion) and transformation of the scores could result in the loss of clinically meaningful data.

Descriptive Data for Sample

The means and standard deviations were calculated for baseline scores on ImPACT and C3Logix, as well as other athlete characteristics. In regards to the history of total concussions for each athlete, an approximate average number of concussions (including the concussion they were being treated for at the time of assessment) was 1.81 (SD = 1.00) for males and 2.27 (SD = 1.10) for females. Overall, the athletes presented a range from 1 to 5 total concussive events. The data are presented in Table 10.

Table 10

Means and Standard Deviations for Athlete Characteristics

Athlete Characteristics			
Variable	**Total** **(*N* = 42)**	**Males** **(*n* = 27)**	**Females** **(*n* = 15)**
Total Concussions	1.98 (1.05)	1.81 (1.00)	2.27 (1.10)

Note. Number includes current concussive injury

The means and standard deviations for ImPACT composite scores are presented in Table 11. Normative data were not available for the ImPACT version given to the athletes at baseline (i.e., Version 2.1). For ImPACT, higher scores are more indicative of symptom severity. The Verbal Memory composite is based on an average of scores from the Word Memory, Symbol

Match, and Three Letters activities, with higher scores better. The Visual Memory composite is based on an average of scores from the Design Memory and X's and O's activities, with higher scores better. The Visual Motor Speed composite is based on an average of scores from X's and O's and Three Letters, with higher scores better. Lower scores are better in regards to the Reaction Time composite, which is established from the time taken to complete X's and O's, Symbol Match, and Color Match. Impulse Control provides a measure of errors on the X's and O's and Color Match subtests; therefore, lower scores are preferable. The Cognitive Efficiency Index was developed to measure the interaction between speed (reaction time) and accuracy (percentage correct) on the Symbol Match subtest, and higher scores are better.

Table 11

Means and Standard Deviations for ImPACT Composite Scores at Baseline

ImPACT Baseline Data			
Variable	**Total (*N* = 42)**	**Males (*n* = 27)**	**Females (*n* = 15)**
ImPACT Verbal Memory	82.97 (12.96)	79.50 (13.95)	89.38 (7.86)
ImPACT Visual Memory	69.73 (16.77)	68.63 (17.76)	71.77 (15.25)
ImPACT Visual Motor Speed	38.53 (9.27)	36.28 (10.17)	42.68 (5.54)
ImPACT Reaction Time	0.60 (0.07)	0.61 (0.07)	0.59 (0.07)
ImPACT Impulse Control	6.38 (4.06)	6.50 (4.22)	6.15 (3.89)
ImPACT Total Symptom Score	4.38 (8.03)	5.33 (9.38)	2.62 (4.41)
ImPACT Cognitive Efficiency Index	0.31 (0.14)	0.28 (0.14)	0.38 (0.10)

Table 12

Means and Standard Deviations for C3Logix Module Scores at Baseline

C3Logix Baseline Data				
Variable	**Total (*N* = 42)**	**Males (*n* = 27)**	**Females (*n* = 15)**	**"Normal" Scores**
C3Logix Symptom Severity (Total Symptoms Score)	3.56 (5.53)	4.19 (6.55)	2.36 (2.41)	Males 1 Females 1
C3Logix SAC (Combined Memory Scores)	26.98 (2.31)	26.19 (2.40)	28.50 (1.02)	Males 27 Females 28
C3Logix Balance (Total Errors)	12.55 (6.83)	13.69 (7.12)	10.43 (5.91)	Males 12 Females 12
C3Logix Trails A (Seconds)	21.95 (7.46)	24.22 (7.61)	17.57 (4.89)	Males 20.82 Females 19.70
C3Logix Trails B (Seconds)	43.92 (16.46)	49.12 (17.82)	34.26 (6.89)	Males 42.46 Females 38.10
C3Logix Processing Speed (Total Number Correct)	63.51 (17.04)	58.56 (15.92)	73.07 (15.41)	Males 59 Females 64
C3Logix Simple Reaction Time (Milliseconds)	280.51 (30.19)	278.19 (28.52)	285.00 (33.85)	Males 286.54 Females 293.00
C3Logix Choice Reaction Time (Milliseconds)	427.45 (66.60)	426.67 (68.73)	429.08 (64.62)	Males 409.14 Females 409.00
C3Logix Visual Acuity (LogMAR Lines Differential)	1.12 (0.75)	0.96 (0.72)	1.43 (0.74)	Males N/A Females N/A

Notes. SAC = Standard Assessment of Concussion Memory; LogMAR = Logarithm of the Minimum Angle of Resolution; "Normal" data are based off 50th percentile norms

The means and standard deviations for C3Logix composite scores are presented in Table 12. For C3Logix, higher scores are more indicative of symptom severity. SAC scores are based on a combination of the total correct on Orientation, Concentration, Immediate Memory, and Delayed Memory; therefore, higher scores are better. The Balance score is based on number of errors, so lower scores are better. Trails A, Trails B, Simple Reaction Time, and Choice Reaction Time module scores are the number of seconds or milliseconds to completion, with lower scores better. Higher scores are better on the Processing Speed module, established on the number of items correct. Visual Acuity is calculated based on the differential in lines with the

Logarithm of the Minimum Angle of Resolution (LogMAR). The lower the score, the better the visual acuity. For reference, the indicators for "normal" performance are provided as well.

Research Question 1. C3Logix module scores

What is the level of agreement between module scores on the C3Logix assessment battery at baseline? This was investigated in order to better understand the relationship between the areas of functioning affected by a concussion. Because the modules on C3Logix measure the areas most commonly affected by concussion (e.g., reaction time, memory, processing speed), it was hypothesized that the module scores would be significantly correlated with each other. In order to test this hypothesis, a correlation matrix was computed for the module scores on C3Logix using a Spearman's *rho* two-tailed test.

As expected, results indicated a significant correlation ($p \leq .01$) between Trails A and Trails B. Trails B was also significantly correlated ($p \leq .01$) with SAC and Processing Speed. Similarly, Trails A was significantly correlated ($p \leq .01$) with Processing Speed as well. Symptom Severity and Balance were also significantly correlated ($p \leq .01$). Finally and unsurprisingly, there was a moderate, significant positive correlation ($p \leq .05$) between Simple Reaction Time and Choice Reaction Time (see Table 13). Notably, the Visual Acuity module did not correlate with any other module.

Table 13

Correlation (r_s) between C3Logix Module Scores at Baseline

C3Logix Module Correlations									
	Sympt. Severity	**SAC**	**Balance**	**Trails A**	**Trails B**	**Proc. Speed**	**Simple RT**	**Choice RT**	**Visual Acu.**
Symptom Severity	1.00	-.04	.48**	-.04	.15	-.04	-.14	.17	.25
SAC	--	1.00	-.07	-.31	-.46**	.29	.08	.25	.28
Balance	--	--	1.00	.11	.16	-.28	.21	.20	.20
Trails A	--	--	--	1.00	.62**	-.48**	.20	.18	-.23
Trails B	--	--	--	--	1.00	-.63**	.08	-.00	-.25
Processing Speed	--	--	--	--	--	1.00	-.26	-.09	.07
Simple RT	--	--	--	--	--	--	1.00	.38*	-.02
Choice RT	--	--	--	--	--	--	--	1.00	.01
Visual Acuity	--	--	--	--	--	--	--	--	1.00

Notes. SAC = Standard Assessment of Concussion Memory; RT = Reaction Time; Sympt. = Symptom; Proc. = Processing; Acu. = Acuity; * $p \leq 0.05$ level (2-tailed), ** $p \leq 0.01$ level (2-tailed)

Research Question 2. ImPACT composite scores

What is the level of agreement between composite scores on the Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT) battery at baseline? Because the modules on ImPACT also measure the areas most commonly affected by concussion (e.g., reaction time, memory, processing speed), it was hypothesized that the composite scores would be significantly correlated with each other. To test these hypotheses, a correlation matrix was computed for the ImPACT composites using a Spearman's *rho* two-tailed test (see Table 14).

Table 14

Correlation (r_s) between ImPACT Composite Scores at Baseline

ImPACT Composite Correlations							
	Verbal Mem.	**Visual Mem.**	**Visual Motor Speed**	**Reaction Time**	**Impulse Control**	**Total Sympt.**	**CEI**
Verbal Memory	1.00	.59**	.54**	-.37*	-.18	-.32	.79**
Visual Memory	--	1.00	.51**	-.36*	-.23	-.40*	.56**
Visual Motor Speed	--	--	1.00	-.58**	-.12	-.34*	.80**
Reaction Time	--	--	--	1.00	-.03	.15	-.62**
Impulse Control	--	--	--	--	1.00	.01	-.14
Total Symptom Score	--	--	--	--	--	1.00	-.35*
Cognitive Efficiency Index	--	--	--	--	--	--	1.00

Notes. Mem. = Memory; Sympt. = Symptom; CEI = Cognitive Efficiency Index; * $p \leq 0.05$ level (2-tailed), ** $p \leq 0.01$ level (2-tailed)

As expected, results indicated a significant correlation ($p \leq .01$) between Verbal Memory and Visual Memory. Verbal Memory was also significantly correlated ($p \leq .01$) with Visual Motor Speed and the Cognitive Efficiency Index (CEI). Verbal Memory was significantly correlated at the $p \leq .05$ level with Reaction Time. Similarly, Visual Memory was also significantly correlated ($p \leq .01$) with Visual Motor Speed and CEI, and then correlated with Reaction Time at $p \leq .05$. Additionally, Visual Memory significantly correlated ($p \leq .05$) with Total Symptom Score. Visual Motor Speed was significantly correlated ($p \leq .01$) with Reaction Time and CEI, in addition to the Total Symptom Score ($p \leq .05$). The Total Symptom Score is also significantly correlated ($p \leq .05$) to CEI. Reaction Time and CEI are correlated to each other ($p \leq .01$), in addition to most of the other composites. Reaction Time is significantly correlated to all except Total Symptom Score and Impulse Control. CEI is significantly correlated to all except Impulse Control. Notably, the Impulse Control composite did not correlate with any other composite.

Research Question 3. C3Logix and ImPACT

What is the level of agreement in the scores obtained with C3Logix and ImPACT at baseline? In order to test the hypothesis that C3Logix module scores (Symptom Severity, SAC Memory, Processing Speed, Simple RT, Choice RT, Trails A, Trails B) will be significantly and directly associated with ImPACT composite scores (Total Symptom, Verbal Memory, Visual Memory, Visual Motor Speed, Cognitive Efficiency, Reaction Time, Impulse Control), a Spearman's *rho* one-tailed correlational matrix was created to see if there was a relationship between these variables. Data are presented in Table 15 with scores shaded according to hypothesized overlap based on the construct measured. The particular constructs were previously summarized by their specific test composite/module on ImPACT or C3Logix in Table 7. Notably, Impulse Control (ImPACT) did not correlate with any of the C3Logix variables and Visual Acuity (C3Logix) was significantly correlated ($p \leq .05$) only with Reaction Time (ImPACT). The original hypothesized associated scores for impulse control are shaded orange on Table 15.

Symptom Reporting. As expected, Symptom Severity (C3Logix) and Total Symptom Score (ImPACT) were significantly correlated ($p \leq .01$). Symptom Severity (C3Logix) also was significantly correlated ($p \leq .05$) with Verbal Memory (ImPACT) and Visual Memory (ImPACT). Total Symptom Score (ImPACT) also was significantly correlated ($p \leq .01$) with

Balance (C3Logix). The original hypothesized associated scores for symptom reporting are shaded yellow on Table 15.

Memory. SAC (C3Logix) was significantly correlated ($p \leq .05$) with Verbal Memory (ImPACT), as expected, but it was not correlated with Visual Memory. SAC was also significantly correlated with the CEI ($p \leq .05$; ImPACT) and Visual Motor Speed ($p \leq .01$; ImPACT). Verbal Memory (ImPACT) was significantly correlated ($p \leq .01$) with Trails A, Trails B, and Processing Speed (C3Logix). On Visual Memory (ImPACT), there was a significant correlation ($p \leq .05$) with Balance and Trails B (C3Logix). Additionally, Visual Memory (ImPACT) was correlated with Trails A and Processing Speed (C3Logix). The original hypothesized associated scores for memory are shaded blue on Table 15.

Reaction Time. Reaction Time (ImPACT) was significantly correlated ($p \leq .01$) with CRT (C3Logix), but not with SRT. Notably, Reaction Time as measured by ImPACT was significantly correlated ($p \leq .01$) with Balance and Processing Speed (C3Logix) as well. Additionally, it was significantly correlated ($p \leq .05$) with Trails A (C3Logix). SRT (C3Logix) was only significantly correlated ($p \leq .05$) with Visual Motor Speed (ImPACT). Similarly, CRT (C3Logix) also was significantly correlated ($p \leq .05$) with Visual Motor Speed. The original hypothesized associated scores for reaction time are shaded pink on Table 15.

Processing/Motor Speed. As expected, Processing Speed (C3Logix), Visual Motor Speed (ImPACT), and CEI (ImPACT) were significantly correlated ($p \leq .01$). Visual Motor Speed (ImPACT) was also significantly correlated ($p \leq .05$) with Balance (C3Logix), and with Trails A and Trails B ($p \leq .01$; C3Logix). Similarly, CEI (ImPACT) was also significantly correlated ($p \leq .01$) with Trails A and Trails B (C3Logix). The original hypothesized associated scores for processing/motor speed are shaded green on Table 15.

Table 15

Correlation (r_s) between C3Logix Module Scores and ImPACT Composites Scores at Baseline

C3Logix & ImPACT Correlations							
	ImPACT Verbal Memory	**ImPACT Visual Memory**	**ImPACT Visual Motor Speed**	**ImPACT Reaction Time**	**ImPACT Impulse Control**	**ImPACT Total Symptom Score**	**ImPACT CEI**
C3Logix Symptom Severity	-.29*	-.30*	-.11	.07	-.12	.63**	-.16
C3Logix SAC	.32*	.22	.43**	-.04	-.07	-.22	.33*
C3Logix Balance	-.23	-.32*	-.30*	.45**	-.13	.45**	-.27
C3Logix Trails A	-.51**	-.42**	-.65**	.37*	.00	.12	-.55**
C3Logix Trails B	-.58**	-.34*	-.55**	.23	.05	.05	-.48**
C3Logix Processing Speed	.60**	.53**	.65**	-.44**	-.24	-.09	.60**
C3Logix Simple RT	-.11	-.23	-.30*	.24	.04	.18	-.20
C3Logix Choice RT	-.08	-.21	-.31*	.42**	-.20	.20	-.24
C3Logix Visual Acuity	-.01	-.17	.07	.35*	.03	.06	.05

Notes. SAC = Standard Assessment of Concussion Memory; RT = Reaction Time; CEI = Cognitive Efficiency Index; * $p \leq 0.05$ level (2-tailed), ** $p \leq 0.01$ level (2-tailed), Yellow Shading = hypothesized associated scores for Symptom Reporting, Blue Shading = hypothesized associated scores for Memory, Green Shading = hypothesized associated scores for Processing/Motor Speed, Orange Shading = hypothesized associated scores for Impulse Control, Pink Shading = hypothesized associated scores for Reaction Time

Research Question 4. Sex differences at baseline

Are there sex differences at baseline for C3Logix module and ImPACT composite scores?

This was investigated in order to gain a better understanding of the performance between sexes.

Based on previous research, it was hypothesized that female athletes would report more symptoms on the graded symptom checklists and would perform higher on tests of verbal memory and processing speed as compared to males. Additionally, it was hypothesized that male athletes would perform better in visual memory and reaction time activities compared to females. These particular constructs were previously summarized by their specific test composite/module on ImPACT or C3Logix in Table 7.

In order to test these hypotheses and compare means of males and females across the seven module scores of C3Logix and seven composite scores of ImPACT, a Multivariate Analysis of Variance (MANOVA) was used to determine if there was a significant difference in scores at baseline. Wilks' Lambda revealed a significant multivariate effect of sex on performance at baseline for C3Logix and ImPACT ($F(14, 20) = 2.66$, $p = .02$, Partial $\eta^2 = .65$). See Table 16.

Table 16

Multivariate Effects of Sex on Baseline ImPACT and C3Logix

ImPACT & C3Logix Performance						
Variable	**Wilks' *Λ***	***F***	***h***	***p***	**Partial *η*²**	**Observed Power**
Sex	.35	2.66	14	.02	.65	.89

Notes. *Λ* = Lambda; *F* = *F* Ratio Statistic; *h* = Hypothesis Degrees of Freedom; *η* = Eta

Subsequent univariate analyses revealed a significant difference on the C3Logix SAC ($p = .004$, Partial $\eta^2 = .23$), Trails A ($p = .01$, Partial $\eta^2 = .19$), Trails B ($p = .01$, Partial $\eta^2 = .22$), and Processing Speed ($p = .01$, Partial $\eta^2 = .22$) modules between the sexes, with female athletes performing better than males in each. There were no significant differences found for any ImPACT composite scores (see Table 17).

Consistent with previous findings, the mean score for female athletes on tests of processing speed (i.e., C3Logix Processing Speed, ImPACT Visual Motor Speed, and ImPACT CEI) was higher compared to males; however, there was only a statistically significant difference with C3Logix. Similarly, females performed better with higher average scores on tests of verbal memory (i.e., C3Logix SAC and ImPACT Verbal Memory), yet once again, the only statistically significant difference was found on C3Logix. Male athletes demonstrated a better reaction time on C3Logix modules (i.e. Simple RT and Choice RT), though not to a statistically significant degree. There were no significant differences found on visual memory tests (i.e. ImPACT Visual Memory). Surprisingly, male athletes reported more symptoms on the graded symptom checklists (i.e., ImPACT Total Symptom Score and C3Logix Symptom Severity) compared to females, yet once again, not to a statistically significant degree.

Table 17

Univariate Effects of Sex on Baseline ImPACT and C3Logix

ImPACT & C3Logix Performance						
Composite/Module	***F***	***p***	**Partial η^2**	**Observed Power**	**Males**	**Females**
ImPACT Verbal Memory	3.92	.06	.11	.49	80.61 (13.14)	88.83 (7.94)
ImPACT Visual Memory	.29	.59	.01	.08	69.39 (17.75)	72.67 (15.56)
ImPACT Visual Motor Speed	3.55	.07	.10	.45	37.35 (8.91)	42.72 (5.78)
ImPACT Reaction Time	.09	.76	.00	.06	.60 (.06)	.59 (.07)
ImPACT Impulse Control	.01	.94	.00	.05	6.52 (4.32)	6.42 (3.94)
ImPACT Total Symptom	1.01	.32	.03	.16	4.83 (9.25)	2.00 (3.98)
ImPACT CEI	3.47	.07	.10	.44	.29 (.14)	.37 (.10)
C3Logix Symptom Severity	1.16	.29	.03	.18	4.00 (6.45)	1.92 (2.31)
C3Logix SAC	9.62	.004	.23	.85	26.13 (2.34)	28.33 (.99)
C3Logix Trails A	7.67	.01	.19	.77	23.76 (6.93)	17.59 (4.63)
C3Logix Trails B	9.06	.01	.22	.83	50.48 (18.47)	33.98 (5.27)
C3Logix Processing Speed	9.27	.01	.22	.84	58.00 (16.53)	75.50 (15.34)
C3Logix Simple RT	1.11	.30	.03	.18	274.74 (24.90)	285.75 (36.69)
C3Logix Choice RT	.38	.54	.01	.09	416.52 (63.22)	430.75 (67.20)

Notes. F = F Ratio Statistic; η = Eta; CEI = Cognitive Efficiency Index; SAC = Standard Assessment of Concussion Memory; RT = Reaction Time

Table 18

Nonparametric Effects of Sex on Baseline ImPACT and C3Logix

ImPACT & C3Logix Performance					
Composite/Module	**Kruskal-Wallis *H***	***df***	***p***	**Sex**	**Mean Rank**
ImPACT Verbal Memory	5.04	1	.03	Male Female	16.06 24.42
ImPACT Visual Memory	.35	1	.56	Male Female	18.23 20.42
ImPACT Visual Motor Speed	4.02	1	.05	Male Female	16.38 23.85
ImPACT Reaction Time	.06	1	.81	Male Female	19.31 18.42
ImPACT Impulse Control	.05	1	.82	Male Female	19.29 18.46
ImPACT Total Symptom	.02	1	.90	Male Female	19.15 18.73
ImPACT CEI	3.35	1	.07	Male Female	16.60 23.42
C3Logix Symptom Severity	.08	1	.78	Male Female	20.63 21.71
C3Logix SAC	12.16	1	< .001	Male Female	16.39 29.89
C3Logix Trails A	8.10	1	.004	Male Female	24.83 13.61
C3Logix Trails B	12.57	1	< .001	Male Female	25.31 11.57
C3Logix Processing Speed	8.67	1	.003	Male Female	17.04 28.64
C3Logix Simple RT	.17	1	.68	Male Female	20.44 22.07
C3Logix Choice RT	.04	1	.84	Male Female	20.44 21.04

Notes. *df* = Degrees of Freedom; CEI = Cognitive Efficiency Index; SAC = Standard Assessment of Concussion Memory; RT = Reaction Time

Because the data were not normally distributed, the decision was made to run a Nonparametric Kruskal-Wallis test in the event there were any differences found. The Kruskal-Wallis test indicated very similar findings to the Wilks' Lambda (MANOVA), with the same C3Logix scores (SAC [p = < .001], Trails A [p = .004], Trails B [p = < .001], and Processing Speed [p = .003]) found as significant. In contrast with Kruskal-Wallis, though, it was revealed that female athletes also performed better to a statistically significant degree on ImPACT Verbal Memory (p = .03) and Visual Motor Speed (p = .05), lining up with the original hypothesis. The results are presented in Table 18.

Research Question 5. Sex differences in baseline and post-injury symptom severity

Are there sex differences in the C3Logix baseline and immediate post-injury Symptom Severity? This was investigated in order to better understand the effects of concussions between sexes. It was hypothesized that females would demonstrate greater differences overall between baseline and post-injury Symptom Severity scores compared to males.

In order to test these hypotheses and compare means of Symptom Severity for males and females at different time points (i.e., baseline and post-injury [follow-up #1]), a Multivariate Analysis of Variance (MANOVA) was used to determine if there was a significant difference. Although a significant difference was found between the sexes at baseline, as discussed in Research Question #4, the investigator opted not to use covariates given spurious results at actual baseline testing. Wilks' Lambda did not reveal a significant effect of sex on Symptom Severity scores across time points ($F(2, 38) = 1.01$, $p = .37$, Partial $\eta^2 = .05$). Results are presented in Table 19. Univariate data are presented in Table 20.

Table 19

Multivariate Effects of Sex on Baseline and Post-Injury C3Logix

C3Logix Baseline & Post-Injury Performance						
Variable	**Wilks' Λ**	***F***	***h***	***P***	**Partial η^2**	**Observed Power**
Sex	.95	1.01	2	.37	.05	.21

Notes. Λ = Lambda; *F* = *F* Ratio Statistic; *h* = Hypothesis Degrees of Freedom; η = Eta

Table 20

Univariate Effects of Sex on Baseline and Post-Injury C3Logix

Performance Between Sexes						
Assessment Time Point	***F***	***p***	**Partial η^2**	**Observed Power**	**Males**	**Females**
C3Logix Symptom Severity *Baseline*	1.01	.32	.03	.17	4.19 (6.55)	2.36 (2.41)
C3Logix Symptom Severity *Follow-Up #1*	.93	.34	.02	.16	39.41 (21.71)	32.57 (21.33)

Notes. *F* = *F* Ratio Statistic; η = Eta

These results for this University sample are inconsistent with the previous literature indicating that females demonstrate greater differences in Symptom Severity scores at the time of concussion compared to males. As was seen in Research Question 4 with baseline scores, on average males reported higher symptoms on immediate follow-up, though not to a statistically significant degree.

Once again these data were investigated using the Nonparametric Kruskal-Wallis test, due to the lack of normality of the sample. As observed with Wilks' Lambda (MANOVA), there was no significant relationship found between sex and the symptom scores across different time points. These results are presented in Table 21.

Table 21

Nonparametric Effects of Sex on Baseline and Post-Injury C3Logix

Performance Between Sexes					
Assessment Time Point	**Kruskal-Wallis *H***	***df***	***p***	**Sex**	**Mean Rank**
C3Logix Symptom Severity *Baseline*	.08	1	.78	Male Female	20.63 21.71
C3Logix Symptom Severity *Follow-Up #1*	1.72	1	.19	Male Female	23.35 18.17

Note. *df* = Degrees of Freedom

Research Question 6. Recovery time

What is the average number of days it takes for an athlete to recover back to baseline with C3Logix? Based on past results and consensus, it was hypothesized that overall, student-athletes would be back to baseline within 3-10 days. Furthermore, it was hypothesized that it would take females a greater number of days on average to recover to baseline compared to males. This was examined through a review of the descriptive statistics (e.g., mean, median, mode, range), and the average number of days between the first and last C3Logix follow-up was determined. The data are presented in Table 22. The mean number of days between the first and last C3Logix follow-up assessment was 9.19 (SD = 8.59) for males and 11.07 (SD = 8.41) for females. In general, males recovered back to baseline within the 3-10 day time frame. Females typically took one extra day outside of that 3-10 day time frame, and they also took two extra days to recover back to baseline on average compared to males. Visual analysis of the trajectory also was conducted. See Figures 5 through 8 in the Appendix for examples. For the 19 athletes who had ImPACT follow-up assessments, limited data was found. There was a maximum number of two follow-up ImPACT assessments, which typically occurred toward the end of the recovery period. As a result, ImPACT follow-up data was not included in these analyses.

Table 22

Means and Standard Deviations for Athlete Recovery Time

Athlete Characteristics			
Variable	**Total** **(*N* = 42)**	**Males** **(*n* = 27)**	**Females** **(*n* = 15)**
Recovery Time	9.86 (8.47)	9.19 (8.59)	11.07 (8.41)

Note. Days from first C3Logix follow-up to last follow-up

Research Question 7. Follow-up assessments

What is the average number of follow-up C3Logix assessments until an athlete recovers to baseline? This was investigated through a review of the descriptive statistics and the mean number of follow-ups for each measure was examined. It was hypothesized that females would exhibit a greater average number of follow-up assessments after a concussive injury compared to males. Both males and females were well within the predicted 3-10 follow-up assessments range. Females did present with an average of two more follow-up assessments compared to male athletes. The mean number of total C3Logix follows up was 5.93 (SD = 3.29) for males and 7.47 (SD = 4.12) for females, with a range from 1 to 18 number of C3Logix follow-ups overall. Because there were more ImPACT follow-up assessments than originally predicted, it should also be noted that males had a mean of 1.22 (SD = 0.43) ImPACT follow-ups, but only one female athlete had one ImPACT follow-up. These results are presented in Table 23.

Table 23

Means and Standard Deviations for Total Assessment Follow-Ups

Athlete Characteristics			
Variable	**Total** **(*N* = 42)**	**Males** **(*n* = 27)**	**Females** **(*n* = 15)**
Total Number of C3Logix Follow-Ups	6.48 (3.64)	5.93 (3.29)	7.47 (4.12)
Total Number of ImPACT Follow-Ups	1.21 (0.42)	1.22 (0.43)	1.00 (0.0)

Research Question 8. Symptom severity, sex, and recovery trajectory

Does the C3Logix immediate post-injury Symptom Severity score and/or sex predict the number of follow-up assessments and recovery time? In order to better understand the effect of symptom severity and sex on the recovery process, a linear regression was conducted to investigate whether or not higher C3Logix Symptom Severity scores and sex predict a longer, more intensive recovery. It was hypothesized that athletes with a higher Symptom Severity score at the time of concussion would have more follow-up assessments over a longer time period of time. Moreover, it was hypothesized that females athletes would report higher Symptom Severity scores at the time of concussion and would require more follow-up assessments over a longer time period.

Table 24 presents the means and standard deviations of the C3Logix Symptom Severity scores by sex at the time of concussion (i.e., follow-up assessment #1). Although results from previous literature indicated that female athletes typically report higher symptoms at the time of concussion, it appears that with this particular sample of athletes that is not the case. Male athletes reported an average Symptom Severity score of 39.41 (SD = 21.71) at the time of concussion, whereas females reported a mean score of 30.40 (SD = 22.21). Even at baseline (discussed previously in the descriptive statistics), males demonstrated a higher Symptom Severity score (4.19 [SD = 6.55]), compared to female athletes (2.36 [2.41]).

Table 24

Means and Standard Deviations for Symptom Severity at Time of Injury

Concussion Symptom Severity			
Variable	**Total (*N* = 42)**	**Males (*n* = 27)**	**Females (*n* = 15)**
C3Logix Symptom Severity Score (#1)	36.19 (22.05)	39.41 (21.71)	30.40 (22.21)

Note. Score at first C3Logix follow-up

A linear regression was calculated to predict the total number of C3Logix assessment follow-ups based on Symptom Severity score at the time of concussion (i.e., follow-up #1) and sex. When the number of follow-up assessments was considered as the outcome variable, it was found that both initial Symptom Severity score ($B = .07, p < .01$) and Sex ($B = 2.20, p \leq .05$) were significant predictors. The overall model fit was $R^2 = .23$, (F (2, 39) = 5.80, $p \leq .01$). These results are presented in Table 25.

Table 25

Linear Regression for Total Assessment Follow-Ups

Predicted Number of C3Logix Follow-Ups					
Variable	***B***	***SE B***	***β***	***t***	***p***
Constant	3.06	1.13	--	2.72	.01
Symptom Severity Score (Follow-Up #1)	.07	.02	.44	3.07	<.001
Sex	2.20	1.08	.29	2.04	.05
R	.48	--	--	--	--
R^2	.23	--	--	--	--
F	5.80	--	--	--	.01

Notes. *B* = Unstandardized Beta; *SE B* = Standard Error for the Unstandardized Beta; *β* = Standardized Beta; *t* = *t* Test Statistic; *p* = probability value; *R* = Regression Coefficient; *F* = *F* Ratio Statistic

Based on the results discussed in Research Question 7 (Table 23) regarding the number of C3Logix follow-up assessments for each sex, with females presenting with an average of two more follow-up assessments compared to male athletes, it was not surprising that sex served as a significant predictor for the number of follow-up assessments.

Additionally, another linear regression was calculated to predict the number of days it takes for an athlete to recover back to baseline with C3Logix (i.e., the number of days from the first C3Logix follow-up to last follow-up). When the number of recovery days was the outcome variable, it was found that neither initial Symptom Severity score (*B* = .11, *p* = .10) nor Sex (*B* =

2.88, p =.07) were significant predictors. The overall model fit was $R^2 = .09$, (F (2, 39) = 1.97, p < .15). This suggests that there are many other factors that might be affecting an athlete's time to recovery. The results are presented in Table 26.

It was unexpected that sex did not appear to be a significant predictor for days of recovery in terms of the linear regression, seeing as females took approximately two extra days to recover back to baseline on average compared to males, as was discussed in Research Question 6 (Table 22). Evidently, this was not a statistically significant amount of time.

Table 26

Linear Regression for Athlete Recovery Time

Predicted Number of Recovery Days					
Variable	***B***	***SE B***	**β**	***t***	***p***
Constant	4.82	2.84	--	1.69	.10
Symptom Severity Score (Follow-Up #1)	.11	.06	.29	1.85	.07
Sex	2.88	2.72	.17	1.06	.30
R	.30	--	--	--	--
R^2	.09	--	--	--	--
F	1.97	--	--	--	.15

Notes. B = Unstandardized Beta; $SE\ B$ = Standard Error for the Unstandardized Beta; β = Standardized Beta; t = t Test Statistic; p = probability value; R = Regression Coefficient; F = F Ratio Statistic

CHAPTER V

DISCUSSION

Concussions within the realm of sports have been a hot-button topic in recent years, and there has been a discrepancy between the increased media exposure on the subject and empirical research to back up the concerns. This has resulted in an increase of public fear regarding the implications for youth and young adult athletes, whose brains are still developing and more vulnerable (Davis & Purcell, 2014; Karlin, 2011; Purcell, Harvey, & Seabrook, 2016). Additionally, questions have arisen based off concerns with certain populations that appear to take longer to recover (e.g., females; Broshek et al., 2005; Kostyun & Hafeez, 2015).

Nevertheless, major sports organizations have made great strides establishing standards and guidelines for RTP and RTL, with neuropsychological assessment emerging as an important piece of the concussion management and recovery process. As a result, there has been an upsurge in the number of neurocognitive measures available on the market and adopted into clinical practice in recent years, with a shift to a more efficient, computerized approach to testing (Echemendia, & Bauer, 2015; Guay et al., 2016; Resch, McCrea, & Cullum, 2013). Yet, the number of clinical studies published on these new assessments has not followed the same trajectory, and there is little information available in regards to the psychometric properties of these measures, leaving professionals at a disadvantage when interpreting results (Echemendia, & Bauer, 2015).

The purpose of this study was to investigate the utility of a newer, computerized neuropsychological assessment (C3Logix), as well as to contribute to the limited literature regarding concussion recovery in young adults, with a focus on sex differences in the recovery process.

Psychometric Properties of C3Logix and ImPACT

One aim of this study was to better understand the relationship between the areas of functioning affected by a concussion, as measured by two different instruments. Based on previous research, it is known that athletes with concussions often experience sensory, motor, and cognitive deficits in reaction time, memory, attention, and processing speed (Ellis, Leddy, & Willer, 2016; Harmon et al., 2013; Purcell, 2014). Because both ImPACT and C3Logix measure these areas most commonly affected by concussion, it was hypothesized that the various module scores for C3Logix would be significantly correlated with each other, and that the composite scores on ImPACT would also be significantly correlated with each other.

C3Logix. For C3Logix, there was a relationship between those athletes who struggled with balance at baseline and who reported more symptoms on the graded symptom checklist. Unsurprisingly, modules like SRT and CRT, which both measure visual-motor response speed and impulse control/response inhibition, were significantly correlated with one another. Furthermore, Trails A and Trails B, which both look at set shifting, psychomotor speed, visual attention, and visual-spatial scanning, also confirmed a significant correlation with each other. The Processing Speed module, which utilizes cognitive efficiency and visual-spatial scanning, demonstrated a significant relationship with Trails A and Trails B, highlighting the importance of that visual-spatial domain. Yet interestingly, the module looking at static and dynamic vision with the vestibulo-oculomotor reflex, Visual Acuity, did not correlate with any other module. In regards to memory, SAC revealed an association with Trails B. These results add to the current information from Simon and colleagues' (2017) study, which found acceptable concurrent validity with standard (comparable) paper-and-pencil measures for Trails A, Trails B, and Processing Speed (i.e., Symbol-Digit Modalities Test).

ImPACT. On ImPACT, scores confirmed a significant relationship between Verbal Memory and Visual Memory. Verbal Memory was also significantly correlated with Visual Motor Speed and Reaction Time, similar to what was seen with SAC (a verbal memory measure) and Trails B on C3Logix. Visual Memory exhibited a comparable pattern of relationship with Visual Motor Speed and Reaction Time, but with the addition of Total Symptoms from the graded concussion severity checklist. Visual Motor Speed was also significantly correlated with Reaction Time and Total Symptoms, once again highlighting the importance of the visual aspect in these tasks. Although CEI only takes information from the Symbol Match subtest (an activity which highlights an individual's visual memory and visual processing speed), CEI was significantly correlated with all other composites except for Impulse Control. Impulse Control did not demonstrate a relationship with any other composite. These results are consistent with those found by Maerlender et al. (2010), where Processing Speed and Reaction Time measures were inter-correlated and significant correlations were found between traditional pencil-and-paper neuropsychological testing domains and all ImPACT composite scores except for the Impulse Control factor.

Convergent Validity. Within the individual C3Logix and ImPACT measures, similar patterns and interactions were displayed between scores representing specific cognitive domains, highlighting the importance of memory, visual motor speed, reaction time, and processing speed. Therefore, one could assume that there would be an association between the two tests, especially seeing as many of the tasks on both ImPACT and C3Logix were developed based on long-standing traditional neurocognitive tests. It was hypothesized that C3Logix module scores would be significantly and directly associated with ImPACT composite scores.

Notably, the two areas that did not correlate to other domains on the individual measures, Impulse Control (ImPACT) and Visual Acuity (C3Logix), also demonstrated little to no association between the measures. Impulse Control (ImPACT) did not correlate with any of the C3Logix variables, and Visual Acuity (C3Logix) only exhibited a relationship with Reaction Time (ImPACT).

Memory. SAC (C3Logix) was significantly correlated with Verbal Memory (ImPACT), as expected, but it was not correlated with Visual Memory. This makes sense as SAC only utilizes verbal memory tasks. SAC was also associated with CEI (i.e., processing speed; ImPACT) and Visual Motor Speed (ImPACT). Similarly, Verbal Memory (ImPACT) was significantly correlated with Trails A, Trails B, and Processing Speed (C3Logix). On Visual Memory (ImPACT), there was a relationship with Trails A, Trails B, and Processing Speed, as well as Balance (C3Logix).

Reaction Time. Reaction Time (ImPACT) was significantly correlated with CRT (C3Logix), but not with SRT. Notably, Reaction Time as measured by ImPACT was also associated with Balance, Trails A, and Processing Speed (C3Logix). Both SRT and CRT (C3Logix) presented a relationship with Visual Motor Speed (ImPACT).

Processing/Motor Speed. As expected, Processing Speed (C3Logix), CEI (ImPACT), and Visual Motor Speed (ImPACT) were significantly correlated. As was seen with Processing Speed on C3Logix individually, CEI (ImPACT) was also correlated with Trails A and Trails B (C3Logix). Visual Motor Speed (ImPACT) demonstrated a relationship with Balance, Trails A, and Trails B (C3Logix).

Symptom Reporting. As expected, Symptom Severity (C3Logix) and Total Symptom Score (ImPACT) were significantly correlated. Symptom Severity (C3Logix) was also associated with Verbal Memory and Visual Memory (ImPACT). As was demonstrated with C3Logix individually, Total Symptom Score (ImPACT) also was significantly correlated with Balance (C3Logix).

Overall, it appears that ImPACT and C3Logix are generally measuring similar domains, and these domains have historically proven to be the most influential areas that are affected by concussion (e.g., memory, processing speed, and so on; Moser et al., 2007). One exception is the Impulse Control composite for ImPACT, which is significant considering that impulse control is an important area of cognitive functioning frequently impacted by a concussion (Ellis, Leddy, & Willer, 2016; Purcell, 2014).

The comparison of pre- and post-injury scores may not only inform a multidisciplinary concussion team about how much a concussion has impacted the functioning of an athlete, but it also aids the process of making critical concussion care decisions, such as RTP and RTL.

Sex Differences

Another goal of the current investigation was to gain a better understanding of the performance between sexes. Previous research has indicated that males and females experience and are impacted by concussions in unique ways. Covassin and Elbin (2011) found that, in general, females tend to perform better neurocognitively on tasks of verbal memory, information processing speed, and perceptual motor speed, whereas males typically perform better in visuospatial, reaction time, and visual memory activities.

The current study revealed a significant multivariate effect of sex on performance at baseline for C3Logix and ImPACT. Specifically, significant differences were found between the sexes on the C3Logix SAC, Trails A, Trails B, and Processing Speed modules and the ImPACT Verbal Memory and Visual Motor Speed composites, with female athletes performing better than males in each. Consistent with previous findings, the mean score for female athletes on tests of processing speed (i.e., C3Logix Processing Speed, ImPACT Visual Motor Speed, and ImPACT CEI) was higher compared to males. Similarly, females performed better with higher average scores on tests of verbal memory (i.e., C3Logix SAC and ImPACT Verbal Memory). Male athletes demonstrated a better reaction time on average for C3Logix modules (i.e. Simple RT and Choice RT), though not to a statistically significant degree. There were no significant differences found on visual memory tests (i.e. ImPACT Visual Memory).

Surprisingly, on average, male athletes reported more symptoms at baseline on the graded symptom checklists (i.e., ImPACT Total Symptom Score and C3Logix Symptom Severity) compared to females, yet not to a statistically significant degree. This is inconsistent with previous findings, which state that females report more symptoms at baseline, even before a concussive injury has occurred (Covassin, Elbin, Harris, Parker, & Kontos, 2012; Zuckerman et al., 2014).

Another aim was to better understand these symptomatic effects of concussions between sexes. It was hypothesized that after a concussion, females would demonstrate greater differences overall between baseline and post-injury C3Logix Symptom Severity scores compared to males. Conversely, a significant effect of sex on Symptom Severity scores across time points (i.e., baseline and post-injury [follow-up #1]) was not found. The results for this University sample are inconsistent with the previous literature indicating that females report greater symptom scores at the time of concussion compared to males (Broshek et al., 2005; Zuckerman et al., 2014).

Recovery Trajectory

In order to better understand recovery after concussive injury, the number of days it took to return back to baseline performance with C3Logix was investigated. Based on past results and consensus (McCrory et al., 2017), it was hypothesized that, overall, student-athletes would be back to baseline within 3-10 days. Furthermore, it was hypothesized that it would take females a greater number of days on average to recover to baseline compared to males. For this sample, the mean number of days between the first and last C3Logix follow-up assessment was about nine days for males and 11 days for females. In general, males recovered back to baseline within the 3-10 day time frame. Females typically took one extra day outside of that 3-10 day time frame, and they took two extra days to recover back to baseline on average compared to males. This is consistent with previous findings stating that females tend to exhibit more prolonged outcomes (Broshek et al., 2005).

Additionally, the number of follow-up C3Logix assessments was examined in order to gain more information on how C3Logix is utilized during this sensitive recovery period. It was hypothesized that, overall, most student-athletes would undergo approximately 3-10 follow-up assessments before he or she recovered back to baseline, based on the previous literature and the University’s serial approach to follow-up. Additionally, because it was expected that females would take a longer number of days to recover, it also was hypothesized that females would exhibit a greater number of follow-up assessments after a concussive injury compared to males.

In general, both males and females were well within the predicted range of 3-10 follow-up assessments. Females did present with two more follow-up assessments compared to male athletes, with about an average of seven follow-up assessments. Males underwent a mean of five follow-ups. Overall, there was a range of 1 to 18 C3Logix follow-up assessments across the 42 athletes.

Predictive Factors. In order to better understand the effect of symptom severity and sex on the recovery process, data were examined to determine whether or not higher C3Logix Symptom Severity scores at the time of the concussive injury and sex predict a longer, more intensive recovery. It was hypothesized that athletes with a higher Symptom Severity score at the time of concussion would have more follow-up assessments over a longer time period of time. Moreover, it was hypothesized that females athletes would report higher Symptom Severity scores at the time of concussion and would require more follow-up assessments over a longer time period.

Although results from previous literature indicated that female athletes typically report higher symptoms at the time of concussion (Broshek et al., 2005; Zuckerman et al., 2014), it appears that with this particular sample of athletes that is not the case. Male athletes reported an average Symptom Severity score of 39 at the time of concussion, whereas females reported a mean score of 30. As discussed previously, even at baseline males demonstrated a higher Symptom Severity score compared to female athletes. This information is important, based off what is known in the previous literature. As Leddy et al. (2016) explained, if the individual suffered from migraines, depression, anxiety, ADHD, or any learning disabilities (i.e., all factors that can contribute to a higher symptom score) before the injury, concussions can exacerbate these conditions, and those conditions in turn can be responsible for ongoing symptoms drawing out recovery.

It was found that both the initial injury Symptom Severity score and sex were significant predictors for the number of follow-up assessments. These results are congruent with the findings in this study that females presented with an average of two more follow-up assessments. Furthermore, the role of initial symptom severity is unsurprising based off the historical criteria for concussion grading scales (Cantu, 2001; Quality Standards Subcommittee of the American Academy of Neurology, 1997).

Conversely, neither initial Symptom Severity score nor sex were significant predictors for the number of recovery days. Although females took approximately two extra days to recover back to baseline on average, this was not a statistically significant amount of time. This suggests that there are many other factors besides sex that might be affecting an athlete's time to recovery.

Implications

The findings of the current study highlight the importance of neuropsychological evaluation in the concussion management and recovery process, while emphasizing and contributing to the literature regarding the significance of the psychometric properties of two commonly used measures: ImPACT and C3Logix. Overall, it appears that the newer C3Logix system is measuring similar domains as the well-established ImPACT system. The domains these assessments are measuring include those that clinicians should consider when working with an individual who has experienced a concussion (e.g., symptoms, memory, reaction time, processing speed).

Neuropsychologists, Athletic Trainers, and others involved in concussion care should utilize their in-depth training in the brain-body relationship and understanding of how concussions impact the whole person, including cognition, sensory-motor, emotion, social, and other aspects of daily functioning (McCrory et al., 2017). Many neuropsychological assessments geared toward concussion evaluation only focus on the neurocognitive piece. C3Logix is unique in its additional assessment of Balance (i.e., postural sway) and Visual Acuity (i.e., oculomotor functioning). While these aspects were not a primary focus of the present investigation, the results that were found demonstrated little to no correlation with the overall C3Logix assessment. As was suggested by Bernstein, Calamia, Pratt, and Mullenix (2018), C3Logix could benefit from including alternative measures of balance and visual acuity, such as tests of balance control or prosaccade/anti-saccade test, which better assess vestibular and oculomotor functioning.

In terms of sex, the current study revealed a significant multivariate effect for sex on performance at baseline for C3Logix and ImPACT, with female athletes performing better than males on the majority of domains. The initial injury Symptom Severity score on C3Logix and the athlete's sex were significant predictors for the number of follow-up assessments completed during recovery.

Given the spurious results at actual baseline testing, the data in the current study also emphasize the importance establishing a valid baseline to be used as a foundation for the concussion management process. Clinicians should emphasize the importance of the baseline assessment and effort given before the athlete begins the evaluation. They should then closely monitor the baseline data and follow-up with any domains that appear impaired even before a concussive injury has happened. This should help decrease the occurrence of "sandbagging" behaviors, or call attention to important clinical characteristics that the provider needs to be aware of in caring for that athlete (e.g., learning disability).

One individual characteristic that is critical and can greatly impact an athletes' performance, even at baseline, is the prior history of concussion. Taking a multidisciplinary approach and gathering detailed background information regarding an athlete's medical, educational, psychosocial, and family history should be equal in priority to the actual neurocognitive and physical assessment. This will help to ensure an individualized approach to concussion care and can reveal or explain outcomes involved with more complex injuries and recovery.

Limitations

One limitation of the current study was the small sample size, as well as certain demographic characteristics (e.g., sex). Out of the 42 athletes included in the study, 27 were male and only 15 were female. The sex distribution of this sample is inconsistent with previous findings that report female athletes experience more concussions than their male counterparts (Kostyun & Hafeez, 2015). The lack of significance found between such variables as sex and symptom severity could be attributable to these unbalanced numbers. Additionally, in order to protect the athletes' identities, demographic information such as race/ethnicity, socioeconomic status, and sport were not available. The sample was also limited geographically, with all of the student-athletes coming from the same southern university.

Because the data was de-identified and no personal interaction was had with the athletes, there was no way to verify history of concussion, which can have a significant impact on an individual's data and recovery trajectory. Another limitation is the validity of the athlete's self-report of symptomatology. Without being able to communicate with the athlete, there was no way to clarify or confirm extreme scores.

Another aspect to be aware of in working with any athletic population is the potential intentions and motivations of the athlete that may drive their effort and honesty on a given assessment. The reported symptomology and trajectories presented here could have been affected by the individual's desire to play.

Moreover, the logistic aspects of this specific Athletic Department could have influenced this sample's results. Each sports team has their own individual Athletic Trainer who administers the measures. These individuals may differ in their approach to the number of follow-up assessments they give or in their approach to RTP or RTL. While all Athletic Trainers at the University received training to administer the ImPACT and C3Logix assessments, it is not known if they are trained to some criterion of accuracy, and there are no indications of inter-rater reliability.

Future Directions

More research is needed about the C3Logix system as a measure, especially in terms of reliability, validity, and specificity. Because the Balance and Visual Acuity aspects are unique to C3Logix, investigations focused on those domains would be beneficial. Furthermore, studies examining the trajectory of other domains besides symptom severity (e.g., processing speed, verbal memory) before and after injury are needed to gain a true understanding of the utility of this measure across the recovery process. Like the preliminary work started by Makwana and Xu (2019), other research is needed comparing C3Logix with both athletes recovering from concussion and also healthy, non-injured control participants. Studies with a larger, more diverse sample population are necessary, and a larger sample size would provide more information on the influence of sex. Control of variables such as sport or concussion history could reduce the effects of potential confounding variables.

CONCLUSION

This study contributed to the current literature regarding the effects of concussion on young adults, sex differences in the recovery process, and psychometric properties of the C3Logix neuropsychological assessment. The newer C3Logix concussion system was compared to the well-established ImPACT system. It was found that C3Logix is measuring similar domains as ImPACT. These domains include those that clinicians should consider when working with an individual who has experienced a concussion (e.g., symptoms, memory, reaction time, processing speed). A significant multivariate effect was revealed for sex on performance at baseline for C3Logix and ImPACT, with female athletes performing better than males on C3Logix SAC, Trails A, Trails B, and Processing Speed modules, and the ImPACT Verbal Memory and Visual Motor Speed composites. The initial injury Symptom Severity score on C3Logix and the athlete's sex were significant predictors for the number of follow-up assessments completed during recovery. Future research involving the C3Logix system should focus on the Balance and Visual Acuity modules, as well as the various domain scores (e.g., reaction time, processing speed) across different time times points in the recovery trajectory.

REFERENCES

Adelson, E. (2017a, June 6). *Setting the record straight on CTE*. Retrieved from https://sports.yahoo.com/setting-record-straight-cte-140859578.html

Adelson, E. (2017b, July 25). *Why the latest round of daunting CTE reports should come with an asterisk*. Retrieved from https://sports.yahoo.com/latest-round-daunting-cte-reports-come-asterisk-013003329.html

Alberts, J.L., & Linder, S.M. (2015). The utilization of biomechanics to understand and manage the acute and long-term effects of concussion. *Kinesiology Review*, *4* (1), 39-51.

American Congress of Rehabilitation Medicine. (1993). Definition of mild traumatic brain injury. *Journal of Head Trauma Rehabilitation*, *8* (3), 86-87.

American Psychiatric Association. (2000). *Diagnostic and statistical manual of mental disorders* (4th ed., text rev.). Washington, DC: Author.

American Psychiatric Association. (2013). *Diagnostic and statistical manual of mental disorders* (5th ed.). Washington, DC: Author.

Asken, B.M., Sullan, M.J., Snyder, A.R., Houck, Z.M., Bryant, V.E., Hizel, L.P., ... & Bauer, R.M. (2016). Factors influencing clinical correlates of chronic traumatic encephalopathy (CTE): a review. *Neuropsychology Review*, *26* (4), 340-363.

Aubry, M., Cantu, R., Dvorak, J., Graf-Baumann, T., Johnston, K., Kelly, J., ... & Schamasch, P. (2002). Summary and agreement statement of the first International Conference on Concussion in Sport, Vienna 2001. *British Journal of Sports Medicine*, *36* (1), 6-7.

Baalen, B.V., Odding, E., Maas, A.I., Ribbers, G.M., Bergen, M.P., & Stam, H.J. (2003). Traumatic brain injury: Classification of initial severity and determination of functional outcome. *Disability and Rehabilitation*, *25* (1), 9-18.

Bailey, C.M. (2017, April). *Neuropsychological management of sports concussion*. Talk presented at the Sports Neuropsychological Society 5th Annual Concussion Symposium, Cleveland, OH.

Bakhos, L.L., Lockhart, G.R., Myers, R., & Linakis, J.G. (2010). Emergency department visits for concussion in young child athletes. *Pediatrics*, *126* (3), 550-556.

Barr, W.B. (2016, April). *CTE debate: Counterpoint*. Talk presented at the Sports Neuropsychological Society 4th Annual Concussion Symposium, Houston, TX.

Barth, J.T., Alves, W.M., Ryan, T.V., Macciocchi, S.N., Rimel, R.W., Jane, J.A., & Nelson, W.E. (1989). Mild head injury in sports: neuropsychological sequelae and recovery of function. In Levin, H.S., Eisenberg, H.M., & Benton, A.L. (Eds.), *Mild Head Injury*, (pp. 257-275). New York, NY: Oxford University Press.

Barth, J.T., Freeman, J.R., Broshek, D.K., & Varney, R.N. (2001). Acceleration-deceleration sport-related concussion: The gravity of it all. *Journal of Athletic Training*, *36* (3), 253-256.

Battista, J. (2016, March 29). New touchback rule: Another step toward eliminating kickoffs? *National Football League Media*. Retrieved from http://www.nfl.com/news/story/0ap3000000648647/article/new-touchback-rule-another-step-toward-eliminating-kickoffs

Bazarian, J.J., Blyth, B., & Cimpello, L. (2006). Bench to bedside: Evidence for brain injury after concussion—looking beyond the computed tomography scan. *Academic Emergency Medicine*, *13* (2), 199-214.

Bernstein, J. P., Calamia, M., Pratt, J., & Mullenix, S. (2018). Assessing the effects of concussion using the C3Logix Test Battery: An exploratory study. *Applied Neuropsychology: Adult*, *26* (3), 275-282.

Bešenski, N. (2002). Traumatic injuries: Imaging of head injuries. *European Radiology*, *12* (6), 1237-1252.

Bey, T., & Ostick, B. (2009). Second impact syndrome. *Western Journal of Emergency Medicine*, *10* (1), 6-10.

Borges, A., Raab, S., & Lininger, M. (2017). A comprehensive instrument for evaluating mild traumatic brain injury (mTBI)/concussion in independent adults: A pilot study. *International Journal of Sports Physical Therapy*, *12* (3), 381-389.

Broshek, D.K., Kaushik, T., Freeman, J.R., Erlanger, D., Webbe, F., & Barth, J.T. (2005). Sex differences in outcome following sports-related concussion. *Journal of Neurosurgery*, *102* (5), 856-863.

Buzzini, S.R.R., & Guskiewicz, K.M. (2006). Sport-related concussion in the young athlete. *Current Opinion in Pediatrics*, *18* (4), 376-382.

Byard, R.W., & Vink, R. (2009). The second impact syndrome. *Forensic Science, Medicine, and Pathology*, *5* (1), 36-38.

Cantu, R.C. (1998). Second-impact syndrome. *Clinics in Sports Medicine*, *17* (1), 37-44.

Cantu, R.C. (2001). Posttraumatic retrograde and anterograde amnesia: Pathophysiology and implications in grading and safe return to play. *Journal of Athletic Training*, *36* (3), 244-248.

Cantu, R.C. & Hyman, M. (2012). *Concussions and our kids*. New York, NY: Houghton Mifflin Harcourt.

Cantu, R.C., Nowinski, C., Robbins, C., & Sports Legacy Institute. (2015). *Safer soccer white paper: The neurological consequences of heading in soccer* [White paper]. Retrieved from http://www.sportslegacy.org/wp-content/uploads/2015/06/Safer-Soccer-White-Paper.pdf

Center for Disease Control and Prevention. (2015). Heads up: What is a concussion? Retrieved from http://www.cdc.gov/headsup/basics/concussion_whatis.html

Concussion in Sport Group. (2017). Sport concussion assessment tool - 5th edition. *British Journal of Sports Medicine*, *51*, 848-850. Retrieved from http://bjsm.bmj.com/content/bjsports/early/2017/04/28/bjsports-2017-097506SCAT5.full.pdf

Cook, R.S., Schweer, L., Shebesta, K.F., Hartjes, K., & Falcone Jr., R.A. (2006). Mild traumatic brain injury in children: Just another bump on the head? *Journal of Trauma Nursing*, *13* (2), 58-65.

Covassin, T., & Elbin, R.J. (2011). The female athlete: The role of sex in the assessment and management of sport-related concussion. *Clinics in Sports Medicine*, *30* (1), 125-131.

Covassin, T., Elbin, R.J., Harris, W., Parker, T., & Kontos, A. (2012). The role of age and sex in symptoms, neurocognitive performance, and postural stability in athletes after concussion. *The American Journal of Sports Medicine*, *40* (6), 1303-1312.

Covassin, T., Elbin, R.J., & Sarmiento, K. (2012). Educating coaches about concussion in sports: Evaluation of the CDC's "Heads Up: Concussion in Youth Sports" initiative. *Journal of School Health*, *82* (5), 233-238.

Cusimano, M.D., Nastis, S., & Zuccaro, L. (2013). Effectiveness of interventions to reduce aggression and injuries among ice hockey players: A systematic review. *Canadian Medical Association Journal*, 185 (1), 57-69.

Dallas Morning News. (2016, January 8). Are sports worth the concussion risk for kids? [Editorial]. *The Dallas Morning News*. Retrieved from https://www.dallasnews.com/opinion/editorials/2016/01/08/editorial-are-sports-worth-the-concussion-risk-for-kids

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.

Davis, G.A., & Purcell, L.K. (2014). The evaluation and management of acute concussion differs in young children. *British Journal of Sports Medicine*, *48* (2), 98-101.

De Beaumont, L., Lassonde, M., Leclerc, S., & Théoret, H. (2007). Long-term and cumulative effects of sports concussion on motor cortex inhibition. *Neurosurgery*, *61* (2), 329-337.

Delaney, J.S., Lacroix, V.J., Leclerc, S., & Johnston, K.M. (2002). Concussions among university football and soccer players. *Clinical Journal of Sport Medicine*, *12* (6), 331-338.

Dennis, K.C. (2009). Current perspectives on traumatic brain injury. *American Speech-Language-Hearing Association*. Retrieved from http://www.asha.org/Articles/Current-Perspectives-on-Traumatic-Brain-Injury/

Echemendia, R.J. (2006). Assessment and management of concussion: A neuropsychological perspective. In Slobounov, S., & Sebastianelli W. (Eds.), *Foundations of Sport-Related Brain Injuries,* (pp. 431-443). New York, NY: Springer Publishing Company.

Echemendia, R.J. (2016, April). *Clinical and ethical considerations in return to play/retirement decisions*. Talk presented at the Sports Neuropsychological Society 4th Annual Concussion Symposium, Houston, TX.

Echemendia, R.J., & Bauer, R.M. (2015). Professional ethics in sports neuropsychology. *Psychological Injury and Law*, *4* (8), 289-299.

Echlin, P.S., Tator, C.H., Cusimano, M.D., Cantu, R.C., Taunton, J.E., Upshur, R.E., ... & Skopelja, E.N. (2010). A prospective study of physician-observed concussions during junior ice hockey: Implications for incidence rates. *Neurosurgical Focus, 29* (5), 1-10.

Ellis, M.J., Leddy, J., & Willer, B. (2016). Multi-disciplinary management of athletes with post-concussion syndrome: An evolving pathophysiological approach. *Frontiers in Neurology*, *7*(136), 1-14.

Emerson, C.S., Headrick, J.P., & Vink, R. (1993). Estrogen improves biochemical and neurologic outcome following traumatic brain injury in male rats, but not in females. *Brain Research*, *608* (1), 95-100.

Erlanger, D., Kaushik, T., Cantu, R.C., Barth, J.T., Broshek, D.K., Freeman, J.R., & Webbe, F.M. (2003). Symptom-based assessment of the severity of a concussion. *Journal of Neurosurgery*, *98* (3), 477-484.

Faul M., Xu L., Wald M.M., Coronado V.G. (2010). *Traumatic brain injury in the United States: Emergency department visits, hospitalizations and deaths 2002–2006*. Atlanta, GA: Centers for Disease Control and Prevention, National Center for Injury Prevention and Control.

Finfer, S.R., & Cohen, J. (2001). Severe traumatic brain injury. *Resuscitation*, *48* (1), 77-90.

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*, *42* (4), 495-503.

Giza, C.C., & Hovda, D.A. (2001). The neurometabolic cascade of concussion. *Journal of Athletic Training*, *36* (3), 228-235.

Giza, C.C., & Hovda, D.A. (2014). The new neurometabolic cascade of concussion. *Neurosurgery*, *75* (4), 1-21.

Gioia, G.A. (2016). Medical-school partnership in guiding return to school following mild traumatic brain injury in youth. *Journal of Child Neurology*, *31* (1), 93-108.

Grady, M.F., Master, C.L., & Gioia, G.A. (2012). Concussion pathophysiology: Rationale for physical and cognitive rest. *Pediatric Annals*, *41* (9), 377-382.

Granito, V.J. (2002). Psychological response to athletic injury: Sex differences. *Journal of Sport Behaviour*, *25* (3), 243-260.

Gregory, S. (September, 2014). The tragic risks of American football. *Time Magazine*, *184* (12), 1-7.

Guay, J.L., Lebretore, B.M., Main, J.M., DeFrangesco, K.E., Taylor, J.L., & Amedoro, S.M. (2016). The era of sport concussion: Evolution of knowledge, practice, and the role of psychology. *American Psychologist*, *71* (9), 875-887.

Guskiewicz, K. (2016, April). *Prevention of concussion in sports*. Talk presented at the Sports Neuropsychological Society 4th Annual Concussion Symposium, Houston, TX.

Guskiewicz, K.M., McCrea, M., Marshall, S.W., Cantu, R.C., Randolph, C., Barr, W., ... & Kelly, J.P. (2003). Cumulative effects associated with recurrent concussion in collegiate football players: The NCAA Concussion Study. *JAMA*, *290* (19), 2549-2555.

Guskiewicz, K.M., & Mihalik, J.P. (2011). Biomechanics of sport concussion: Quest for the elusive injury threshold. *Exercise and Sport Sciences Reviews*, *39* (1), 4-11.

Hainline, B. (2017, April). *Improving sport safety: A public health matter*. Talk presented at the Sports Neuropsychological Society 5th Annual Concussion Symposium, Cleveland, OH.

Halstead, M.E., & Walter, K.D. (2010). Sport-related concussion in children and adolescents. *Pediatrics*, *126* (3), 597-615.

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.

Hootman, J.M., Dick, R., & Agel, J. (2007). Epidemiology of collegiate injuries for 15 sports: Summary and recommendations for injury prevention initiatives. *Journal of Athletic Training*, *42* (2), 311-319.

ImPACT Applications Inc. (2007). *Immediate post-concussion assessment testing (ImPACT) test: Technical manual*. Retrieved from https://www.impacttest.com.

Iverson, G.L., Gardner, A.J., McCrory, P., Zafonte, R., & Castellani, R.J. (2015). A critical review of chronic traumatic encephalopathy. *Neuroscience & Biobehavioral Reviews*, *56*, 276-293.

Iverson, G.L., & Lange, R.T. (2011). Post-concussion syndrome. In Schoenberg, M.R., & Scott, J.G. (Eds.), *The Little Black Book of Neuropsychology,* (pp. 745-763). New York, NY: Springer Publishing Company.

Iverson, G.L., Lovell, M.R., & Collins, M.W. (2005). Validity of ImPACT for measuring processing speed following sports-related concussion. *Journal of Clinical and Experimental Neuropsychology*, *27* (6), 683-689

Johnson, G. (2013, October 23). NCAA announces tighter targeting rules to take effect in upcoming season. *National Collegiate Athletic Association*. Retrieved from http://www.ncaa.com/news/football/article/2013-08-27/ncaa-announces-tighter-targeting-rules-take-effect-upcoming-season

Jotwani, V., & Harmon, K.G. (2010). Postconcussion syndrome in athletes. *Current Sports Medicine Reports*, *9* (1), 21-26.

Karlin, A.M. (2011). Concussion in the pediatric and adolescent population: 'Different population, different concerns'. *PM&R*, *3* (10), 369-379.

Kelly, J.P. (2001). Loss of consciousness: Pathophysiology and implications in grading and safe return to play. *Journal of Athletic Training*, *36* (3), 249-252.

Kelly, J.P., & Rosenberg, J.H. (1997). Diagnosis and management of concussion in sports. *Neurology*, *48* (3), 575-580.

Kieslich, M., Fiedler, A., Heller, C., Kreuz, W., & Jacobi, G. (2002). Minor head injury as cause and co-factor in the aetiology of stroke in childhood: A report of eight cases. *Journal of Neurology, Neurosurgery & Psychiatry*, *73* (1), 13-16.

Kirkwood, M.W., Yeates, K.O., Taylor, H.G., Randolph, C., McCrea, M., & Anderson, V.A. (2008). Management of pediatric mild traumatic brain injury: A neuropsychological review from injury through recovery. *The Clinical Neuropsychologist*, *22* (5), 769-800.

Kontos, A.P., Collins, M., & Russo, S.A. (2004). An introduction to sports concussion for the sport psychology consultant. *Journal of Applied Sport Psychology*, *16* (3), 220-235.

Korioth, T. (2014, May 26). AAP policy: Raise body checking age to 15 to cut concussions among hockey players. *AAP News*. Retrieved from http://www.aappublications.org/content/35/6/22

Kostyun, R.O., & Hafeez, I. (2015). Protracted recovery from a concussion a focus on sex and treatment interventions in an adolescent population. *Sports Health: A Multidisciplinary Approach*, *7* (1), 52-57.

Langlois, J.A., Rutland-Brown, W., & Wald, M.M. (2006). The epidemiology and impact of traumatic brain injury: A brief overview. *The Journal of Head Trauma Rehabilitation*, *21* (5), 375-378.

Lax, I.D., Paniccia, M., Agnihotri, S., Reed, N., Garmaise, E., Azadbakhsh, M., ... & Keightley, M. (2015). Developmental and sex influences on executive function following concussion in youth hockey players. *Brain Injury*, *29* (12), 1409-1419.

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.

Leddy, J.J., Kozlowski, K., Donnelly, J.P., Pendergast, D.R., Epstein, L.H., & Willer, B. (2010). A preliminary study of subsymptom threshold exercise training for refractory post-concussion syndrome. *Clinical Journal of Sport Medicine*, *20* (1), 21-27.

Leddy, J.J., Sandhu, H., Sodhi, V., Baker, J.G., & Willer, B. (2012). Rehabilitation of concussion and post-concussion syndrome. *Sports Health*, *4* (2), 147-154.

Lovell, M.R., & Collins, M.W. (1998). Neuropsychological assessment of the college football player. *Head Trauma Rehabilitation, 13* (2), 9-26.

Luna, B. (2009). Developmental changes in cognitive control through adolescence. *Advances in Child Development and Behavior*, *37*, 233-278.

Lyall, J. (2015, October 3). Rugby world cup 2015: Brain expert warns of concussion "anxiety". Retrieved from http://www.bbc.com/sport/rugby-union/34404888

Maas, A.I., Stocchetti, N., & Bullock, R. (2008). Moderate and severe traumatic brain injury in adults. *The Lancet Neurology*, *7* (8), 728-741.

Maerlender, A., Flashman, L., Kessler, A., Kumbhani, S., Greenwald, R., Tosteson, T., & McAllister, T. (2010). Examination of the construct validity of ImPACT™ computerized test, traditional, and experimental neuropsychological measures. *The Clinical Neuropsychologist*, *24* (8), 1309-1325.

Mahaffey, B.L. (2012). Concussions in high school sports: Are they worth the risk? Should school football be banned? *Missouri Medicine*, *109* (6), 445-449.

Makwana, B. & Xu, X. (2019). C3Logix assessment of neuropsychological performance in athletes and nonathletes. *Applied Neuropsychology: Adult*, 1-7.

Marar, M., McIlvain, N.M., Fields, S.K., & Comstock, R.D. (2012). Epidemiology of concussions among United States high school athletes in 20 sports. *The American Journal of Sports Medicine*, *40* (4), 747-755.

Maroon, J.C., Lovell, M.R., Norwig, J., Podell, K., Powell, J.W., & Hartl, R. (2000). Cerebral concussion in athletes: Evaluation and neuropsychological testing. *Neurosurgery*, *47* (3), 659-672.

Master, C.L., Gioia, G.A., Leddy, J.J., & Grady, M.F. (2012). Importance of 'return-to-learn' in pediatric and adolescent concussion. *Pediatric Annals*, *41* (9), 180-185.

McCrea, M., Hammeke, T., Olsen, G., Leo, P., & Guskiewicz, K. (2004). Unreported concussion in high school football players: Implications for prevention. *Clinical Journal of Sport Medicine*, *14* (1), 13-17.

McCrory, P. (2001). Does second impact syndrome exist? *Clinical Journal of Sport Medicine*, *11* (3), 144-149.

McCrory, P., & Berkovic, S.F. (1998). Second impact syndrome. *Neurology*, *50* (3), 677-683.

McCrory, P., Collie, A., Anderson, V., & Davis, G. (2004). Can we manage sport related concussion in children the same as in adults? *British Journal of Sports Medicine, 38* (5), 516-519.

McCrory, P., Davis, G., & Makdissi, M. (2012). Second impact syndrome or cerebral swelling after sporting head injury. *Current Sports Medicine Reports*, *11* (1), 21-23.

McCrory, P., Johnston, K., Meeuwisse, W., Aubry, M., Cantu, R., Dvorak, J., ... & Schamasch, P. (2005). Summary and agreement statement of the 2nd International Conference on Concussion in Sport, Prague 2004. *British Journal of Sports Medicine*, *39* (1), 78-86.

McCrory, P., Meeuwisse, W. H., Aubry, M., Cantu, B., Dvořák, 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. *British Journal of Sports Medicine*, *47* (5), 250-258.

McCrory, P., Meeuwisse, W.H., Dvořák, J., Aubry, M., Bailes, J., Broglio, S., ... & Davis, G.A. (2017). Consensus statement on concussion in sport: The 5th International Conference on Concussion in Sport held in Berlin, October 2016. *British Journal of Sports Medicine*, *51*, 838-847.

McKee, A.C. (2014, November). *Sports and military TBI: Pathways to neurogeneration*. Talk presented at the 2014 Sydney & J.L. Huffines Institute for Sports Medicine & Human Performance Discussion, College Station, TX.

McKee, A.C., Cantu, R.C., Nowinski, C.J., Hedley-Whyte, E.T., Gavett, B.E., Budson, A.E., ... & Stern, R.A. (2009). Chronic traumatic encephalopathy in athletes: Progressive tauopathy following repetitive head injury. *Journal of Neuropathology and Experimental Neurology*, *68* (7), 709-735.

McKeever, C.K., & Schatz, P. (2003). Current issues in the identification, assessment, and management of concussions in sports-related injuries. *Applied Neuropsychology*, *10* (1), 4-11.

Meehan III, W.P., Mannix, R.C., O'Brien, M.J., & Collins, M.W. (2013). The prevalence of undiagnosed concussions in athletes. *Clinical Journal of Sport Medicine: Official Journal of the Canadian Academy of Sport Medicine*, *23* (5), 339-342.

Merkel, D.L. (2013). Youth sport: Positive and negative impact on young athletes. *Journal of Sports Medicine*, *4*, 151-160.

Moscote-Salazar, L.R., & Satyarthee, G.D. (2016). A sensible approach to pediatric mild traumatic brain injury: New roads and new vistas. *Clinical Pediatrics*, *1* (2), 104.

Moser, R.S., Iverson, G.L., Echemendia, R.J., Lovell, M.R., Schatz, P., Webbe, F.M., ... & Bush, S.S. (2007). Neuropsychological evaluation in the diagnosis and management of sports-related concussion. *Archives of Clinical Neuropsychology*, *22* (8), 909-916.

Nakayama, Y., Covassin, T., Schatz, P., Nogle, S., & Kovan, J. (2014). Examination of the test-retest reliability of a computerized neurocognitive test battery. *The American Journal of Sports Medicine*, *42* (8), 2000-2005.

National Collegiate Athletic Association. (2015). *Concussion safety*. Retrieved from http://www.ncaa.org/health-and-safety/concussion-safety

National Collegiate Athletic Association Sport Science Institute. (2017). I*nterassociation consensus: Diagnosis and management of sport-related concussion best practices*.

Retrieved from http://www.ncaa.org/sites/default/files/SSI_ConcussionBestPractices_20170616.pdf

National Council of Youth Sports. (2008). *Report on trends and participation in organized youth sports*. Stuart, FL: National Council of Youth Sports.

Noble, J.M., & Hesdorffer, D.C. (2013). Sport-related concussions: A review of epidemiology, challenges in diagnosis, and potential risk factors. *Neuropsychology Review*, *23* (4), 273-284.

Nowinski, C. (2013). Hit parade: The future of the sports concussion crisis. *Cerebrum: The Dana Forum on Brain Science, 2,* 1-11.

Oliver, J., Abbas, K., Lightfoot, J. T., Baskin, K., Collins, B., Wier, D., ... & Puschett, J. B. (2015). Comparison of neurocognitive testing and the measurement of marinobufagenin in mild traumatic brain injury: A preliminary report. *Journal of Experimental Neuroscience*, *9*, 67-72.

Omalu, B. (2014). Chronic traumatic encephalopathy. *Concussion*, *28*, 38-49.

Ommaya, A.K., Goldsmith, W., & Thibault, L. (2002). Biomechanics and neuropathology of adult and paediatric head injury. *British Journal of Neurosurgery*, *16* (3), 220-242.

Pardini, J.E., Johnson, E.W., & Lovell, M.R. (2011). Concussion management programs in college and professional sport. In Webbe, F.M. (Ed.), *The Handbook of Sport Neuropsychology*, (pp. 209-233). New York, NY: Springer Publishing Company.

Polites, S.F., Sebastian, A.S., Habermann, E.B., Iqbal, C.W., Stuart, M.J., & Ishitani, M.B. (2014). Youth ice hockey injuries over 16 years at a pediatric trauma center. *Pediatrics*, *133* (6), 1601-1607.

Purcell, L.K. (2014). Sport-related concussion: Evaluation and management. *Paediatrics & Child Health*, *19* (3), 1-9.

Purcell, L., Harvey, J., & Seabrook, J.A. (2016). Patterns of recovery following sport-related concussion in children and adolescents. *Clinical Pediatrics*, *55* (5), 452-458.

Quality Standards Subcommittee of the American Academy of Neurology. (1997). Practice parameter: The management of concussion in sports (summary statement). *Neurology*, *48* (3), 581-585.

Randolph, C. (2011). Baseline neuropsychological testing in managing sport-related concussion: Does it modify risk? *Current Sports Medicine Reports*, *10* (1), 21-26.

Resch, J.E., McCrea, M.A., & Cullum, C.M. (2013). Computerized neurocognitive testing in the management of sport-related concussion: An update. *Neuropsychology Review*, *23* (4), 335-349.

Rose, S.C., McNally, K.A., & Heyer, G.L. (2016). Returning the student to school after concussion: What do clinicians need to know? *Concussion*, *1* (1), 37-47.

Ruff, R.M., & Jamora, C.W. (2009). Myths and mild traumatic brain injury. *Psychological Injury and Law*, *2* (1), 34-42.

Sady, M.D., Vaughan, C.G., & Gioia, G.A. (2011). School and the concussed youth: Recommendations for concussion education and management. *Physical Medicine and Rehabilitation Clinics of North America*, *22* (4), 701-719.

Sarmiento, K., Mitchko, J., Klein, C., & Wong, S. (2010). Evaluation of the Centers for Disease Control and Prevention's concussion initiative for high school coaches: “Heads Up: Concussion in High School Sports”. *Journal of School Health*, *80* (3), 112-118.

Saunders, R.L., & Harbaugh, R.E. (1984). The second impact in catastrophic contact-sports head trauma. *JAMA*, *252* (4), 538-539.

Schatz, P., Moser, R.S., Solomon, G.S., Ott, S.D., & Karpf, R. (2012). Prevalence of invalid computerized baseline neurocognitive test results in high school and collegiate athletes. *Journal of Athletic Training*, *47* (3), 289-296.

Schatz, P., & Putz, B.O. (2006). Cross-validation of measures used for computer-based assessment of concussion. *Applied Neuropsychology*, *13* (3), 151-159.

Shapiro, S.S., & Wilk, M.B. (1965). An analysis of variance test for normality (complete samples). *Biometrika*, *52* (3/4), 591-611.

Simon, M., Maerlender, A., Metzger, K., Decoster, L., Hollingworth, A., & McLeod, T. V. (2017). Reliability and concurrent validity of select C3 Logix test components. *Developmental neuropsychology*, *42* (7-8), 446-459.

Smith, D.H., Meaney, D.F., & Shull, W.H. (2003). Diffuse axonal injury in head trauma. *The Journal of Head Trauma Rehabilitation*, *18* (4), 307-316.

Teasdale, G., & Jennett, B. (1974). Assessment of coma and impaired consciousness: A practical scale. *The Lancet*, *304* (7872), 81-84.

Thomas, D.G. (2012). Acute treatment of concussion. In Apps, J.N., & Walter, K.D. (Eds.), *Pediatric and Adolescent Concussion: Diagnosis, Management, and Outcomes* (pp. 73-80). New York, NY: Springer Publishing Company.

Tierney, R.T., Sitler, M.R., Swanik, C.B., Swanik, K.A., Higgins, M., & Torg, J. (2005). Sex differences in head–neck segment dynamic stabilization during head acceleration. *Medicine & Science in Sports & Exercise*, *37* (2), 272-279.

Tomei, K.L., Doe, C., Prestigiacomo, C.J., & Gandhi, C.D. (2012). Comparative analysis of state-level concussion legislation and review of current practices in concussion. *Neurosurgical Focus*, *33* (6), 1-9.

Wilberger, J., Ortega, J., & Slobounov, S.M. (2006) Concussion mechanisms and pathophysiology. In Slobounov, S.M., & Sebastianelli, W.J. (Eds.), *Foundations of Sport-Related Brain Injuries* (p. 45-64). New York: Springer Science & Business Media.

Willer, B., & Leddy, J.J. (2006). Management of concussion and post-concussion syndrome. *Current Treatment Options in Neurology*, *8* (5), 415-426.

World Health Organization. (2004). *International statistical classification of diseases and related health problems* (10th ed.). Geneva, Switzerland: World Health Organization.

Wortzel, H.S. & Arciniegas, D.B. (2014). The DSM-5 approach to evaluating traumatic brain injury [Powerpoint slides]. *U.S. Department of Veterans Affairs.* Retrieved from https://www.hsrd.research.va.gov/for_researchers/cyber_seminars/archives/882-notes.pdf

Yi, J., Padalino, D.J., Chin, L.S., Montenegro, P., & Cantu, R.C. (2013). Chronic traumatic encephalopathy. *Current Sports Medicine Reports*, *12* (1), 28-32.

Zillmer, E.A., Hong, E., Weidensaul, R., & Westerfer, M. (2011). Concussion management and neuropsychological concerns from the perspective of an athletic department. In Webbe, F.M. (Ed.), *The Handbook of Sport Neuropsychology*, (pp. 295-324). New York, NY: Springer Publishing Company.

Zuckerman, S.L., Apple, R.P., Odom, M.J., Lee, Y.M., Solomon, G.S., & Sills, A.K. (2014). Effect of sex on symptoms and return to baseline in sport-related concussion: Clinical article. *Journal of Neurosurgery: Pediatrics*, *13* (1), 72-81.

APPENDIX

Visual Analyses of Recovery Time by Number of Follow-Up C3Logix Assessments

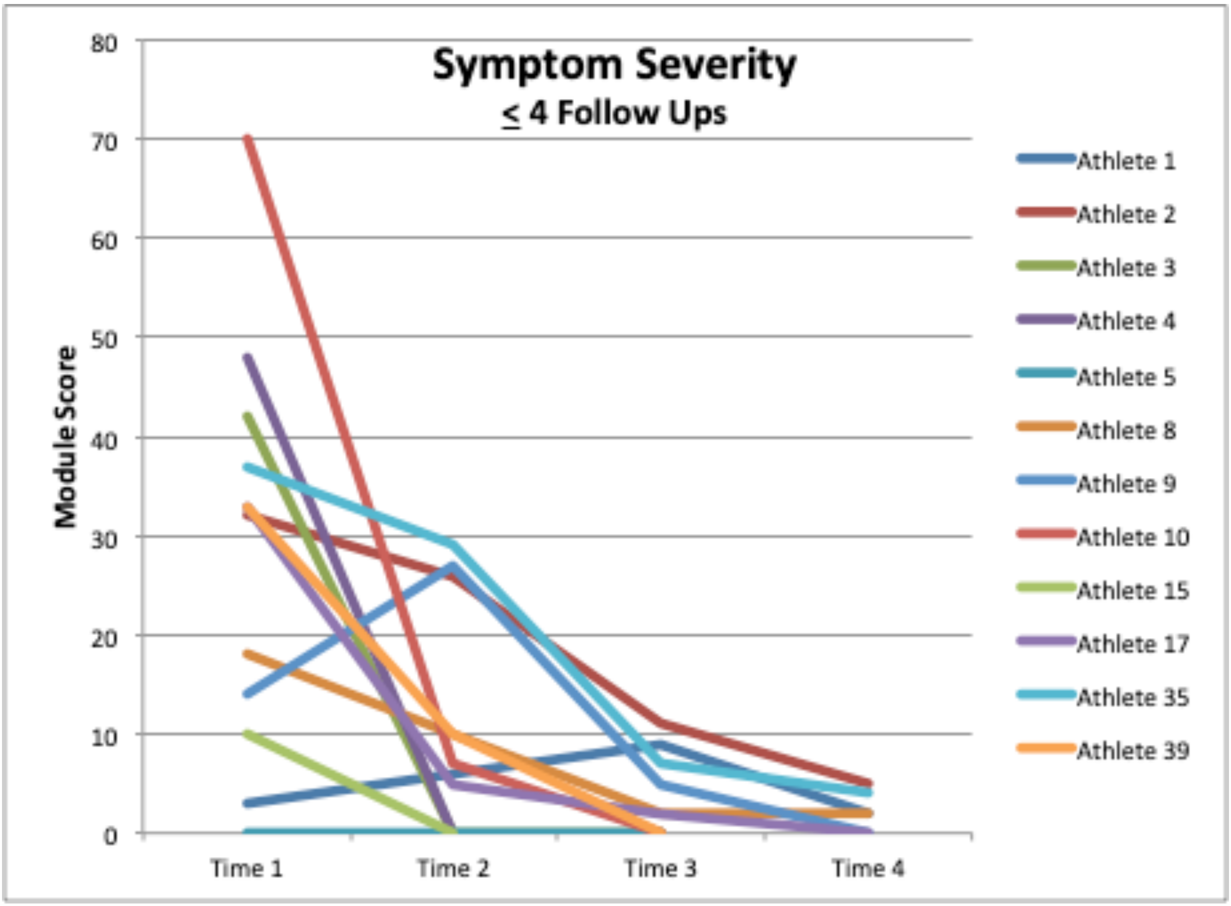

Figure 5. Trajectory of C3Logix symptom severity for athletes with four follow-up assessments or less. Given spurious results at actual baseline testing, scores that would be considered normal baseline were used for plotting the trajectories.

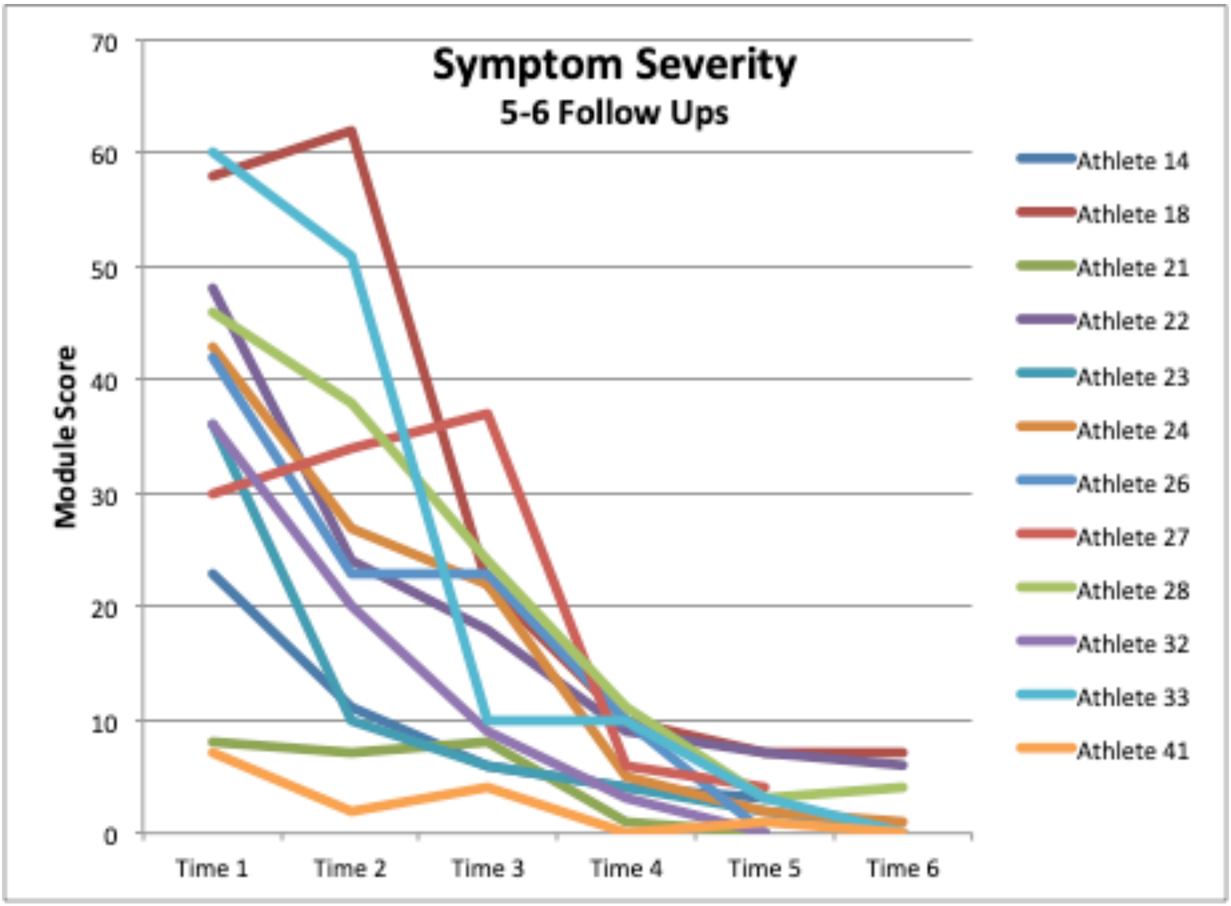

Figure 6. Trajectory of C3Logix symptom severity for athletes with five to six follow-up assessments. Given spurious results at actual baseline testing, scores that would be considered normal baseline were used for plotting the trajectories.

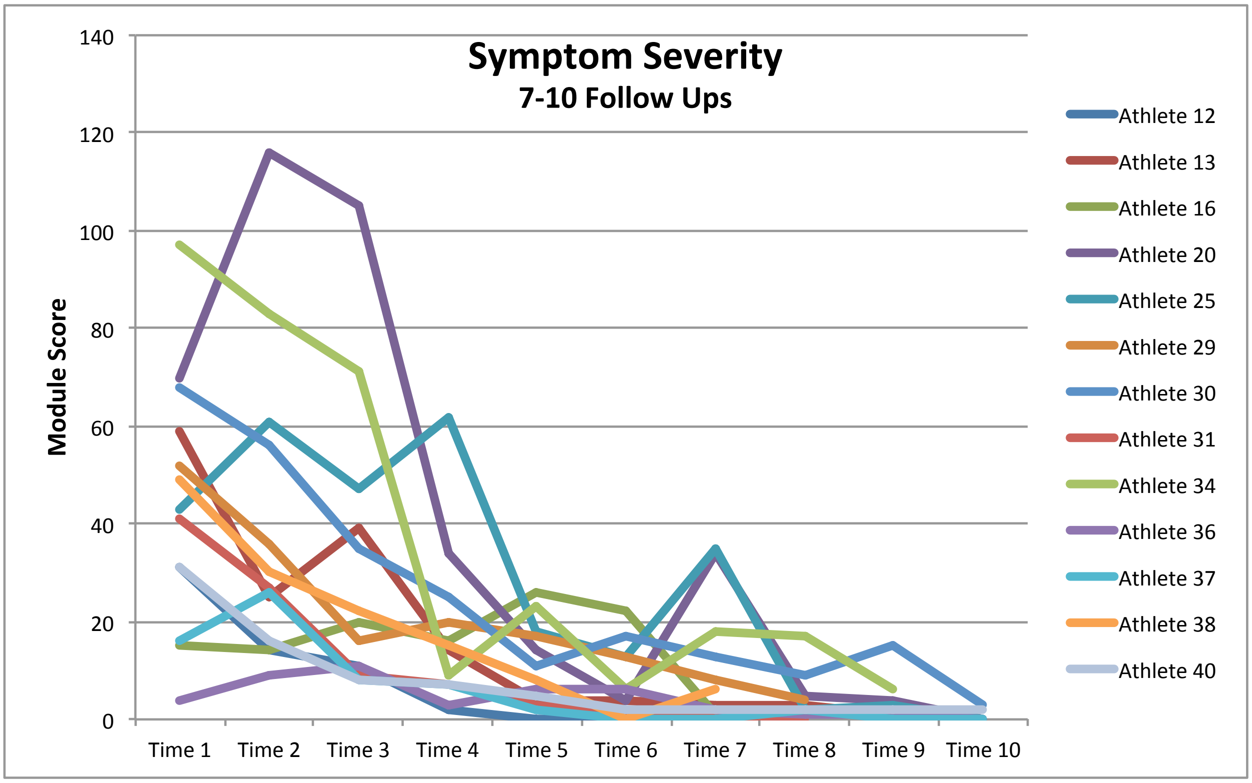

Figure 7. Trajectory of C3Logix symptom severity for athletes with seven to ten follow-up assessments. Given spurious results at actual baseline testing, scores that would be considered normal baseline were used for plotting the trajectories.

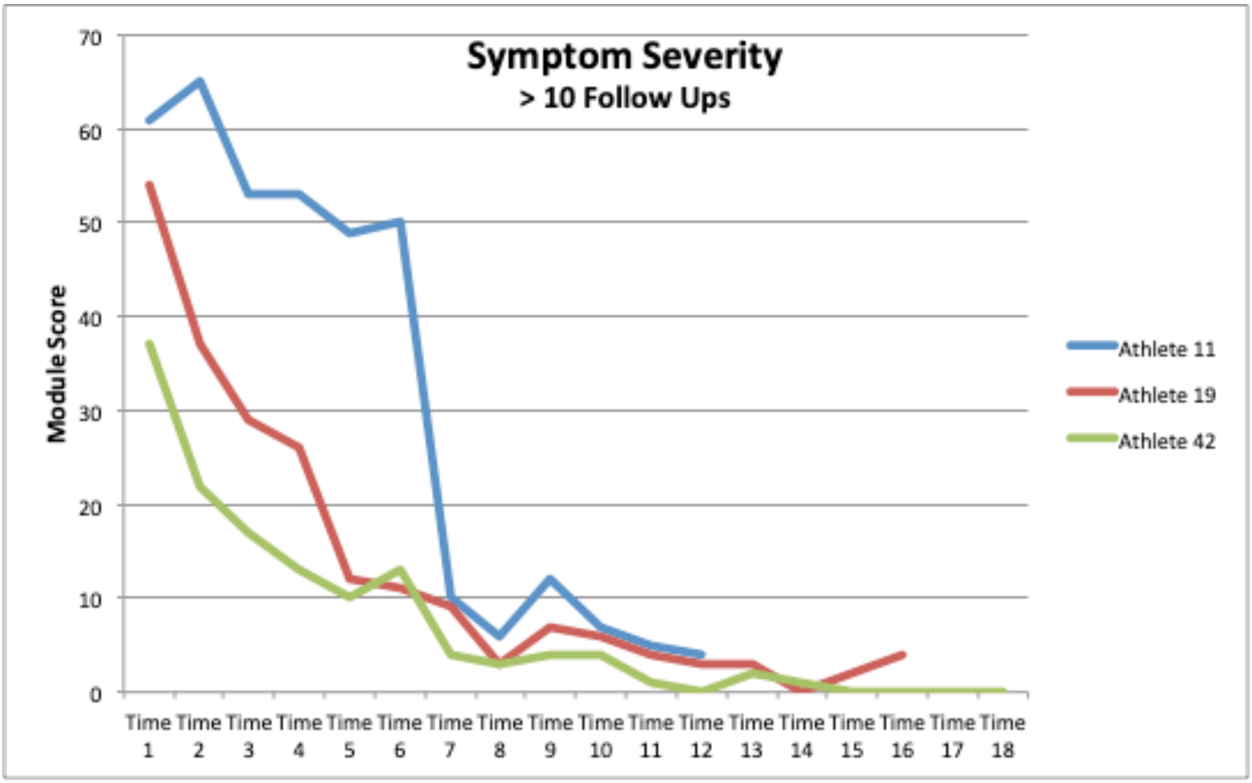

Figure 8. Trajectory of C3Logix symptom severity for athletes with more than ten follow-up assessments. Given spurious results at actual baseline testing, scores that would be considered normal baseline were used for plotting the trajectories.