SPORTS RELATED CONCUSSION AND RETURN TO PLAY TRAJECTORIES IN STUDENT ATHLETES

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Abstract: The United States CDC reported between 1.6 and 3.8 million participants in sports and recreational activities sustain a concussion annually. Sports related concussion (SRC) management requires a blend clinical judgement and an analysis of symptomatology, cognition, and physical performance. This retrospective study examines the relationship between return to play trajectory (RTP_t) and three common clinical measures, symptoms, balance, and reaction time. **Methods: S**tudent athletes (30 males, 39 females)**,** age, $M = 14.2$, $SD = 2.2$ years, medical records were reviewed. Pre-treatment concussion symptom scale (PCSS), balance (mBESS) and simple reaction time (RT) measures were compared to RTP_t. Pearson's coefficients were calculated for independent variables PCSS, mBESS, RT against RTP_t. Male and female differences were assessed through independent t-tests. The alpha was set at $p < .05$. Hedge's *g* calculated the effect size. **Findings** There was a moderate positive association between PCSS and RTP_t, ($r = .323$, $p = .003$), a moderate positive association between time till treatment (TTT) and RTP_t ($r = .471$, $p < .000$) a small negative correlation between mBESS and RTP_t ($r = -.147$, $p = .114$) and a weak negative association between RT and RTP_t ($r = -.023$, $p = .426$). Sex differences for RTP_t, mBESS and RT were not statistically significant. Females on average took almost two weeks longer to recover than males, $M = 13.6$, SD ±10.6, days longer ($p = .202$). A loss of conscious (LOC), accounted for 17.3% of athletes and this group had a longer RTP_t, ($M = 14.5$, SE ±13.9 days) than negative for LOC. These differences were not significant. Sixty-six percent of athletes were positive for visual ocular-motor screen with differences in RTP_t for athletes positive for VOMS were not statistically different to athletes who were negative ($p = .300$). Regression model for PCSS on RTP_t revealed an adjusted R^2 of 9.1% ($p = .009$) and for TTT and PCSS on RTP_t an R^2 of 42.7%, and an adjusted R^2 of 41% ($p < 001$). **Conclusions:** TTT and PCSS have a moderate association with RTP_t in a population of sub-acute and chronic SRCs. PCSS as a predictor of RTP_t indicated a .655-day increase in RTP_t for every 1-point increase in PCSS. There was 1.01-day increase in RTP_t for every 1-day increase in TTT.

Key Words: Return to Play, SRC, mBESS, PCSS, Simple Reaction Time

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CHAPTER I

INTRODUCTION

Concerns regarding Sports Related Concussion (SRC) have evolved in the United States since the emergence of college football in the early 1900's. In a 1903 speech, President Roosevelt defended college football stating; *"I believe in rough games and in rough, manly sports. I do not feel any particular sympathy for the person who gets battered about a good deal so long as it is not fatal"* (Roosevelt, 1904, p. 1). On November 26, 1905, The Chicago Sunday Tribune reported the death of nineteen football players in a single season, the paper called for the game to be abolished if there were no major reforms (Roosevelt, 1905). Clearly, young college age football players were dying every year, most from internal injuries, broken necks and spines (Zezima, 2014). On October 9, 1905, New York University chancellor H.M. McCracken assembled coaches and administrators from the big three collegiate powers (Harvard, Yale, and Princeton) to discuss the future of college football. The Washington meeting called for the schools to set an example of "fair play" for gridiron nationally (Zezima, 2014). This standard of "fair play" or "do no harm" speaks to importance of developing best practices for recognizing and treating concussion and the need for objective reliable measures.

The National Association of College Athletics (NCAA) was formed in 1910 on the urging of President Roosevelt after he expressed concerns about 19 game related deaths in college football over a single season (Fleisher, Goff, & Tollison, 1992). The core objectives of the NCAA were originally based on providing public benefit through the reduction of injury and rule standardization. The NCAA, and other sports governing bodies, have undergone increasing levels of scrutiny in recent years regarding liability and overall duty of care for Traumatic Brain Injuries (TBIs) (Greenhow, 2011; Harris, 2015). This is particularly true for high school and collegiate sports, as well as professional and semi-professional sport, such as the National Football League (NFL), Major League Soccer (MLS), Australian Football League (AFL), and the Australian National Rugby League (NRL) (Greenhow, 2011; Holm & McNamee, 2009).

A. The Prevalence of Concussion

The United States Center for Disease Control reported that between 1.6 to 3.8 million participants in sports and recreational activities sustain a concussion each year (Langlois, Rutland-Brown, & Wald, 2006). In 2009, US legislation mandated concussion education programs and professional management of concussion for high school and college sports (Harvey, 2013). Unfortunately, these laws do not consider primary prevention and instead focus on the diagnosis, treatment and risk reduction for a repeated concussion. While concussion education and management laws have been a major catalyst for the increase in Athletic Trainers (ATs) at the secondary school level, only about half of secondary school athletic programs in the US have an AT present at practices and competitions (Guskiewicz, 2015). Furthermore, high school concussion management programs remain focused on post injury protocols rather than education and prevention. Additional evaluation of these programs is required to assess their effectiveness in reducing the risk for a SRC (Harvey, 2013).

A recent study by the Concussion and Research Education (CARE) consortium, compared SRC clinical management and return to play (RTP) practices for NCAA athletes from 1999-2001 (n=184) to CARE data from 2014-2017 (n=701). Investigators found that clinical practices over the past 15 years have reduced the prevalence of a same season second concussion by extending the symptom free rest period from a median of 2 days to 5.9 days (McCrea et al., 2020). The increase of symptom free rest allows more time for the athlete to achieve a complete recovery. The extended recovery of six-days is more aligned with 7–10-day period of metabolic dysfunction typical seen after a SRC which will be further discussed in the literature review. A key point here is the importance of establishing a culture around an appropriate time interval for RTP after a SRC. In addition, all diagnostic tests must be reliable (test-retest repeatability), sensitive (detects the impaired patient), specific (no false positives or negatives) and valid (measures true impairment present) (Mayers & Redick, 2012). A multi-disciplinary approach is best, with no single test used to make a clinical decision on the RTP status of an athlete. (Collins et al., 2016; Meehan, d'Hemecourt, Collins, & Comstock, 2011).

B. The Culture of Concussion

Decisions made by clinicians should always consider the best interest of the athlete above the team's interests or any other secondary gain (Holm & McNamee, 2009; Partridge & Hall, 2014). Clearly, a conflict of interest can arise when coaches or parents are involved in return to school, RTP or subsequent SRC treatment options. The traditional patient-doctor relationship can be burdened by a third-party influence, (e.g. coach, team owner, manager, peers or parents). This burden may encourage a premature return to sport and increased risk for a SRC or other injuries (Master, Gioia, Leddy, & Grady, 2012). In some cases the athletes themselves may deny having any symptoms at all, when clearly, there are objective indications that something is wrong (Kroshus, Garnett, Hawrilenko, Baugh, & Calzo, 2015; Meier et al., 2015). Kroshus et al. (2015), in a recent study, reported approximately 25% of collegiate athletes' experienced external pressure to continue playing after a SRC. Furthermore, Kroshus and colleagues (2015), found about two-thirds of physicians had experienced pressure from athletes to return to play prematurely. These external influences are problematic regarding effective management of a SRC, as the physician-patient relationship may no longer be bound by trust and verification.

For contact sports, most governing bodies have implemented same-day rules that prevent a concussed player from returning to play immediately on the day of injury (Heptig, 2016; NRL, 2017). However, these rules may in fact discourage the team physician from either assessing a player or determining a diagnosis of concussion for fear of having to immediately remove the athlete from the game (McNamee, Partridge, & Anderson, 2016). Compared to professional sports, recreational or non-professional contact sport organizations have a greater potential for underreporting and recognizing SRC. The increased potential for a missed diagnosis may be due to limited sports medical resources, poor administrative oversight, inexperienced coaches and parents ignorant of the potential issues. (Brennan & Khojasteh, 2020; McNamee et al., 2016).

C. Study Purpose

Physicians and other healthcare providers are responsible for making clinical decisions regarding the evaluation and treatment of an SRC and the athlete's subsequent trajectory for return to play. Most coaches, parents and athletes are interested in the length of time an athlete may need for recovery before safely returning to play. As such, this study involved a multi-modal approach to assessment of a SRC and RTP utilizing common clinical metrics symptoms, balance and simple reaction time.

The return to play return to trajectory (RTP_t) was defined as the number of days between the date of injury (DOI) and the date of return to play (RTP). The main purpose of this study was to evaluate the relationship between post-concussion symptomatology, balance and reaction time and the RTP. There were four primary research questions in this study.

i. Are RTP trajectories positively associated with symptom scores?

ii. Are RTP trajectories positively associated with balance performance scores?

iii. Are RTP trajectories negatively associated with simple reaction time performances scores?

iv. Are RTP trajectories (number of days), symptoms, balance scores and reaction time scores significantly different between sexes?

CHAPTER II

REVIEW OF LITERATURE

The writings of Hippocrates refer to the term concussion as, “commotion cerebri” or shaking, yet it is not clear if he was describing the mechanism of injury, loss of consciousness or a broad labeling of a traumatic head injury (McCrory & Berkovic, 2001). The first clear separate recognition of concussion was made by the Persian physician, Rhazes, in the 10th century (McCrory & Berkovic, 2001). By the end of the 16th century a clinical description defining concussion across several clinical stages was developed which included ringing in the ears, falls, swooning, slumbering, dazzling eyes and transient giddiness (Read, 1687).

A. Defining Concussion

In general, position statements or guidelines addressing the diagnosis and treatment of traumatic brain injury (TBI) or mild transient traumatic brain injury (mTBI) rely on a blend of expert opinion and current research. Most, if not all position statements, focus on distinguishing concussion as an mTBI as opposed to the more severe TBI (Alla, Sullivan, McCrory, & Hale, 2011). There are numerous position statements on the management of sports concussion emanating from an abundance of both international and national medical professional groups (Alla et al., 2011; Giza et al., 2013; Harmon et al., 2019; McCrory et al., 2017).

Most of these groups are interested in presenting a working definition for the diagnosis of a SRC. For instance, the American Medical Society for Sports Medicine position statement defines concussion as *"a traumatically induced transient disturbance of brain function that involved a complex pathophysiological process...a subset of mTBI which is classified based on acute injury characteristics at the less severe end of the braining injury spectrum"* (Harmon et al., 2019, p. 213). A second group, the American Academy of Neurology, defines concussion as *"An injury resulting from a blow to the head, causing an alteration in mental status and one or more symptoms of headache, nausea, vomiting dizziness/balance problems, fatigue, difficulty sleeping, drowsiness, sensitivity to light or noise, blurred vision, memory difficulty and difficulty concentrating"* (Giza et al., 2013, p. 2253).

Another professional organization, the Concussion in Sport Group (CISG) recently published the Fifth Consensus Statement. Experts in the field of Neurology, Sports Medicine, Neuropsychology and Athletic Training convene every 4 years to discuss and determine best practices for the diagnosis and management of SRC. The CISG has also develop recommendations for the management of SRC that emphasize rest, followed by symptom limited progressive physical activity, and when appropriate, vestibular rehabilitation and neuropsychological counseling. This current statement evolved from principles outlined in four previous statements published since 2001. The 2016 consensus also reflects the CISG's consistent focus on sport specific concussion over the past 20 years (McCrory et al., 2017). Alla et al. (2011), reviewed citations of published statements on SRC from 2000-2009. Investigators found that the highest number of citations came from the CISG consensus statements and that the greatest number of citations for any one year occurred in 2009. According to the CISG statement a SRC *"A complex pathophysiological process affecting the brain which can be characterized by immediate and transient neurologic dysfunction induced by biomechanical forces, either a direct or indirect blow that may or may not involve loss of consciousness"* (McCrory et al., 2017, p. 2).

Pathophysiology of Concussion.

The human brain consists of an interconnection of billions of small neurons (Webbe, 2006). This vast neural network serves to receive, sort, store and transmit neurological signals throughout the body. Neural networks interlace in a gelatin like substance that offer a protective infrastructure. Suspended inside a hard bony skull, the brain is susceptible to the consequences of blunt trauma or rapid acceleration-deceleration. Anatomically, the brain has four distinct sections: the brain-stem, cerebral cortex, thalamus and cerebrum. Each section has a specialized role in overall neurological function, as well as a unique vulnerability to damage from linear and rotational forces following a concussion (Webbe, 2006). The following is a brief overview of the functional anatomy of the brain and those structures that are susceptible to excessive force following a concussion.

Brainstem. Made up of the medulla oblongata, the pons and the mid brain, the primary function of the brainstem is to control vital functions, such as breathing, heart rate, blood pressure and digestion. Injury to the brainstem can cause speech impairment, breathing difficulties, sleep apnea and difficulty swallowing. In acute cases, there may be personality changes and memory loss, for severe cases, the result can be loss of consciousness (LOC), coma and paralysis (Webbe, 2006).

Arbogast et al., examined animal models representing the structural geometry of the central nervous system and found high tissue strains in the region of the brainstem and corpus callosum after a mTBI. The mechanical properties of these regions increase tissue sensitivity to rotational stressors (Arbogast & Margulies, 1998). The brainstem and the corpus callosum are different from the other CNS regions in that they have a less random structure, and a longitudinal arrangement of axonal fibers. By comparison, with similar tests on cerebral tissue, the brainstem displays a stiffer biomechanical response then cerebral tissue (Gennarelli et al., 1987).

Cerebellum. The cerebellum is located posterior to the brain stem and responsible for motor coordination, motor planning and behavior. Spanos et al. (2007) utilized quantitative Magnetic Resonance Imaging (MRI) to measure cerebellar white and gray matter and lesion volumes in children aged nine to sixteen over a 10-year period. Researchers found that cerebellar white and gray matter volume in the mTBI group consistently showed smaller volumes than the non mTBI group and these differences were associated with significant changes in cognitive performance and behavior (Spanos et al., 2007). These results are consistent with evidence from previous studies that support the vulnerability of the cerebellum to high tissue strains, (and its related projection areas) to neurodegeneration including; Diffuse Axonal Injury (DAI), fiber degeneration, a loss of Purkinje cells (Arbogast & Margulies, 1998; Fukuda et al., 1996) and marked activation of microglia (Mautes, Fukuda, & Noble, 1996). This injury results from a shearing of the axonal projections at the white and grey matter borders. Tissue shearing is due to extreme rotational forces and is typically associated with LOC and significant post injury cerebral edema. These forces result in cerebellar damage due to an activation of Microglia and subsequent Purkinje cell death. The mechanisms for Purkinje cell loss are not well understood but can result in long-term cognitive dysfunction beyond and acute SRC.

Thalamus. The thalamus lies superior to the brain stem and inferior to the cerebral cortex. Described as a router or central relay station, the thalamus connects to the entire cerebral cortex and plays a vital role in the movement of information between the sensory and motor function of the brain. Pathological studies have shown that the anterior limb and genu regions of the internal capsule of the thalamus are related to disorders of attention and executive functioning (Sherman & Guillery, 2009), poor visuospatial memory, and reduced perceptional-motor skill. (Tatemichi, Desmond, Cross, Gropen, & Mohr, 1992). Considerable evidence links the activity of cholinergic neurons to arousal and REM sleep through their projections to the thalamus and medial pontine reticular formations (Leonard, Rao, & Sanchez, 1995). A TBI results in early axonal injury, followed by an associated ventral basal complex neurological degradation. Destruction of these thalamic "neural circuits" could be the underlying cause of several common post mTBI cognitive dysfunctions, including but not limited to attention deficits, diminished motor performance and executive function (Mittl et al., 1994).

Cerebrum. The cerebrum has a right hemisphere and a left hemisphere, separated by a deep groove known as the longitudinal fissure. The right half of the cerebrum controls the left side of the body and the left half controls the right side of the body. Five lobes make up the cerebrum: the frontal, parietal, temporal, occipital, and insula lobes. As the largest section of the brain, the cerebrum is responsible for the integration of neural information. The cerebrum contains both gray and white matter. The gray matter makes up the cerebral cortex, a 2-4mm outer surface on the cerebrum (Webbe, 2006). The cerebrum contains over ten billion nerve cells, accounts for about 80% of brain weight and is the site of most of the brain's neural activity. Based on function or activity, the regions of the cerebral cortex can be divided into three general categories, the motor cortex (movement), the sensory cortex (sound, vision, tactile), and the associative cortex (high order cognitive function) (Webbe, 2006). White matter makes up most of the deep parts of the brain and consists of glial cells and myelinated axons that connect the various grey matter areas. The cerebrum may be particularly sensitive to repetitive "micro impacts" over time and these impacts may contribute to development of more serious permanent brain injury even decades after the athlete stops participation (Stern et al., 2011).

Mechanism of Injury

The mechanisms of injury associated with a SRC are heterogenic in nature, and result in a broad spectrum of injury responses. There is significant evidence to support that most concussions result from inertial (acceleration) loading and that linear type of collisions tend to be associated with a more serious skull fracture and epidural bleeding (Cepeda et al., 2016; Denny-Browne, 1941; Gennarelli et al., 1987; Hirad et al., 2019; Meaney & Smith, 2011; Ommaya & Gennarelli, 1974; Webbe, 2006). Concussions are associated with a direct impact or impulse force to the brain and may or may not involve a skull fracture or penetration. Concussive forces typically result in a coupling effect of acceleration (coup), followed by a deceleration force occurring on the opposite side of the brain (counter-coup) (Cepeda et al., 2016; Webbe, 2006). Two types of forces can insult the brain during a concussive event, linear and rotational (Webbe, 2006). Linear or straight-line forces usually result from a direct collision and a sudden restraint on forward momentum (Meaney & Smith, 2011; Webbe, 2006). Rotational forces however, typically result from a blow to the side of the head and result in high angular velocities (Webbe, 2006). These forces may result in damage to the marginal areas of grey-white matter and possibly the brain stem resulting in a loss of consciousness (Meaney & Smith, 2011; Webbe, 2006).

Theoretical constructs for the mechanisms of concussion have evolved and continue to represent the "current knowledge" of the time (McCrory et al., 2013). Most theories on the mechanism of concussion attempt to link tissue damage with symptom characteristics, severity and persistence. Advances in imaging and other emergent technologies has afforded the clinician to match concussion pathology with emergent symptomatology and objective physical performance deficits. The following section present several theories on mechanism of injury in concussion.

Vascular Theory. One early hypothesis, the Vascular Theory, proposed by Symonds (1935), attributed concussion to a temporary ischemia, resulting in vasoconstriction, and decreased cerebral blood flow. Furthermore, Symonds' 1935 theory supported the notion that a loss of consciousness (LOC) results in a gradual recovery and the rate of recovery is inversely proportional to the depth of the tissue insult. Thus, concussions may still occur without LOC and that recovery time will still depend on the severity of ischemia and the return of cerebral blood flow.

The Reticular Theory. An early theory proposed by Denny-Brown and Russel (1941), expanded upon the previous theory by Symonds explained the immediate effects of a concussion (Denny-Browne, 1941). This theory was rooted in the concept that the brainstem plays a major role in the loss of consciousness . The brainstem serves as a critical relay station controlling the communication between the spinal cord and the brain. A loss of conscious may be due to a loss of this communication secondary to acute tissue trauma, Unfortunately, this theory does not account for some of the immediate symptomatology or any of the protracted effects of amnesia that may be evident after a concussion (Webbe, 2006).

The Centripetal Theory. A third hypothesis; the Centripetal Theory, emerged in the early 1970's and was similar to the earlier reticular theory of axonal shearing. The Centripetal Theory hypothesized that concussion was the result of rotational forces rather than linear forces and

LOC and the severity of the concussion are directly related. (Ommaya & Gennarelli, 1974). However, this theory fails to explain the genesis of other concussion symptoms that are independent of brainstem and LOC anomalies (Webbe, 2006).

The Convulsive Theory. Another proposed theory related to mechanism of injury, the Convulsive Theory, which portrays some clinical signs and symptoms of an acute concussion as similar to those seen in epileptic seizures (Webb, Humphreys, & Heath, 2018; Webbe, 2006). One immediate observation after a concussion is the potential behavior called “posturing”. While all concussions do not result in this malady posturing, typically results from a high impact event, where a player freezes into a rigid protective posture for a few seconds, then returns to normal posture, not unlike a mild epileptic seizure. The theoretic construct of Convulsive Theory however is limited to a specific acute event and not inclusive of a broader spectrum of protracted post-concussion symptomatology. However, this theory may offer promise for future EEG studies comparing concussed brains with those in epileptic patients.

Regardless of which theory one may ascribe to, there are specific biological changes that occur due to trauma. Giza and Hovda (2001) described the biological changes within the brain after a concussion as a combination of axonal shearing, and an associated neuro-metabolic cascade (Giza & Hovda, 2001). This progressive biological collapse results in an immediate neuronal depolarization, followed by a release of excitatory neurotransmitters, a rapid change in ionic balance, decreased glucose metabolism, augmented cerebral blood-flow, and diminished axonal function. Post-concussion metabolic cascade can be associated with a period of increased vulnerability for further injury and neuro-behavioral anomalies. A Diffuse Axonal Injury (DAI) is a more a severe mTBI and is correlated with an injury resulting from rapid rotational acceleration, as well as repetitive sub-concussive impacts (Hirad et al., 2019). DAI’s result in significant white matter changes in the mid-brain and are proportional to the amount of rotational impact exposure (Hirad et al., 2019). Computer Tomography (CT) or traditional Magnetic Resonance Image (MRI) scans are not sensitive to DAI's and should not be a part of the diagnostic process for this injury. While histochemical staining of brain white matter remains a standard invasive tool for detecting a DAI, diffusion tensor imaging (DTI) and blood samples for specific biomarkers are emerging as a possible proxies for confirming a DAI or tau pathologies in mTBI and CTE (Hirad et al., 2019; Stern et al., 2011; Toledo et al., 2012).

These theories highlight the fact that no one single theory can explain the broad heterogenic neurological dysfunction presented after a concussive event (McCrory & Berkovic, 2001). Each theory was uniquely influenced by the current knowledge and technology available at the time of their inception. The aforementioned theories vary, yet they do provide a practical framework to describe the nature and severity of the concussion. Theories on the management of concussion will continue to evolve, influenced by a blend of professional judgment and emergent medical technology (Aubry et al., 2002; McCrory & Berkovic, 2001; McCrory et al., 2017; McCrory et al., 2013). This section has primarily presented the acute response to a SRC, the next section will illuminate the effects sub-concussive trauma and the possible link to a more serious condition, Chronic Traumatic Encephalopathy.

B. Chronic Traumatic Encephalopathy

An insidious neuro degenerative disease of the brain, Chronic Traumatic Encephalopathy (CTE) is associated with motor function deficits, emotional control disorders and diminished cognitive function including memory deficits, disorientation, confusion, intermittent headaches and dizziness (McKee et al., 2009). Overwhelming evidence shows that CTE is the result of repeated sub-concussive forces that often occurs well before the development of clinical pathology (Baugh et al., 2012; Belanger, Vanderploeg, & McAllister, 2016; Gavett, Stern, & McKee, 2011; Tsushima, Geling, Arnold, & Oshiro, 2016). Repeated micro-trauma is of particular concern to college and professional athletes who may play a contact sport for 15-20 years and remain unaware of the progressive structural damage that occurs after an accumulation of thousands of micro impacts over an extended time-frame (McKee et al., 2009).

Unfortunately, present conformation of a diagnosis of CTE relies on a post-mortem dissection of the brain. While advances in imaging are promising, at present, there is no definitive test, scan or biomarker currently available that can reliably differentiate between other neurodegenerative diseases that may be occurring as a part of the normal primary aging process versus CTE. (Hartman et al., 2002; McKee et al., 2009). As CTE progresses, additional symptoms emerge, including impaired judgement, diminished insight and dementia. In severe cases symptoms may include poor muscular coordination, ataxic gait patterns, speech impediments, tremors, vertigo, and hearing deficits (Millspaugh, 1937). CTE is a distinct, slowly progressive disease. Common gross pathology includes; a small reduction in overall brain weight, an expansion of the lateral and third ventricles, a thinning of the corpus colosseum, cavum septum damage and scaring of the cerebella tonsils (Webbe, 2006). At a cellular level CTE results in extensive tau-immuno-reactive neurofibrillary tangles (NFTs), astrocyte tangles, and threadlike neurites dispersion throughout the superficial cortical layers and deposits of globular neurites (McKee et al., 2009).

Hartman et al. (2002), examined lateral cortical impact after a concussion and its effect on mice with the Apo lipoprotein E4 (APOe4) gene (Hartman et al., 2002). Hartman concluded that APOe4 and mTBI are both risk factors for the development of Alzheimer Disease (AD) pathology. These factors could act together in the progression of CTE and related pathophysiology and CTE may share some features of AD. In addition, individuals with the gene APO4 are more likely to develop dementia after a TBI. (Hartman et al., 2002). Development of CTE is a serious health condition that has profound effect on quality of life, particularly with regard to poor memory and physical or emotional function. Athletes considering a long-term career in contact sports must evaluate the risks of CTE against the benefits of participation. Currently CTE and second impact syndrome are the two most pressing issues for healthcare providers and administrators of contact sports. The next section will discuss second impact syndrome and why, it is an important issue in sport.

C. Second Impact Syndrome.

The importance of removing an athlete suspected of sustaining a SRC cannot be over emphasized, particularly when one considers the pressure on the healthcare provider to return the athlete to competition and the consequence of catastrophic injury. Early re-entry into participation may place the athlete at high risk for a second concussion and possibly second impact syndrome. Considerable controversy exists regarding risk factors for a second concussion, and with few prospective studies available, more work is required to establish a possible cause-and-effect relationship (Weinstein, Turner, Kuzma, & Feuer, 2013). While rare, Second Impact Syndrome (SIS) is usually fatal and more likely to occur in the young developing brain (Khurana & Kaye, 2012). The pathophysiology of SIS is associated with an interruption of the brain's blood supply and the subsequent increase in intracranial pressure and possible herniation. While not well understood, animal models examining SIS have revealed that two or more concussions within a short period of time results in synergistic damage and impairment that would be greater than that seen in a single impact (Bowen, 2003; Weinstein et al., 2013). Conversely, Iverson et al.(2006), examined Impact™ memory, reaction time, processing speed, and post-concussion symptom composite scores and found no significant measurable effect of one or two previous concussions on athletes' preseason neuropsychological test performance or symptom reporting (Iverson, Brooks, Lovell, & Collins, 2006). These findings raise reliability issues regarding the sensitivity of standardized neuropsychological tests and their efficacy in measuring cognitive impairment after a second concussion. Memory, reaction time, processing speed and post-concussion symptoms are important measures for determining the severity of a concussion yet may lack the level of specificity and sensitivity to detect those at high risk for SIS and death.

Approximately 80% of repeat SRC's occur within ten days of the original SRC with the overall risk of a repeat concussion in the same season being relatively low at just 3.8%. (McCrea et al., 2020; McCrea et al., 2009). Recovery from a second concussion is often delayed or incomplete compared to the initial concussion. A second concussion may require a more conservative and rigorous approach to recovery and RTP. A prospective study by McCrea et al. (2009), examined the effect of a symptom free waiting period in high school and college athletes and found that a symptom free waiting period had no bearing on clinical recovery, nor the risk of a repeat concussion occurring in the same season (McCrea et al., 2009). Mounting evidence suggests that accumulation of three or more concussions is associated with impaired neurophysiology, an increase in post-concussion symptoms, decreased neurocognitive performance and a higher probability of experiencing a future concussion (Guskiewicz, 2015; Stern et al., 2011).

D. Comorbidities of Concussion.

Studies on pediatric concussion patients have shown that post-concussion symptoms are more prevalent and persistent in children with mTBI than an extra-cranial type injury. A prospective study by Bartow et al. (2010), compared 670 children seen in the emergency room with concussion (mTBI), to 197 controls with a TBI or other factors (i.e. a traumatic event, preexisting psychosocial problems, or previous medical conditions) (Barlow et al., 2010). The most common symptoms for both groups at one-month post injury were fatigue, headache, emotional instability and irritability. At three-months post injury, 11% of children with mTBI remained symptomatic compared to less than 1% of TBI controls. The prevalence of persistent symptoms at one year was 2.3% in the mTBI group and 0.01% in the TBI group. Protracted retrograde amnesia or confusion has been associated with longer RTP trajectories and increased risk of prolonged Post-Concussion Syndrome (PCS) (Blume & Hawash, 2012). PCS is associated with a broad spectrum of symptomatology with considerable variability occurring among individuals presenting with mTBI or TBI (Blume & Hawash, 2012; Merritt, Meyer, & Arnett, 2015; Truss et al., 2017). Post-concussion syndromes fit into four major domains or symptom clusters. The following is a brief description of each as described in Blume et al. (2012, p. 725).

i. *"Physical Domain; (e.g. headache, pressure in the head, photophobia, phono phobia, vision anomalies, nausea, vomiting and balance deficits).*

ii. *Sleeping Domain; (e.g. insomnia, excessive sleep, fatigue and drowsiness).*

iii. *Cognitive Domain; (e.g. memory deficits, slow processing, feeling "foggy", poor mental concentration, attention deficits.*

iv. *Emotional Domain; (e.g. irritability, anxiety, depression, changes in mood and/or personality)".*

Lagretta et al, in a retrospective study of 154 high school athletes with documented SRC, determined that a positive Family Psychiatric History (FPH) and Personal Psychiatric History (PPH) increased risk for PCS when compared to non-concussed controls and found that those with FPH had an increased risk of PCS (Legarreta, Brett, Solomon, & Zuckerman, 2018). Concussed high school athletes with FPH and PPH were 5 times more likely to develop PCS, while athletes with FPH only were over 2.5 times more likely to develop PCS than controls. A FPH of anxiety or bipolar disorder is associated with an increased risk for developing PCS (Legarreta et al., 2018). Both FPH and PPH should be considered as factors for developing PCS and possible protracted return to play trajectories.

Kuehl et al. (2010), investigated self-reported concussion history's effect on Health-Related Quality of Life (HRQOL) in intercollegiate athletes (Kuehl, Snyder, Erickson, & Valovich McLeod, 2010). Athletes (210 males, 92 females) were placed in groups in accordance to number of SRCs, zero concussions (55.4%), 1-2 concussions (30.7%) and 3+ concussions (13.1%). Most SRC (52.7%) occurred more than 12 months before the survey. Outcome measures included the SF-36, a thirty-six item instrument to access HRQOL across eight sub-scales, and the Head Impact test (HIT-6). Significant differences we found between groups for body pain, vitality and social function, with the 3+ concussed group having lower scores, indicative of a greater impact of the SRC on the athlete's mental health status (Kuehl et al., 2010). Another instrument, The Profile of Mood States saw similar results when utilized to measure mood disturbances in college and retired NFL players with mild traumatic brain injury (mTBI) (Kuehl et al., 2010). It is important to recognize that after three or more SRCs there is significant negative impact on the athlete's mental health and quality of life.

E. Age and Sex Differences

Intuitively, one would expect sex differences exist between prevalence and injury response in male and female athletes after an SRC. Overall, males are more likely to sustain a SRC from a contact sport (Coronado et al., 2015) and experience LOC, confusion or amnesia (Tanveer, Zecavati, Delasobera, & Oyegbile, 2017). Males have twice the rate of RTP protocol non-compliance than females (Yard & Comstock, 2009). On the other hand, females have an increased risk of sustaining neck injury after a SRC (Sutton et al., 2019) and are more likely to have both more severe and prolonged post-concussion symptoms (N. S. King, 2014; Tanveer et al., 2017). Headaches are common and persistent in SRC regardless of age or sex, with females more likely than males to seek treatment for this symptom (Tanveer et al., 2017). Females, aged 9-18 years, often demonstrate a performance degradation in inhibitory control, cognitive dynamics (Lax et al., 2015), memory (Colvin et al., 2009) and processing speed (Sufrinko et al., 2017) than males. The influence of sex on RTP trajectory is inconclusive with several studies suggesting females take longer to recover (Berz et al., 2013; Sicard, Moore, & Ellemberg, 2019; Zuckerman et al., 2014), while another study reported females return to baseline performance levels over shorter time frames than males (Lax et al., 2015).

Sex differences were identified when utilizing balance as a measure. Female athletes performed significantly better than males on baseline balance tests (Brett, Zuckerman, Terry, Solomon, & Iverson, 2018; Moran, Meek, Allen, & Robinson, 2020; Nedović, Adamović, & Sretenović, 2019). Brett et al. (2018), retrospectively examined age and sex differences in 3,763 youth aged 9 to 21 years after completing an instrumented balance and reaction time protocol and a multivariate analysis of variance confirmed significant age and sex differences for balance and reaction time scores. (*p* < .001). Post hoc analyses revealed that older groups (adolescents) generally had better scores than younger groups (children) on all balance comparisons (*p* < .001) and reaction a significant number of time comparisons (*p* < .001). Overall, females performed better than males on balance (*p* < .001) and males had faster reaction time scores (*p* < .001). (Brett et al., 2018).

Recently, a retrospective study by Anderson et al. (2019), determined balance and reaction time scores significantly differed by age, with older (13-18 years) groups generally having better scores than younger groups (< 13 years) on all balance (*p* < .001) and many reaction time comparisons (Anderson, Gatens, Glatts, & Russo, 2019). Females performed better when compared to males on balance tasks (*p* < .001) and males had significantly faster reaction times (*p* < .001). Sex effects on balance are present in single-leg stances, with females again outperforming males. Reaction times were faster in males and improved with age, peaking from 13-17 years old and slowing in 18-year-olds (Anderson et al., 2019).

Age specific evaluation and treatment guidelines are important considerations for both children (5-12 years) and adolescents (13-18 years). Most children recover from an SRC after four weeks, while most adults may only require 7-10 days to recover (McCrory et al., 2017; Meehan et al., 2011). Symptom rating scales, neuro-cognitive tests and other clinical tests or norms must be reconsidered in light of age specific norms and subsequent utility and reliability of the diagnostic tools (McCrory et al., 2017). Clearly, student athletes should have regular follow up healthcare provider visits after sustaining a SRC to effectively manage both academic and physical recovery.

Recently, a large study by McCrory et al. (2017), determined that preadolescent children should be considered as a “distinct” group and that adult or adolescent responses to a SRC are unlike those seen in preadolescent child after an SRC (McCrory et al., 2017). Overall, as expected males are stronger, quicker and are more likely to sustain a SRC than females. Females on the other hand have superior balance and are more compliant with their treatment plan when compared to males. Unfortunately, current published guidelines for the management of concussion do not consider sex differences despite evidence that suggest males and females have different treatment needs (Tanveer et al., 2017). Nevertheless, males and female difference in presentation of symptoms and response to treatments are considered in the overall treatment plan.

F. Epidemiology of Concussion

In The United States, over 150 million students participate in high school sport and almost nine-million participate in college sport (Daneshvar, Nowinski, McKee, & Cantu, 2011). Male participation rates are approximately double that of females for both high school and college sports. An estimated 300,000 SRCs , occur each year in the United States and these injuries are second only to motor vehicle accidents as a leading cause of mTBI among people aged 15-24 years (Gessel, Fields, Collins, Dick, & Comstock, 2007). Unfortunately, not all SRCs are likely to be reported by players and in fact SRC estimates may fall short of the true prevalence of SRCs United States contact sport (Faul, Xu, Wald, & Coronado, 2010; Langlois et al., 2006; Meier et al., 2015). A cross sectional study by Meehan, et al. (2013), reported about one- third of athletes evaluated at a sports medicine clinic had sustained a previous undiagnosed concussion(Meehan, Mannix, O'Brien, & Collins, 2013). Furthermore, unreported concussed athletes had a significantly ($p < .004$) higher mean post-concussion symptom scores and were more likely to have lost consciousness. From 1995-1997 the National Association of Athletic Trainers conducted a large study of 4.4 million athletic exposures in 235 high schools across ten sports (football, male-female basketball male -female soccer, female volley ball, softball, baseball, wrestling and field hockey).

An Athletic Exposure (AE) equals one athlete participating in one game or practice. Of a total of 1,219 sports injuries, 5.5% were concussions, with football making up 63.4% of total concussions and tackling being the most prevalent concussive event with six subdural hematomas and intra-cranial injury (Powell & Barber-Foss, 1999). This study estimated 62,816 cases of concussion occur in the US each year across the ten sports examined, and for football estimated an average of only two SRC's per team per year (Powell & Barber-Foss, 1999). Other studies on high velocity elite contact sports, such as Rugby League or Australian Rules have reported significantly higher rates of SRCs at five to seven per team per season (Brennan & Khojasteh, 2020; Khurana & Kaye, 2012; NRL, 2017). Clearly, reported concussions may not represent the true prevalence of concussion in contact sport, mostly due to a systemic under reporting by athletes and the inherent bias of a very competitive high school and college sport culture (Meier et al., 2015; Williamson & Goodman, 2006).

Meehan et al (2011), utilized the High School Reporting Information Online (HSRIO) injury surveillance system, and assessed 1,056 athletes, across 20 sports, for school year 2009-2010 who had at least one affiliated NATA athletic trainer (AT). All concussions occurred during practice or competition and resulted in medical care or the attention of an AT. Of the 7,257 total sports related HSRIO injuries reported, 14.6% were concussions, of those , 88.6% were new injuries and 11.4% recurrent SRCs. Male sports of football, hockey and lacrosse had the highest exposure to concussions at 76.9, 61.9 and 46.6 per 100,000 exposures respectively. Concussions distribution was even across freshman (21.1%), sophomore (26.4%), and juniors (22.7%) but rose for varsity players (53.2%). The most common reported symptoms of concussion in this group were headache (93%), dizziness or unsteadiness (75%), difficulty concentrating (53.9%) confusion disorientation (44.0%) and visual disturbances/sensitivity (34%). Loss of consciousness (LOC) was rare, making up only 4.2% of all concussions (Meehan et al., 2011). One out of four athletes (23.5%) had a resolution of their concussion within 24 hours, 77% resolved symptoms within 7 days and 19.2% resolved between 1 week and 1 month. Only 2.8% of concussed high school athletes had symptoms lasting longer than 1 month (Meehan et al., 2011).

A 2006 NCAA study on contact sports found an all sport concussion rate of approximately 2.5 concussions for every 10,000 athletic exposures, up from 1.7 per 10,000 athletic exposures recorded in 1988 (Guerriero, Proctor, Mannix, & Meehan, 2012). This increased rate may actually represent a broader awareness of concussion and duty of care among medical teams and sport administrators (Daneshvar et al., 2011; Greenhow, 2011). Another descriptive study by Marar et al (2012), reported an overall concussion rate of 2.5 per 10,000 AEs across twenty high school sports. Football related concussion in this study was responsible for 47% of the total all sport concussions, with female soccer second at only 8.2% of all reported concussions. Male youth hockey had the greatest number of concussions proportionally, with 22% of all ice hockey injury categorized as a concussion (Marar, McIlvain, Fields, & Comstock, 2012). Overall concussion rates across all sports were higher in competition (6.4 per 10,000 AEs) than in practice (1.1 per 10,000 AEs). Table 1 shows concussion prevalence rates for two different studies one from 2005-2006 and the other from 2008-2010. Male and Female soccer players had the highest practice to competition ratio at 13.5 and 11.7 per 10,000 AEs respectively.

Table 1.

High School Sports Concussion Rates per 10, 000 AEs

	2005-2006[a]		2008-2010[b]		
Sport	Practice	Game	Practice	Game	Ratio Rate[c]
Football	2.1	15.5	3.1	22.9	7.4 (6.5-8.4)
Girls Soccer	0.9	9.7	0.8	9.2	11.6 (7.6-17.6)
Girls Basketball	0.6	6.0	0.6	5.5	9.2 (5.5-14.1)
Boys Soccer	0.4	5.9	0.4	5.3	13.5 (7.8-23.3)
Boys Wrestling	1.3	6.1	1.3	4.8	3.6 (2.5-5.2)
Boys Basketball	0.6	1.1	0.6	3.9	6.8 (4.3-10.7)
Girls Softball	0.7	0.9	0.9	2.9	3.2 (1.9-5.4)
Boys Baseball	0.3	0.8	0.1	1.1	11.0 (3.0-26.1)
Girls Volleyball	0.5	0.5	0.5	1.0	2.1 (1.04-4.3)

Source: [a] (Daneshvar et al., 2011) [b] (Marar et al., 2012). [c] Means 95% CI with practice as the referent group.

Several other studies have also reported higher instances of concussion during competition compared to practice (Bartley et al., 2017; Daneshvar et al., 2011; Powell & Barber-Foss, 1999). In twenty high school sports, concussions represented 13% of all reported injuries, up from 5.5 % reported over the prior decade (Marar et al., 2012; Powell & Barber-Foss, 1999). Player to surface contact was most prevalent in female volleyball, male wrestling, female gymnastics, track and diving. Female field hockey and lacrosse athletes had the highest level of collisions with equipment (Marar et al., 2012).

G. Diagnostics

Diagnosis of an acute SRC requires the assessment of clinical symptoms, physical signs, cognitive impairment, neurobehavioral, sleep disturbances and a detailed concussion history. A SRC can be assumed if one or more of the following clinical domains are present; somatic issues, cognitive dysfunction, emotional changes, physiologic impairment, (e.g. loss of consciousness, amnesia, neurological deficits and balance anomalies), behavioral changes, cognitive impairment (slowed reaction time) and sleep disturbance (Harmon et al., 2019; McCrory et al., 2017).

Clinicians have previously used grading systems to help define the severity of a concussion (Cantu, 2001, 2006; Iverson, Lovell, & Collins, 2005). For example, a grade one (Mild) concussion, results in no loss of conscious, yet retrograde amnesia may be present. For a grade two concussion (Moderate), the injury may involve a brief loss of concussion and accompanied by retrograde amnesia. A grade three concussion (Severe) concussion, involves a prolonged loss of conscious (>5 min) and prolonged retrograde amnesia (>25 hours) (Cantu, 2001). Most healthcare providers do not use the grading system for the diagnosis and subsequent treatment of concussion due to the heterogenetic nature of the injury and a lack of agreement on grading scales. For example, Kelly et al. (2014), examined the concussion management practices of several hundred NCAA Division I. ATs and revealed only about a third (36%) ATs surveyed utilized a multi-level grading system for side-line and acute management of SRC .

Following an SRC, a rapid but brief period of neurological dysfunction occurs that may emerge over a number of minutes to hours. Acute clinical signs and symptoms of concussion mirror the functional disturbance of the brain more so than evidence of a structural injury. Structural injury is usually not evident on standard structural neuroimaging studies. Furthermore, SRCs result in a broad spectrum of symptoms that may or may not involve loss of consciousness and in some athletes, these symptoms may be prolonged (McCrea et al., 2013). The clinical signs and symptoms of a SRC are viewed in the context of related injuries (e.g. cervical fracture), drug or alcohol use and other medical issues (e.g. prescription medications or vestibular dysfunction). Psychological factors can also influence symptom expression and may be more associated with psychiatric factors, particularly in those cases that have prolonged post-concussion syndrome. (Belanger, Barwick, Kip, Kretzmer, & Vanderploeg, 2013). The subjective nature of self-reported SRC symptoms present a significant challenge to the health care provider with regard to verifying a clinical diagnosis, healing and return to play status of the athlete. Furthermore, symptom expression can mimic those seen in other health issues not related to concussion. Best practices calls for objective tests that can support or refute self-reported symptomatology. The next section will discuss the importance of multi-facet neurocognitive assessments and symptomatology.

***Neurocognitive Assessment*s**

Neurocognitive (NC) tests are common tools used in the diagnosis and management of concussion across elementary school, high school, college and professional sports (Barth et al., 1989; Kelly, Jordan, Joyner, Burdette, & Buckley, 2014; Patricios et al., 2017). Clinically, NC assessments typically measure cognitive abilities, psychological function and sensory-motor function. In most cases, NC evaluations supplement a patient’s clinical history, neuroimaging and blood work. Healthcare providers can draw conclusions from NC evaluations regarding the prevalence and nature of a brain disorder (i.e. Developmental or SRC acquired).

The NC test is a well-established method for quantifying both immediate and residual cognitive or behavioral deficits that may result after sustaining a mTBI. These tests have shown to be sensitive to cognitive decline associated with a SRC (Iverson et al., 2005; Mark R. Lovell

& Collins, 1998; Randolph, McCrea, & Barr, 2005). Neurocognitive evaluations for sport differ from clinical neurological assessment, in that they often administered to a large group of people, over short time frames. NC tests have evolved from clinical application to use in sports and measure certain aspects of memory, cognitive processing speed, working memory or executive function, typically effected by a brain injury.

Standard pencil and paper NC tests rarely accomplish a high test-retest coefficient of .90 required for making observations in individual change. A study by Barr on high school athletes revealed test re-test stability coefficients between 0.39 -0.79, all below what is considered the required standard for test retest reliability (Barr, 2003). Each SRC patient must be treated individually, taking into account a large number of factors, many of which may be independent of NC individual test results at hand. Furthermore, NC tests results provide only one data point for RTP consideration (Barr, 2003; Iverson et al., 2005).

The Automated Neuropsychological Assessment Metric (ANAM), CogSport™, HeadMinder™ and the Immediate Post-Concussion Assessment and Cognitive Test (ImPACT™) have emerged as popular instruments for measuring NC function and symptoms after a SRC. Randolph et al, reviewed these instruments against paper and pencil test for reliability, sensitivity, validity, change score rates and clinical utility and found that despite their popularity, none met all of the criteria necessary for routine clinical application. Several studies have called for the establishment of durable test-retest coefficients (≥.90) through prospective controlled studies that establish reliability, sensitivity, specificity, reliable change scores and detect concussion in the absence of SRC symptomatology (Randolph, 2011; Randolph et al., 2005).

Guskiewicz, et al, (2001) reported small, observed effects in a controlled study of four neurocognitive tests (Hopkins verbal learning, Weschsler Digit Span, Stroop Color word, and

Trail Making). Repeated measures analysis of variance at one, three and seven days post-concussion revealed three of the seven univariate variable were significant on day one only (Guskiewicz, 2001). These results bring into question the reliability and utility of these tests beyond the early stages of the return to play trajectory. A subsequent controlled stability reliability study by Broglio et al (2007), had participants complete three commercial computerized NC tests (Impact™, Concussion Sentinel™, and Headminder™) at baseline, day-45, and day-50. Intra-class correlation coefficients (test-retest), calculated for each computer program and from baseline to day forty-five ranges were low to moderate at .15 to .39 for ImPACT, .23 to .64 for Concussion Sentinel™, and .15 to .66 for the Concussion Resolution Index. At day-45 through day-50 correlation coefficients estimates again were low to moderate ranging from .39 to .61 for ImPACT, .39 to .66 for Concussion Sentinel™, and .03 to .66 for the Concussion Resolution Index. These evaluation inconsistencies in reliability may confound treatment or return to play decisions due to low specificity and sensitivity and the increased potential for false positives and false negatives.

ImPact™ exemplifies the genesis of sports NC testing in the United States. In general, the instrument has a legacy of wide spread adoption, without robust test reliability across a broad spectrum of RTP trajectories and time points (Mayers & Redick, 2012; Randolph et al., 2005). ImPACT™ consists of a demographic/health history questionnaire, the 22 item Post Concussion Symptom Scale (PCSS) and five neurocognitive tests (memory, attention, learning, processing speed and reaction time). ImPACT™ evaluations are predominantly administered by a qualified physician, neuro-psychologist or mid-level provider (Kelly et al., 2014). A brief interview is used to access vestibular-oculomotor status including; vestibular symptoms, impairment, dizziness and balance. The modified Dizziness Handicap Inventory (DHI), a seven point Likert scale instrument is part of the overall ocular motor evaluation and provides a total dizziness score.

Iverson et al, used an ImPACT™ computerized NC test battery to examine attention and processing speed of 72 amateur athletes who had sustained a SRC within the previous 21 days. The Symbol Digit Modalities Test (SDMT), which measures processing speeds, reaction time, verbal and visual memory scores, was compared to ImPACT™ scores and was found to be highly correlated with regards to test processing speeds and reaction time measures (Iverson et al., 2005). Another study by Mayers et al (2012), deconstructed the levels of acceptance by researchers and practitioners utilizing the ImPACT™ tool. A key point in Mayers and Redicks paper is the importance of establishing a proper time interval for RTP, one driven by data and best practices. Multiple measures of test-retest reliability would be desirable and that other metrics such as reliable change indices (RCIs) and regression based methods (RBM) may be relevant for individual RTP decisions following a SRC (Lau, Collins, & Lovell, 2012). These approaches could provide a more robust assessment of neurocognitive function and selection of certain test at specific across within the return to play trajectory.

Variations in human performance over time (practice effect), and the current position of the ImPACT™ protocol, who recommends testing every two years, is somewhat problematic when using ImPACT™ as a non-concussed or preseason baseline measure. According to Mayers et al. (2012), practice effects on ImPACT™ verbal and visual memory, processing speed and reaction time complicate baseline comparisons after a SRC. The sensitivity of the ImPACT™ instrument may be questionable as one in five concussed athletes were classified incorrectly as normal while approximately one in three non-concussed athletes incorrectly classified as concussed (Mayers & Redick, 2012). In view of the high risk of sustaining a second concussion within two weeks of a previous SRC, RTP protocols and recovery may require at least four to six weeks. Clearly, for evaluation and RTP decisions after a concussion ImPACT™ is not a stand-alone tool for clinical judgement (Mayers & Redick, 2012; McCrory et al., 2017; Partridge & Hall, 2014).

A recent prospective study by Henry and colleagues, presents the characteristics of post-concussion recovery at one-week time intervals utilizing multiple variables including symptomatology, neurocognitive and vestibular- oculomotor outcomes (Henry, Elbin, Collins, Marchetti, & Kontos, 2016). This prospective study examined 55 participants between the ages of 14 and 22 years (63% males, 36.4% females). The ImPACT™ tool was used to access SRC outcome measures including neuro-cognitive composite scores, total symptom scores, dizziness and vestibular-oculomotor responses at subsequent one-week interval post SRC over four weeks. Fisher exact test and repeated-measures ANOVA assessed neurocognitive composite scores, total symptom score, dizziness and vestibular-oculomotor scores. A cox proportional hazards model was used for sex as a between group factor ($p <.05$). Total symptoms scores demonstrated the greatest change across the four-week time period and symptom improvement at each one-week interval ($p< .001$). Males had significantly lower scores than females at week two after a SRC. For neurocognitive symptoms, both verbal memory and visual memory improved across all four weeks. There were no significant differences between weeks three and four post injury, suggesting a gradual improvement from week one to three and a plateau effect between week three and four. There were no significant sex differences across weeks one through four with regard to neurocognitive scores. Vestibular-oculomotor dizziness scores decreased significantly after SRC when comparing week one with weeks two, three, and four. ($p < .001$) (Henry et al., 2016). These results reinforce the importance of utilizing a multi-modal comprehensive assessment of SRC, one that includes symptoms, neurocognitive testing, and vestibular-oculomotor outcomes (balance). Recovery from a SRC is not a simple singular trajectory but a composite of symptoms and dysfunctions, each with their own variable trajectory (Henry et al., 2016).

Recently, Sicard et al. (2019), recommended using raw scores over clinical variables to increases the sensitivity of the Cogstate™ NC test battery (Sicard et al., 2019). The Cogstate™ test measures processing speed, attention, verbal and visual learning, working memory, visual motor function, executive function and social cognition. This study looked at evidence of long-term alterations in higher cognition after a SRC and that these changes may not have been evident had the researchers relied on automated published clinical norms alone.

Alterations in sleep patterns are common after a concussion or other traumatic event and may in fact influence performance on a neurocognitive test. A recent cross-sectional retrospective study by Kosttyn et al. (2015), investigated the relationship between self-reported sleep characteristics and recovery from a SRC of 545 outpatient adolescent athletes. Patients (Age 11-18 years) completed a neurocognitive test within 90 days of sustaining a SRC. Of the 520 athletes, 320 reported zero SRCs, 148 had one previous concussion, 53 had two and 23 athletes had three of more. Composite scores on the ImPACT™ test, including the PCSS, were collected to measure neurocognitive function. Athletes, who perceived their sleep as disrupted, reported a greater number of total concussion symptoms on the PCSS than patients who did not perceive sleep disturbance symptoms throughout their recovery from a SRC. Patients reporting sleep disturbances on the first ImPACT™ test averaged a PCSS score of 25 compared to an average score of nine for asymptomatic patients. For a second ImPACT™ test the average score for self-reported sleep disturbance patients dropped 16 points, significantly different from those patients who were asymptomatic for sleep disturbances. Patients who received fewer than 7 hours of sleep scored higher on the PCSS than those who get an adequate amount of sleep regardless of the presence of a SRC (Kostyun, Milewski, & Hafeez, 2015).

Sleep disturbances are important considerations when establishing neurocognitive baseline testing. This is of particularly concern for the adolescent athlete impacted by a history of sleep disturbances that may be unrelated to a SRC. Additional sleep studies utilizing wearable technology (e.g. accelerometers, cloud-based biosensors, heart rate monitors) are required to define objectively, the relationship between sleeping patterns and recovery from an SRC.

Vestibular Ocular Motor Screening (VOMS)

Ocular motor dysfunction is common after a SRC and presents significant challenges with regard to evaluation of postural stability and post-concussion symptomatology. Health care providers consistently utilize the VOMs as an expedient evaluation tool to determine vestibular system dysfunction (Kelly et al., 2014). The vestibular system consists of the inner ear sensory organs, the brain stem, the cerebellum, cerebral cortex, ocular system and postural muscles. Two distinct sub-system exists within that system, the vestibular-ocular sub-system (i.e. visual stability during head movement) and the vestibular-spinal (i.e. postural control, balance). These two sub-systems do not share the same neural circuits (central versus peripheral) and thus one can be disabled independently from the other (Allum, 2012; Cullen, 2012). This is an important clinical distinction for assessment of concussion.

Visual Ocular Motor Screen (VOMS) is a symptom provocation-screening tool used to evaluate both vestibular, and ocular motor deficits following a SRC. Visual or ocular motor deficits can present as blurred vision, diplopia, impaired eye movements, reading difficulties, dizziness, headaches, eye pain, and poor visual focus. The VOMS consists of five ocular motor performance categories; Smooth Pursuit, Saccades (horizontal and vertical), Convergence (near point measure), Vestibular Ocular Reflex (VOR) and the Visual Motion Sensitivity Test. On completion of each task, athletes subjectively rate symptoms for headache dizziness, nausea, and fogginess on a zero (no symptoms) to ten (severe symptoms) Likert scale (Mucha et al., 2014). A study by Kontos et al. (2012), reported dizziness in approximately half of concussed athletes. Dizziness may be clinically indicative of vestibular or ocular motor issues and is highly predictive of a RTP trajectory greater than 21 days(Kontos et al., 2012).

A controlled study by Mucha et al (2014), reported symptom provocation on sixty-one percent of high school athletes after performing at least one VOMS item within 5 days of sustaining a SRC and positively correlated with PCSS scores. The VOR (OR, 3.89; p <.001) and VOMS (OR, 3.37; p <.01) components of the VOMS were most predictive of an athlete being in the concussed group. The VOMS has an advantage over static balance measures (e.g. mBESS) as it measures the dynamic aspects of vestibule-ocular control and function (Mucha et al., 2014). Sensory and vestibular evaluations may help the clinician better understand the specific functional deficit presented (vision, hearing or vestibular) for each individual case and craft a more appropriate, individualized post SRC rehabilitation plan (Moore, Kay, & Ellemberg, 2018). Despite the fact that VOMs is accepted by most healthcare providers as a best practice clinical diagnostic tool, additional research is required to verify the specificity and sensitivity characteristics across the RTP trajectory.

Balance Assessments

A disturbance in balance is a common symptom of concussion. Of the estimated 300,000 SRC’s sustained in the US each year, approximately 30% have balance disturbances (L. A. King et al., 2014). An examination of multiple balance assessment tools used in the evaluation of a SRC revealed that balance and dizziness are two related symptoms of concussion. These symptoms have been observed to return to normal as early as 72 hours after a SRC, with some cases lasting significantly beyond seven days post injury (Murray, Salvatore, Powell, & Reed-Jones, 2014).

Post- concussion disturbances in the vestibular system are reflected in an athlete's inability to maintain postural stability or balance. Murray et al. (2014), examined five common balance assessment methods for SRC 1) the Clinical Test of Sensory Organization and Balance (CTSIB), 2) the Sensory Organization and Balance Test (SOT), 3) the Balance Error Scoring System (BESS), 4) the Romberg Scale (RS) and 5) the NCAA sponsored Wii-Fit (WF) postural control measures. The CTSIB, BESS, and Romberg test are subjective measures of balance and rely on "trained evaluators" to determine balance deficits. Tests are performed across four conditions, 1) eyes open firm surface, 2) eyes closed firm surface, 3) eyes open foam surface and 4) eyes closed foam surface resulting in the calculation of an index for each condition. The BESS protocol calls for three stances, double leg stance, single leg stance and tandem. Balance errors included hands off iliac crest, opening eyes, stepping, stumbling or falling, lifting forefoot or heel and out of test position longer than 5sec. Maximum error was ten, total BESS scores calculations required the summing of the errors from all six stances. Mean total BESS scores for pre and post testing were calculated. The simpler Romberg evaluation requires the subject to stand on a firm surface with feet together and the eyes open. The subject is then asked to maintain balance for up to thirty seconds. The test is performed a second time with the eyes closed. Test interpretation is based time until a loss of balance. The SOT is a high tech computerized protocol and through six different conditions challenges visual, vestibular somatic sensor function. Again the test is performed both eyes open and closed. The Wii-Fit test requires the use of commercially produced mat sensor to measure and transmit data to a host computer. The Wii-fit software provides test instructions to challenge the subjects balance and weight distribution until they experience a loss of balance. Investigators found no reliability, validity, sensitivity or specificity data exists to support the use of the CTSIB, and SOT tests. (Murray et al., 2014). The Romberg and Wi-Fit tests were reliable for elderly populations. Given the multitude of balance test available, clinicians must be aware of test validity and appropriately match tests to specific populations of interest.

The BESS test had high reliability (0.87) high specificity (0.96) but low sensitivity (0.34). Low test sensitivity is most likely due to low inter-rater reliability due the subjectivity of the assessment. The BESS test, a common standardized tool for post SRC across multiple populations, has moderate to high reliability for evaluation of a post SRC balance anomalies (Murray et al., 2014). One limitation of the standard BESS include an inability of the test to detect balance deficits at seven days post SRC. Furthermore the test may be more appropriate for use as a pre-screening “side-line” test and/or in the later stages of concussion management and return to play (Murray et al., 2014). Improvements in inter-rater and intra-rater reliability measures for the BESS must rely on objective instrumented measurement of postural sway. Use of tri-axial accelerometers and other motion sensors are precise tools that can consistently measure small differences in balance over time after a SRC, particularly when comparing baseline measures to concussed values (Patterson, Amick, Pandya, Hakansson, & Jorgensen, 2014a).

Burk et al. (2013) evaluated the changes in BESS scores after a competitive athletic season. This study had three specific concerns regarding the reliability of the BESS; 1) inter and intra-rater reliability, 2) the influence of fatigue on performance and 3) functional ankle stability. Two other confounding variables that might improve BESS score (decreased balance error scores) are repeated test performance (learning effect) and the effect of concurrent neuromuscular balance training. Fifty-eight NCAA Division I college female student athletes from Soccer (n=18) Volleyball (n=15) and physically active controls (n=17) participated in the study. A three-level one-way ANOVA's determined group differences between pre and post season scores. For BESS score changes between pre and post-tests, there was no interaction between group and time. There was a significant main effect for time on BESS for all 50 study subjects for pre (*M* = 9.00, *SD* ±2.9) and post (*M* = 7.29, *SD* ±2.8) season error scores, with a medium (0.38) effect size. The primary finding of this study was a statistically significant improvement in BESS over a season, suggesting even at 90 day intervals a practice effect may influence the BESS (1.08 error improvement) (Burk, Munkasy, Joyner, & Buckley, 2013). Additionally, strength and conditioning programs as part of the regular season training may play a role in a post season reduction in balance errors scores (improvement). According to Burk et al (2013), this may confound return to play (RTP) decisions resulting in a clinician incorrectly classifying an impaired athlete as healthy (improved BESS score) and ready for RTP.

Powers et al, (2014), utilized Center of Pressure (COP) measures during static balance to determine if balance impairments have resolved or persisted on return to play (RTP) after a SRC. (Powers, Kalmar, & Cinelli, 2014). Measures of the COP provides an indirect objective measure of movement of the center of mass during postural control. A force plate connected to a computer use used to measure small changes in balance. Nine concussed varsity football players were matched by age and position with nine non- concussed controls. Exclusion criteria included no medications or other injury that would influence balance or gait. The control group was negative for a concussion within the last 12-months. Concussed subjects were tested during the acute phase (symptomatic but able to perform task) and at RTP. Static balance testing required subjects to stand on a force plate with feet together hand by their sides. Force plate samples were set at 50Hz for three trials of 60 seconds duration for both eyes open and closed with the order of visual conditions randomized. Root Mean Squares (RMS) of the COP for both displacement (mm) and velocity (mm/sec), as well as anterior/posterior (A/P) and medial-lateral (M/L) planes, were calculated. During the acute phase, concussed athletes had a greater COP displacement with eyes closed than eyes open when compared to non-concussed controls (Powers et al., 2014). COP displacement was not different between visual conditions for controls. For COP AP velocity, concussed athletes were higher with eyes closed compared to eyes open and athletes had faster adjustment velocities than controls with closed eyes. This supports the notion that vestibular function is impaired and the athlete cannot make the adjustments to maintain postural stability.

On average concussed players in this study returned to play in 26.4 days, *SD* = 14, after a SRC. At RTP, concussed players had higher COP velocities than controls, across M/L and A/P conditions, and COP velocity was greater with eyes closed compare to eyes open. Researchers also found that balance control in concussed athletes, was not fully restored upon RTP. For the acute post concussive phase, impaired vestibular and visual CNS input increased COP displacement. This study revealed, for concussed players, COP displacement recovered, but COP velocity remained elevated at RTP (persistent vestibular impairment). Furthermore, balance deficits were more profound for the A/P direction measures than medial lateral motion. Symptom evaluation and subjective balance tests (no-instrumented) may not be sufficient in terms of sensitivity to SRC across the RTP trajectory (Powers et al., 2014). There is a need for an objective (instrumented) balance assessment tool to avoid a player returning to play with any sensory motor impairment.

The US National Institute of Health has recently encouraged the use of "instrumented" Balance Error Scoring System (BESS) to assess general balance through the measurement of postural sway (L. A. King et al., 2014). King and colleagues (2014) examined BESS scores and the clinicians' ability to classify the patient's TBI status. Twenty-six TBI patients were diagnosed by a sports medicine physician with a TBI (n=13). The average post-injury duration was five months (*SD* ±3.3). Four primary measures were involved; 1) BESS, 2) modified BESS (mBess), 3) instrumented BESS and 4) the instrumented mBESS. The mBESS test involves five standardized standing postures (feet together, tandem left and right, single leg stance left and right). Unlike the standard BESS, the mBESS is performed with eyes closed only and while standing on a firm surface. An inertial sensor was used to measure lateral/medial and anterior/posterior postural sway. Root mean Squares (RMS) calculated around the mean acceleration, showed a loss of balance (LOB) reflected in a larger RMS value. Scores on the non-instrumented BESS/mBESS were similar across time points but were significantly different for the instrumented measure for BESS/mBESS. The addition of foam during the full BESS for both instrumented and non-instrumented did not improve the test ability to identify the difference between TBI or control subjects. Using the instrumented modified mBESS resulted in highest degree of diagnostic accuracy by reducing classification error (L. A. King et al., 2014). Study limitations included, small sample size, no external criterion standard for "abnormal" balance, and that "self-reported data" can often result in "under-reporting" of a TBI. Finally, the investigators were privy to subject's diagnosis, representing a risk for examiner bias limitations. The limitation was reported as non-significant by the authors. This study emboldened the clinical value of utilizing inertial sensors to objectively measure specific domains of balance in adolescents who sustained a mTBI. A subsequent study by King et al. (2017) utilizing accelerometers, compared fifty-two college athletes in the acute phase of concussion and seventy-six non-concussed controls. The instrumented mBESS measures significantly out-performed the clinical error count measures or manual mBESS ($p < .001$ and $p = .06$ respectively) when distinguishing concussed from non-concussed athletes (L. A. King et al., 2017).

Reaction Time Assessments

Numerous studies support the notion of a prolonged reaction time (RT) immediately after sport-related concussion and that prolongation is typically, followed by a progressive improvement in RT with an eventual return to baseline (Collie, Makdissi, Maruff, Bennell, & McCrory, 2006; Collins et al., 2003; Eckner, Kutcher, & Richardson, 2010; Warden et al., 2001). In addition to a prolonged RT, individual response variability have shown to increase after concussion. Two studies suggest the importance of base line testing for RT prior to participating in contact sports (Eckner et al., 2010; Hugenholtz, Stuss, Stethem, & Richard, 1988). One study had some limitations including small sample size, lack of multiple measures over time for RT and the study failed to control for performance motivation (Eckner et al., 2010). Other studies have reported a prolonged nature of RT after concussion and that RT seems to mirror the trajectory of post-concussive symptoms (Collie et al., 2006; Collins et al., 2003). Additionally, Warden et al. (2001) concluded that it is possible that a “slowed” RT may remain despite a full resolution of self-reported symptoms and return to sport based on clinical evaluation criteria (Warden et al., 2001). These findings suggest that RT values may increase sensitivity to the clinical assessment of concussion compared with self-reported symptoms and a general physical examination alone. Additional study is required to determine whether RT is sensitive to the known effects of concussion and whether this test is feasible for concussed athletes on the sideline, in the training room immediately after an injury and across the RTP trajectory (Eckner et al., 2010).

Sideline Assessments

Recognizing a SRC typical involves a rapid assessment by the healthcare provider. It is important that the on-field evaluation of player after a possible concussive event begin with a cervical spine evaluation to rule out a structural cervical injury. Following an SRC, a brief period of neurological dysfunction occurs that may emerge over a number of minutes to hours. Acute clinical signs and symptoms of concussion mirror functional disturbance as opposed to structural injury, and the injury is often not evident on standard structural neuroimaging studies (McCrory et al., 2017) . When a player presents with signs and symptoms of a SRC, an evaluation by a qualified healthcare professional for a cervical injury is imperative. If no healthcare professional provider is available, the player should be immediately and carefully, removed from the game. Sideline evaluation should include a brief neuro-psychological evaluation with the goal of recognizing an emergent SRC through screening rather than working on a differential diagnosis (McCrea et al., 2020; McCrory et al., 2017).

The Sports Concussion Assessment Tool, 5th edition (SCAT5), is a common accessible paper based sideline assessment tool that can help distinguish between a concussed and non-concussed player immediately after the injury. The tool was developed by CISG, and designed for use by physicians or licensed healthcare providers. (Davis et al., 2017; Echemendia et al., 2017; McCrory et al., 2017). Intended to supplement the ImPACT™ test, SCAT5 has a stepwise approach to acute management of an SRC. The SCAT5 identifies “red flags”, including observable signs of concussion, a memory assessment, the Glasgow Coma Scale, a cervical spine assessment, a 22-item symptom evaluation post-concussion symptom scale (PCSS), cognitive screen and the non-instrumented mBESS. The diagnosis of a SRC is a clinical judgment by the healthcare professional and the SCAT5 is not designed as a stand-alone tool for a diagnosis of a SRC. Other limitations include test administration time, subjective nature of the test items (e.g. subjective scoring system for mBESS) and limited access to paper based records (Guskiewicz, 2001; Kelly et al., 2014).

In SRCs, it is common for the concussed athlete to deny symptoms even when they are present and obvious to the health care provider (Meier et al., 2015). The SCAT 5 is a rapid and cost effective SRC sideline evaluation tool. This tool is particularly useful for game day or side-line assessments and provides important information to the clinician regarding the return to play question and need for additional medical care. Unfortunately, the SCAT5 utility begins to decrease after three to five days post-injury. The concussion symptom checklist does however provide clinical utility beyond that time point (Echemendia et al., 2017; Giza et al., 2013; McCrory et al., 2017).

After the initial sideline assessment, an in office re-evaluation should be performed by a qualified healthcare provider with 24-48 hours. This procedure includes a comprehensive patient history, detailed neurological examination, cognitive function assessment, sleep pattern assessment, Visual Ocular Vestibular Screen (VOMS) and an assessment of signs and symptoms status (improvement or worse since injury) (McCrory et al., 2017). The clinician should also consider the need for any neuroimaging to rule out a possible structural injury or more serious TBI.

Instrumented Assessments

In 2010 Sway™ Medical, a small medical technology concern introduced a cell phone application that utilizes a tri-axial accelerometer and proprietary algorithm to access symptomatology, balance and reaction time after a SRC. The application can transmit cognition and balance performance data to a secure cloud based server, and allows for an easy comparison of post SRC values to pre-season non-concussed baseline values. Age and sex specific normative data are also accessible for additional comparison. A secure internet portal allows healthcare providers easy access to an athlete's data for analysis across the RTP trajectory. The Sway™ application has approval from the FDA as a medical device.

The Sway™ Sports Plus protocol contains four cognitive tests, memory (delayed recall, working memory), inspection time (differentiation of line length), impulse control (go, no go) and simple reaction time (go). The clinician can exclude or include any specific component of the sports testing protocol depending on the evaluations main purpose (e.g. sideline assessment clinical assessment, RTP status). Variables are scored from 0-100, with 100 being a perfect performance or no error. Reaction time values are in milliseconds or on a 0-100 scale. The use of a smart-phone based accelerometer to measure reaction time significantly reduces response latency to just 9.2-11.3 milliseconds compared to greater than 44 milliseconds latency typically seen in touch screens or mouse clicks (Jota, Forlines, Leigh, Sanders, & Wigdor, 2014).

The balance portion of the Sway™ application utilizes an instrumented version of the modified Balance Error Scoring System (mBESS) eliminating both soft surface and eyes open portions of the original BESS test. The instrumented mBESS and has a strong inverse correlation ($r = -.767$, $p < .01$) with the manual mBESS. Patterson et al. (2014) found a mean manual mBESS score of was 5.93, *SD* ±4.45, and the mean Sway™ score was 81.8, *SD* ±4.1. The

Sway™ balance score significantly predicted the manual mBESS score (*p* < .0001), where the Sway™ balance score accounted for 36.1% of the variance observed in the mBESS score (Patterson et al., 2014a).

The Sway™ instrumented mBESS sports protocol consists of five test stances; bipedal (feet together), tandem stance (left foot forward), tandem stance (right foot forward), single leg stance (right), and single leg stance (left). Unlike the BESS, the mBESS stances are on a firm surface only, with eyes closed for a period of 10 seconds. Patterson et al., (2014) compared Sway™ balance assessments with an industry standard clinical balance system. (Patterson, Amick, Thummar, & Rogers, 2014b). Thirty healthy college aged individuals balanced on a Biodex™ balance system while concurrently activating the Sway™ phone based system. A significant correlation between the two data sets was found with a mean difference of (0.030 ± 0.713) ($r = 0.632$, $p < 0.01$). Despite the small sample size, these balance measures were considered consistent (Patterson et al., 2014b) This study does provide external concurrent validation of a smart phone based measuring system with an industry standard balance measuring system.

Burghart et al (2017), concluded that lower Sway™ balance scores were associated with instability, and that these scores provide a valid and reliable tool for the evaluation of college age populations. Mean Sway™ balance scores ranged from 86.9 to 89.9. A repeated measures ANOVA revealed no significant mean difference between Sway™ balance scores for the experimental trials, F (5,115) 0.673; $p < 0.65$, with inter-class correlation (ICC) for re-test reliability of 0.76 (SEM 5.39) (Burghart, Craig, Radel, & Huisinga, 2017). This study also recommends a familiarization trial at the beginning of each testing session to eliminate novel task errors. Finally, Sway™ balance scores may demonstrate a ceiling effect when assessing balance improvements in those who already demonstrate good balance (e.g. gymnasts or cheerleaders) (Burghart et al., 2017).

Simple reaction time (RT) portion of Sway™ is recorded as an average of five trials and is computed as a raw score in milliseconds (a low score is good) or normalized score 0-100 (high score indicates a fast RT). (Patterson et al., 2014b). Sway™ balance scores are compared to pre-season non-concussed baseline score or age and sex appropriate norms. (Brett et al., 2018). The Sway™ instrumented protocol provides a more comparable score, without the inherent bias of the test administrator or low rater reliability, typically associated with a non-instrumented BESS (Amick, Chaparro, Patterson, & Jorgensen, 2015). This smart phone application is a particularly effective sideline tool due to test brevity and ability to provide objective balance and reaction time measures, through a simple user interface (Burghart et al., 2017).

Treadmill Stress Tests

A treadmill evaluation to determine exercise tolerance after a SRC provides valuable prognostic information on symptom response to exercise. In fact, this evaluation will lead to a safer, more precise return to physical activity. A controlled randomized trial by Leddy et al. (2018) compared the effect of exercise testing one-week after an SRC and found no significant difference in symptoms between those who performed the exercise testing and those who did not. For the treadmill group, those who had a low symptom provocation threshold for exercise (<135 beat per min) had longer recovery trajectories (J. Leddy et al., 2018). Another study by Cordingley et al, (2016) evaluated the safety and clinical application of treadmill testing in one-hundred and forty-one pediatric SRC patients and found no serious side effects after exercise testing. Furthermore, treadmill testing confirmed physiological recovery in 96% of patients evaluated, and proved to be safe, tolerable and useful in the management of SRC (Cordingley et al., 2016). Clearly graded treadmill tests negative for symptom provocation can provide objective locomotion (dynamic balance) information valuable in the overall assessment of the athlete's recovery status.

H. Provider Evaluation Practices

The need for careful coordination of evaluation, treatment and RTP trajectories by all healthcare providers is paramount. Sports medicine physicians, ER physicians, primary care physicians, neuropsychologists, physical therapists, exercise physiologists and ATs all have a specific role as part of a multi-discipline team approach to recovery from a SRC (McCrory et al., 2017; McCrory et al., 2013). The collective measures of balance, cognition, neuro-physical performance and SRC symptomatology have high sensitivity rates (0.96) for detecting a concussion while no single independent measures exceed moderate (0.70) sensitivity rates (Broglio, Ferrara, Macciocchi, Baumgartner, & Elliott, 2007; Register-Mihalik, Mihalik, & Guskiewicz, 2008). Recently, Patricios et al. (2017) reported high sideline evaluation sensitivity and specificity for PCSS and multi-modal assessments. Balance and cognitive tests had low sensitivity but high specificity for side line evaluation (Patricios et al., 2017). These sensitivity ratings speak to the importance of RTP decisions not relying on a single test alone. Sound clinical judgement considers the examination of all tests within the context of each individual SRC case. It is beyond the scope of this paper to discuss the roles and responsibilities of every clinical discipline involved in the management of SRC. This section will present information on two important providers, athletic trainers, and physicians.

Athletic Trainers

A cross-sectional study by Kelly et al (2014) surveyed the evaluation practices of 610-experienced NCAA Division I ATs. The survey included respondent's institutional demographics as well as SRC assessment, recovery and RTP practices. Most ATs reported utilizing at least three different standardized SRC evaluation tools across pre-season baseline (71.2%), acute evaluation (79.2%) and RTP evaluation (66.9%). Additionally, the number of standardized tests performed were positively correlated ($r = 0.851, p < .01$) for baseline and acute measures, slightly less for baseline and RTP ($r = 0.468, p < .01$) and acute and RTP ($r = 0.460, p < .01$) measurement time points (Kelly et al., 2014). By far, the most common post SRC balance tests used by ATs in this study was the mBESS (73.9%). Very few ATs used the computerized force plate test (1.3%) or the SOT (0.2%) evaluation methods. NC evaluations were used by 90% of ATs surveyed and typically involved a physician (63%) for interpretation or consultation. Only 9.7% ATs reported utilizing neuropsychologists as part of the provider mix (Kelly et al., 2014).

A large portion of ATCs (93.6%) utilized a SRC symptom checklist with a clinical examination (96.6%). A little over a third (36%) of ATs reported the use of a multi-level concussion grading scale as part of their assessment during the acute assessment time point. The most common clinical elements were cognitive screening questions including the Standardized Assessment of Concussion (SAC). Both mBESS and SAC are excellent sideline assessment tools when they are compared to baseline values, yet few (10-20%), of ATs in this study, depending on the test platform, had access to electronic recorded baselines (Kelly et al., 2014). Clearly, lack of access to paper based baseline data makes it impractical for timely baseline to post SRC sideline comparisons.

A study by Meehan et al. (2011), reported that ATs assessed 94% of concussed athletes, primary care physicians accessed a little over half (58%), with 67% of SRC's accessed by both providers. In terms of return to play, physicians as opposed to AT's were more likely to use computerized neuropsychological testing (52% vs 35%) and an MRI study (5.5% vs 0.6%) yet, CT scans are most likely ordered if the assessment is performed by an emergency physician (75% vs 20.2%) or neurologists (72% vs 19.9%). Decisions for RTP were mostly made by a physician (50.1%) or an AT (46.2%). However, about 2.5% of athletes were returned to play by non-medical personnel (i.e. coaches/parents) (Meehan et al., 2011).

Primary Care Providers

Pleacher and Dexter (2006) surveyed physician interest in utilizing neuropsychological testing for SRC assessments as a part of their overall clinical judgement. An 11-item questionnaire sent to 723-providers via email, resulted in a 50.8% (367/732) response rate. The respondents included family practice physicians (56.9%), pediatricians (27.8%), nurse practitioners (8.4%) and physician's assistants (6%). Slightly more than half of the respondents had treated one to four concussion. Of note, only a small number (6%) of primary care providers were involved in sideline medical coverage for sports events (Pleacher & Dexter, 2006).

An examination of clinical directives for concussion revealed 68.4% of respondents used published guidelines for the management of concussions, with the majority (55.4%) of physicians utilizing the American Academy of Neurology Guidelines. Unfortunately, only 16% of the respondents said they could access neuropsychological testing within a week of the injury. Overall, 55.8% of the surveyed respondents indicated they would be likely to use neuropsychological testing in the future. The most frequent reported reason for physicians not using the standard concussion guidelines was, lack of awareness that they exist as well as considerable barriers with regard to cost, availability and ease of deployment of recommended tests (Pleacher & Dexter, 2006).

Arbogast et al. (2013) surveyed 89 primary care providers regarding pediatric treatment practices for cognitive rest and recovery from a SRC (Arbogast et al., 2013). The providers reported 10-18% of concussion patients demonstrated cognitive performance difficulties at school (e.g., poor concentration, fatigue, feeling in a fog, and vision problems). Most patients (63-85%) reported having a headache during on either the initial or the follow-up visit. These symptoms significantly influenced academic performance with approximately 30% of their SRC patients reporting a decline in school performance or attendance. The majority (64%) of providers identified cognitive rest as important component of concussion management yet few provided written recommendations for return to academic activities (Arbogast et al., 2013).

Additional efforts are required to make the primary care provider more aware of the concussion assessment and treatment guidelines, including the limitations of neuropsychological and other tests. The use of objective multi-faceted, cloud-based evaluation tools provide an array of data that enhances “clinical judgement” and improves post-concussion recovery outcomes across the RTP trajectory (Buckley, Burdette, & Kelly, 2015; McCrory et al., 2017; Schneider et al., 2017). Healthcare providers specializing in concussion should continue to build multi-disciplinary injury management teams to address the individual needs of concussed athletes. Teams should span a broad spectrum of health care disciplines including physicians, ATs, physical therapists, exercise physiologists, nutritionists and neuro-psychologists. A multi-disciplinary approach to the treatment of SRC will be an important component of improving recovery outcomes.

I. Treatment

Physical and cognitive rest is the most widely used treatment strategies for treating a SRC, particularly for the initial 24 to 48-hour post injury period (McCrory et al., 2017). Appropriate rest, typically reduces symptomatology during the acute phase of recovery and can have significant impact on minimizing cerebral energy demand in the initial stages of recovery (Giza et al., 2013; McCrory et al., 2017). There are conflicting findings regarding the efficacy of complete rest as opposed to a progressive increase in symptom limited physical and cognitive activity (Collins et al., 2016; Harmon et al., 2019; McCrory & Berkovic, 2001; McCrory et al., 2017; Schneider et al., 2017). The majority of concussion consensus statements recommend that athletes limit activity until they become symptom free (Harmon et al., 2019; McCrory et al., 2017). While this would help mitigate symptoms during the very early acute phase of an SRC, there is sufficient evidence to support complete rest as being less effective than a progressive symptom limited physical and cognitive activity (Haider et al., 2021; J. J. Leddy et al., 2019; McCrea et al., 2009; Thomas, Apps, Hoffmann, McCrea, & Hammeke, 2015). Clearly, the heterogenic nature of SRC requires a multitude of treatment options, carefully crafted and considerate of each individual athlete's clinical presentation.

Rehabilitation

After sufficient rest, athletes are encouraged to increase progressively both physical and cognitive workloads provided there is no symptom exacerbation (Giza et al., 2013; McCrea et al., 2003). For prolonged (> 14 days) symptoms or impairment after a SRC, psychological, cervical and vestibular rehabilitation may be effective treatment options (McCrory et al., 2017). A systematic review by Schneider et al. (2017) considered nineteen SRC treatment studies, and found moderate evidence that cervical and vestibular therapies are more effective than rest alone. These studies revealed minimal evidence supporting improved outcomes after cognitive behavioral therapy or pharmacological intervention and were of low methodological quality (Schneider et al., 2017).

Exercise, applied at the right time, and appropriate intensity, has shown to improve neurological function, advance neural repair, and increase cerebral blood flow (Alderman, Arent, Landers, & Rogers, 2007). Functional MRI studies have support the notion that moderate aerobic exercise (60% of maximum), improved brain cortical activity, thus, adding support to concept of a positive effect of exercise on recovery after a SRC (Colcombe, Kramer, McAuley, Erickson, & Scalf, 2004). Several studies have reported progressive, symptom limited cardiovascular exercise as having a positive effect on symptom reduction, as well as an overall reduction in recovery time (Grool et al., 2016; J. Leddy et al., 2018; J. J. Leddy & Willer, 2013; Schneider et al., 2017). The CISG has endorsed a 5 stage critical path for the progressive application of exercise across the RTP trajectory (McCrory et al., 2013). If symptoms persist longer than 4 weeks in children and greater than 10-14 days for adults, a referral for a detailed clinical evaluation is appropriate. The main objective prior to referral, is to differentiate between the primary clinical issues and possible secondary pathologies that might involve post-traumatic stress and related symptomatology (McCrory et al., 2017). Prolonged post-concussion symptoms can be ascribed to a combination of pre-exiting conditions, individual biological resilience and psych-social disposition (Blume & Hawash, 2012).

Truss et al (2017), reported that sixteen percent of children (age 8-18 years) had clinically significant post-traumatic stress symptoms (PTSS) two weeks post injury and that this number was reduced to six percent by three months post injury. Age, sex, mechanism of injury, loss of consciousness, previous health history and previous diagnosis of anxiety and depression were significant predictors of a prolonged recovery from concussion. An appropriate and timely provider referral for PTSS is critical for the resolution of related symptoms and a safe return to school or sport.

Return to Play and Academics

According to the CISG consensus statement, the most reliable predictor of a protracted recovery time after an SRC is the initial severity of symptomatology. Minimal symptoms typically correspond with a shorter recovery time frames whereas, longer time frames, are associated with persistent symptoms and a greater probability of PTSS (McCrory et al., 2017; Truss et al., 2017). Recovery after a SRC should begin with a brief period (24-48 hours) of cognitive and physical rest. Following a brief rest period, the athlete should embark upon a tailored progressive increase in schoolwork, and physical activity. Initially, return to school should be the primary objective, RTP the secondary objective, both follow a written plan. (Arbogast et al., 2013; McCrory et al., 2013). Tables 2 and 3 present examples of progressive return to school and RTP plans. Academic accommodation can include frequent cognitive breaks (in a quiet place), preprinted class notes, protracted assignment due dates, elimination of nonessential work (including make-up work) and the provision of tutors. No academic exams should be attempted prior to the athlete tolerating a full day of school without symptom provocation (Master et al., 2012). Focusing on returning to school, does not exclude low intensity exercise provided there is no significant symptom provocation during or after exercise.

Table 2
Staged Return to Academics Protocol: Activity and Objectives

Stage:	**Activity:**	**Objective**
No Activity	Complete cognitive rest No school, homework, reading, texting, video games, computer.	Cognitive Recovery
Reintroduction of Cognitive activity	Revoke previous restrictions Short exposure times (5-15 min) per tolerance	Gradual controlled increase in sub-symptom threshold cognitive activities
Homework	Home work (at home) in longer increments (20-30 minutes)	Increase cognitive stamina through short periods of self-pace cognitive activity
School re-entry	Partial day of school after toleration of 1-2 cumulative hours of homework (at home)	Re-entry into school with accommodations to control sub-symptom threshold increases in cognitive load
Gradual reintegration into school	Increase to full day of school	Accommodations decrease
Resumption of full cognitive workload	Introduce testing Catch up with essential school work	Full return to school. Can begin phase 2 of RTP protocol

(Source: Master et al, 2012)

Table 3.

Staged Return to Play Protocol: Activity and Objectives

Stage	**Activity**	**Objective**
Symptom Limited Activity	Complete physical and cognitive rest until Medical clearance	Recovery - gradual re-introduction of school or work
Light Aerobic	Symptom limited walking or stationary cycling (< 70% max HR for 15 min) NO! resistance training	Progressive increase in training Heart Rate
Sport Specific Exercise	Running, skating, cycling, drills (<80% max HR for 45 min) NO! head impact activities	Introduce sport specific movements
Non-contact Training Drills	Higher intensity drills (e.g. passing drills) (<90% max HR) Start resistance training	Exercise coordination Improved cognition
Full Contact Practice	After medical clearance return to full PRACTICE activity	Restoration of player confidence, functional assessment by coaches
Return to Play	Normal game play	Return to pre-injury performance

Source: Consensus Statement on Concussion in Sport: the 3rd International Conference on Concussion in Sport (Cantu, 2009) Note: HR = Age predicted maximal heart rate

Risk Reduction

The reduction of risk for a SRC begins with a pre-participation evaluation by a trained healthcare provider. The importance of a pre-season a physical examination, injury history, base line neurocognitive and physiological testing cannot be overstated. This data can provide valuable information for categorizing the risk status of an individual athlete prior to exposure to a contact sport. Possible modifiable risk factors should be identified, evaluated and when possible implemented. Unfortunately, current research on preventative strategies for SRC remain inconclusive, lack robust design characteristics and are inflicted with inherent study bias (McCrory et al., 2017; Partridge & Hall, 2014).

Protective equipment such as helmets, pads and mouth-guards offer some impact protection from an open head injury or cranial facture. However, they do not provide protection against intracranial impulse forces (brain shake), particularly for SRC resulting from high velocity rotational forces (Benson, Hamilton, Meeuwisse, McCrory, & Dvorak, 2009). Helmet technology currently focuses on developing an array of tri-axil accelerometers and other sensors that measure helmet impact (impulse) forces during a collision and the number of collisions over time (Bailes, Petraglia, Omalu, Nauman, & Talavage, 2013).

Animal and segregate brain model studies have reported mixed results for a direct linkage between measured impact forces and structural or functional changes in the brain (Meaney & Smith, 2011). These devices have potential to measure sub-concussive thresholds and may be useful for understanding the role of long-term repetitive micro-impacts and CTE (Bailes et al., 2013) Clearly sub-concussive impact are not reported and are remain both difficult and expensive to detect in situ. Future studies should require the use of technology that considers both cost and ease of deployment to larger populations.

Figure 1. The Q-Collar™- (Smith et al., 2012)

One innovated protective device, the Q-Collar™, is made of high tensile plastic designed to apply very mild pressure on the jugular vein. This device may actually reduce the amount of brain "shake" associated with a SRC. The specially designed and fitted collar worn during play. The collar increases intra-cranial blood volume and thus decreases intra-cranial movement (slosh effect) during a concussion related event. Animal models have shown that a small increase in cerebral vascular pressure compliance for those animals fitted with the Q-collar™ had no negative effect on physical performance (Smith et al., 2012). Furthermore, axonal injury was reduced by >80% in animals wearing the collar. Several Q-Collar™ human studies on football, soccer and hockey players have shown a reduction white matter post season changes for those wearing the Q-collar™ compared to controls, despite similar impact exposure (Dudley et al., 2020; Myer et al., 2019; Myer et al., 2016; Yuan et al., 2018). The Q-collar™ may prove to be an effective cost effective device that could reduce the incidence and the severity of a SRC by reducing the slosh effect. Larger, controlled studies looking at player (team) compliance and the Q-collar's influence on sports performance are required.

Finally, the prognostic value of genetic information for the management of concussion has yet to be determined. According to a study by Hartman et al., (2002), the presence of the gene, Apo lipoprotein E (APOE) and a history of TBI are both risk factors for the development of Alzheimer's disease (Hartman et al., 2002; Merritt & Arnett, 2016). In the case of a SRC, these factors may act synergistically by negatively influencing post-concussion neurodegenerative cascade, and increasing the severity of symptomatology (Merritt & Arnett, 2016). Additional human studies are required to clarify the possible predictive role of genetics in management of SRC and CTE.

In summary, defining a SRC remains difficult due to differences in terminology, and the lack of clear standardization among researchers. Furthermore the pathophysiology of concussion is complexed and the response to tissue injury extremely diverse across and gender. Key issues such second impact syndrome and CTE will continue to put pressure on healthcare providers to adopt best practices through ongoing robust research. Healthcare providers are consistently seeking out the best clinical and diagnostic techniques to improve the diagnosis of SRC. Finally, emergent technology will drive objective innovated approaches to the diagnosis and treatment of a SRC across the RTP trajectory.

CHAPTER III

METHODOLOGY

A. Research Design

This study was a retrospective analysis of clinical measures of symptoms, balance (mBESS), and reaction time across return to play trajectories. This study had the approval of The University of Oklahoma Institutional Review Board (IRB) and Oklahoma State University IRB.

Sixty-nine (30 males, 39 Females, age: *M* = 14.6 ±2.5 years) student athletes, were selected from an original cohort of 187 patients who sought out evaluation and treatment for a Sports Related Concussion (SRC) by a sports medicine physician from The University of Oklahoma Sports Medicine Department in Tulsa. Oklahoma during the period from January 1, 2017, through December 31, 2019. These subjects were individuals who sustained a concussion and either did not have access to an AT or had extended post-concussive symptoms and were referred for further evaluation and treatment.

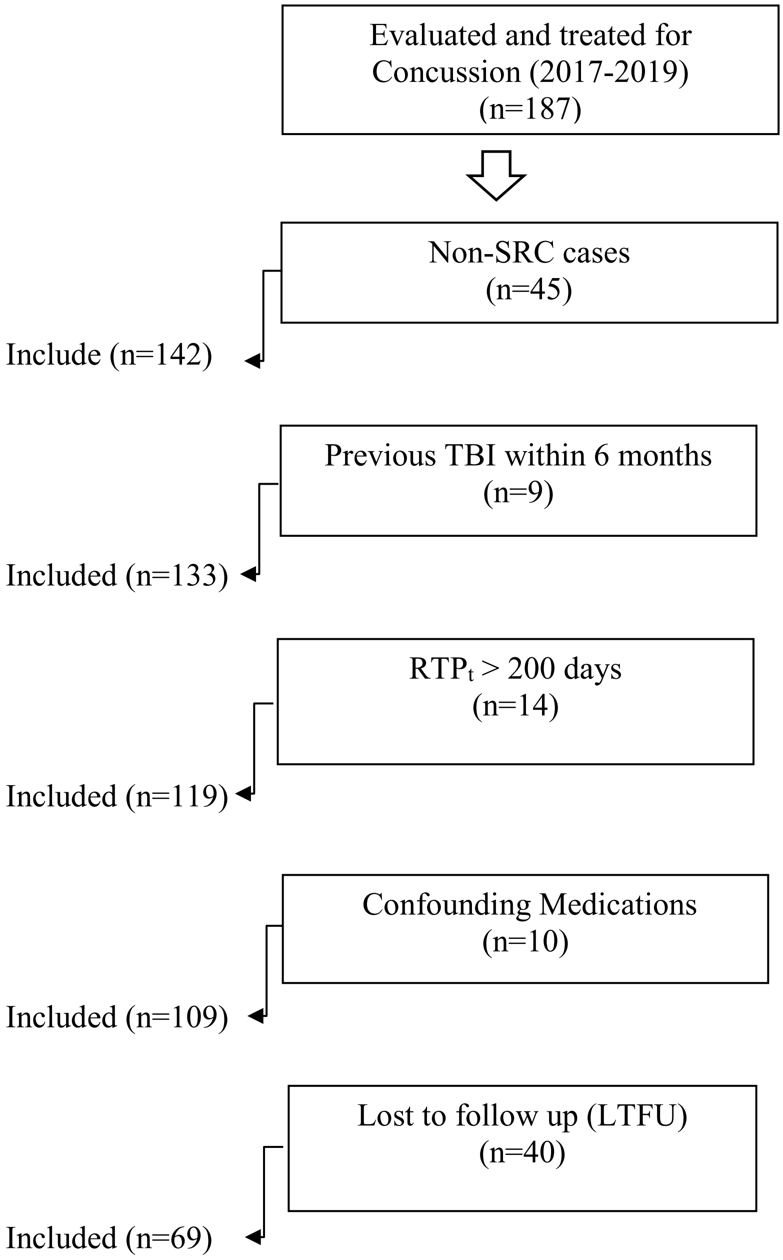
Exclusion Criteria

Athletes with a history of psychological or behavioral disorders or a previous clinical history of concussion within the last 6 months were not included in the study.

Other exclusions included, athletes taking medications that might influence balance or reaction time (e.g. narcotics, tricyclic, gamma-aminobutyric acid drugs, anti-epileptic drugs and barbiturates), those who had no return to play date (lost to follow up) and those with a RTP_t greater than 200 days from date of injury. Figure 1 depicts study exclusion criteria.

Figure 2.

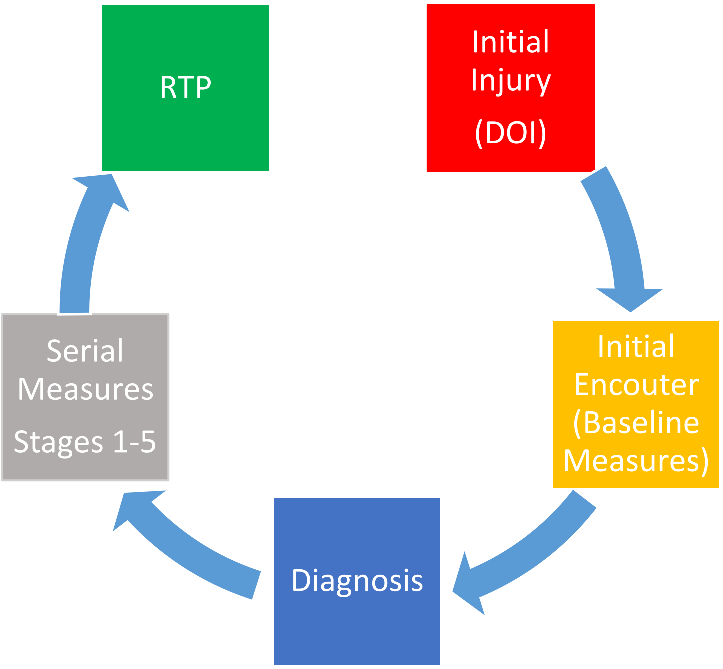
Exclusion Criteria Flow Chart



Evaluation and Treatment Criteria

Athletes were evaluated and treated in accordance with the standards contained in the CISG 4th Consensus statement on the management of SRC (McCrory et al., 2017). All four treating physicians from the University of Oklahoma (OU) sports medicine team followed the CISG 4th consensus guidelines in the development of their SRC treatment plans. Figure 3 presents a flow chart for the key clinical interactions throughout the RTP_t.

Figure 3. Clinical Management Model for SRC - University of Oklahoma Center for Concussion.



Initial Encounter. All athletes completed a standardized OU Sports Medicine History and Physical Form (HPF). The HPF included self-reported information on family and personal health history, symptomology, symptom provocation characteristics, medications, allergies, health behaviors, review of physiological systems and measurement of vital signs including:

i. Vital signs, resting blood pressure (BP), heart rate (HR)

ii. A “concussed baseline” measure for instrumented mBESS test and simple reaction tests

iii. Completion of the PCSS 22 item symptom check list resulting in a total symptom score (0-132) and symptom number (0-22)

iv. Instructional session for monitoring cognitive workloads including a progressive plan for return to school within the limits of current symptom response to cognitive load (See table 3)

Subsequent Encounters. Follow-up visits typically occurred at 2–4-week intervals depending on the availability of the physician and athlete or the severity of symptoms. Each subsequent visit followed a similar protocol of assessment and directives as listed below:

i. Vital signs (resting HR, BP, O2-pulse, temperature)

ii. Completion of the PCSS 22 item symptom check list resulting in a total symptom score (0-132) and symptom number (0-22)

iii. Pre treadmill Instrumented mBESS test and simple reaction time tests

iv. Treadmill Graded Exercise Test (GXT) to determine appropriate symptom limited intensity and duration of exercise during recovery. After a brief warm up at 1.7 mph patients began walking at 2.5 mph increasing their velocity by 0.5 mph every two-minutes until HR reach approximately 80% of age predicted maximal HR. At that point, the subsequent stages reduced to one-minute duration until exhaustion. Treadmill Elevation remained at zero throughout the test. Tests termination criteria included any apparent cardiac or respiratory anomaly (e.g., chest pain, breathing difficulties), dizziness, or significant increase (> 2 points for any PCSS item). Peak treadmill speed, HR and Rating of Perceived Exertion were utilized in determine training workloads.

v. Post exercise instrumented (Sway™) mBESS, simple reaction tests and PCSS

vi. Exercise prescription, a two-to-four-week individualized program including, target heart rates, speeds, duration, and progression.

vii. Exercise programs designed in the context of the athlete's level of symptom provocation during and after a GXT.

Return to Play Criteria.

The RTP criteria was congruent with recommendations contained in the 2016 CISG consensus statement, as well as each individual OU sports medicine physician's clinical judgement for RTP. Several common variables determined an athletes RTP status:

i. Low PCSS (< 8).

ii. No significant balance (mBESS), reaction time or cognitive deficits.

iii. No significant increase in post PCSS, or no significant decrease (5 points) in mBESS and RT performance 10 minutes post exercise (>90% max predicted HR).

iv. The athlete demonstrated tolerance for full academic load without any significant exacerbation of post SRC symptom (e.g., headache, dizziness, photo-phono phobia, nausea, memory).

v. The athlete demonstrated tolerance for full contact in a practice setting and expresses intrinsic confidence in their fitness levels, cognitive status and overall ability to return to play.

No single variable determined clinical decisions regarding treatment options and subsequent RTP trajectories. The dependent measure or outcome measure was RTP trajectory (number of days between date of injury and RTP). PCSS, mBESS and reaction time (RT) were independent predictor variables. All Measures occurred during multiple clinical visits across the RTP trajectory. Final RTP decisions were those of the individual treating physician and closely followed the stepwise approach endorsed by the CISG RTP guidelines previously mentioned in the literature review section of this manuscript (McCrory et al., 2017).

B. Medical Records

Electronic medical records were reviewed for the following information: Date of Injury (DOI), date Returned to Play (RTP), clinical diagnosis, previous concussion history, pre-exiting conditions, SRC treatment history (balance or vestibular training) and medications that would confound performance on a balance or reaction time test and exclude an athlete for this study.

Sway™ Balance application installed on smart phone collected serial measures of PCSS, mBESS and RT. The Sway™ application uses a smart phone bases tri-axial accelerometer to determine a balance (stability) and simple RT score. The measurement units representing the balance and RT score are interpretations of the acceleration of deflection within the accelerometers, and are also determined by undisclosed calculations from Sway™ Medical (Patterson et al., 2014b). The Sway™ application is an FDA approved medical device designed to record SRC symptoms and objectively measure balance and reaction time.

Symptom Scores

Symptom composite score (PCSS) were determined by the Sum of scores on a six- point Likert scale (mild 1-2, moderate 3-4 and Severe 5-6) across 22 common concussion symptoms. Symptomatology included headache, pressure in the head, neck pain, nausea or vomiting, dizziness, blurred vision, balance problems, sensitivity to light, sensitivity to noise, feeling slowed down, feeling like "in fog, don't feel right, difficulty concentrating, difficulty remembering, fatigue or low energy, confusion, drowsiness, trouble falling asleep, more emotional, irritability, sadness and nervous or anxious (Mark R. Lovell et al., 2006).

Balance and Simple Reaction Time

The Sway™ application applies a proprietary algorithm to calculate a composite score (0-100) and simple reaction time (milliseconds) over three individual trials. The first trial serves as a familiarization period, the last two trials used for the determination of a pre-treatment baseline score. A higher score for mBESS indicates better balance control a lower score on the RT indicates faster reaction time (cognition) (Patterson et al., 2014b).

Tests for mBESS involved five standardized standing postures (feet together, tandem left and right, single leg stance left and right). The eyes remain closed throughout each test while and the phone held with both hand flat against the chest to avoid any unnecessary motion. Sample duration was 10 seconds for each posture (see figure 2) and the application provides auditory cues for starting and finishing each segment of the test.

The RT score is an average of five responses and computed as a raw score in milliseconds. As part of the treatment protocol, clinicians compared mBESS and RT performance data to either pre-season non-concussed baseline (when available) or age and sex dependent normative data developed by Brett et al. (Brett et al., 2018). Total symptom score, number of symptoms, mBESS and RT scores were recorded for each visit using the Sway™ smart phone application.

C. Statistical Analysis

Descriptive statistics for age, sex, sport, height weight, BMI, concussion history, RTP trajectory and other clinical metrics (e.g., medications, nystagmus status, balance training, vestibular training, and physical therapy) were calculated. A single outcome variable, return to play trajectory ($RTP_{t)}$, was examined against three predictor variables PCSS (total symptom score), mBESS (Sway™ score) and RT (milliseconds). Four hypothesizes were tested:

H_1 – RTP_t is positively associated with pre-treatment PCSS.

H_2 – RTP_t is positively associated with pre-treatment mBESS performance.

H_3 - RTP_t is negatively associated with pretreatment RT performance.

H_4 - Female RTP_t, PCSS, mBESS, and RT are significantly different when compared to Male RTP_t PCSS, mBESS and RT.

Pearson's correlation coefficients determined the relationship of the outcome variable RTP_t to all three independent variables (PCSS, mBESS and RT). A multiple regression model was calculated for predictor variables PCSS, mBESS and RT against the outcome variable RTP_t. Independent t-tests assessed differences in RTP_t, for PCSS, mBESS and RT. An alpha of $< .05$ and *CI* of 95% was established unless otherwise stated. For effect size, Hedges' *g* correction was used to adjust for sample mean bias related to small and different sample sizes (Hedges & Olkin, 1985). Calculated effect size were classified as Small = 0.2, medium = 0.5 and large = 0.8 (Cohen, 1988).

CHAPTER IV

FINDINGS

A. Participant Demographics

This study reviewed one hundred and eighty-seven concussed athlete's electronic medical records. Exclusions included, 45 non-sports related cases, nine athletes who had sustained a previous concussion within the last six months, 14 athletes with $RTP_t > 200$ days and 10 athletes who were prescribed confounding medications including: tricyclic ($n = 5$), gamma-aminobutyric acid ($n = 2$), anti-epileptic drug ($n = 1$) and barbiturates ($n = 1$). These drugs may have negative influences on clinical measures of balance or reaction time.

Forty athletes were lost to follow-up (LTFU) and were not included in the primary data analysis. Tables 4A and 4B present the characteristics of LTFU athletes, those athletes included in the analysis for raw, and Log 10 transformed data, respectively. Time-till treatment, PCSS, mBESS, and RT were log10 transformed to address skewness and kurtosis violations. Independent t-tests for LTFU and athletes included in the analysis were calculated for mean TTT height, weight, age, BMI, mBESS and RT. A Bonferroni Correction ($\alpha = .0125$) was applied to control for family wise Type I error for PCSS, mBESS, RT and TTT. Homogeneity of variance was assumed for TTT, $F(107) = .002$, $p = .965$, PCSS, $F(107) = .1.637$, $p = .129$, mBESS, $F(107) = .056$, $p = .814$ and RT $F(107) = .636$, $p = .427$.

Table 4A.

A. Descriptive Characteristics Included (n=69) and LTFU (n=40) Raw Data

	Cohort	*M (SD)*	*95% CI*	*Skew*	*Kurtosis*	*p*	*ES (g)*
Age	Included	14.2 (2.24)	13.6,14.8	.211	0.183	.288	0.223
(Years)	LTFU	14.7 (2.23)	14.1,15.4	.514	0.782		
Height	Included	64.9 (4.8)	63.7,66.1	-.142	.226	.244	0.248
(Inches)	LTFU	66.0 (3.7)	64.8,67.1	.042	.046		
Weight	Included	134.3 (38.3)	125.1,143.6	.887	2.402	.418	0.144
(Pounds)	LTFU	140.7 (41.5)	127.2,154.3	.972	1.411		
TTT	Included	15.9 (17.4)	11.7,20.1	2.326	7.23	.002*	0.107
(Days)	LTFU	36.8 (38.1)	24.6,48.9	1.954	4.863		
PCSS	Included	19.1 (21.4)	13.9,24.2	1.646	2.641	.017	0.510
(Score)	LTFU	30.8 (25.3)	22.1,38.3	.866	.044		
mBESS	Included	81.2 (14.3)	77.8,84.7	-1.278	1.366	.146	0.286
(1-100)	LTFU	77.2 (13.3)	72.9,81.4	-.528	-.044		
RT	Included	298 (92.1)	276.3,320.6	.933	.532	.589	0.107
(Milliseconds)	LTFU	287.7 (110.5)	252.4,323.1	2.399	6.478		

Table 4B

Log 10 Descriptive Characteristics: Included (n=69), LTFU (n=40)

	Cohort	*M (SD)*	*95% CI*	*Skew*	*Kurtosis*	*p*
TTT$_{\text{log10}}$	Included	0.97 (.50)	0.80,1.05	-.278	-.799	.001*
(Days)	LTFU	1.32 (.54)	1.42,1.50	-.607	-.122	
PCSS$_{\text{log10}}$	Included	11.9 (3.3)	8.8,16.2	-.392	-.655	.014
(Score)	LTFU	1.34 (.47)	1.18,1.49	-1.01	.424	
mBESS$_{\text{log10}}$	Included	1.90 (.09)	1.88,1.92	-1.96	4.79	.233
(1-100)	LTFU	1.88 (.08)	1.85,1.90	-1.05	1.33	
RT$_{\text{log10}}$	Included	2.45 (.14)	2.42,2.49	.394	-.463	.438
(Milliseconds)	LTFU	2.44 (.13)	2.39,2.48	1.092	1.092	2.245

Note: LTFU = Lost to follow-up, TTT = Time-till Treatment (Days from DOI to treatment), PCSS = post-concussion symptom score, mBESS = modified Balance Error Scoring System Score, RT = reaction time, *M* = Mean, *SD* = standard deviation, *CI* = 95% confidence intervals, * significant at *p* < .013

The LTFU group mean for TTT was 10 days longer, $t(107) = 3.598$, $p <.001$, $g = 3.707$ than the group included in the study analysis. Mean LTFU PCSS, mBESS and RT values were not statistically significantly different when compared to the inclusive group of athletes.

B. Statistical Analysis

Descriptive and inferential statistics were calculated utilizing IBM SPSS Statistics software, Version 25.0 (Armonk, NY, IBM Corporation). Sixty-nine student athletes (30 males and 39 females), $M = 14.2$, $SD = \pm 2.2$ years of age, were included in the analysis. These subjects are individuals who at the initial injury did not have access to a healthcare provider or had extended post-concussive symptoms that led to a referral to a physician. A show in Table 5, RTP_t was on average 60.4, SD = ±43.8, days with only 8.6% athletes (6/69) returning to play in less than two weeks. Participants were drawn from 11 different sports. Soccer players represented the greatest number of concussions at 37.6% (26/69. Football and basketball players accounted for 23.1% (16/69) and 14.4% (10/69) of SRC injuries respectively. Collectively, cheerleading, gymnastics and strength training were responsible for 14.3% (10/69) of SRCs and 9.8% (7/69) with the remaining SRCs attributed to lacrosse, cross-country, motor-cross, rodeo, volleyball, and an unknown category. Across sports, females playing soccer and basketball had higher incidence of SRC than males at 80% (8/10) and 73% (18/26) respectively. There were no male SRCs for gymnastics and no female SRCs for lacrosse.

The study population (n=69) outcome variable (RTP_t) and predictor, variables (PCSS, mBESS, and RT) were log10 transformed to address skewness and kurtosis. Shapiro-Wilk tests for normality were not significant ($\alpha < 0.05$) for RTP_t, $F(69) = .982$, $p = .405$, mBESS, $F(69) = 975$, $p = .174$ and RT, $F(69) = 974$, $p = .161$. For PCSS Shapiro-Wilks was significant $F(69) = .960$, $p = .026$ and a Kolmogorov-Smirnov test was applied and verified normal distribution, *D*(69) = 0.084, *p* = 0.200. Assumptions for skewness and (±1.0) and kurtosis (±2) were satisfied. Residual error plots met the requirements of homogeneity of variance. Scatter plots reviewed

Figure 4.
Distribution of Concussion by Sport (n=69)

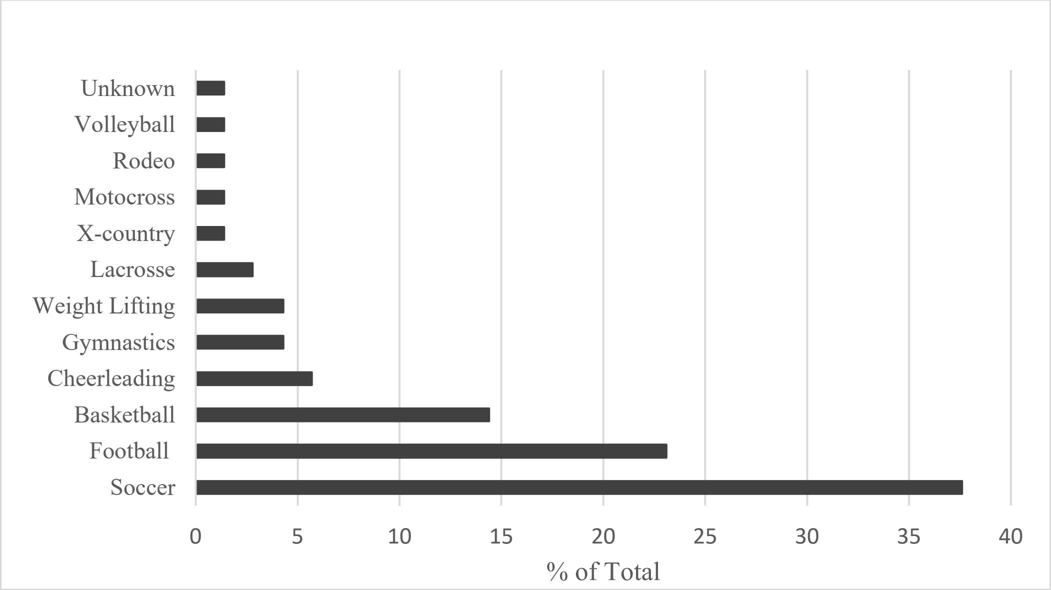


Table 5
Study Population (n=69) Descriptive statistics for Raw (A) and Log 10 transformed (B)

A. Raw Data

	Min	**Max**	***M***	***SD***	**Skewness**	**Kurtosis**	***p* value**
RTP_t	6	197	60.4	43.8	1.305	1.48	<.001[1]
PCSS	0	98	19.1	21.4	1.64	2.64	<.001[1]
mBESS	31.9	99.1	81.2	14.8	-1.27	1.0	<.001[2]
RT	169	573	298.4	92.1	2.39	0.53	>.05[2]

B. Log 10 Data

	Min	**Max**	***M***	***SD***	**Skewness**	**Kurtosis**	***p* value**
$\text{RTP}_{t\text{-Log10}}$	.78	2.29	1.66	.338	-.408	-.106	.405[1]
$\text{PCSS}_{\text{Log10}}$	.00	2.00	1.04	.535	-.388	-.639	.200[2]
$\text{mBESS}_{\text{Log10}}$	.00	1.83	1.14	.365	-.565	.495	.174[1]
RT_{Log10}	2.23	2.76	2.45	.126	.383	-.448	.161[1]

[1] Shapiro-Wilks, [2] Kolmogorov-Smirnov, RTP_t (days), PCSS (Score), mBESS (1-100) RT (milliseconds)

Visually and confirmed linear relationships between the outcome variable and predictor variables. Table 5a and 5b depicts descriptive statistics for raw data and log-10 transformed RTP_t, PCSS, mBESS and RT variables, respectively.

Pearson's correlational coefficients were calculated to test hypotheses one, two, and three and to examine the relationship between TTT and RTP_t. When compared to mBESS and RT, both TTT ($r = .471$, $p =.000$) and PCSS ($r = .369$, $p =.001$) had the highest correlation with RTP_t. Paired sample t-tests derived the differences between pre-treatment and post treatment values for RTP_t, PCSS, mBESS and RT. Multiple linear regression determined the predictive value of TTT, PCSS, mBESS and RT on RTP_t. Three prediction models are presented. For hypothesis four, sex differences, independent t-tests determined sex differences for RTP_t, PCSS, mBESS, and RT variables. Data is presented in both raw and log-10 format to aid in interpretation.

Hypothesis I.

Bivariate correlation determined the strength of the relationship between pre-treatment PCSS and RTP_t. A moderate positive correlation was found between PCSS and RTP_t. Pearson's $r(69) = .323$, $p = .003$, and the null hypothesis was rejected. Log-10 transformed data, $PCSS_{log10}$, however had a smaller positive correlation with $RTP_{t\text{-}log10}$, Pearson's $r(69) = .231$, $p = .056$.

The difference between mean pre-treatment ($M = 19.3$, SD± 21.1) and post treatment values ($M = 2.0$, $SD \pm 3.5$) for PCSS was statistically significant, with a mean reduction of 17.2 points, $SD \pm 20.5$, CI 12.2, 22.1, $t(68) = -6.952$, $p < .001$, $g = 1.13$. There was a large effect size for PCSS.

Hypothesis II.

Bivariate correlation determined the relationship between mBESS and RTP_t. A small negative correlation was found between the mBESS and RTP_t, Pearson's r (69) = -.147, p = .114.

The relationship between mBESS and RTP_t, was not statistically significant. Log-10 transformed data, $mBESS_{log10}$, also showed a small statistically non-significant negative correlation for $mBESS_{log10}$ and $RTP_{t\text{-}log10}$, Pearson's r(69) = -.065 , p = .596. The null hypothesis was retained.

There was a very small, but statistically significant difference, between pre-treatment mBESS values (M = 81.1, SD ± 14.4) and mBESS post treatment values (M = 84.6 SD ± 10.2) for mBESS with a mean difference of - 3.5 points, SD ±13.9, CI -6.88,-0.19, t(68) = -2.107, p = .039, g = 0.283. A small effect size was observed for pre-treatment post-treatment changes in mBESS.

Hypothesis III

Bivariate correlation determined the relationship between RT and RTP_t. A weak negative correlation was found between the variables, Pearson's r(69) = -.023, p = .426, The relationship between RT and RTP_t, was not statistically significant. Log10 transformed RT data revealed a weak, statistically non-significant positive correlation for RT_{log10} and $RTP_{t\text{-}log10}$, Pearson's r(69) = .037 , p = .761. The null hypothesis was retained.

There was a significant difference between mean pre-treatment RT (M = 298.5, SD ± 92.1) and post treatment RT (M = 247.3 SD ± 59.5) for RT, with a reduction of M = 51.1, SD ±13.9 milliseconds, CI 31.6, 70.5, t(68) = -2.107, p <.001, g = 0.659. A medium effect size was determined for changes in RT across the RTP_t.

Regression Equations

Multiple linear regression was used to develop three prediction models for $RTP_{t.}$ Model 1 utilized three predictor variables; PCSS, mBESS and RT. Assumptions were met for linearity of PCSS, mBESS, RT and RTP_t. Tolerance, variance inflation factor (VIF) and Pearson's *r* were within normal limits confirming no multi-collinearity for all model variables. Model-1 was significant for the prediction of RTP_t, $F(3,65) = 2.922$, $p = .038$ but not for $RTP_{t\text{-}Log10}$, $F(3,62) = 2.416$, $p = .075$ as shown in the ANOVA in Table 6A (Raw data) and Table 6B (Log 10 data) respectively.

Table 6A

Raw Data ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	15743.460	3	5247.820	2.968	.038[b]
	Residual	114923.352	65	1768.052		
	Total	130666.812	68			
2	Regression	13632.174	1	13632.174	7.804	.007[c]
	Residual	117034.638	67	1746.786		
	Total	130666.812	68			

Table 6B

Log10 Transformed ANOVA[a]

Model$_{log10}$		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	.424	3	.141	1.249	.0299[b]
	Residual	7.350	65	.111		
	Total	7.774	68			
2	Regression	.416	1	.416	3.787	.056[c]
	Residual	7.358	67	.110		
	Total	7.74	68			

a. Dependent Variable: $RTP_{t\text{-}Log10}$ b. Predictors: (Constant), RT_{log10}, $mBESS_{Log10}$, $PCSS_{log10}$ c. Predictors: (Constant), $PCSS_{log10}$

The model had only one statistically significant predictor variable, PCSS ($t = 2.676$, $p = .009$, $\beta = .318$). $\text{PCSS}_{\text{log10}}$ ($t = 1.884$, $p = .070$, $\beta = .229$). mBESS ($t = -.853$, $p = .397$, $\beta = -.101$), $\text{mBESS}_{\text{Log10}}$ ($t = -.252$, $p = .802$, $\beta = -.031$), RT($t = -.398$, $p = .692$, $\beta = -.051$) and RT_{Log10} ($t = -.110$, $p = .913$, $\beta = -.014$ were not statistically significant predictors of RTP_{t} or $\text{RTP}_{\text{t-Log10}}$. Tables 7A and 7B present regression coefficients for RTP_{t} and $\text{RTP}_{\text{t-Log10}}$.

The following regression equations were derived:

$\text{RTP}_{\text{t}} = 85.59 + .655\ (\text{PCSS}) - .332\ (\text{mBESS}) - .037\ (\text{RT})$ and

$\text{RTP}_{\text{t-log10}} = 2.835 + .137\ (\text{PCSS}_{\text{Log10}}) - .144\ (\text{mBESS}_{\text{Log10}}) - .036\ (\text{RT}_{\text{Log10}})$

A second regression model excluding mBESS and RT revealed an R^2 of 10.4%, and an adjusted R^2 of 9.1%. As shown in Table 7A and Table 7B, the second single predictor (PCSS) model remained a significant predictor, $t = 2.794$, $p = .007$, $\beta = .323$ when regressed on RTP_{t} but not for $\text{PCSS}_{\text{log10}}$ on $\text{RTPt}_{\text{-Log10}}$ ($t = 1.946$, $p = .056$, $\beta = .231$). The predictive value of Model-2 was close to those described previously in model one. The following regression equations were derived using model 2 for PCSS on RTP_{t} and $\text{PCSS}_{\text{log10}}$ on $\text{RTP}_{\text{t-Log10}}$:

$\text{RTP}_{\text{t}} = 47.59 + .655\ (\text{PCSS})$ and $\text{RTP}_{\text{t-log10}} = 2.527 + .138\ (\text{PCSS}_{\text{Log10}})$

Table 7A:
Regression Co-efficients for PCSS, mBESS and RT

		Coefficients					95% *CI*		Correlations	
Model		B	SEM	β	t	Sig.	Lower	Upper	Partial	Part
1	(Constant)	85.591	35.5		2.406	.019	14.54	156.63		
	PCSS	.655	.244	.318	2.683	.009*	.168	1.142	.316	.312
	mBESS	-.332	.360	-.109	-.922	.360	-1.050	.386	-.114	-.107
	RT	-.037	.056	-.077	-.652	.517	-.148	.075	-.081	-.076
2	(Constant)	47.595	6.811		6.988	.000	34.000	61.190		
	PCSS	.665	.238	.323	2.794	.007*	.190	1.141	.323	.323

a. Dependent Variable: RTP_{t}, *Significant $p < .01$.

Table 7B:

Regression Co-efficient for PCSS$_{log10}$*, mBESS*$_{log10}$ *and RT*$_{Log10}$

		Coefficients					95% *CI*		Correlations	
Model		B	SEM	*β*	t	Sig.	Lower	Upper	Partial	Part
1	(Constant)	2.835	1.243		2.280	.026	.351	5.318		
	PCSS$_{Log10}$	.137	.074	.229	1.884	.070	.-.011	.286	.223	.222
	mBESS$_{Log10}$	-.114	.452	-.031	-.252	.802	-1.018	.789	-.031	-.030
	RT$_{log10}$	-.036	.331	-.014	-.110	.913	-.698	.625	-.014	-.013
2	(Constant)	2.527	.080		31.621	.000*	2.367	2.686		
	PCSS$_{log10}$	.138	.071	.231	1.946	.056	-.004	.280	.231	.231

a. Dependent Variable: RTP$_{t\text{-}Log10}$, *Significant $p < .001$.

A third regression model utilizing two predictor variables, TTT and PCSS on RTP$_t$ revealed an R^2 of 42.7%, and an adjusted R^2 of 41.% (p < 001). Both TTT and PCSS had moderate correlation with RTP$_t$ at $r(69) = 0.471$, $p = .000$ and $r(69)= 0.369$, $p = .001$) respectively and were considered more robust predictors of RTP$_t$ than mBESS and RT. The model had significant improvement in fit when compared to models 1 and 2. Table 7A and 7B shows regression coefficients for TTT, PCSS, TTT$_{log10}$, PCSS$_{log10}$ respectively. Model-3 had two statistically significant predictor variable, TTT ($t = 5.787$, $p = .000$, $\beta = .318$) and PCSS ($t = 1.884$, $p = .000$, $\beta = .229$). The following regression equations were derived using Model-3 for TTT and PCSS on RTP$_t$ and TTT$_{log10}$ and PCSS$_{log10}$ on RTP$_{t\text{-}Log10}$ respectively: RTP$_t$ = 9.66 + 1.379 (TTT) + 1.005 (PCSS) and RTP$_{t\text{-}log10}$ = 2.020 + 0.407 (TTT$_{log10)}$ + 0.241 (PCSS$_{Log10}$)

Table 8a:

Regression Co-efficients^a *for TTT and PCSS.*

		Coefficients					95% *CI*		Correlations	
Model		B	SEM	*β*	t	Sig.	Lower	Upper	Partial	Part
3	(Constant)	9.66	7.073		2.781	.007*	5.546	33.789		
	TTT	1.379	.238	.547	5.787	.000*	.903	1.855	.580	.539
	PCSS	1.005	.360	-.109	-.922	.000*	.592	1.418	.513	.415

a. Dependent variable: RTP$_t$ * significant $p < .001$

Table 8B:

Regression Co-efficients[a] *for* TTT_{log10}*, and* $PCSS_{log10}$*,*

		Coefficients					95% *CI*		Correlations	
Model		B	SEM	*β*	t	Sig.	Lower	Upper	Partial	Part
3	(Constant)	2.020	1.00		20.184	.000*	1.820	2.220		
	TTT_{log10}	0.407	.066	.591	6.190	.000*	.276	.539	.624	.590
	$PCSS_{log10}$	0.241	.0.66	.350	3.670	.001*	.109	.372	.428	.350

a. Dependent variable: $RTP_{t\text{-}log10}$ * significant $p < .001$

Symptoms and Return to Play

The positive slope for PCSS as a predictor of RTP_t indicated a .655-day increase in RTP_t for every 1-point increase in PCSS. For Model-1, the squared semi-partial coefficient (.312) estimated that RTP_t was predicable from PCSS, with 31.2% of the variance in RTP_t uniquely accounted for by PCSS when mBESS and RT are controlled. For model two, the squared semi-partial coefficient (.323) estimated that RTP_t was predicable from PCSS, with 32.3% of the variance in RTP_t uniquely accounted for by PCSS. The results for model two were comparable to model one. For model three, the squared semi-partial coefficient (.539) estimated that RTP_t was predicable from PCSS with 41.5% of the variance in RTP_t uniquely accounted for by PCSS when accounting for TTT. The positive slope for PCSS as a predictor of RTP_t indicated a 1.01-day increase in the RTP_t. for every 1-point increase in PCSS. The results for Model-3 were superior to Model-1 and Model-3.

Hypothesis IV

Independent t-tests (2-tailed) were conducted to explore sex differences for Age, RTP_t, TTT, PCSS, mBESS, and RT. An initial alpha of .05 was set. TTT, PCSS, mBESS and RT. Variables were log 10 transformed to address skewness and kurtosis. Levine's test revealed homogeneity of variance for age, RTP_t, $F(1,67) = 2.927$, $p = .092$, PCSS, $F(1,67) = 0.045$, $p = .832$, mBESS, $F(1,67) = 1.402$, $p = .241$, and RT, $F(1,67) = 0.499$, $p = .482$. Equal variances were not assumed for TTT, $F(1, 67) = 6.311$, $p = .014$. Tables 8A and 8B show group means, standard deviations, confidence intervals and p values by sex for raw and log10 transformed data, respectively.

Sex differences for RTP_t, mBESS and RT had small effect sizes and were not statistically significant. For RTP_t, females on average took almost two weeks longer to recover than males, M =13.6, SD ±10.6, days longer, $t(67) = 1.289$, $p = .202$, $g = 0.357$, $RTP_{t\text{-Log 10}}$ $t(67) = .807$, $p = .442$. For TTT, females took slightly longer than males to seek treatment, $M = 3.25$, SD ±5.1, days difference, $t(67) = 0.655$, $p = .514$, $g = 0.159$, TTT_{Log10} $t(65.9) = -.944$, $p = .349$. Differences in female PCSS scores (symptoms) were marginally higher than males, M =3.25, SD ±5.1, points, $t(67) = 0.628$, $p = .532$, $g = 0.170$, $PCSS_{Log10}$ $t(67) = 1.846$, $p = .069$. For mBESS, female balance scores were marginally higher than males, $M = 4.9$, SD ± 3.4 points difference, $t(67) = 1.426$, $p = .158$, $g = 0.323$, $mBESS_{Log10}$ $t(67) = 1.447$, $p = .152$. Male RT scores were faster than females, $M = 42.1$, SD ±21.9 milliseconds quicker, $t(67) = 1.197$, $p = .059$, $g = .465$, RT_{Log10} $t(67) = 2.028$, $p = .047$. Overall, effect sizes for sex were small for RTP_t, PCSS, mBESS and RT. For TTT, there was a medium effect size for sex.

Male and female paired t-test for pre-treatment and post-treatment across PCSS, mBESS and RT variables are presented in Figure 5. For PCSS scores females decreased by M 18.3, SD ±20.4, points $t(38) = 5.589$, $p < .001$, $g = 1.204$ and were statistically significant and had a large effect size. Male PCSS scores decreased by M 15.8, SD ±21.1, points $t(30) = 4.124$, $p < .001$, $g = 1.025$ and were also statistically significant and had a large effect size. For RT females improved by M 58.7, SD ±80.0 milliseconds $t(39) = 4.582$, $p < .001$, $g = 0.729$ and males improved by M 41.2, SD ±82.5 milliseconds, points $t(30) = 2.736$, $p = .011$, $g = 0.587$. Effect sizes were moderate to large (see Table 9A). There were no significant differences between pre-treatment and post treatment mBESS for either females (*M* -3.51, *SD* ±11.6, points *t* (38) = -1.890, *p* = .066, *g* = 0.318 or males (*M* -3.55, *SD* ±16,6, points *t*(29) = -1.168, *p* = .252, g = 0.264. Effect sizes were small.

Table 9A

Raw Descriptive Statistics (Males n= 30, Females n = 39)

	Sex	*M (SD)*	*95% CI*	*Skew*	*Kurtosis*	*p*	*ES*
Age	Female	14.2 (2.8)	13.3, 15.1	.350	.340	.937	0.020
(Years)	Male	14.3 (2.1)	13.4, 15.0	-.214	-.787		
RTP_t	Female	65.7 (47.5)	50.2,81.1	1.038	.636	.202	0.357
(Days)	Male	52.7 (38.3)	38.3,67.0	1.875	4.370		
TTT	Female	17.1 (21.1)	10.3,24.0	2.17	5.178	.514	0.159
(Days)	Male	14.3 (11.1)	10.2,18.5	1.014	.525		
PCSS	Female	20.6 (21.1)	13.8,27.5	1.820	3.888	.832	0.170
(Score)	Male	17.4 (21.6)	8.2, 22.0	1.685	2.678		
mBESS	Female	83.1 (12.8)	79.3,87.5	-1.262	.802	.188	0.323
(1-100)	Male	78.5 (16.0)	72.5,84.4	-1.196	1.342		
RT	Female	316.7 (96.3)	285.5,348.0	.975	.318	.059	0.465
(Milliseconds)	Male	274.7 (81.9)	244.1,305.2	1.014	.525		

Table 9B:

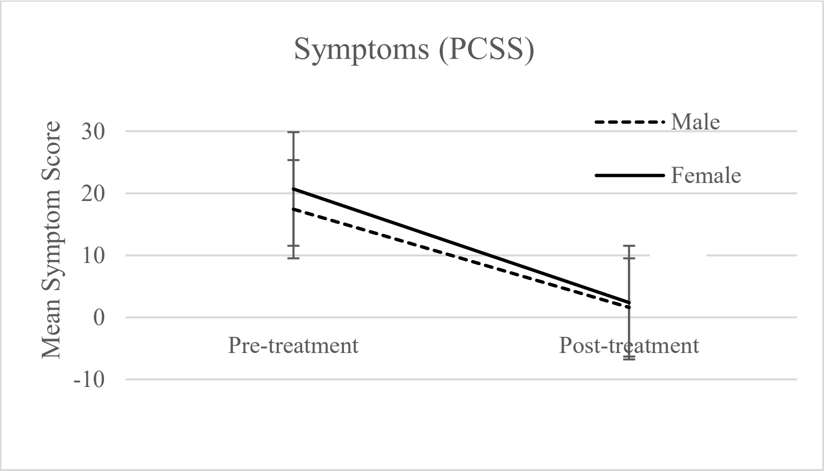
Log 10 Descriptive Statistics (Males n= 30, Females n = 39)

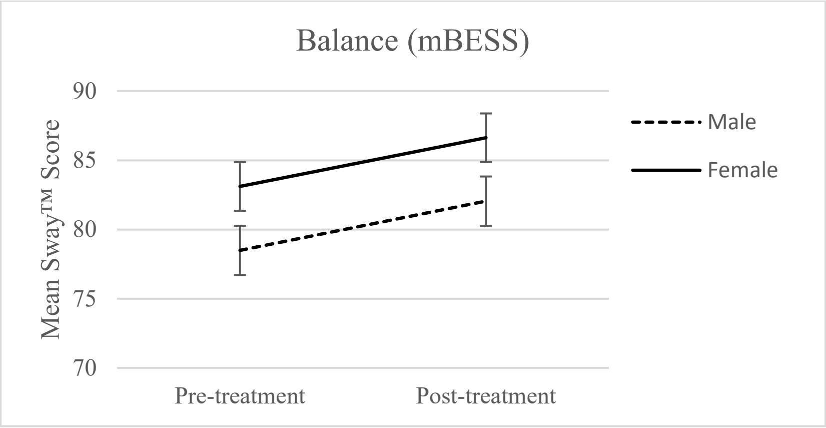
	Sex	*M (SD)*	*95% CI*	*Skew*	*Kurtosis*	*p*
$\text{RTP}_{\text{t-Log10}}$	Female	2.69 (0.36)	2.57,2.81	-.626	-.222	.422
(Days)	Male	2.60 (2.1)	2.47,2.73	-.086	-.202	
$\text{TTT}_{\text{Log10}}$	Female	0.90 (0.56)	0.71,1.09	-.126	-1.148	.349
(Days)	Male	0.96 (0.39)	0.80,1,12	-.586	.283	
$\text{PCSS}_{\text{Log10}}$	Female	1.082 (0.51)	0.91,1,25	-.463	-.367	.163
(Score)	Male	0.834 (0.62)	0.60,1.06	-.085	-.367	
$\text{mBESS}_{\text{Log10}}$	Female	1.91 (0.07)	1.88,1.93	-1.48	-1.15	.349
(1-100)	Male	1.88 (0.11)	1.84,1.93	-.2.11	5.44	
RT_{Log10}	Female	2.48 (0.12)	2.44,2.52	.364	-.496	.047
(Milliseconds)	Male	2.42 (1.3)	2.37, 2.47	.328	-.709	

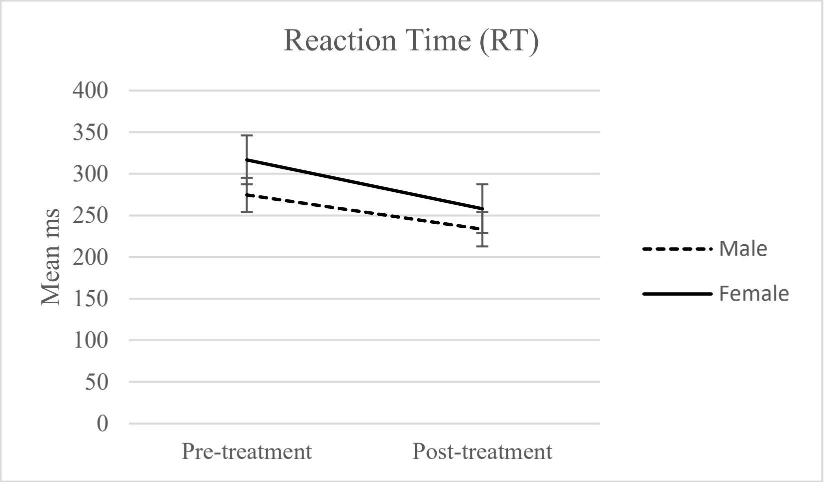
Legend: RTPt = Return to play trajectory, TTT = Time till treatment, PCSS = pre-treatment symptom score, mBESS = pre-treatment balance score, RT = pre-treatment, reaction time score, 95% *CI* = confidence levels, *ES* = effect size (*Hedges g)*

Figure 5.

Pre-treatment and Post-treatment Mean and Standard Deviation for Symptoms, Balance and Re-action Time. Males (n =30) and Females (n = 39).







C. Secondary Data Analysis

Secondary data analysis included examination of two important clinical measures, loss of conscious (LOC) and vestibular ocular motor sensory (VOMS) dysfunction and their influence on RTP_t. PCSS, mBESS and RT. The LOC group, accounted for 17.3% (12/69) of athletes and this group had a longer RTP_t, M =14.5, SE ±13.9, days than those who did not experience a LOC. A Bonferroni correction ($\alpha = .0125$) was applied to control for family wise Type-I error. Table 9 shows group statistics for athletes positive for LOC and those negative for LOC. Group mean differences were not statistically significant for RTP_t, $t(67) = 1.044$, $p = .300$, $g = 0.364$, PCSS, $t(67) = 0.420$, $p = .676$, $g = 0.133$, mBESS, $t(67) = 0.548$, $p = .585$, $g = 0.173$, and RT, $t(67) = 0.125$, $p = .901$, $g = 0.044$. Effect size for LOC on RTP_t was small, for mBESS and RT and was extremely small (< 0.1).

When looking at VOMS dysfunction sixty-six percent of athletes (46/69) were positive for dysfunction. Breaking VOMS down, 27.5% (19/69) of athletes were positive for nystagmus only, 31% (21/69) were positive for both nystagmus and convergence and 7.2% (5/69) tested positive for convergence only. Independent t-tests for RTP_t, PCSS, mBESS and RT determined the influence of vestibular dysfunction on these variables. A Bonferroni correction ($\alpha = .0125$) was applied to control for family wise Type-I error. Mean differences for athletes positive for VOMS dysfunction were not statistically significantly different for RTP_t, $t(67) = -\ 0.894$, $p = .300$, $g = 0.228$, PCSS, $t(67) = -\ .183$, $p = .676$, $g = 0.046$, mBESS, $t(67) = -\ 2.301$, $p = .024$, $g = .646$ and RT $t(67) = 1.044$, $p = .901$, $g = 0.001$. Effect size was moderate for mBESS, small for RTP_t and exceedingly small for PCSS and RT.

Table 10.
Loss of Conscious Group Statistics No LOC (n=57), LOC (n =12)

	LOC	*M*	*SD*	*95% CI*
RTP_t	-	57.8	42.3	46.6,69.1
(Days)	+	72.4	50.3	40.4,104.4
PCSS	-	19.7	22.5	13.8,25.8
(Score)	+	16.9	13.9	8.0,25.8
mBESS	-	81.5	14.3	77.7,85.3
(1-100)	+	79.0	14.8	69.6,88.4
RT	-	299.1	88.2	299.1,322.5
(msec.)	+	295.4	113.5	223.2,367.5

Table 11.
Group Statistics; VOMS positive (n = 46), VOMS negative (n = 23)

	VOMS	*M*	*SD*	*95% CI*
RTP_t	-	53.7	42.3	35.4,72.0
(days)	+	63.8	44.6	50.5,77.0
PCSS	-	18.6	22.7	8.7,28.4
(Score)	+	19.6	20.7	13.4,25.7
mBESS	-	75.6	16.2	68.6,82.6
(1=100)	+	83.8	12.6	80.1,87.6
RT	-	298.3	86.6	260.9,335.9
(msec.)	+	298.5	95.7	298.5,326.9

Note: LOC = Loss of conscious, VOMS = Vestibular Ocular-motor Screen
RTP_t = Return to Play Trajectory, PCSS = Post Concussion Symptom Score
mBESS = Modified Balance Error Scoring System, RT = Reaction Time
95% *CI* = Confidence intervals,

CHAPTER V

CONCLUSIONS

The primary objective of this study was to examine the relationship between post-concussion RTP_t and three independent clinical variables, PCSS, (symptoms), mBESS (balance) and RT (reaction time). Post-concussion symptoms, mBESS and RT are common variables used in the clinical evaluation and treatment of SRC. The sample population's RTP_t was elongated, (*M* = 60.4, *SD* = 43.8, days) when compared to previous studies. Previous research has shown RTP_t for most athletes is between 7-28 days (Blume & Hawash, 2012; Henry et al., 2016). In the sample population only 8.6% athletes (6/69) returned to play in less than two weeks. This difference may be due to the fact that previous research included patients that were seen by a healthcare provider on the initial date of injury versus the delayed TTT (*M* = 15.9 *SD* ±17.4 days) seen in this study. Thus, the findings of this study may more applicable to those athletes who have suffered from sustained post-concussive symptoms rather than generalized to the overall concussion population.

A. Symptoms

There was a moderate positive association between PCSS and RTP_t, ($r = .323$, $p = .003$). PCSS had a small, but significant influence on the number of days it takes to recover from an SRC, with 10.4% of variability in RTP_t explained by the variability in

PCSS. The positive slope for PCSS as a predictor of RTP_t indicated a .655-day increase in RTP_t for every one-point increase in PCSS. This result was expected. The study population's pre-treatment PCSS (*M* = 19.1 ±21.4) and were similar to PCSS values reported by Custer et al (2016), M = 21.2 ± 17.4) and slightly had higher than PCSS values (Median = 13 (4-29) reported in a pediatric population study by Ellis et al (2015)(Custer et al., 2016; Ellis et al., 2015). Previous studies have associated prolonged recovery time after SRC in athletes with high symptom scores and a wide spectrum of symptoms. (Lau et al., 2012; McCrea et al., 2013). PCSS is a useful, statistically significant ($p = 0.026$) predictor of RTP_t (Zuckerman et al., 2012). Furthermore, athletes with a personal and/or family history of mood disorders, other psychiatric illness, and/or migraine headaches have higher mean PCSS scores (33 v. 25; $p < 0.004$) than those who have not sustained a previous concussion (Meehan et al., 2013). These variables can be potential "symptom inflators" and should be by considered by health care providers when accessing the influence of PCSS scores on RTP_t.

B. Balance

Balance (mBESS) had a weak negative association with RTP_t, with only 2.1% of variability in RTP_t explained by the variability in mBESS scores. One explanation for this association could be that athletes included in the study had considerable time lag between their date of injury (DOI) and time-till treatment (TTT) (*M* = 15.9, *SD* ±17.4 days). Some limitations of the mBESS may be present, including an inability of the instrument to detect changes in balance beyond the acute stage of a SRC. Previous research by Murray et al. (2014) suggests a non-instrumented BESS test fails to detect balance deficits beyond 7 days post SRC and that this tool is more applicable as pre-screening "side-line" test or evaluation in the early stages of concussion management (Murray et al., 2014). McCrea et al, (2005) reported balance impairments on a non-instrumented BESS for 36% of concussed college athletes compared to 5% for non-concussed controls immediately following a SRC. By day seven post-injury, only 9% of concussed athletes demonstrated balance impairments (McCrea et al., 2005). Clinician's must recognize the temporal limitations of evaluative tools for balance and their respective measurement reliability across the RTP trajectory.

C. Reaction Time

Reaction time (RT) had a very weak negative association with RTP_t. The weakness of the relationship was unexpected. Again, an average two-week time lag between DOI and TTT may have influenced pre-treatment RT values. Unlike this study, previous studies had reported slowed RT after a SRC and changes in RT tend to mirror the trajectory of post-concussive symptoms throughout the RTP_t (Collie et al., 2006; Collins et al., 2003). Conversely, it is possible for a slowed RT to remain, despite a full resolution PCSS scores (McCrea et al., 2005; Warden et al., 2001). As a predictor for RTP_t, RT may be more reflective of this specific cognitive dysfunction, when measured in the early stages (1-7 days) of recovery from a SRC and less reflective beyond that specific time-frame. Clinicians must consider the changes in RT test sensitivity and specificity across the RTP_t.

D. Sex Differences

In the sample population females on average, when compared to males, required almost two weeks longer to recover from a SRC, had slightly higher baseline PCSS scores, marginally better mBESS scores and slower RT scores. Sample population sex differences were not statistically significant for TTT, RTP_t, PCSS, mBESS and RT. Previous studies on sex and RTP_t trajectories are conflicting, several studies confirmed that females overall take longer to recover than males (Berz et al., 2013; Sicard et al., 2019; Zuckerman et al., 2014). Conversely, another study reported females returning to pre-concussion baseline performance levels over shorter time frames than males (Lax et al., 2015). King et al, and Tanveer et al, found females more likely to have severe and prolonged post-concussion symptoms than males (N. S. King, 2014; Tanveer et al., 2017).

For balance, several studies have reported significantly better balance composite scores in non-concussed females when compared to non-concussed male scores (Brett et al., 2018; Moran et al., 2020; Nedović et al., 2019). Brett et al (2018) determined non-concussed female athletes performed better than males on balance ($p < .001$). Conversely, males had faster reaction time scores ($p < 0.001$) than females. Finally, balance scores may have a ceiling effect for certain populations, particularly when assessing balance improvements in those who already demonstrate good balance (e.g. gymnasts or cheerleaders) (Burghart et al., 2017). Clinicians must consider the differences in male and female balance performance. Post SRC balance measures should be compared to non-concussed baseline scores. If non-concussed base-line scores are unavailable, then gender and age specific norms would be the appropriate comparison.

E. Secondary Data

Almost one-fifth (17.3%) of athletes in the sample population experienced a LOC. The portion of athletes in the study population who suffered a LOC was considerably higher than the 4.2% reported previously by Meehan and colleagues in 2011. Athletes from the study population experiencing a LOC on average, had an RTP_t two weeks longer than athletes who did not experience a LOC. These values were not clinically significant ($ES = 0.364$) or statistically significant ($p = .300$). There were no statistically significant differences between those athletes positive for LOC and those negative for LOC, for PCSS ($p = .676$), mBESS ($p = .585$) and RT ($p = .901$). Lavell et al., (1999) in a larger study ($n = 383$) did not find a relationship between LOC and severity of injury. The study concluded that clinicians should not use guidelines that rely heavily on LOC in making return-to-play decisions (M. R. Lovell, Iverson, Collins, McKeag, &

Maroon, 1999). Conversely, in an earlier study, Ommaya et al (1974) posit a direct link between LOC and the severity of the concussion and the potential for a protracted RTP Meehan et al, (2013), found that unreported concussed athletes overall, had a significantly ($p < 0.004$) higher mean post-concussion symptom scores and were more likely to have lost consciousness. The small difference in RTP_t. in the LOC group for the current study's sample population may not be reflective of the severity of the injury alone. Psychological factors can also influence symptom expression and may be more associated with psychiatric factors, particularly in those cases that have prolonged post-concussion syndrome (Belanger et al., 2013). While not statistically significant clinicians must acknowledge that LOC may result in slightly longer RTP_t in some athletes.

A substantial number (66%) of athletes in the sample population were positive for vestibular ocular-motor screening (VOMS) dysfunction. Mucha et al (2014) in a previous study reported 61% of concussed patients experienced symptom provocation after completing the VOMS. Athletes' positive for VOMS had on average, a RTP_t ten days longer than those without VOMS dysfunction. There were no statistically significantly differences between VOMS positive and VOMS negative athletes for RTP_t ($p = .300$), PCSS ($p = .676$), mBESS ($p = .024$), and RT ($p = .901$). Effect size was moderate for mBESS, small for RTP_t and very small for PCSS and RT. The VOMS may have one advantage over static balance measures mBESS in that it measures the dynamic aspects of vestibule-ocular control and function (Mucha et al., 2014). Sensory and vestibular evaluations may also help the clinician better understand the specific functional deficit presented (vision, hearing or vestibular) for each individual case and craft a more appropriate, individualized post SRC rehabilitation plan (Moore et al., 2018). The

VOMs appears to be an appropriate tool for determining vestibular-ocular dysfunction. However, a positive VOMs did not significantly influence the RTP_t.

F. Study Limitations:

For the study sample population, only 23% of athletes seen in the clinic had an RTP_t of less than thirty days duration. Most athletes (77%), in the study population, had an RTP_t beyond the previously mentioned acute status window of 30 days. Furthermore, mean TTT duration for the sample population was on average two-weeks, resulting in a significant time lag between DOI and the initial clinical evaluation. A delayed post SRC clinical evaluation most likely resulted in lower symptom presentation with cognitive and balance tests that are not representative of the early stages of the injury.

A second and related study limitation was the lack of access by the clinician to non-concussed baseline data for each individual athlete. Many schools in Oklahoma and adjacent states currently perform pre-season baseline evaluations for PCSS, mBESS and RT. Baseline scores are potentially accessible through cloud-based servers. For this study, non-concussed preseason baselines were either not performed or were inaccessible due to institutional barriers related to protected health information policies. Access to pre-season PCSS, mBESS and RT baseline data allows for direct comparison of individual's performance for sideline management, clinical assessment, and evaluation throughout the RTP_t (Guskiewicz, 2001; McCrory et al., 2017).

This study confirmed a modest association between PCSS and RTP_t and a strong association between TTT and RTP_t, $r(69) = 0.471$, $p = .000$, in a population of sub-acute and chronic SRCs. For the sample population, mBESS and RT pre-treatment scores were not robust predictors of RTP_t. The protracted TTT, $M = 15.9 \pm 17.4$, and RTP_t characteristics of the sample population may be more representative of a chronic rather than acute SRC. Non-concussed preseason base line and DOI sideline evaluation scores for PCSS, mBESS and RT were not included in the overall clinical evaluation and treatment process and were a significant study limitation. Sex, LOC and VOMs did not significantly influence RTP_t duration for the sample population.

Clinicians will continue to embrace objective multi-faceted, cloud based evaluation tools as they provide a wide array useful cognitive and physiologic performance data. These tools can improve SRC sideline management, SRC diagnostics, RTP_t and overall post-concussion recovery outcomes only if they meet generally accepted standards of reliability, specificity and sensitivity (> .80). The heterogenetic nature of symptomatology, cognitive performance, and mental status of a concussed athlete calls for an individualized approach to treatment and their subsequent RTP_t. Addressing heterogeneity will require the use of a multi-disciplinary team of ATs, Physicians, Physical Therapists, Exercise Physiologists, Neuro-psychologists, nutritionists and other providers that are aligned with the matched . Use of Multi-disciplinary teams can create challenges with regard to timely access to clinical data and coordinating care, particularly if the team resides across multiple medical organizations.

Finally, healthcare providers through "duty of care" are charged to reduce the incidence of concussion in sports and provide best practices in care. Pre-participation examinations and non-concussed baselines should be mandatory. Concussion education programs should meet the diverse needs of coaches, athletes and parents and subsequently change the "culture" around concussion and poor decisions with regard to RTP. Sensible rule changes and appropriate strength and conditioning techniques may help to limit the impact forces experienced by the head and neck. Properly trained coaches, athletic trainers, and medical staff are on the front line in concussion education, diagnosis and management, and will be crucial to reducing the incidence and severity of concussions.

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