THE INFLUENCE OF SPORT-RELATED CONCUSSION ON SENSORIMOTOR SKILLS IN COLLEGIATE ATHLETES

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ABSTRACT

Background: Recent research suggests that subtle deficits in sensorimotor skills may be present following recovery from sport-related concussion (SRC). These underlying issues are hypothesized to contribute to a greater risk of subsequent injury when an athlete returns to sport. However, little is known about which sensorimotor skills are affected throughout recovery following SRC in collegiate athletes and how other factors, such as SRC symptoms, are related.

Purpose: The purpose of this dissertation was to 1) determine the reliability of 10 sensorimotor skills assessed by a computerized sensory station, 2) examine sensorimotor skills throughout recovery following SRC in collegiate athletes compared to healthy matched controls, and 3) examine the relationship between groups of symptoms and sensorimotor skills in collegiate athletes following SRC at the acute visit, followed by determining if symptoms or sensorimotor skills were associated with recovery time.

Methods: For study one, 100 participants completed 10 sensorimotor skills on a computerized sensory station (Senaptec Sensory Station, Senaptec Inc., Beaverton, OR) at two testing sessions within one week of each other. For study two, 25 participants diagnosed with SRC by a physician completed an acute visit within 5 days of injury, a second visit at the time of medical clearance (+3 days), and a third visit at least one month post return to play (RTP). Control participants (n = 15), who were matched to SRC participants based on biologic sex, age, and sport, completed three visits according to the same schedule as their matched participant with SRC. All participants for study two completed demographic, injury, medical history, and recovery information, along with a symptom checklist and 10 sensorimotor skill assessments on a computerized sensory station at each visit. For study three, 64 participants who were diagnosed with SRC by a physician completed an acute visit within 5 days of injury and a second visit at the time of medical clearance. All participants in study three completed the same procedures as participants in study two. Symptoms from the acute visit were grouped into migraine-fatigue, affective, and cognitive-ocular "factors" to determine relationships.

Results: For study one, go/no-go, multiple-object tracking, eye-hand coordination, depth perception, and reaction time assessments demonstrated good reliability; target capture and perception span demonstrated moderate reliability; visual clarity, contrast sensitivity, and near-far quickness demonstrated poor reliability. For study two, reaction time was statistically significantly worse in the SRC group compared to the control group at the acute visit. In the SRC group, reaction time significantly improved between acute and medical clearance visits and between the acute and one-month post-RTP visits. For study three, statistically significant correlations were found between all three symptom factors with go/no-go, eye-hand coordination, and reaction time assessments. Scores on the symptom factors and sensorimotor assessments were not significantly associated with recovery time following SRC in collegiate athletes.

Conclusion: Go/no-go, multiple-object tracking, eye-hand coordination, depth perception, and reaction time assessments from the computerized sensory station were reliable and can be administered clinically. An examination of these sensorimotor skills in collegiate athletes following SRC revealed significantly worse reaction time acutely and after RTP compared to healthy matched controls. Clinicians should be aware of these potential deficits and incorporate reaction time assessment in SRC management. Additionally, cognitive-ocular, migraine-fatigue, and affective symptom factors were significantly correlated with go/no-go, eye-hand coordination, and reaction time assessments at the acute visit in collegiate athletes following SRC. These findings further help inform SRC management and clinical decision-making.

I dedicate this dissertation to my fiancé, Janhvi Patel. Thank you for coming along with me on this journey and being there for me every step of the way. You were my rock, and I will repay you forever. Kobe! I also dedicate this dissertation to Alexandria, Arielle, and Brian. You will never be forgotten.

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CHAPTER 1: INTRODUCTION

1.1. Overview of the Problem

Concussion, commonly referred to as a mild traumatic brain injury (mTBI), has become one of the most discussed, publicized, and studied health concerns facing society over the past several decades. Sport-related concussion (SRC), in particular, has become increasingly recognized as a public health issue affecting athletes, parents, coaches, sports organizations, and the scientific and medical community. Epidemiological studies have reported that around 3.8 million sport and recreation-related concussions occur annually in the US,[1,2] with SRC in children and adolescents accounting for up to 1.9 million annually.[3] Altogether, SRC accounts for 5-9% of all sports injuries each year.[2] The injury has garnered massive amounts of media attention, especially with the growing concern over the potential long-term sequelae of concussion in collision sports, most notably American football.[4] In fact, some have claimed that there is a concussion "epidemic" or "crisis" in sport.[5] This has led to a tremendous surge in the pace of concussion research, with the hope of expanding knowledge and mitigating negative consequences in the short and long-term. Although knowledge and awareness has increased drastically, gaps in the current body of evidence are still widespread.

An SRC is defined as a traumatic brain injury (TBI) induced by biomechanical forces.[6] There are a number of features that are used to assist in clinically defining SRC since it is an "invisible" injury by nature. First, an SRC may be the result of a direct blow to the head, face, neck, or elsewhere on the body where an impulse is indirectly transmitted to the brain.[6] This classically leads to a rapid onset of impairment in neurological functioning, which resolves spontaneously over time. Second, an SRC is accompanied by a wide range of signs and symptoms that reflect a functional disturbance rather than a structural injury, which prevents abnormalities from being observed on neuroimaging studies.[6] Third, an SRC may impact multiple sign and symptom domains, including physical (e.g., headache, nausea, fatigue), emotional (e.g., irritability, sadness, anxiousness), cognitive (e.g., difficulty remembering, difficulty concentrating), and sleep (e.g., sleeping more/less, trouble falling asleep), and often causes difficulty with school, work, and time away from sport.[7] Lastly, concussion typically follows a sequential course to injury with the majority of individuals recovering within a few weeks, but some may experience persistent symptoms and prolonged recovery.[1,8] Overall, the variable nature of the injury makes recognition, assessment, and management of SRC a daunting responsibility for healthcare professionals.

Medical consensus advocates for a multifaceted approach to SRC management involving different assessments to provide more detailed information at the time of evaluation and throughout the recovery period.[1,7,9] This multifaceted approach often consists of a clinical examination, symptom checklist, balance assessment, vestibular/oculomotor assessment, and neurocognitive testing. While many SRC tools have been validated and are used regularly, there is no "gold-standard" evaluation tool for the diagnosis or determination of recovery.[10] The most recent American Academy of Pediatrics (AAP) clinical report identified this as a large gap, problem, and a focal point where more research is needed.[1] Moreover, there remains a lack of robust metrics for clinicians to use to adequately assess function prior to return to play (RTP) following SRC. Due to this clinical limitation, there is a critical need to identify evaluation tools that can advance the multifaceted SRC assessment approach and improve management of SRC. Failure to identify robust metrics and improve SRC management may lead to negative consequences following SRC, such as a subsequent SRC or musculoskeletal injury.[11,12]

1.2. Significance of the Problem

One of the more recent developments in SRC research is the assessment of the sensorimotor system. Sensorimotor skills, which involve the process of receiving sensory input and producing a motor output, play a crucial role in athletic performance and RTP from injury.[13,14] Research has demonstrated that components of the sensorimotor system are affected following SRC and that deficits may persist beyond clinical recovery. Clinical recovery is defined as the return to normal activities (i.e., sport, school), and typically occurs within 10-14 days for adults and one month for pediatric patients.[1,6,15] Acutely, deficits in vestibular (e.g., vestibular-ocular reflex) and oculomotor function (e.g., saccades) are common, which negatively influences balance and coordination.[16-18] Cognitive impairments are also common and may result in slowed processing, decreased attention, and delayed decision-making.[19] These performance-based deficits, along with accompanying symptoms (e.g., headache, dizziness, blurred vision), inhibit sensorimotor skills that are used in sport.[20-22] Even after clinical recovery from SRC, some studies have found cognitive, ocular, perceptual, and motor dysfunction.[23-26] This supports extant evidence revealing that neurophysiological measures are altered following SRC, even when clinical symptoms have resolved.[27] This contributes to a dysregulated perception-action coupling process,[28] which results in subtle deficits in sensorimotor skills used during sport (e.g., multiple-object tracking, reaction time) and an inability to re-attune to the dynamics of the environment (e.g., inability to accurately judge the "passability" of gap between defenders).[29] Unfortunately, deficits in sensorimotor skills have been linked to increased risk of subsequent SRC and lower extremity musculoskeletal injury.[11,12,30]

Rigorous assessment of sensorimotor skills following SRC may bridge a critical gap in post-SRC care and clearance for RTP. Common SRC assessments used to test ocular function are the King-Devick and Vestibular-Ocular Motor Screening tests.[16,31] Balance, postural stability, and motor speed, have been evaluated using the Star Excursion Balance Test,[32] Multiple Hop Test,[32] and Grooved Pegboard Test.[23] Assessments of sensorimotor skills, such as reaction time, have been measured using computer programs or clinic-friendly adaptations (e.g., stick drop for reaction time).[33-36] While there are a variety of assessments for sensorimotor function, the critical barrier is that these assessments only measure components of sensorimotor ability in isolation and may not adequately test the complex integration of skills used when athletes RTP. Not only does existing research utilize a variety of assessment methods, but key studies that have examined sensorimotor deficits following concussion were conducted in adults,[37] non-athletes,[23,38,39] or cross-sectionally.[37] This leaves a gap in the literature surrounding longitudinal SRC recovery and recovery of collegiate athletes following SRC.[40] Sensorimotor skills are particularly important to evaluate in developing collegiate athletes, as they are already at increased risk of SRC and their immature sensorimotor mechanisms make them vulnerable to injury.[41,42]

Assessment tools that measure a battery of sensorimotor skills, such as the Senaptec Sensory Station (Senaptec),[43] should be utilized to obtain a comprehensive understanding of deficits following SRC. Senaptec is a computerized device that tests 10 sensorimotor skills: visual clarity, contrast sensitivity, depth perception, near-far quickness, perception span, multiple-object tracking, reaction time, target capture, eye-hand coordination, and go/no-go. Extant literature has used this computerized sensory station to examine the relationship between sensorimotor performance and head impact biomechanics and to compare sensorimotor performance in combat soldiers with and without SRC history.[44-46] However, this device has not been used to evaluate collegiate athletes following SRC, and there are limited longitudinal investigations as well.

This dissertation aims to examine this novel assessment device for sensorimotor skills, to identify sensorimotor impairments following SRC in collegiate athletes, and to examine if symptom factors and sensorimotor skills are related and which are associated with prolonged recovery. Hopefully, implementing this novel device will provide a more robust assessment of sensorimotor skills and inform clinicians of deficits that may contribute to subsequent injury in the collegiate athlete population.

1.3. Purpose of the Study

The overall purpose of this dissertation was to determine the influence of SRC on sensorimotor skills in collegiate athletes. Three studies were conducted to achieve this overall purpose. The first dissertation study (Chapter 3) sought to determine the test-retest reliability of 10 sensorimotor skills assessed by a novel computerized sensory station. The second dissertation study (Chapter 4) aimed to examine sensorimotor skill performance throughout recovery and after RTP following SRC in collegiate athletes compared to healthy matched controls. The third dissertation study (Chapter 5) aimed to examine the relationship between symptom factors and sensorimotor skills in collegiate athletes following SRC at the acute visit. The secondary purpose of the third dissertation study was to determine if symptom factors or sensorimotor skills were associated with recovery time.

1.4. Specific Aims

Specific Aim 1: To determine the test-retest reliability of 10 sensorimotor skills assessed by a novel computerized sensory station in a healthy, college-aged population.

Specific Aim 2: To determine differences in sensorimotor skills between participants with SRC and healthy matched controls acutely (within 5 days of SRC), at the time of medical clearance for unrestricted sport participation (+3 days), and at least one month following medical clearance and RTP.

Specific Aim 3a: To examine the relationship between symptom factors and sensorimotor skills in collegiate athletes following SRC at the acute visit.

Specific Aim 3b: To determine if symptom factors or sensorimotor skills at the acute visit were associated with recovery time in collegiate athletes following SRC.

1.5. Hypotheses

Hypothesis 1: Based on evidence from a previous iteration of the computerized sensory station,[47] the visual clarity, contrast sensitivity, depth perception, near-far quickness, perception span, multiple object tracking, reaction time, target capture, eye-hand coordination, and go/no-go assessments will demonstrate moderate to good reliability (ICC=0.5-0.9) in a healthy, college-aged population.

Hypothesis 2: Based on evidence of widespread cognitive, motor, vestibular, and ocular deficits acutely,[16-19] the SRC group will perform worse on all sensorimotor skills tested with the computerized sensory station at the acute visit when compared to healthy matched controls. Based on evidence of persistent deficits in response inhibition and reaction time after recovery from SRC,[48,49] the SRC group will perform worse on go/no-go, eye-hand coordination, and reaction time assessments at the time of medical clearance and one-month post-RTP compared to healthy matched controls.

Hypothesis 3a: Based on evidence of acute symptom burden and symptom factors being associated with worse SRC assessment outcomes,[26,50,51] higher cognitive-ocular, migraine-fatigue, and affective symptom factor scores will be associated with worse performance on go/no-go, eye-hand coordination, multiple-object tracking, depth perception, and reaction time assessments.

Hypothesis 3b: Based on evidence showing initial symptom factors and sensorimotor skills are not associated with recovery time,[51] scores on the three symptom factors and sensorimotor assessments at the acute visit will not be associated with recovery time following SRC in collegiate athletes.

1.6. Operational Definition of Terms

Contrast Sensitivity: A computerized sensory station assessment that determines how well individuals can judge differences in contrast or shading. Participants swipe in the direction of the circle containing the pattern of concentric rings (assessed at 6 and 18 cycles per degree).

Clinical Recovery: The time when an individual returns to normal activities (i.e., sport, school) following SRC.[6]

Depth Perception: A computerized sensory station assessment that determines how well individuals can judge depth and distance. With 3D anaglyph glasses on, participants swipe in the direction of the one circle that appears to be floating (3-dimensional) amongst the diamond pattern of four circles.

Eye-Hand Coordination: A computerized sensory station assessment that tests how rapidly and accurately individuals can respond to a changing target. Using either hand, participants touch green circles that appear within the grid of equally spaced targets as quickly as possible (must hit 80 green circles total).

Go/No-Go: A computerized sensory station assessment that tests how rapidly and accurately individuals can decide about a target and respond to changes. Participants touch the green circles that appear within the grid of equally spaced targets as quickly as possible while not touching the red distractor circles.

Good Reliability: A degree of reliability obtained by administering the same assessment twice one week apart to a group of individuals and obtaining an intraclass correlation coefficient between 0.75-0.9.[52] Established evidence recommends a minimum reliability threshold of 0.7 for clinical applicability.[53]

Medical Clearance: The time when the physician cleared the participant for full unrestricted activity. Participants with SRC had to report resolution of symptoms, reach a baseline vestibular/ocular motor assessment, complete all 5 stages of the Concussion in Sport RTP step-wise protocol,[6] and be cleared by a physician. Participants were in the protocol for 5 days unless symptoms returned, at which point the participant remained in that particular stage until symptoms resolved.

Multiple-Object Tracking: A computerized sensory station assessment that tests how well individuals can divide attention between moving objects and track them at various speeds. Participants select the varying number of dots that flash red at the beginning of the tests once they are done rotating.

Near-Far Quickness: A computerized sensory station assessment that determines how rapidly and accurately individuals can shift their gaze between near and far targets. Participants swipe in the direction of the opening in the C-shaped ring, also known as Landolt ring, as it alternates the focal point between tablet and remote display.

Perception Span: A computerized sensory station assessment that tests the scope of an individual’s visual field and how well visual information is acquired and retained. Participants replicate the pattern of dots flashed in the circles within the grid by memory.

Reaction Time: A computerized sensory station assessment that tests how rapidly individuals can react in response to a visual stimulus. Participants remove the dominant or non-dominant index finger as quickly as possible when the circle it is placed on turns red (stimulus).

Sensorimotor Skills: Skills that involve the process of receiving sensory input and producing a motor output.[13]

Sport-Related Concussion: A traumatic brain injury induced by biomechanical forces from a direct or indirect blow to the head, face, or body that occurred during organized sport and resulted in a variety of clinical signs and symptoms.[6] All SRCs were assessed by physicians and involved the following criteria: a) the presence of at least one or more on-field signs (e.g., loss of consciousness, amnesia, disorientation/confusion, balance difficulties), b) symptoms (e.g., headache, nausea, dizziness), and/or c) any impairment on sideline assessments (e.g., SCAT5).

Subconcussive Impact: An impact to the head, neck, or body that does not result in symptoms or a clinical diagnosis of a concussion.[54]

Symptom Factor: A group of individual SRC symptoms aggregated into meaningful groupings, or factors, using factor analytic statistical methods to better inform the clinical assessment and management of SRC.[55]

Target Capture: A computerized sensory station assessment that tests how quickly individuals can shift their gaze and recognize a target in their periphery. Participants track the C-shaped ring, or Landolt ring, as it appears in different corners of the screen and swipe in the direction of the opening before it disappears.

Visual Clarity: A computerized sensory station assessment that determines how well individuals can see visual details. Participants swipe in the direction of the opening in the C-shaped ring, or Landolt ring, to complete the assessment. This is a modified Snellen procedure.

CHAPTER 2: REVIEW OF THE LITERATURE

This review of the literature provides a comprehensive summary of the research on sport-related concussion (SRC), sensorimotor assessments utilized following SRC, and common sensorimotor impairments following SRC and throughout the recovery process. The definition of concussion and SRC is discussed first, followed by the pathophysiology of concussion, epidemiology, and risk factors of SRC. Next, the assessment and management of SRC is highlighted, including an emphasis on commonly used tools from the multifaceted SRC approach. An overview of the sensorimotor system is presented and connected to impairments following SRC, along with current sensorimotor skill assessments. This is followed by an examination of the RTP process following recovery from SRC and discussion of the risk for subsequent injury. This chapter concludes with a summary of relevant gaps in the extant evidence and the purposes of the three studies performed in this dissertation.

2.1. Definition of Concussion

Concussion has become one of the most debated, publicized, and studied injuries facing society over the past two decades. However, historical origins of concussion date back even further to the late 19th century.[56] In 1941, the British Medical Research Council Brain Injuries Committee defined concussion as "a state of unconsciousness, or impaired consciousness, however fleeting suddenly produced by mechanical force applied to the skull and usually followed by retrograde amnesia".[57] Since that time, a number of definitions have been used to define the injury as recognition, knowledge, and evidence advanced. In the early 1980's, it became understood that an individual does not have to lose consciousness for a concussion to occur, but that a concussion may only involve amnesia or being stunned.[56] In 1997, the American Academy of Neurology (AAN) defined concussion as a "trauma-induced alteration in mental status that may or may not involve loss of consciousness".[58] In these earlier decades, the term concussion was often used synonymously with "cerebral concussion", as evidenced in the first published guidelines of return to contact sports.[59] Past evidence has also used descriptors such as "ding", "banged up", "bell-ringer", and "clearing the cobwebs", which have since been removed from the nomenclature completely.

Beginning in the early 2000's, an international group, the Concussion in Sport Group, was convened and focused on developing a consensus statement for concussion in sport. The first symposium was held in Vienna in 2001, and the panel came to an agreement that concussion should be defined as "a complex pathophysiological process affecting the brain, induced by traumatic biomechanical forces".[60] They also presented several features of concussion incorporating clinical, pathological, and biomechanical constructs. There have been five Concussion in Sport Group symposiums since, and the definitions that resulted from these meetings have become well-accepted, although there is no single "gold-standard" definition to this day. Other consensus statements from organizations including the AAN, National Athletic Trainer's Association (NATA), American Medical Society of Sports Medicine (AMSSM), and American Academy of Pediatrics (AAP) have used the same or similar definitions.[1,7,9,61]

The most recent consensus statement on concussion in sport defines an SRC as "a traumatic brain injury induced by biomechanical forces".[6] The injury is either the result of a direct blow to the head, face, neck, or the result of an indirect blow elsewhere on the body where an impulse is transmitted to the head. This typically leads to a rapid onset of impairment in neurological functioning, which resolves after some time. However, there may be a delayed onset of clinical signs and symptoms, which can appear and evolve over the next few hours. The most recent consensus also states that an SRC may result in neuropathological changes (e.g., changes to white matter tissue), but the acute clinical signs and symptoms represent a functional disturbance rather than a structural injury, such as a fractured bone. This lack of structural change prohibits any abnormalities from being observed in standard neuroimaging studies (e.g., X-ray). An SRC results in wide range of clinical signs and symptoms, which does not always include loss of consciousness and cannot be explained by drugs, alcohol, medication use, concomitant injuries, or comorbidities. The resolution of the clinical signs and symptoms typically follows a predictable course, but some cases may be prolonged. Concussion is often used interchangeably with mTBI and, while concussion does represent the immediate and transient symptoms of TBI, the Concussion in Sport Group states this terminology is too vague and not based on validated criteria.[6] As such, the latest Concussion in Sport Group definition and the terminology "concussion" or "SRC" will be used throughout this dissertation.

2.2. Pathophysiology of Concussion

Similar to the definition of concussion, the scientific community's understanding of post-concussive pathophysiology has evolved significantly in recent decades in an effort to better understand deficits that occur following injury. The first comprehensive review of concussion pathophysiology describes a "neurometabolic cascade" that occurs immediately following injury and evolves over the next several hours to days.[62] This cascade of events is characterized by 1) ionic flux and neurotransmitter release, 2) an energy crisis, 3) cytoskeletal damage, 4) axonal dysfunction, 5) altered neurotransmission, 6) inflammation, and eventually 7) cell death. These physiological changes and their corresponding clinical correlates will be discussed in detail in the subsequent paragraphs.

Shearing and stretching forces caused by the concussion result in temporary perturbations in the plasmalemmal membrane.[63] This causes a sudden release of neurotransmitters and unhindered ionic flux, or "mechanoporation", which leads to acute and subacute alterations in cellular physiology.[62-64] This primarily involves the profuse excitatory neurotransmitter, glutamate, which binds to the N-methyl-D-aspartate (NMDA) receptor and leads to neuronal depolarization, or an excitatory cellular state.[62,65] These changes trigger voltage-gated ion channels, which creates a diffuse and spreading depression.[63,64] It is hypothesized that this depression-like state is responsible for post-concussive impairments, notably symptom presentation.[64] There is then an efflux of potassium and an influx of sodium and calcium, which triggers the sodium-potassium pump to attempt to restore the neuronal membrane potential and cellular homeostasis. The adenosine triphosphate (ATP) needed to activate the pump triggers hyperglycolysis, or "hypermetabolism", which results in a disparity between glucose supply and demand.[64] This mismatch in the brain is referred to as the "energy crisis".

The energy crisis often occurs in a setting of reduced cerebral blood flow and is when the brain is at its most vulnerable (i.e., unable to respond to subsequent injury).[64] Furthermore, the intracellular calcium flux lasts longer than the other ionic shifts and sequesters in the mitochondria. This can lead to mitochondrial dysfunction and issues with oxidative metabolism.[66] Additional stress is then placed on the brain with the generation of free radicals and shifting metabolic pathways, which contributes to the aforementioned vulnerability to a subsequent injury.[64] This hypermetabolic period can last up to 10 days post-injury.[67]

In addition to the energy crisis, cytoskeletal damage, axonal dysfunction, and altered neurotransmission occurs. Following the calcium influx, the axons lose their structural integrity, which diminishes normal neurotransmission capabilities.[63,68] Damage to the neurofilaments and microtubules lead to further axonal dysfunction and the potential for axonal disconnection.[63] Neurotransmission is also altered by changes in inhibitory neurotransmitters including gammaamino-butyric-acid (GABA), whose main role is to reduce neuronal activity.[63] Studies have demonstrated a decrease in GABA post-concussion,[63,69] which suggests a decreased neuronal inhibitory effect and could be an explanation for symptoms (e.g., anxiety or nervousness) post-concussion.

More recent evidence has examined inflammation and cell death following concussion. Although inflammatory markers are well-reported in TBI literature,[70] studies suggest that inflammatory changes are triggered following concussion as well. The activation and upregulation of microglia and cytokines contribute to ongoing cellular damage and are speculated to be the cause of tissue inflammation.[71,72] This neuroinflammation is suspected to correlate with symptom presentation and duration following concussion and many researchers believe the extent of it is more damaging than the blow itself.[71,73,74] Cell death, however, is less common or very limited in most animal models.[75] Cell death has been shown in the cortex and anterior thalamus in rats after concussion,[76] while human studies have shown diffuse volume loss and atrophy in the limbic and precuneal cortex.[77]

2.3. Biomechanics of Concussion

As noted previously, a concussion is by definition, “induced by biomechanical forces”.[6] Therefore, understanding the various biomechanical mechanisms that may lead to a concussion are important, especially in sport and athletic populations where a multitude of forces are common. The analysis of these biomechanical forces (i.e., linear and rotational acceleration) can help to establish a threshold at which an SRC “occurs”. While the majority of evidence has been limited to laboratory studies, emerging evidence is capturing real-time head impact biomechanical data during sport. Altogether, understanding the biomechanics of SRC may contribute to concussion prevention, evaluation, diagnosis, and management.

When an impulse is transmitted to the brain, either from a direct or indirect impact, the skull accelerates first while the brain follows inside the skull as the result of inertia. This results in a strain and pressure gradient in the brain tissue, which results in injury.[78] Characterizing the precise motion of the brain within the skull at impact has proven difficult in research, but research has described a concussion as a coup and contrecoup injury. The coup injury is said to occur from the stationary brain being struck by a moving object followed by the contrecoup, where the moving brain rebounds and strikes the opposite side of the skull.[79] This conception led to the notion that the brain "sloshes around" inside the skull like Jell-O in a bowl; however, evidence from cadaveric research has revealed that there is less brain motion (7 millimeter relative to skull) involved in concussive impacts than anticipated.[80]

While internal measurements and characteristics are challenging in vivo, kinematic characteristics of head impacts are easier to measure and may indicate the inertial response and strain placed on the brain. The two kinematic parameters thought to be involved in concussion are linear and rotational acceleration and were first described by Ommaya and Gennarelli.[81] Linear acceleration has been speculated to cause injury through transient intracranial pressure gradients from direct contact, which were found in animal and cadaveric studies.[78] Rotational acceleration has been speculated to cause injury through shear strain in the brain tissue from inertial and non-contact mechanisms.[78] While debate has occurred regarding which type of acceleration causes concussion, it is likely a combination of the two, as both occur in real-world impacts. In fact, studies of primates have found that concussion could only be intentionally caused by both forces.[82] Still, the relative contribution of each type of acceleration to injury has not been definitively established.

Over the years, a number of brain injury impact criteria have been developed using a variety of approaches, including quantitative video analysis and wearable accelerometers or sensors. Impacts in the NFL using crash test dummies reconstructed from video analysis reported average head accelerations of 98 ± 28 g and 6432 ± 1813 rad/s^2.[83] Meanwhile, concussive impacts from wearable head sensors in football players yielded average head accelerations of 105 ± 27 g and 5022 ± 1791 rad/s^2.[84,85] More recently, a systematic review of concussion kinematics in male athletes using wearable head sensors reported a mean of 98.7 g and 5776 rad/s^2.[86] The study with the most concussive impacts (105 SRCs) identified via an instrumented helmet in college and high school football players found an average linear acceleration of 102.5 g and rotational acceleration of 3977 rad/s^2.[87] While research in non-football populations is limited, Wilcox et al. found an average peak linear head acceleration of 43 ± 12 g and a peak rotational acceleration of 4030 ± 1435 rad/s^2 in female hockey players.[88] Meanwhile, reconstructions of SRCs from soccer matches had an average linear acceleration of 87 g and an average rotational acceleration of 7033 rad/s^2,[89] while reconstructions from baseball games had impacts ranging from 26 to 42 g for linear acceleration and 1974 to 5266 rad/s^2 for rotational acceleration.[90] In addition to the magnitude of acceleration, the location of impacts has also been examined. In a study of adolescent football players, a linear acceleration of over 96.1 g, rotational acceleration between 5882-8445 rad/s^2, and impact location at the front, top, or back of the head were associated with increased risk of SRC.[91] Conversely, head impact data from 33 collegiate football players diagnosed with SRC had a lower percentage of impacts to the front of the head and a greater frequency to the sides and top compared to a matched control group.[92] While biomechanical research related to SRC continues to evolve, this work has helped shed light onto what it takes for injury to occur.

2.4. Epidemiology of Concussion in Sport

The occurrence of SRC has been studied in a variety of settings and populations over the past several decades. However, a precise prevalence and incidence is difficult to ascertain due to a number of factors. Concussion symptoms often go completely unreported,[93-95] or individuals experience a delayed onset of symptoms,[96] which also influences reporting of the injury. As such, it is hypothesized that current estimates of the burden of SRCs are significantly less than the true burden.[93] Current research estimates that only 1 out of every 9 SRCs are captured across the United States (US).[40] Furthermore, studies have used different metrics and forms of measurement, which makes comparison difficult between samples and populations. For example, some use a concussion rate, which is the total number of injuries divided by the total number of player exposures (i.e., player-minutes, athlete-exposure).[97] Other studies use injury risk, the injured athletes divided number of athletes at risk within a certain time period, and injury odds, which is calculated by dividing injury risk by one minus injury risk.[97] Overall, the setting, time period, underreporting, and metric all need to be considered when determining the epidemiology and burden of SRC.

The most widely cited study from the Centers for Disease Control (CDC) reported that anywhere from 1.6 to 3.8 million sport and recreation-related concussions occur annually in the US.[98] Additional evidence has reported that SRCs in children and adolescents account for up to 1.9 million annually.[1,3] Altogether, SRC accounts for 5-9% of all sports injuries each year.[2] However, as mentioned previously, these figures vastly underestimate the total burden, as many SRCs go unreported, or the individual does not seek medical advice. Overall, the incidence of SRC has increased substantially over the last 15 years with improved awareness and concussion legislation that has been enacted.[99-102]

2.4.1. Collegiate Sports

The vast majority of epidemiological studies have focused on high school and college students-athletes. At the collegiate level, the National Collegiate Athletic Association (NCAA) has been a focal point of SRC epidemiology research due to its stature in amateur sports, number of participants, and the unique access to research that the setting provides. Most data have been collected through a national web-based injury surveillance system called the NCAA Injury Surveillance System (ISS). Earlier NCAA-ISS research from 2009-2014 demonstrated an SRC rate of approximately 4.5 per 10,000 athlete exposures (AEs), which was an increase from the rate observed during the 1988-2004 study period.[103,104] However, the most recent study of NCAA-ISS data from 2014-2019 reported an SRC rate of 4.13 per 10,000 AEs.[105] The most recent data will be discussed in greater detail below.

Of the 3,500 SRCs reported from 2014-2019, over half of these were sustained during competition, resulting in an SRC rate of 10.39 per 10,000 AEs.[105] This was much higher than the practice SRC rate of 2.52 per 10,000 AEs (IRR, 4.12; 95% CI, 3.86-4.41). Seventy four percent of SRCs at the collegiate level were reported in-season (4.47 per 10,000 AEs), followed by preseason (22%; 3.63 per 10,000 AEs) and postseason (4%; 2.61 per 10,000 AEs). Across all sports examined, the highest SRC rates were found in men's ice hockey (7.35 per 10,000 AEs), followed by women's soccer (7.15 per 10,000 AEs), men's football (6.99 per 10,000 AEs), and women's ice hockey (6.98 per 10,000 AEs).[105]

The highest SRC rates in collision sports were men's ice hockey (7.35 per 10,000 AEs), followed by men's football (6.99 per 10,000 AEs) and women's ice hockey (6.98 per 10,000 AEs).[105] While SRC rates in collision sports were higher in competition than in practice, practice-related SRCs accounted for a greater proportion of injuries. High-contact sports saw the highest SRC rate in women's soccer (7.15 per 10,000 AEs), followed by women's gymnastics (6.68 per 10,000 AEs) and women's field hockey (5.38 per 10,000 AEs). The highest SRC rates for men's high-contact sports were in men's soccer (4.43 per 10,000 AEs) and men's basketball (3.35 per 10,000 AEs). Among limited-contact sports, the highest SRC rates were in women's volleyball (4.93 per 10,000 AEs) and women's softball (2.67 per 10,000 AEs), while the highest rate amongst men's limited-contact sports was baseball (0.95 per 10,000 AEs). In non-contact sports, very few SRCs were reported, but the highest rate was found in men's tennis (1.23 per 10,000 AEs) and women's tennis (0.96 per 10,000 AEs).[105]

Similar to previous evidence, notable differences in SRC rates were found in sex-comparable sports.[105] Overall SRC rates were higher in women's soccer (7.15 per 10,000 AEs), basketball (5.25 per 10,000 AEs), and softball/baseball (2.67 per 10,000 AEs) compared to their male counterparts. This was consistent with older findings from the NCAA-ISS that showed women were more likely to sustain SRC than men (RR=1.23).[106,107] In a meta-analysis of 38 studies, Cheng et al. found that SRC incidence rates were significantly higher in women's soccer and basketball compared to males.[108] Researchers suspect these differences are due to better SRC knowledge, reporting behaviors, and attitudes in women compared to men,[109,110] which result in a higher number of reported and diagnosed SRCs. Other potential reasons include neck strength or musculature and contextual factors (e.g., rules, field dimensions).[105,111,112]

While SRC rates are higher in women than men in the majority of studies, the SRC rates by injury mechanism varies. In men's sports, player-to-player contact accounted for the largest proportion of SRCs, except in men's baseball where equipment/apparatus contact accounted for the largest proportion.[105] This was consistent with extant literature from the NCAA-ISS and other studies.[103,104] On the contrary, the majority of SRCs in women's sports were caused by equipment/apparatus mechanisms, with the exception of women's basketball, which had over 50% related to player contact.[105] These differences can likely be attributed to differences in rules within each sport and gameplay dynamics.

2.4.2. High School Sports

While this dissertation is focused on collegiate athletes, it is important to acknowledge the epidemiology of concussions in high school athletes to understand how injury rates change from one athletic setting to the next. A prominent sports injury surveillance system at the high school level is the High School Reporting Information Online (RIO) database. Similar to the NCAA-ISS, this system is web-based and requires athletic trainers (ATs) at participating sites to enter injury and exposure data. Since both systems use injuries and AE over the same time period, the data is comparable. Pierpoint and Collins reports the leading concussion rates per 10,000 AE and rate ratios comparing competitions versus practices in high school and college sports from these two databases from the 2004/05 to 2013/14 seasons.[40]

General trends in the data revealed that concussion rates are higher in college athletes compared to high school athletes and in competitions compared to practices.[40] Data in sex-comparable sports showed that women report higher concussion rates than men in high school and college, which is consistent with previous literature.[40,107,113,114] In collegiate athletes, the highest overall rate was found in men's ice hockey (6.95 per 10,000 AEs), followed by men's wrestling (6.72 per 10,000 AEs), women's soccer (6.44 per 10,000 AEs), and men's football (6.31 per 10,000 AEs).[40] Comparatively, in high school sports, the highest overall rates were in men's football (7.28 per 10,000 AEs), followed by men's ice hockey (6.83 per 10,000 AEs), men's lacrosse (4.87 per 10,000 AEs), and women's soccer (4.50 per 10,000 AEs). At both levels, competition SRC rates were higher than in practice, with the largest rate ratio in men's ice hockey (RR=11.74).[40]

Previous literature has conflicted with the aforementioned data. An epidemiology study of high school football players from the High School RIO system and college football players from the NCAA-ISS found a greater proportion of SRC in high school athletes, although the overall injury rate was higher in college.[115] Furthermore, Dompier et al. compared college football data from the NCAA-ISS with high school data from the National Athletic Treatment, Injury and Outcomes Network (NATION) and found high school football players to have the highest one-season SRC risk.[116] Evidence in sports other than football have also demonstrated that SRC incidence is higher in high school athletes compared to older athletes.[117,118] However, data from the NATION and NCAA-ISS found SRC incidence to be higher in collegiate athletes.[119] This is aligned with an older study from Gessel et al. in 2007 and most recent data presented previously from Pierpoint et al. and Chandran et al.[2,40,105]

2.5. Risk Factors for Sport-Related Concussion

While the epidemiological data above described the distribution of concussion in sport, high school vs. college athletes, and event type, there are several risk factors that increase the likelihood and susceptibility of an individual sustaining an SRC. Contact sports are an intuitive risk factor for SRC, as demonstrated above and in numerous studies.[42,120,121] Sex and age are also common risk factors and were introduced above, but will be discussed in greater detail below. Additional risk factors include history of concussion, history of headache or migraine disorder, history of learning disability or attention deficit disorders, and history of psychiatric disorders (e.g., anxiety and depression).

2.5.1. Age and Maturation

Despite that the majority of SRCs sustained annually occur in pediatric and collegiate populations,[3] two demographics undergoing a multitude of changes, relatively limited evidence has focused on the influence of age, growth, development, and maturation on SRC. As introduced earlier, most evidence examining differences in age have focused on comparing high school athletes with collegiate athletes. An epidemiology study of high school football players from the HS-RIO system and college football players from the NCAA-ISS found a greater proportion of SRCs in high school athletes, although the overall injury rate was higher in college athletes.[115] A study comparing college football data from the NCAA-ISS with high school data from the NATION found high school football players to have the highest SRC risk over a one-season period.[116] These studies support earlier findings from Guskiewicz et al. who found a higher concussion incidence in a prospective cohort of high school football players compared to college football players.[122] A survey of 12- to 24-year-olds also found that younger age was associated with increased reporting of concussions.[123] Several other studies across multiple sports have also demonstrated that SRC incidence is higher in high school athletes compared to older athletes.[117,118] However, the most recent data presented earlier conflicts with these studies, suggesting that SRC incidence is higher in collegiate athletes.

The explanation for these differences has been debated, although few studies have looked further into them. Findings that high school athletes are at greater risk of sustaining an SRC support the notion that this is due to their developing and vulnerable brain, which requires less to disturb the neurometabolic processes and initiate the events following SRC.[116] Research has demonstrated increased swelling in the pediatric brain compared to adults, potentially due to differences in glutamate receptor expression and brain water content at younger ages.[124] Studies have also shown that increased vulnerability to oxidative stress, differences in dopaminergic activity, vascular response to injury, and differences in susceptibility of glutamate receptors between the developing and adult brains may play a role in brain injury incidence.[124,125] Furthermore, a number of studies have suggested that incomplete myelination of axons in the developing brain place it at greater risk for shear injury from SRC.[126,127] Lastly, thinner cranial bones and a smaller subarachnoid space in the brain have also been proposed as reasons for increased SRC incidence in younger ages.[128]

While there is evidence to explain higher SRC incidence in high school compared to college-aged individuals, much of it is focused on more severe TBI. The concept is also challenged by evidence that shows brain development continues into the mid-20s when an athlete would likely be in college.[129,130] Studies that found higher SRC incidence in collegiate athletes have speculated that the difference may be due to a gap in healthcare access at the high school level resulting in less recognition and guidance when an SRC does occur, as opposed to at the collegiate level where an AT is readily available.[119] Moreover, no studies of young children (<14 years) have reported SRC incidence by athlete exposure, which makes it difficult to compare data with those in high school and college.[1] Studies have shown that SRCs in children ages 6 to 16 years are more likely to occur during organized sports than other activities.[131] A study of football players ages 8 to 12 years even found higher concussion rates than in high school, which may support the developing brain hypothesis and pathophysiological differences mentioned earlier.[132] Overall, the notion that younger age is a risk factor for SRC is supported, but further research in this area is needed.

Although limited, there is evidence surrounding growth and maturation that supports younger age and its role in SRC risk. As Buzzini and Guskiewicz described,[133] gains in weight and body mass associated with the adolescent growth spurt increase the force and momentum of collisions during sport. In adults, cervical muscle strength functions to dissipate the resultant acceleration of a sustained force, protecting the brain from injury. However, in children, the development of neck and shoulder musculature is usually not consistent with the rest of the body, which results in the decreased ability to limit head acceleration and an increased risk of SRC from a collision.[134,135] Collins et al. captured anthropometric characteristics from 25 states for 6,704 high school athletes in soccer, basketball, and lacrosse, along with SRC incidence data.[136] The authors found that smaller mean neck circumference, smaller mean neck to head circumference ratio, and weaker mean neck strength were significantly associated with SRC, which are all common in younger individuals.

It is possible that maturation also plays a role in SRC incidence. Studies have revealed that skeletal maturity status and tempo are risk factors for certain injury types in adolescent athletes.[137] Differences in SRC incidence between youth, high school, and collegiate athletes may result from greater variability in athlete size, strength, speed, and skill that is a result of maturity-associated variation. At the youth and high school levels, early maturing athletes are generally taller, heavier, and stronger than average or late maturing athletes, all of which may result in more frequent mismatches during sport. Yeargin et al. used maturity offset to examine the effect of maturational status variability on head impact biomechanics in youth football players.[138] They found that post-PHV (peak height velocity) boys who were taller, older, and had a longer leg length had greater head impacts compared to boys who were pre-PHV. Studies have also reported that smaller player size and lighter weights were independent risk factors for injury in youth ice hockey.[139,140] A study of youth hockey in two provinces in Canada revealed a 3-fold increased risk of SRC in leagues that allowed body checking compared with leagues that did not at the same age.[139] A separate study also found that menarche was a risk factor for injury in female ice hockey players.[141] As there is extremely limited evidence investigating maturation status as a risk factor for SRC, these studies highlight the need for more research in this area.

2.5.2. Sex Differences

As highlighted earlier, female sex is a risk factor for SRC, and this is supported by numerous studies of sex-comparable sports.[2,105-108,142-144] In a recent meta-analysis and systematic review of 38 studies, Cheng et al. found that concussion incidence rates were significantly higher in women's soccer and basketball compared to males.[108] A systematic review from 2013 found that 10 studies showed that women had a greater risk of concussion.[120] While four studies showed men were at higher risk, these studies involved the bias of men in high-collision sports including football. An older systematic review of prospective studies found that 9 of 10 reported higher concussion rates for females.[142] The most recent data in collegiate athletes from Chandran et al. found that SRC rates were higher in women's soccer, basketball, and softball compared to in men's sports.[105] This was consistent with older findings from the NCAA-ISS that revealed women were 1.23 and 1.5 times as likely to sustain SRC than men.[106,107] Female basketball and soccer players had a 1.4 times greater SRC incidence, while female softball players had a two-fold greater incidence compared to male counterparts.[107]

Researchers suspect these differences are due to better SRC knowledge, reporting behaviors, and attitudes in women compared to men,[109,110] which result in a higher number of reported and diagnosed SRCs. It has been hypothesized that females report more symptoms because it is socially acceptable to display vulnerability,[109] whereas the perception is not the same for men in a "masculine sport culture". Hormonal factors may also play a role, as circulating estrogens may lead to different symptom responses compared to males.[107,145] Other potential reasons include neck strength and musculature,[112,146] lower biomechanical thresholds,[147] and contextual factors.[105,111]

2.5.3. History of Concussion

In multiple studies with high-quality levels of evidence, a history of one or more concussions confers increased risk of sustaining a subsequent SRC.[120,121,148-151] In an earlier prospective study of approximately 3,000 NCAA football players, there was an association between number of previous SRCs and likelihood of a subsequent SRC.[148] In particular, players with 3 or more prior SRCs were 3 times more likely to sustain another SRC compared to players with no concussion history. Similarly, a prospective study of 3,200 rugby players over multiple seasons found a 2 times higher likelihood of mTBI among players reporting 1 or more mTBIs in the year before enrollment.[149] A study in North Carolina of high school athletes also found greater than a two-fold increase in SRC rate for those with a history of concussion compared to those without a history.[152] In a systematic review, 10 of 13 studies identified an increased risk of SRC in those with a history of concussion.[120] Lastly, a recent study of 12,320 student-athletes found previous concussion to be the strongest predictor of SRC risk, with an odds ratio of 9.14 for those with concussion history predicting the occurrence of subsequent SRC.[121]

The increased risk of SRC for those with a concussion history is indicative of increased neuronal vulnerability that follows the neurometabolic cascade described earlier. Evidence on the neurometabolic cascade suggests that the vulnerability for subsequent SRC is caused by the generation of free radicals and shifting of metabolic pathways following alterations in the intracellular redox state.[64] Studies have also speculated that reinjury could be due to increased lactate from accelerated glycolysis, which leaves neurons vulnerable.[148] Furthermore, the impairment in neurocognitive and neurobehavioral function from SRC could contribute to future poor behavior or functioning (e.g., decision-making) during sport,[75] resulting in re-injury, although there are few high-quality studies supporting this.[120] While there is a high level of certainty for concussion history as a risk factor, research following brain injury legislation have shown a decline in recurrent concussion rates,[102] indicating that improved education, awareness, and knowledge may reduce the association.

2.5.4. Treatment History

Evidence for additional risk factors is limited and much weaker than that of age, sex, history of concussion, and contact sports. A recent study of 12,320 student-athletes found prior headache treatment increased the odds of SRC by 1.87 times.[121] This is supported by an earlier study of 330 survey respondents ages 12-24 years, where headache or migraine was associated with increased risk of SRC.[123] However, the authors noted much is unanswered within this area, as headache and migraine may be more common already in those at greater risk of SRC. A history of learning disorders or attention deficit disorders (ADD/ADHD) have also been posited as risk factors of SRC. Nelson et al. found that ADHD and learning disorders were associated with 2.93 and 2.08 times the prevalence of 3 or more SRCs.[153] Brett et al. also found ADHD and learning disorder diagnoses increased the odds of SRC by 1.24 times.[121] Lastly, within the same study, Brett et al. revealed that psychiatric history was a significant predictor of SRC.[121] However, it was not significant in the multivariable model, which suggests one of the other covariates mediated the association between SRC risk and psychiatric history.

2.6. Assessment of Sport-Related Concussion

The management and assessment of SRC has advanced dramatically in the past two decades. The first pivotal step in the management of SRC occurs prior to injury in the form of baseline assessments. Baseline SRC assessments are meant to aid clinicians in the post-injury evaluation process by providing subjective and objective information on how the individual performed in the various domains of concussion assessment (i.e., symptoms and cognitive/balance/vestibular/sensorimotor performance) in a healthy, uninjured state. Several sport organizations and athletic associations (e.g., NCAA) require baseline testing prior to the first practice or contact activity, but medical consensus recommends individuals at greater risk of SRC (i.e., females, those with prior concussion history, etc.) receive a baseline evaluation before sport participation.[6,42,120] A baseline assessment battery should involve a neurological and medical history, clinical examination, symptom checklist, balance assessment, and neurocognitive testing at the minimum.[9] This assessment battery can usually be incorporated into the preparticipation physical evaluation (PPE), which is already a traditional and legal requirement by governing bodies of sport.[154] While pre-existing factors (e.g., psychiatric condition, treatment for headaches/migraines) and "sandbagging" by the participant may limit the utility of some tests,[155-157] baseline assessments are an important aspect of SRC management.

In terms of immediate management of SRC, the enactment of brain injury legislation in all 50 states and the District of Columbia has increased the percentage of concussions reported.[101,158-160] In 2009, the State of Washington was the first to pass legislation, informally known as the "Lystedt Law", addressing the timely management of SRC.[101] This law contains three essential components: mandatory education of athletes and parents, removal from play at the time of suspected head injury, and return to play only with written permission of a licensed, concussion-trained healthcare provider after a minimum of 24 hours. By 2014, every state established similar legislation with common themes being "immediate removal from play" and "no same day return to play" following concussion.[161] In addition to state legislation, consensus and position statements from numerous medical organizations, including the American Academy of Pediatrics, American Medical Society for Sports Medicine, National Athletic Trainers' Association, and the Concussion in Sport Group, have all called for the same core principles when an SRC is suspected.[1,6,7,9]

In terms of SRC assessment and management of the injury, medical organizations and consensus statements advocate for a multidimensional approach involving a variety of assessments specific to the individual presentation to provide more detailed information at the time of evaluation and throughout recovery.[1,9,162] This multifaceted approach is necessary for diagnosis because SRC is a functional disturbance rather than a structural injury, which prevents abnormalities from being observed on neuroimaging studies.[6] The multifaceted approach usually consists of at least a clinical examination, symptom checklist, balance assessment, and neurocognitive testing.[1,9,162] While this approach is used by providers nationwide, there is no "gold-standard" assessment battery available. As such, identifying the best and most accurate battery of SRC assessments has been deemed a focal point by medical organizations.[1,6] Furthermore, there is currently a lack of effective tools for clinicians to use to assess clinical recovery and make a safe determination that the athlete is ready RTP. As a result, other types of measurements, such as gait, vestibular/oculomotor, and sensorimotor assessments, have been added to the multifaceted SRC approach. These various assessment domains and how they aid in SRC management will be discussed in detail below.

2.6.1. Symptom Assessment

One of the oldest and most useful components of the multifaceted approach to SRC evaluation is the subjective reporting of symptoms an individual is experiencing following SRC. In fact, symptoms have shown to be the most sensitive indicator of concussion on a number of occasions.[163,164] Symptom checklists allow for a depiction of how the individual is feeling in a variety of areas, along with the severity and duration of each symptom. The symptom evaluation is important at baseline, during the sideline assessment, and at the time of clinical examination following injury to better understand the trajectory of symptoms throughout recovery.

There are numerous different symptom evaluation tools that have been validated and are psychometrically sound,[165] but the symptom checklists from the Sport Concussion Assessment Tool-5 (SCAT5) and the Child SCAT5 are recommended for use by the Concussion in Sport Group.[6,166,167] The symptom checklist of the SCAT5 consists of 22 symptoms, such as headache, dizziness, and nausea, and are graded on a Guttman scale of 0-6, 0 being "none" and 6 being "severe".[168] The total number of symptoms (sum of how many symptoms reported) is calculated, along with the severity of symptoms (sum of graded scores on each symptom). The Child SCAT5 is similar, but there are 21 symptoms, and the symptom descriptions are adapted for understanding for a child (e.g., difficulty remembering changed to "I forget things").[167] There is also a parent symptom checklist to allow the parent of the child to report their perception of their child's symptoms side by side. The Post-Concussion Symptom Scale (PCSS) is another widely used and well-validated symptom inventory, which also involves 22 symptoms graded on a 7-point scale.[169] However, this scale only captures a PCSS total score and includes different symptom descriptions, such as "excessive sleep" and "visual problems".

Multiple studies have reported baseline symptom scores from these tools in various populations. While no reported symptoms are ideal at baseline, that is not always the case due to medical history and comorbidities. Research has demonstrated that anywhere from 50-85% of athletes experience one or more symptoms during their baseline assessment, and adolescents in particular have shown to report a higher percentage of baselines symptoms compared to adults.[170,171] Females have also been shown to report more symptoms at baseline compared to males.[172] In general, the most commonly reported symptoms at baseline are headache, fatigue, difficulty concentrating, drowsiness, trouble falling asleep, and nervous/anxiousness.[172-174] Extant evidence has also utilized groups of related symptoms, called symptom factors, and found higher levels of cognitive-sensory symptoms and vestibular-somatic symptoms at baseline.[55] Furthermore, research has demonstrated that athletes reporting baseline symptoms are more likely to report a higher number and severity of those same symptoms following SRC, which emphasizes the importance of capturing this data preinjury at baseline.[175]

Following SRC, the most commonly reported symptom is headache, with up to 95% of individuals reporting headache in previous studies.[148,173,176] Other symptoms commonly reported following SRC include dizziness, confusion, disorientation, and fatigue.[122,173] In high school and collegiate athletes, the five most common symptoms following SRC are headache, dizziness, difficulty concentrating, confusion, and visual problems/sensitivity to light.[177,178] Similar to baseline, females are more likely to report more symptoms of concussion compared to males, with the exception of confusion.[179]

While symptom inventories are useful in identifying SRC and tracking recovery, they are not without limitations. One limitation of symptom reporting is that they are subjective by nature, which means symptoms may not be reported precisely. Symptoms are often underreported or not reported at all,[93-95] which limits the utility of these scales. Furthermore, symptom reporting is influenced by SRC knowledge, and awareness of common symptoms following SRC may be lacking.[114,180,181] Another limitation is that prior medical history, such as history of concussion, ADD/ADHD, learning disorders, and psychiatric disorders, impact symptom reporting.[182-184] Even with baseline assessments, several of the aforementioned comorbidities share symptoms of SRC and make it difficult to know what to attribute the symptoms to, the SRC or the other condition.[1]

2.6.2. Neurocognitive and Neuropsychological Assessment

Neurocognitive and neuropsychological assessments have become increasingly popular in the past decade, with research from the NCAA demonstrating it is the most used baseline and post-injury assessment for SRC.[185] Currently, computerized versions of these assessments are used instead of traditional paper and pencil tests, due to the feasibility of administration, scoring, and detection of invalid test attempts. These assessments offer insight into the executive functioning of an individual, including their information processing, motor planning, and attentional capacity, which is often impacted following SRC.[19] Extant literature has demonstrated at length that declines in cognitive functioning following SRC affect performance on reaction time, memory, depth perception, hand-eye coordination, and related tasks.[19,186-188] As a result, an examination of how each individual performs at baseline in these areas is crucial.

There are a number of neurocognitive and neuropsychological assessments available, but the Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT) test has become the most popular tool for evaluating cognition in athletes following SRC. The ImPACT test battery consists of 8 tasks and 5 composite scores including verbal memory, visual memory, reaction time, visual motor speed processing, and impulse control. The ImPACT also includes a symptom inventory and questions about the athlete. A systematic review identified that ImPACT demonstrates convergent validity, but findings regarding discriminant validity, predictive validity, diagnostic accuracy, and usefulness after symptom resolution were inconclusive.[189]

Similar to symptom inventories, obtaining a baseline and/or pre-season ImPACT assessment for each athlete is paramount for accurate comparison with the post-SRC assessments. However, unlike symptom inventories, objective measures, such as ImPACT, capture individual differences in cognitive performance and make it difficult for athletes to underreport their injury. Even in the absence of substantial symptoms, the ImPACT may contribute to detection of SRC by demonstrating declines in cognitive performance from the athlete's baseline. If a baseline neurocognitive assessment is not available, normative ImPACT data allows clinicians to compare their athlete's performance to averages based on age, sex, and education level.[190] Prior evidence has demonstrated that ImPACT can accurately detect concussion-related cognitive impairment during the acute injury phase.[191,192] In a sample of high school and collegiate athletes following SRC, 83% of the concussed sample demonstrated significantly poorer ImPACT performance 2 days post-injury compared to baseline.[192] Furthermore, the addition of ImPACT testing to the symptom inventory resulted in a net increase in sensitivity of 19%. While ImPACT has been used extensively due to its feasibility for application and testing in team settings, recent evidence suggests other tools, such as the Defense Automated Neurobehavioral Assessment (DANA), may have a better ability to discriminate between individuals with and without SRC.[23] A composite score of DANA rapid assessments correctly classified adolescents with SRC and healthy controls.[23] Additionally, research in collegiate athletes reveals that their ImPACT scores return to baseline in as early as 5 days following injury.[193]

While neurocognitive and neuropsychological assessments are vital, like symptom checklists, they should not be used alone due to their limitations. One limitation encountered on objective baseline assessments is a lack of effort or "sandbagging" to allow for a more rapid RTP or lack of diagnosed SRC altogether.[156,157] To mitigate this, built into the ImPACT test battery is software that detects invalid attempts due to suspected lack of effort.[194] Among Division 1 college athletes, approximately 15% failed to meet the ImPACT automated validity standard.[194] In addition to sandbagging, strenuous exercise prior to testing, poor sleep quality, motivation, and ADHD may influence performance on and validity of the ImPACT.[189,195] Last of all, neurocognitive assessments including ImPACT are subject to practice effects, which are increases in scores as a result of memorizing test items, developing strategies for successful completion, or other characteristics that complicate the interpretation of true change.[196] Previous research has determined that practice effects in ImPACT and other neurocognitive and neuropsychological assessments do occur.[197-199] With evidence displaying these assessments have little clinical utility beyond the sub-acute injury phase (within 8 days),[200] additional objective assessments should be used to determine when an athlete is ready to RTP.

2.6.3. Postural Control and Gait Assessment

In addition to the determination of signs, symptoms, and neurocognitive functioning, assessments of postural control and gait help to ascertain motor functioning following SRC. These assessments add another domain to the multifaceted approach to SRC management, since symptom severity, neurocognitive functioning, and motor functioning are not always related to one another or altered to the same degree.[201] Furthermore, recovery of cognitive processing capabilities occurs independent of postural control/gait,[10,202] which emphasizes the need for more than symptom resolution and a clear neurocognitive test to determine readiness to RTP. Assessments of postural stability have been utilized in SRC management for over two decades, while examinations of gait have only been incorporated more recently. In regards to postural stability, or balance, impairments that occur following SRC are thought to result from the combination of deficits in the somatosensory, visual, and vestibular systems.[17] The vestibular system consists of two main functional units, the vestibulospinal reflex and vestibulo-ocular reflex, but impairment to the former has the greatest influence on postural control and balance.[203] While assessments specific to vestibular-ocular reflex and oculomotor functioning will be discussed in the next section, assessments that are related to the vestibulospinal reflex, sensory, motor, and cognitive systems (i.e., static single-task challenges vs. dynamic dual-task challenges) will be discussed here.

One of the first assessments of balance post-SRC was the Romberg test, which evaluates the sway of an individual during quiet stance with eyes open and then with eyes closed.[204] This test is meant to remove the visual and vestibular components that contribute to balance to determine how the dorsal column, which deals with proprioception, is functioning. However, this test was deemed too subjective and unreliable (i.e., clinician determines level of sway as minimal or increased), which led to the development of a more objective balance assessment, the Balance Error Scoring System (BESS).[204,205] The BESS, which is included in the SCAT5, is the most commonly used balance assessment for SRC in collegiate athletes due to its cost effectiveness and ability to be administered feasibly in clinic or on the sidelines.[206] The BESS involves the athlete performing double limb, single limb, and tandem stances on both a firm, flat surface and a foam pad for 20 seconds each with their hands on their hips and eyes closed.[201,205] The test administrator counts the number of errors from a predefined list placed at the end of the SCAT5 manual (e.g., step/fall, opening eyes, hands lifted off). The BESS has demonstrated strong correlations with force plate measures and good to excellent intertester reliability [intraclass correlation coefficient (ICC) of 0.78-0.96].[207] Impaired balance is a commonly reported symptom and observed sign following SRC, with approximately 40% of athletes reporting balance issues.[208] This is supported by evidence using the BESS which shows an increase in 3-6 errors 24 hours post-injury compared to baseline.[17,209]

While the BESS is administered frequently, it has several limitations, especially in use beyond the acute phase (~3 days). First, the total BESS score (i.e., summation of errors from each stance) has demonstrated only moderate ICC values (~0.57), which raises reliability concerns for clinical interpretation.[204,205] Second, studies have shown that BESS scores return to baseline within 5 days following SRC despite continued symptomology and cognitive deficits.[209] Third, significant learning effects for the BESS have been found with serial testing, especially in the tandem stance.[210] On top of all that, environmental distractions (i.e., busy sideline),[211] fatigue and dehydration,[212] and prior ankle injury and instability may influence performance on the BESS.[213] With these limitations in mind, additional assessments of postural stability have been developed, such as the Sensory Organization Test (SOT).[17] The SOT is similar to the BESS, but adds a sway component through the use of a tilting force plate or test apparatus. It also includes composite scores for somatosensory, visual, and vestibular systems, which provides a more objective and valid assessment of overall impairment. However, recovery patterns of collegiate athletes on the SOT were similar to the BESS (3-5 days) and the lack of portability, cost, and clinical expertise of the test limits its utility.[17,206] More recent biomechanical studies of center of pressure (CoP) displacement have identified residual postural abnormalities over 30 days following SRC in collegiate athletes[202,214]; however, clinical feasibility of these techniques is limited.

To address the static nature of the BESS and SOT, assessments that replicate the more dynamic movement patterns athletes perform in sport have been developed. Dynamic postural control assessment and gait analysis can be used to help diagnose SRC, but may be even more useful in determining recovery. Biomechanical assessments of an athlete’s gait speed, cadence, step/stride, sway, and CoP and center of mass (COM) displacement tell clinicians if an altered gait strategy is present and may predispose the athlete to further injury. These variables can be assessed using single-task conditions (i.e., normal gait on level ground),[215] or using dual-task conditions, where additional motor (i.e., obstacle avoidance, tray-carrying) or cognitive tasks (i.e., serial subtraction) are added.[216]

A plethora of studies have identified a conservative gait strategy following SRC in collegiate and high school athletes.[25,38,193,217-220] These studies found a slower gait velocity, increased mediolateral range of motion, and greater time spent in double support, or the proportion of time that both feet are touching the ground during walking. Additional evidence in collegiate athletes found difficulty with gait initiation following SRC, indicating impaired postural control.[221,222] A separate study identified slower tandem gait following SRC in collegiate athletes compared to healthy controls, while no significant differences were seen for the BESS.[223] This again shows the limitation of the static measures of postural control and speaks to the utility of measures of gait. During dual-task conditions, the aforementioned gait deficits are intensified.[216,220] A systematic review and meta-analysis found gait velocity and mediolateral range of motion were the most sensitive measures during dual-task conditions in those with SRC.[216] Adolescent athletes following SRC demonstrated greater dual-task costs for gait speed and mediolateral COM across five time points and were more prone to errors on an auditory task while walking.[224] With increased difficulty of the dual-task condition, these athletes displayed greater COM displacement and decreased peak COM anterior velocity compared to controls.[225] Moreover, a systematic review determined that COM displacement during gait was higher in concussion groups with a taxing task and may be an indicator of ongoing injury even after clinical indications of deficits have subsided.[226] Even beyond traditional gait assessment, research has identified impaired propulsive and braking forces following SRC, which also persist beyond recovery.[227] While single and dual-task gait demonstrate utility in identifying deficits in dynamic postural control, complex gait analysis (i.e., walking on uneven surfaces in crowded environments) and non-linear assessments of postural control (i.e., approximate entropy) may be even more sensitive to lingering impairments following SRC,[220,228] although current evidence in these areas is limited.

2.6.4. Visual, Vestibular, and Oculomotor Assessment

As mentioned previously, the visual and vestibular systems are often affected following SRC and can manifest in different symptoms and impairments, adding another assessment piece to the "concussion puzzle". The visual or ocular system is impacted following SRC through disrupted neural communication between the brain and eyes, which is unsurprising given that half the brains circuits are involved in vision.[229] This results in post-SRC visual symptoms, including blurred vision, double vision, and sensitivity to light.[230,231] It is suspected that sensitivity to light following SRC is a result of disordered central processing and may be associated with headache or migraine symptoms.[230] Vision also plays a major role in postural control by allowing the individual to orient their motion relative to other individuals, objects, or structures in their visual field,[232,233] and can thereby indirectly influence balance symptoms as well. Altogether, evidence has shown that approximately 30% of athletes report visual disturbances in the week after SRC, up to 65% of individuals have oculomotor dysfunction after concussion, and that vision disorders are commonly seen in adolescents that present to tertiary clinics following concussion.[55,234,235] Visual symptoms have also been associated with prolonged recovery following SRC,[18] emphasizing the need for assessment of visual disturbances in the multifaceted approach for SRC assessment.

Assessments of vision or eye movement following SRC examine saccades (horizontal and vertical), near-point convergence, accommodation, smooth pursuit, and photosensitivity. One of the most popular tests of eye movement is the King-Devick (KD) test due its objectivity and feasibility to administer.[236] The KD involves having the individual read numbers with variable spacing and patterns on a tablet as quickly as they can, which is scored by calculating the time required to complete the test. This task requires the use of saccades, attention, and areas of the brain involved in reading, which thereby evaluates functioning of the brainstem, cerebellum, and cerebral cortex.[236,237] In a systematic review and meta-analysis of the KD, authors found a baseline average of 43.8 seconds to complete the test, with a sensitivity of 86% and specificity of 90%.[238] Studies have also reported normative values for comparison post-SRC in a variety of athletic populations.[239,240] Following SRC, studies have shown a 5-7 second increase in scores compared to baseline.[236,237] In a separate study of youth and collegiate athletes, KD scores worsened in 75% of athletes following SRC and had greater capacity to distinguish concussion versus controls compared to tandem gait and the SCAT.[241] However, the KD has several limitations, including a high number of errors at baseline,[240] a significant practice/learning effect,[236] and it does not assess other areas of vision/ocular function.

Eye tracking is another type of assessment of visual function that has emerged in recent years and demonstrated efficiency in detecting abnormalities in oculomotor neural pathways.[242,243] Eye tracking software, such as the Eyelink 1000 eye tracker, records eye movements while participants watch a video as it moves around a screen.[244] In a study of 56 children with concussion and 83 healthy controls, 12 eye tracking metrics were significantly different between those with and without concussion.[245] Eye tracking detected poor convergence and accommodation capabilities and correlated with symptoms in the concussion group. In a separate study of adolescents, eye tracking identified pupillary disturbances in those with concussion compared to healthy controls.[246] Slightly different than eye tracking technology, pupillary light reflex has also been utilized to detect change in pupillary response following SRC.[247] Metrics of pupillary light reflex include maximum and minimum pupillary diameter, constriction/dilation velocity, percentage constriction, and pupillary re-dilation. A prospective study of 98 athletes following SRC and 134 healthy controls found that 8 of 9 pupillary light reflex metrics were significantly different among those with SRC.[247] While eye tracking and pupillary light reflex may serve as objective physiologic biomarkers of concussion in athletes, evidence remains limited at this time.

As vision plays such a vital role in the vestibular system, the two sensorimotor components are often assessed together. The vestibular system is complex sensory organization system that involves communication between the vestibular apparatus, the ocular system, postural muscles, brainstem, cerebellum, and the cerebral cortex.[203] As a whole, the vestibular system helps an individual maintain balance, visual stability, and sense of spatial orientation as their head moves and body changes position. The various organs and structures provide different types of information to the brain as movement occurs. The semicircular canals or ducts are interconnected tubes positioned in the innermost part of each ear that provide information about angular rotation based on the plane of motion they are positioned in. The otolith organs, the utricle and saccule, are located in the inner ear and detect gravitational forces and linear acceleration of the head. Together, these sensory organs contribute to the two main components of the vestibular system, the vestibulospinal reflex and vestibulo-ocular reflex. The vestibulospinal reflex coordinates positioning of the head, trunk, and body during movement, and is vital to maintain posture and balance. Meanwhile, the vestibulo-ocular reflex maintains gaze stabilization during head movements involving acceleration and rotation.[203] Accordingly, these reflexes and the vestibular system are critical for performing dynamic movements in response to the changing environmental conditions that occur in sport, which emphasizes the need to evaluate vestibular deficits following SRC.

As discussed previously, impairment to the vestibulospinal reflex results in postural control issues and can be assessed using tools such as the BESS, SOT, and single/dual-task gait analysis.[17,220] However, impairment to the vestibulo-ocular reflex (VOR) may occur separately and manifests in different symptoms. In a study of youth athletes with SRC, 81% exhibited vestibular deficits, with 69% scoring abnormally on the test of their VOR.[248] Prior evidence has demonstrated that impairment or dysfunction of the VOR results in symptoms of dizziness, headache, fogginess, nausea, and lightheadedness.[249] Along with balance, dizziness is the most commonly reported vestibular symptom following SRC,[55] and the second most commonly reported symptom overall.[250] Notably, dizziness occurs in approximately 50-77% of athletes following SRC.[249,251] Not only are vestibular symptoms such as dizziness common following SRC, but deficits to the VOR and vestibular system have been linked with prolonged recovery.[248,252-254] In a large retrospective study of patients with acute SRC (n=306) and post-concussion syndrome (n=93), 30% of those with SRC and 43% of those with post-concussion syndrome had vestibular-ocular dysfunction.[253] Vestibular-ocular dysfunction at the initial clinic visit was associated with prolonged recovery and was an independent predictor of the development of post-concussion syndrome. In a separate study of 79 collegiate athletes following SRC, abnormal scores on tests of vestibular and oculomotor functioning were associated with increased time to medical clearance.[254] With the high likelihood of VOR impairment, dizziness symptoms, and prolonged recovery following SRC, it is important to assess VOR and oculomotor functioning separate from the vestibulospinal reflex.

The primary VOR and oculomotor assessment is the Vestibular-Ocular Motor Screening Tool (VOMS).[255] The VOMS was developed to be a brief sideline assessment tool of SRC that examines symptom provocation following vestibular and oculomotor tasks. The test asks individuals to rate their symptoms of headache, dizziness, nausea, and fogginess on a scale of 0-10, with 0 being none and 10 being severe, prior to beginning the actual testing. Then, the test administrator conducts 7 vestibular and oculomotor tasks: smooth pursuits, horizontal saccades, vertical saccades, near-point convergence, horizontal VOR, vertical VOR, and visual motion sensitivity. After each task, the individual rates their symptoms of headache, dizziness, nausea, and fogginess again to determine if any symptoms were elicited. The near-point convergence task also involves the test administrator measuring the distance in centimeters between the individual's nose and the point where double vision occurred using a measuring tape. Each task is scored individually, with the total symptom score and the change in symptom scores from pre-test.

In general, the VOMS has displayed great accuracy in identifying individuals with SRC from healthy controls, with an internal consistency of 0.92 in adolescent athletes with SRC and 0.97 in controls.[255] The VOMS also has a combined sensitivity of 89% for near-point convergence distance, VOR, and visual motion sensitivity. In this same study of 64 adolescent athletes following SRC and 78 healthy controls, a total symptom score of $\geq$2 on any of the VOMS tasks and $\geq$5 centimeters on the near-point convergence task distinguished SRC from controls and became clinical cutoffs in adolescents.[255] In a separate study of 263 collegiate athletes at baseline, internal consistency was 0.97 and 89% of athletes scored below the adolescent cutoffs.[256] Furthermore, female sex and history of motion sickness were risk factors for VOMS scores above the clinical cutoff. In a later study of 285 collegiate athletes following recent SRC (≤3 days) and 285 healthy controls, a score ≥1 on each VOMS item and a horizontal VOR score of ≥2 significantly discriminated SRC from control, establishing clinical cutoffs for this population.[257] The total VOMS score had the highest discriminative utility (AUC=0.91), with an optimal cutoff score of ≥8. Contrary to previous research in adolescents, near-point convergence distance did not significantly identify SRC from controls.[257] In addition to total scores on the VOMS, evidence has shown that change scores also reveal impairments following SRC for all VOMS tasks within 7 days, and vertical VOR and visual motion sensitivity within 14 days.[16] Research using the VOMS in collegiate athletes following SRC has also shown that abnormal scores (≥2) on smooth pursuits, saccades, and convergence were associated with increased time to medical clearance compared to healthy controls.[254]

Overall, the VOMS is a useful and valid tool for identifying SRC and predicting those at risk of prolonged recovery. Additionally, the VOMS is more comprehensive than purely visual/ocular assessments, such as the KD, because it incorporates evaluations of oculomotor function (e.g., pursuits, convergence) and vestibular function (e.g., VOR), which are both robust discriminators of SRC.[257] While the VOMS is an important component of the multifaceted concussion approach, it is not without limitations. First, the VOMS involves subjective symptom reporting, which inherently introduces bias compared to more objective measures. Athletes may not understand what the symptoms are or do not wish to report symptoms for fear of being diagnosed with SRC.[258] The symptom scale also differs from that of the SCAT5, for example, which may introduce confusion. Second, evidence has shown post-test symptom improvement compared to pre-test on the VOMS in some individuals,[16] which may dilute the utility of comparing to baseline following SRC. Last, there is limited evidence beyond the acute recovery period following SRC, which limits the use of the VOMS in determining when an athlete is ready to RTP.

2.6.5. Clinical Examination and Profiles

The heterogeneity of SRC presentation and variety of assessment domains mentioned above has led to the proposal of clinical profile-based approaches to SRC management. The determination of clinical profiles occurs during the clinical examination phase and helps to inform the types of assessments administered, along with targeted therapies and rehabilitation programs for athletes with SRC. The initial clinical profile approaches and classification systems were developed in 2014 to accelerate safe RTP for athletes following SRC.[259,260] These profiles were originally developed in concussion specialty clinics, but can be applied to care in a variety of environments. The updated clinical profile-based conceptual model for SRC will be discussed below.[249]

The current clinical profiles or trajectories following SRC include cognitive/fatigue, vestibular, ocular, post-traumatic migraine, anxiety/mood, and cervical/sleep.[249] Common symptoms, clinical examination findings, risk factors, and targeted treatment strategies for each clinical profile can be found in Kontos et al.[249] Since prior iterations of the model, the cervical profile has been joined with sleep-related problems as emerging modifiers of SRC. In some instances, athletes may present with one clearly defined clinical profile, but most typically present with multiple profiles that often overlap with one another.[259] As such, the prioritization of these profiles is important and should be informed by the comprehensive list of assessments discussed previously. Obtaining detailed medical history, injury characteristics, and relevant risk factors is also vital to ascertain the interplay among primary, secondary, and even tertiary profiles.

A study of 236 participants between the ages of 11 and 40 years following concussion found the following frequency distribution for primary profiles: 26% migraine, 24% anxiety/mood, 19% vestibular, 16% ocular, 11% cognitive/fatigue, and 4% no clear profile.[249] Notably, almost half of the participants presented with vestibular-ocular and cognitive/fatigue profiles, which all may contribute to broader scale sensorimotor deficits. In this study, the migraine clinical profile was associated with an increased likelihood of a secondary vestibular profile, suggesting that these profiles should be anticipated and planned for together. Altogether, these findings highlight the importance of a multifaceted, comprehensive assessment approach following SRC.

2.7. The Sensorimotor System and Assessment of Sport-Related Concussion

The sensorimotor system encompasses all of the somatosensory, motor, visual, vestibular, and central integration and processing components involved in the simple and complex movements that occur in sport.[261] Broadly, it governs an individual's ability to perceive and respond to stimuli from the external environment, as well as the ability to move and perform functional activities. While the sensorimotor system incorporates all afferent, efferent, and central integration and processing components, the somatosensory and motor regions of the brain are referred to as the primary sensorimotor cortex.[262] Representations of different body parts in the primary sensorimotor cortex are organized from the toe at the top of the cortex to the mouth at the bottom, and the amount devoted to a body part is related to the precision required for somatic sensation and/or motor control.[262,263]

Similarly, sensorimotor functions can be organized into various functions and mechanisms. Visual functions/mechanisms help detect objects and orientation of the body in space.[41,264] Vestibular functions/mechanisms detect linear and rotational acceleration of the head. Neurocognitive processing functions/mechanisms relate to how efficiently and effectively sensory cues are received and processed into movement. Somatosensory functions/mechanisms, such as cutaneous sensations, provide information about the body relative to other surfaces. Neuromuscular and postural control functions/mechanisms use somatosensory, visual, and vestibular signals to provide reference frames for where the body is in space, which helps with accuracy and inhibition of motion.[41,264]

So far, many areas of SRC assessment have been covered in this dissertation, but the majority of these assessments evaluate types of functioning (e.g., symptoms, neurocognitive, motor, visual) individually and seldom test the integration of multiple systems. However, assessments of sensorimotor functioning inherently accomplish that and, therefore, hold promise to contribute to the multifaceted concussion approach. While examination of sensorimotor functioning has been occurring for decades,[265] evidence is severely limited following SRC. If individual systems (e.g., visual, vestibular) are not revealing impairments following SRC, sensorimotor assessments may be able to determine if integration processes in the sensorimotor system are where the underlying deficits exist.

2.7.1. Sensorimotor Skills

The characterization of sensorimotor function into the various functions/mechanisms can also be described as "sensorimotor skills".[266] For example, visually-based sensorimotor skills include depth perception and near-far quickness, vestibular-based sensorimotor skills include eye-hand coordination, and cognitive processing-based sensorimotor skills include reaction time

(RT). Specific sensorimotor skills, which still all involve the process of receiving sensory input and producing a motor output, play a crucial role in athletic performance and RTP from injury.[13,14] While there is a paucity of evidence examining sensorimotor integration following SRC, a number of studies have examined specific sensorimotor skills. In the absence of a comprehensive sensorimotor assessment, these may be utilized as a proxy of sensorimotor function.

Reaction time is the sensorimotor skill that has been explored the most following SRC. It is important to note that, in the concussion literature, RT is misclassified as the response time, which is the total time from stimulus presentation to movement completion, instead of true RT, which is the time from stimulus presentation to movement initiation.[48] Since RT is standard terminology in the literature, it will be used to signify response time throughout this dissertation. Reaction time is usually examined using computerized neurocognitive testing, such as the ImPACT test.[48] Studies have demonstrated that RT is worse in concussed athletes compared to controls.[33,183,267-270] Eckner et al. compared clinically-measured and computerized RT in 9 collegiate athletes at baseline and following SRC and found that RT measured clinically was prolonged in more concussed athletes compared to computerized RT.[34] In a study of visual reaction time, athletes with SRC had significantly worse dual-task RT compared controls.[270] Central and peripheral visual RTs were significantly prolonged following SRC compared to those without a SRC history.[267] Slower RT during driving simulation has also been detected amongst asymptomatic athletes with concussion compared to controls (mean difference = 292.86 ms).[268] Lastly, video oculography has demonstrated increased RT in high school athletes following SRC compared to control athletes.[269]

There is limited research on sensorimotor skills outside of RT. Ellemberg et al. found that collegiate female soccer players following SRC performed significantly worse on decision-making, response inhibition, and planning compared to age-matched controls.[271] Schneider et al. found that ice hockey players following SRC had altered measures of split attention during a complex task involving walking while talking.[272] Halterman et al. found worse visuospatial attention and orientation one-month following SRC.[273] A separate study by Catena et al. found that spatial attention is lacking following concussion and results in increased probability of obstacle contact.[274] Another study examined multiple-object tracking following SRC in professional athletes using a three-dimensional multiple-object tracking test (3D-MOT).[275] Athletes with SRC exhibited poor performance on 3D-MOT at 2 days following their injury compared with healthy controls. Lastly, attention, multi-tasking, and decision-making were disrupted in concussed adolescent athletes for up to 2 months after injury when compared with a healthy cohort of matched control subjects.[24] While these studies have identified deficits in sensorimotor skills following SRC, they are often associated with another assessment tool (e.g., ImPACT) and may not adequately test the integration of skills used when athletes return to sport.

2.7.2. Sensorimotor Integration

To this point, performance on complex gait analyses or balance following SRC may be the best assessments of sensorimotor function and integration since these perturb multiple systems of the brain at once.[228] However, these tests must challenge athletes in sensorimotor integration situations enough to elicit the underlying deficits from SRC, which few do.[276] Complex gait tasks, such as walking on uneven surfaces in crowded environments requiring obstacle avoidance and navigation while performing serial subtraction, stress the cognitive, vestibular, and motor systems and may elicit responses not identified through other assessments.

These tasks require sensorimotor skills including spatial awareness, coordination, response inhibition, and more, and are commonly used in sport for successful performance and injury avoidance. An example of a multi-modal assessment of complex gait is the High Level Mobility Assessment Tool, which has shown sensitivity to concussion.[228] However, there is limited evidence of complex gait following SRC and the tests need to be performed in a research laboratory, take considerable time, and can be costly.

Many balance assessments attempt to perturb the sensorimotor system through manipulation of sensory feedback. Since balance is regulated via "sensory integration" and "sensory-to-motor" components, researchers have attempted to functionally characterize each balance control mechanism to improve clinical assessment.[277] The Central Sensorimotor Integration (CSMI) test uses a commercially available balance device and generates pseudorandom stimuli that apply intermittently-repeated rotations of the stance surface and/or visual surroundings.[277] This protocol measures COM body sway, frequency response functions (FRFs), sensory weights, and sensory-to-motor transformation properties (i.e., feedback time delay).[277] A study of 52 individuals with chronic concussion balance symptoms and 58 matched controls were tested using the CSMI and SOT.[278] The study team found increased sway, longer time delays, reduced stiffness, and decreased motor activation in the concussion group across a variety of conditions, suggesting that ongoing balance impairments are the result of sensory integration deficits and not damaged vestibular organs.[278] This supports previous evidence in individuals with chronic concussion balance symptoms that found no oculomotor or vestibular deficits.[279] While these studies do support the assessment of balance to determine sensorimotor integration following SRC, these were performed in chronic populations and not in the acute or sub-acute recovery phase. Furthermore, as indicated by the developers of the CSMI, most clinicians lack the educational background to adequately complete and analyze the test, which limits its translatability to the multifaceted concussion approach.[277]

2.7.3. Perception-Action Coupling

Emerging evidence is exploring sensorimotor function through examination of the perception-action coupling behavior, which is based on the Direct Perception Theory. The Direct Perception Theory, posits that sensory perception is the direct result of information from the environment.[280] Applying this theoretical framework to sport, stimuli from the game/practice (e.g., environment) is directly detected by the athlete (perceiver) and continuously acted upon, without a need to expand upon the information internally, which proceeds in a perception-action coupling loop.[281] This is a bottom-up processing approach, where sensory information (e.g., vision, hearing) is necessary for understanding stimuli from the environment instead of perception being passive and computational. Gibson later expounded on this idea by theorizing that the athlete actively seeks the sensory information through exploratory movements.[282] This brings about affordances, or possibilities for action for an athlete in their sport. Exploratory movements, such as a field hockey player scanning the field, allows them to detect affordances and provide sensory information for action, such as making a juke to avoid an oncoming defender. However, these affordances have boundaries (i.e., limitations to action) and require athletes to "actualize" them based on their physical abilities (e.g., strength, speed, height).[281] The actions available to the athlete are constantly changing throughout the game/practice as they compete, in addition to state of the athlete (i.e., fatigue, injury). If the athlete is negatively impaired in any way (i.e., SRC), they may overestimate their capability to complete an action and actualize an affordance, which may contribute to increased risk of injury.[283] For example, an athlete who does not have the height or jumping ability to dunk a basketball may incur additional injury risk if they attempt the action in a game/practice. The perception-action paradigm also applies to future movements, where the athlete detects similarities and differences in their environment after repeated action and adapts to them for prospective action.[284-286] With experience and practice in sport, athletes adapt to the constraints imposed on them and become more capable of actualizing affordances and overcoming boundaries, but are still required to calibrate to the environment.[281,286]

The potential theoretical relationship with SRC led to the development of the Perception Action Coupling Task (PACT), which is a reliable and valid measure of alertness and perception of one's limitations to actions.[287] This assessment requires participants to make judgements about whether a virtual ball will fit into an opening in several cycles. Athletes with a history of SRC demonstrated longer movement and RT on the PACT compared to controls, which suggests deficits in actualization of affordances and perception accuracy.[288] While more research needs to be conducted on the PACT in various populations following SRC, this is an efficient and feasible tool for clinic that can be added to the current SRC management approach and as a step in the gradual RTP protocol.

2.7.4. Virtual Reality

To further address sensorimotor integration and a dysregulated perception-action coupling state, clinicians can implement advanced sport-specific scenarios conducted within extended reality, which includes virtual reality (VR), augmented reality (AR), and mixed reality (MR). Virtual reality involves computer-generated simulated environments in real or created worlds where the individual interacts with the virtual space using digital recreations of themselves.[289] Immersive VR involves a head-mounted display where the user is placed into a 3D environment, while non-immersive VR involves interacting with the simulated world using a remote. Augmented reality involves the projection of virtual objects into the real world where the individual is not able to interact with the virtual overlay. Mixed reality involves the virtual object being projected into the real world at which point they are able to interact with it.[289]

Virtual reality has demonstrated ecological validity and reliable results, and has the unique ability to provide an interactive 3D environment that can challenge sensorimotor integration.[290] Unlike traditional assessments that examine components of sensorimotor function in isolation, they are able to target the complex integration of cognitive, motor, visual, and vestibular functioning. One such use of VR following SRC is to test the “moving room” paradigm, which observes postural sway induced by optic flow.[291] Following SRC in a group of student-athletes, participants were unable to view the “moving room” and experienced dizziness symptoms.[292,293] Furthermore, participants had an increased CoP area and decreased CoP coherence up to 30 days following SRC, which suggests perceptual-motion disintegration.[292,293] Teel et al. used this VR paradigm clinically with postural control scores (0-10 scale, 10 being best performance) and found a cutoff score of 8.25 had 85.7% sensitivity and 87.8% specificity in distinguishing SRC from control within 7-10 days.[294] Evidence using Nintendo Wii games within 3 days of SRC found those with concussion had a greater number of gaze deviations and possible disruption of the VOR response, despite weak predictive ability of concussion vs. control group (AUC=0.61-0.69).[295,296] A recent study of 11 participants with concussion and 10 controls found that sensorimotor conflicts (e.g., platform perturbations, visual scene perturbations) introduced in an immersive VR environment brought out hidden balance impairments in those with concussion.[297] Lastly, a review of VR as an assessment tool for SRC found that visual motion is destabilizing following SRC and that VR-based assessments may be more sensitive than traditional assessments, such as the BESS.[298]

While novel technology using extended reality is promising, there are a number of limitations that make its use questionable. First and foremost, the majority of the studies of VR following SRC involve a small sample size and limited scope, and the validity has not been established to inform evidence-based practice.[298] Additionally, the use of "moving room" VR paradigms may exacerbate symptoms of motion sickness, dizziness, and disorientation in the acute phase following SRC, without understanding of long-term effects on recovery.[292] Lastly, the cost, technical expertise, and space requirements to invest in such systems may be too unrealistic for a clinical setting.

2.7.5. Computerized Sensory Stations

While the assessments of sensorimotor function discussed in previous sections hold promise, there are a few critical barriers to these modalities that limit their utility moving forward. First, the assessments of individual sensorimotor skills, such as RT, only measure sensorimotor function in isolation and may not adequately test the wide range of skills or integration of systems used when athletes return to the complexities of their sports. Second, more advanced protocols, such as complex gait analyses, CSMI, and VR, come with significant limitations, including cost, feasibility, and a high level of required training and expertise to execute. Third, all of these assessments, including the PACT, lack evidence in populations following SRC, study designs that limit bias (e.g., prospective studies, RCTs, meta-analyses), and adequate sample sizes. One solution to these limitations has been the development of computerized sensory stations, which test a variety of sensorimotor parameters in one battery. The sensory stations, often called vision trainers, on the market provide objective data on performance in sensorimotor skill areas compared to normative data or athletes of a similar level (i.e., sport, position, experience), along with recommendations for improvement. Changes in performance can be objectively tracked over time, which may be useful in determining recovery from injury as well. The systems range in cost based on function ($1,000-$25,000) and most include a license that can be used with a headset, laptop, smartphone, or monitor.

Popular sensory stations or vision trainers used in clinical care include the Neurotracker, Bertec Vision Trainer, and Senaptec Sensory Station. The Neurotracker involves viewing multiple 3D moving targets in increasing levels of difficulty, which tests visual processing, awareness, executive function, working memory. The Bertec Vision Trainer trains visual, motor coordination, and balance skills using a mounted touchscreen and force plate. There have been some studies conducted using the Neurotracker in a population with concussion, but no studies involving the Bertec Vision Trainer at this time. Using the Neurotracker, a study of pediatric patients found smaller improvements in 3D multiple object tracking following concussion compared to controls.[299] A separate study in collegiate athletes before two different athletic seasons found the Neurotracker demonstrated acceptable test-retest reliability, while only the visual motor speed test of the ImPACT demonstrated retest reliability.[300] Aside from the lack of evidence, these systems only evaluate cognitive, postural control, or visual systems through one test, instead of a variety of tests, which may be needed to tax the sensorimotor system to the necessary degree to elicit deficits following SRC. A computerized sensory station that measures a battery of sensorimotor skills, such as the Senaptec Sensory Station (Senaptec),[43] should be utilized to obtain a comprehensive understanding of sensorimotor deficits following SRC.

Senaptec is comprised of interactive touch screen devices and a remote utilized to test 10 sensorimotor skills: visual clarity, contrast sensitivity, depth perception, near-far quickness, perception span, multiple object tracking, reaction time, target capture, eye-hand coordination, and go/no-go.[43] Senaptec's 7-test predecessor, the Nike SPARQ, demonstrated repeatability and minimal learning effects over time.[47] Extant literature using this device has examined the effect of sensorimotor performance on head impact biomechanics (i.e., linear and rotational acceleration) and to compare sensorimotor performance in combat soldiers with and without concussion history.[45,46] However, there is no evidence reporting the retest reliability of Senaptec or using its sensorimotor assessments in the collegiate population following SRC and throughout recovery. Exploring these gaps in the literature is the overall goal of this dissertation.

2.8. Return to Sport Following Concussion

Since SRC cannot be observed on neuroimaging studies,[6] clinicians rely on the multifaceted assessment battery to determine when an athlete's signs, symptoms, and functional deficits of SRC have resolved. Clinicians repeat the assessments used in the initial examination and subsequent visits throughout recovery, such as the SCAT5, ImPACT, and VOMS, and compare them to the athlete's baseline or to normative data if baseline assessments were not available. If they have returned to baseline or pre-injury levels, the clinician will then use their professional discretion to determine the athlete is ready to progress back to school, work, and sport. This process of returning to normal activities, deemed "clinical recovery", involves the completion of an exertion protocol, which is known as the RTP protocol. The laws differ by state, but most require written permission from a physician or advanced practitioner before the athlete is allowed to begin their RTP protocol.[161]

The RTP protocol most commonly used to progress athletes back to sport was developed by the Concussion in Sport Group.[6] This RTP protocol is a stepwise or graduated protocol, meaning that one stage must be successfully completed without the return of symptoms before the athlete can proceed to the next stage. The RTP protocol is usually conducted by an AT who monitors the athlete's progress and is able to address any setbacks. If symptoms do occur or return at any point in the protocol, the athlete must repeat that stage until they no longer experience symptoms related to SRC. There are 6 stages in total the athlete must pass before they are allowed to RTP. Each of these stages should be performed for at least 24 hours before the next stage is initiated. After an initial period of 24-48 hours of physical and cognitive rest, the athlete can begin stage 1. Stage 1 consists of symptom-limited activity involving daily activities, such as work and school activities, which do not provoke symptoms. Stage 2 consists of light aerobic exercise, such as walking and stationary cycling, with the goal of increasing the athlete's heart rate. Stage 3 consists of sport-specific exercises, such as running or skating drills, with the goal of adding movement back into the athlete's life. Stage 4 consists of non-contact training drills, such as passing drills and progressive resistance training, with the goal of exercise, coordination, and increased thinking. Stage 5 consists of a full contact practice where the main goal is to restore confidence in their abilities and assess functional skills. Finally, Stage 6 consists of returning to sport where normal game play occurs. An extended or more conservative RTP protocol may be necessary for youth athletes and those athletes that have been held out of play for an extended period of time.[6] Lastly, the clinician needs to consider additional factors, such as risk factors for prolonged recovery and subsequent injury, regarding appropriate timing for a safe RTP.

Historically, clinical recovery has been 10-14 days for adults and one month for pediatric patients.[1,6,15,301,302] A recent study of 1,751 collegiate athletes following SRC found a median total RTP duration of 12.8 days,[303] which fits within the "normal" clinical recovery timeline. However, a number of collegiate athletes in this sample were not cleared to begin their RTP protocol or for unrestricted sport participation until one month following SRC. Some of the reasons for the extended time included less frequent post-injury assessments, greater initial visit symptom severity, and three or more prior concussions.[303] This also is in accordance with previous evidence, which shows that some athletes may experience persistent symptoms and prolonged recovery.[1,8,42]

Research on risk factors for prolonged recovery or longer duration to RTP following SRC has advanced significantly in the past decade. Similar to risk factors for sustaining an SRC, female sex,[107,208,303] those with recurring migraines,[42,304] and those with a history of concussion are also at risk of protracted recovery.[148,303] More well-established evidence has shown that younger age,[6,15] severe acute symptoms (e.g. amnesia, headache, trouble concentrating, loss of consciousness),[42,303] mental health disorders (e.g. anxiety, depression),[15] and delayed removal from play result in prolonged recovery.[305,306] Recent evidence has also demonstrated that delayed initiation of clinical care or longer time to initial clinic visit is associated with longer recovery after SRC.[307]

2.9. Subsequent Injury Risk Following Sport-Related Concussion

Although the process described in the previous section has been in place clinically for years, a recurring dilemma in management of SRC is determining when athletes are truly recovered. The main concern is that clinical recovery may not signify complete neurophysiological recovery of the brain, which may place the athlete at risk for additional injury and potential long-term sequelae. A primary short-term risk of premature RTP is a repeat or subsequent SRC.[12,148] Multiple SRCs can lead to future negative consequences, including more physical, cognitive, and emotional symptoms before sport participation, and in some cases, slower recovery from additional SRCs.[6] A growing body of literature has also found that athletes are at increased risk of musculoskeletal (MSK) injury in the year following SRC, with odds ranging from 1.5 to 5 times the risk.[11,308-310] These increased odds of subsequent injury may be due to underlying sensorimotor deficits (e.g., neuromuscular control, reaction time) that prohibit the athlete from adjusting to the complexities of their sport.[28,29,308] Thus, thorough examination and assessment of these potential deficits after clinical recovery from SRC is warranted.

Extant research has found that sensorimotor function is altered following SRC, even when clinical symptoms have resolved.[27] Neurophysiological changes to the primary motor cortex following SRC, such as increased cortical inhibition and motor activation threshold, have been directly connected to alterations in motor function that negatively influence action.[311,312] This is supported by a number of cross-sectional and prospective studies of motor performance after concussion.[23,25,308,313,314] Servatius et al. examined motor deficits in asymptomatic adolescents after concussion and found deficits in RT, response inhibition, and motor speed.[23] Another study examined how RTP affected gait balance control strategies and found adolescents with concussion demonstrated increased medial and lateral displacement of their COM during dual-task gait, which revealed a regression of gait balance control after RTP.[25] A separate study found dual-task gait cost worsening after recovery was associated with time-loss injuries during sport the year after SRC.[313] In addition to neurophysiological impairments, changes to the somatosensory cortex and abnormalities in white matter tracts can be present after clinical recovery from SRC,[315,316] which affects systems that are crucial for movement planning (e.g., visual, spatial). All of these studies support evidence documenting the neurometabolic cascade of concussion, which posits that the existence of underlying pathophysiological changes after recovery from SRC may be responsible for increased risk for subsequent injury.[62,64,317]

The Direct Perception Theory can be used to explain the increased risk of MSK injury following RTP from SRC. The lingering impairments to the sensorimotor system following clinical recovery from SRC mentioned above may disrupt the perception-action coupling loop.

Furthermore, specific persistent symptoms may also result in a dysregulated perception-action coupling and lead to subsequent injury. Anxiety, sleep, blurred vision, dizziness, and balance problems are common following SRC and could contribute to subsequent injury by disrupting the perception-action coupling loop.[249] Anxiety has been directly associated with alterations in perception and action capabilities. Daviaux et al. carefully induced anxiety in participants by restricting breathing during a seated reach-and-grab task and found that increases in anxiety were associated with underestimating action capabilities.[318] Anxiety can also impair attention,[319] which may inhibit detection of affordances in exploratory movements.[282] Sleep abnormalities, such as sleep disturbances and insomnia, have also been linked with alterations in perception and action capabilities. Researchers investigated the effect of sleep deprivation on a step task and found that selection of affordances was influenced by sleep.[320] Lastly, ocular and vestibular symptoms (e.g., blurred vision, dizziness) play a major role in the perception-action coupling loop, as these abilities are key to guiding movement through the environment. Blurry or foggy vision will inhibit the detection of affordances and changes that occur during play,[249] which interferes with prospective movements.[321] Dizziness and balance problems may disrupt spatial orientation and proprioception, which influences the perception of action boundaries based on an athlete's physical capabilities.[29]

Unfortunately, there remains a dearth of evidence examining these underlying sensorimotor deficits and related symptoms that may lead to subsequent injury after SRC. One major reason for this is that the sensorimotor deficits are subtle and often not detectable in a clinical setting. As mentioned previously, while vestibular-ocular and postural control tests assess components of sensorimotor control, they may not translate to the sport environment or include the integration of sensorimotor components that are used in sport. Moreover, many symptoms go unreported, which makes it difficult for clinicians to treat them.[94,95] Nonetheless, the current literature suggests that failure to address impairments to the sensorimotor system and symptoms that exist after clinical recovery from SRC may increase the risk of subsequent injury in athletes. Assessments to detect sensorimotor deficiencies and elicit underlying symptoms, along with interventions to address these factors, can help to protect athletes when they RTP.

2.10. Summary

Clinicians lack robust metrics to adequately assess functional deficits following SRC. Medical consensus supports a multifaceted approach to SRC management involving a variety of assessments (e.g., clinical exam, neurocognitive test).[1,9,162,322] However, there is no "gold-standard" evaluation tool for diagnosis or assessment of recovery, which may result in deficiencies being missed.[10] Due to this clinical limitation, there is a critical need to identify evaluation tools that can advance the multi-faceted concussion assessment approach and improve management of SRC. Failure to identify robust metrics and improve SRC management may lead to negative consequences following SRC, such as a subsequent SRC or MSK injury.[11,12]

Deficits in sensorimotor function following SRC may result in subsequent injury. Sensorimotor skills, which involve the process of receiving sensory input and producing a motor output, play a crucial role in athletic performance and helping an athlete reacclimate injury.[13,14] However, research has demonstrated that components of the sensorimotor system are affected following SRC and that deficits may persist beyond clinical recovery. Clinical recovery typically occurs within two weeks for adults and one month for pediatric patients,[1,303] although some cases may take longer to recover. Within the first three days following SRC, deficits in vestibular and oculomotor function are regular, which negatively influences postural stability and coordination.[16-18] Cognitive impairments are also widespread and result in decreased processing, attention, and decision-making.[19] Even after clinical recovery from SRC, research has shown lingering sensorimotor dysfunction,[23-26,313] which supports evidence of disrupted neurophysiological measures following SRC.[27] Concerningly, deficits in sensorimotor function have been associated with increased risk of subsequent injury,[11,30] which is the motivation behind this dissertation.

A more in-depth assessment of sensorimotor function following SRC may address the crucial gap in the concussion multifaceted approach regarding determination of underlying deficits. Ocular and vestibular functioning are assessed using the KD and VOMS,[31,255] cognitive functioning is assessed using the ImPACT,[189,191] and postural stability is assessed using the BESS,[17,205] SOT,[17] and gait analyses.[218,220] Assessments of specific sensorimotor skills, such as response inhibition, use computer software or tests adapted for clinic.[33] While several assessments for individual types of sensorimotor function have been discussed in this dissertation, the major problem is that these assessments do not test a battery of sensorimotor skills at one time and may not perturb the athlete's sensorimotor system enough to provoke underlying deficits. Assessment tools that comprehensively measure sensorimotor function, such as Senaptec,[43] may help address this issue of understanding deficits following SRC. While the reliability of previous computerized sensory stations have been determined,[47] the test-retest reliability of Senaptec in a collegiate population has not been studied. This computerized sensory station has also not been used to evaluate collegiate athletes following SRC. Furthermore, as certain symptoms may alter sensorimotor function differently,[28,318,320] the association between symptom factors and performance on sensorimotor assessments in the acute phase after SRC should be investigated.

CHAPTER 3: THE RELIABILITY OF A COMPUTERIZED SENSORY STATION FOR THE COMPREHENSIVE ASSESSMENT OF SENSORIMOTOR SKILLS IN COLLEGE-AGED INDIVIDUALS

3.1. Abstract

Background: Various assessment modalities exist to evaluate performance of individual sensorimotor skills, such as computer programs for reaction time. However, there is limited research examining the reliability of an assessment tool that measures a comprehensive battery of sensorimotor skills.

Purpose: To determine the test-retest reliability of 10 sensorimotor skills assessed by a novel computerized sensory station.

Methods: A test-retest reliability design was employed. Participants included college-aged individuals (18-30 years) without a history of neurologic condition (e.g., moderate/greater TBI, epilepsy). Participants completed 10 sensorimotor skill assessments on a computerized sensory station (Senaptec Sensory Station, Senaptec Inc., Beaverton, OR) at two testing sessions one week apart (± 1 day). These skills included visual clarity, contrast sensitivity, depth perception, near-far quickness, perception span, multiple object tracking, reaction time, target capture, eye-hand coordination, and go/no-go. Separate intraclass correlation coefficients (ICCs) with a two-way mixed-effects model, absolute agreement, and 95% confidence intervals (CIs) were calculated to determine the test-retest reliability of each assessment. ICCs were interpreted as poor (<0.50), moderate (0.50–0.75), good (0.75–0.90), and excellent (>0.90). The standard error of measurement and minimal detectable change values were determined to examine clinical applicability.

Results: One hundred participants (80 female, age=21.6 ± 2.8 years) completed the study. Go/no-go, multiple-object tracking, eye-hand coordination, depth perception, and reaction time

demonstrated good reliability (ICCs = 0.81-0.88). Target capture and perception span demonstrated moderate reliability (ICCs = 0.51-0.63). Visual clarity, contrast sensitivity, and near-far quickness demonstrated poor reliability (ICCs = 0.28-0.43).

Conclusions: Assessments involving decision-making, anticipation, and spatial awareness demonstrated good reliability, while most assessments of visual skills demonstrated poor reliability. Sensorimotor assessments from this computerized sensory station are reliable and can be administered clinically in a healthy, college-aged population.

3.2. Introduction

The sensorimotor system involves the integration of somatosensory, motor, visual, vestibular, and processing components, which results in an individual's ability to complete simple and complex movements.[261] Generally speaking, the sensorimotor system dictates an individual's ability to perceive and respond to stimuli from the environment around them. While the sensorimotor system incorporates all afferent, efferent, and central integration and processing components, sensorimotor function can be largely characterized into "sensorimotor skills".[266] Visual skills help detect objects and orientation of the body in space, vestibular skills detect linear and rotational acceleration of the head, and somatosensory skills provide information about the body relative to other surfaces.[41,264] Neuromuscular and postural control skills use somatosensory, visual, and vestibular signals to provide reference frames for where the body is in space, which helps with accuracy and inhibition of motion.[41,264]

Sensorimotor skills play a crucial role in athletic performance, injury prevention, and return to sport from injury.[13,14] Athletes demonstrate superior visual-based skills, including static and dynamic visual acuity, contrast sensitivity, and depth perception compared to nonathletes.[323-327] Poor visual acuity has been repeatedly associated with injury risk in a variety of sports,[14,328] while depth perception is worse in athletes with a history of sport-related concussion (SRC).[186] Vestibular skills, such as accommodative-vergence responses, have exhibited deficits following SRC as well,[18,329,330] but also improvements through vestibular rehabilitation and training programs.[249] Visual-motor reactions, response times, and eye-hand coordination are crucial to performance and extant evidence has demonstrated these skills are discriminators between expertise level in sport.[327,331,332] Previous evidence has shown that slower reaction time is associated with increased injury risk,[333] and that reaction time is worse in athletes with SRC compared to controls.[33,267-270] Multiple-object tracking, spatial attention, and orientation are also key to successful performance in sport and deficits can lead to decreased obstacle avoidance.[273-275]

Due to the importance of sensorimotor skills in sport, researchers and clinicians have sought the most efficient, accurate, and repeatable tools to evaluate performance. While there are a variety of assessments of sensorimotor function, such as the Sensory Organization Test,[17] Grooved Pegboard Test,[23] and weighted stick drop,[33] the critical barrier is that the majority of available assessments only measure components of sensorimotor function in isolation, which may not provide a complete picture of sensorimotor function or be efficient in a clinical setting. Therefore, stakeholders have turned their attention to commercial technology-aided assessments, such as computerized sensory stations, that can augment sporting contexts and test a variety of skills at one time.[334,335] Computerized sensory stations have been used to predict performance in sport,[336] determine sensorimotor skill expertise by sport,[327] examine the effect of sensorimotor performance on head impact biomechanics,[45] and compare sensorimotor performance in combat soldiers with and without concussion history.[46] One such device, the Senaptec Sensory Station (Senaptec),[43] tests 10 sensorimotor skills: visual clarity, contrast sensitivity, depth perception, near-far quickness, perception span, multiple-object tracking, reaction time, target capture, eye-hand coordination, and go/no-go. While the test-retest reliability and reliable change indices of previous computerized sensory stations have been determined,[47,337] the reliability of this novel device has not been studied. In order to confidently use this device for training purposes or the assessment of injury, the reliability of this comprehensive computerized sensory station needs to be determined. Therefore, the purpose of this study was to determine the test-retest reliability of 10 sensorimotor skills assessed by this novel computerized sensory station. We hypothesized that the visual clarity, contrast sensitivity, depth perception, near-far quickness, perception span, multiple object tracking, reaction time, target capture, eye-hand coordination, and go/no-go assessments will demonstrate moderate to good reliability (ICC=0.5-0.9) in a healthy, college-aged population.

3.3. Methodology

Design

A test-retest design was used to determine the reliability of 10 different sensorimotor assessments administered using a computerized sensory station. The independent variable was time (session 1 and session 2) and the dependent variables were the individual scores from each sensorimotor assessment (**Table 1**). This study was approved by the Michigan State University (MSU) Institutional Review Board for Human Subjects Research, and all participants provided informed written consent.

Table 1. Computerized Sensory Station Assessments, Descriptions, Procedures, and Units.

Assessment	Description	Procedures	Units
Visual Clarity	How well can participant see distant details	Swipe in the direction of the opening in the C-shaped ring	LogMAR (Lower is better)
Contrast Sensitivity	How well can participant judge contrast differences	Swipe in the direction of the circle containing a pattern of rings	LogCS (Higher is better)
Depth Perception	How well can participant judge depth and distance	With 3D glasses on, swipe in the direction of the ring that appears closest	Arcsec (Lower is better)
Near-Far Quickness	How rapidly and accurately participant can shift their gaze between near and far	Swipe in the direction of the opening in the C-shaped ring as it alternates between tablet and remote display	Number correct (Higher is better)
Perception Span	Tests scope of participant's visual field and how well visual information is acquired	Replicate the pattern of dots flashed in the circles within the grid	Total score (Higher is better)
Multiple-Object Tracking	How well participant can divide attention between moving objects and track them at various speeds	Select the dots that flashed red at the beginning of the tests once they are done rotating	Composite score (Higher is better)
Reaction Time	How rapidly participant can react in response to a visual stimulus	Remove the required index finger when the pattern turns red as quickly as possible	Msec (Lower is better)
Target Capture	How quickly participant can shift their gaze and recognize a target in their periphery	Track the C-shaped ring as it appears in different corners of the screen and swipe in the direction of the opening	Msec (Lower is better)
Eye-Hand Coordination	How rapidly and accurately participant can respond to changing target	Touch the green dots that appear within the grid as quickly as possible	Msec (Lower is better)
Go/No-Go	How rapidly and accurately participant can decide about a target and respond to changes	Touch the green dots that appear within the grid as quickly as possible while not touching the red dots	Total score (Higher is better)

Abbreviations: LogMAR = Logarithm of the Minimum Angle of Resolution; LogCS = Logarithm of Contrast Sensitivity; Arcsec = Arcsecond; Msec = Millisecond

Participants

Participants were recruited from the general student population at a large university and the surrounding colleges using recruitment flyers and in-person visits to class settings. Participants were included if they were between the ages of 18 and 30 years and were excluded if they had an SRC within the past 6 months, a diagnosed neurological brain condition (e.g., epilepsy), or previously completed the testing battery.

Sample Size Estimation

The sample size of 100 participants acquired for this study was based on a previously published reliability study of a similar computerized sensory station.[47] Additionally, a power analysis revealed that 32 participants would be needed to achieve 90% power at an alpha of 0.05 if R_0 is 0.5 and R_1 is 0.7,[338] which is met by this sample.

Procedures

Participants completed 2 testing sessions one week apart (± 1 day), which is a typical timeframe used for test-retest reliability to minimize learning effects.[47,339] After informed consent was obtained, participants completed an intake form with demographic and medical history information. Next, participants completed the computerized sensory station assessment battery with the assistance of trained research coordinators who followed standard operating procedures for each session. At the end of the first session, the second session was scheduled, and the same testing procedures were completed.

Instrumentation

The Senaptec Sensory Station (Senaptec Inc., Beaverton, OR) uses an adjustable television screen, mounted tablet, and an Android remote to complete 10 sensorimotor assessments (**Figure 1**).[43] The device is designed to allow for multiple testers without concerns of skewing the data due to multiple raters. As such, custom software controls the displays, input acquisition, and test procedures based on participant responses. The entire computerized sensory station battery takes approximately 25 minutes. The study team member conducting the testing session followed an established standard operating procedure where the participant was presented with a brief video demonstration prior to the start of each test, followed by a condensed practice round, and initiation of the test. No additional coaching was provided by the study team member other than the standardized instructions.[47]

Figure 1. (A) The adjustable television screen, mounted tablet, and floor mat with 10 foot line of the computerized sensory station. **(B)** The Android remote used with the computerized sensory station.

Participants first completed visual clarity, contrast sensitivity, depth perception, and near-far quickness tests, in that order, using the remote at a distance of 10 feet from the mounted tablet, which is adjusted to eye-level. To ensure consistency of the distance that the participant stands from the device, a floor mat with a line delineating 10 feet from the device was used. For visual clarity, participants were provided an eye occluder to cover their left and right eye when prompted to on the device. For depth perception, participants were provided a pair of 3D anaglyph glasses to complete the test. Perception span, multiple-object tracking, and reaction time were then completed, in that order, at the mounted tablet (still set to eye-level) at a distance within arm's length. Target capture was completed next on the television screen using the remote at a distance of 10 feet. The television screen is also adjusted to eye-level using a blue line that appears prior to the start of the brief video demonstration. Eye-hand coordination and go/no-go were completed last at the television screen (still set to eye-level) at a distance within arm's length. Data acquired from each sensorimotor assessment is collected in raw form and composite scores are produced (**Figure 2**). As clinicians are most likely to use these composite scores in evaluation, the variables that produce the composite score for each assessment were used in the test-retest reliability calculations.

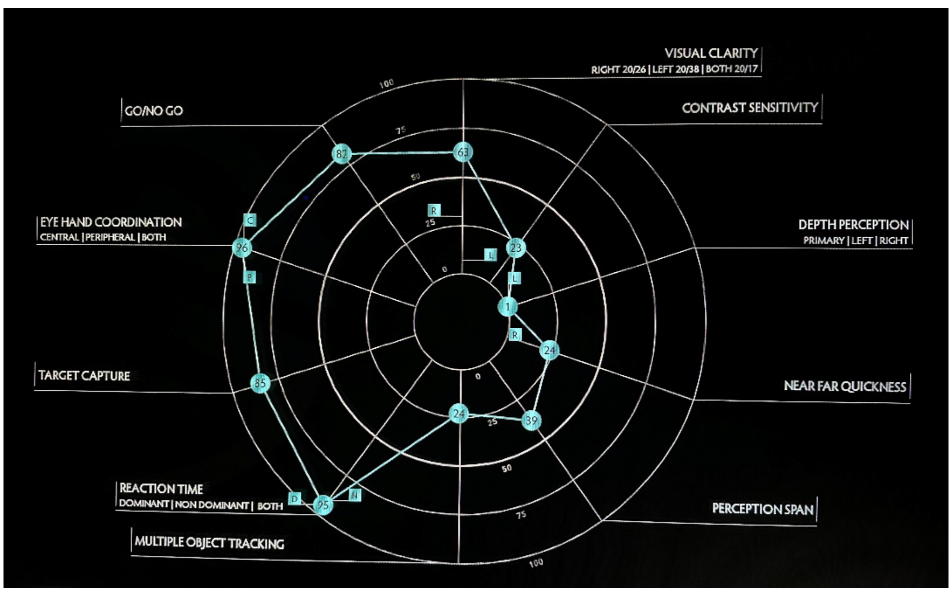

Figure 2. The performance matrix is produced following completion of the computerized sensory station testing battery. A composite score is produced for each sensorimotor assessment and displayed as a percentile rank comparing the participant to others in the same sport, position, and level of play.

Statistical Analysis

Descriptive statistics were calculated for demographic and medical history variables, with continuous variables reported as mean (SD) and categorical variables reported as frequencies

(%). Test–retest reliability was determined using intraclass correlation coefficients (ICCs) with corresponding 95% confidence intervals (CIs). Separate ICCs with a two-way mixed-effects model, absolute agreement, and 95% CIs were calculated for each sensorimotor assessment. The ICCs were interpreted as poor (<0.50), moderate (0.50–0.75), good (0.75–0.90), and excellent (>0.90).[52] For each ICC, the standard error of measurement (SEM) and minimal detectable change at the 95% confidence (MDC95) were calculated. For estimating SEM, the standard deviation from Session 1 (SD_{S1}) and the test–retest reliability ICC for each assessment were used in the following formula: $SD_{S1} \times (\sqrt{1\text{-ICC}})$.[340,341] For estimating the MDC95, the following formula was used: $SEM \times 1.96 \times \sqrt{2}$.[340,341] All statistical analyses were performed using SPSS software (version 27.0; SPSS, Inc, Chicago, IL).

3.4. Results

Overall, 107 participants were enrolled, but only 100 participants completed the study. Seven participants completed the initial visit, but did not return for the second visit due to leaving the state (n=5), non-study-related emergency (n=1), and device malfunction (n=1). No issues or deviations from the typical testing protocol among the 100 participants included were noted. Descriptive statistics for demographic and medical history variables are reported in **Table 2**.

Table 2. Descriptive Statistics for Demographic and Medical History Variables of Study Participants.

Variable	N (%)	Mean (SD)
Age in years	100 (100)	21.6 (2.8)
Sex		
Female	80 (80)	-
Male	20 (20)	
Dominant Hand		
Right	95 (95)	-
Left	5 (5)	
Primary Sport		
Soccer	21 (21)	
Track & Field	9 (9)	
Volleyball	7 (7)	
Swimming & Diving	6 (6)	
Softball	5 (5)	-
Rowing	4 (4)	
Ice Hockey	4 (4)	
Other	27 (27)	
Unknown	17 (17)	
Ocular Correction		
No	50 (50)	-
Yes	50 (50)	
Ocular Correction Type		
None	66 (66)	-
Contact Lenses	27 (27)	
Glasses	7 (7)	
Eye Surgery History		
No	96 (96)	-
Yes	4 (4)	
Concussion History		
No	60 (60)	-
Yes	40 (40)	
Number of Prior Concussion		
0	60 (60)	
1	20 (20)	-
2	11 (11)	
3 or more	9 (9)	

Mean scores (SD) for each sensorimotor assessment at the initial and second visit, along with the ICC values (95% CI) ordered from good to poor reliability, are presented in **Table 3**.

The SEM and MDC for each ICC are presented in **Table 4**. Go/no-go, multiple-object tracking, eye-hand coordination, reaction time, and depth perception demonstrated good reliability (ICCs = 0.81-0.88). Target capture and perception span demonstrated moderate reliability (ICCs = 0.51-0.63). Visual clarity, contrast sensitivity, and near-far quickness demonstrated poor reliability (ICCs = 0.28-0.43).

Table 3. Test-Retest Reliability for the Computerized Sensory Station Assessments.

Assessment	Visit 1 [Mean (SD)]	Visit 2 [Mean (SD)]	ICC (95% CI)
Go/No-Go (Total Score; higher is better)	5.6 (5.22)	7.2 (5.61)	0.88 (0.77-0.93)
Eye-Hand Coordination (Msec; lower is better)	50718.2 (44926.4)	47871.01 (4767.7)	0.85 (0.15-0.95)
Multiple-Object Tracking (Composite Score; higher is better)	1620.43 (580.84)	1682.19 (588.13)	0.85 (0.78-0.9)
Depth Perception (Arcsec; lower is better)	141.1 (87.57)	153.8 (91.77)	0.81 (0.71-0.87)
Reaction Time (Msec; lower is better)	332.4 (32.33)	324.7 (32.11)	0.81 (0.7-0.87)
Perception Span (Total Score; higher is better)	42.04 (10.82)	45.7 (13.44)	0.63 (0.45-0.75)
Target Capture (Msec; lower is better)	208 (77.52)	204.5 (71.9)	0.51 (0.26-0.67)
Contrast Sensitivity (LogCS; higher is better)	1.5 (0.26)	1.5 (0.26)	0.43 (0.15-0.62)
Visual Clarity (LogMAR; lower is better)	-0.1 (0.14)	-0.09 (0.21)	0.42 (0.14-0.61)
Near-Far Quickness (# Correct; higher is better)	21.2 (6.12)	23.7 (7.24)	0.28 (-0.05-0.51)

Table 4. Standard Error Measurement and Minimal Detectable Change for the Computerized Sensory Station Assessments.

Domain	ICC (95% CI)	SEM	$MDC_{95\%}$
Go/No-Go (Total Score; higher is better)	0.88 (0.77-0.93)	1.81	5.01
Eye-Hand Coordination (Msec; lower is better)	0.85 (0.15-0.95)	17399.92	48230.12
Multiple-Object Tracking (Composite Score; higher is better)	0.85 (0.78-0.9)	627.59	1739.59
Depth Perception (Arcsec; lower is better)	0.81 (0.71-0.87)	38.2	105.8
Reaction Time (Msec; lower is better)	0.81 (0.7-0.87)	14.09	39.06
Perception Span (Total Score; higher is better)	0.63 (0.45-0.75)	6.58	18.24
Target Capture (Msec; lower is better)	0.51 (0.26-0.67)	54.26	150.41
Contrast Sensitivity (LogCS; higher is better)	0.43 (0.15-0.62)	0.2	0.54
Visual Clarity (LogMAR; lower is better)	0.42 (0.14-0.61)	0.11	0.3
Near-Far Quickness (# Correct; higher is better)	0.28 (-0.05-0.51)	5.19	14.39

3.5. Discussion

The findings of our study indicated that assessments of sensorimotor skills including go/no-go, multiple-object tracking, eye-hand coordination, depth perception, and reaction time, demonstrated good reliability in a healthy, largely athletic, college-aged population. Meanwhile, assessments of visual skills including visual clarity, contrast sensitivity, and near-far quickness demonstrated poor reliability. Therefore, only some of the sensorimotor assessments included in this computerized sensory station demonstrated clinically acceptable reliability for evaluation of performance improvements and injuries, such as SRC, in a clinical setting. While the visual-based assessments can be used in a clinical setting, results should be compared to existing reliable visual assessments for clinical decision making and performance evaluations.[237,241-244,246,247]

We tested a comprehensive battery of 10 sensorimotor assessments using the Senaptec Sensory Station. To our knowledge, this is the first study examining the test-retest reliability of this commercially available assessment device. A recent study by Fraser et al. collected data using the Senaptec Sensory Station as part of concussion baseline testing in collegiate athletes,[342] but did not perform reliability analyses. They found similar initial mean scores to previously published values of the Nike SPARQ,[47,343] despite different testing parameters, and improvement in scores with retesting due to invalid scores from lack of effort, inattention, or misunderstanding directions.[342] The reliability of the Nike SPARQ, Senaptec's predecessor, was previously examined and found to have good repeatability with minimal learning effects.[47,337] Their results showed no significant change between visits on visual clarity, contrast sensitivity, depth perception, target capture, perception span, and reaction time assessments. This differs from our study, which demonstrated poor reliability on visual clarity and contrast sensitivity. Among the measures that did change across sessions in their study, including near-far quickness, eye-hand coordination, and go/no-go, they noted this was likely due to an expected learning effect caused by the motor response characteristic being measured.[47] Again, our study differed slightly from their results, with eye-hand coordination and go/no-go demonstrating good reliability. However, the Nike SPARQ is an older, discontinued model of the current device that had fewer assessments (e.g., lacking multiple-object tracking), different specifications (e.g., polarized glasses for depth perception replaced with 3D anaglyph lenses), and a different testing protocol.[47,337] Furthermore, Erickson et al. altered the instrumentation between visits (e.g., plastic sleeve was placed on the remote to improve swipe accuracy), used different statistical analyses, and did not focus on a college-aged population.[47] Therefore, the results from the current study provide important updated reliability data on the newest version of this computerized sensory station in a college-aged population. Our findings also contribute to the current evidence base of reliable assessments for sensorimotor function,[17,23,33,36,48,299,300] and adds information on a tool that tests numerous sensorimotor skills at once, which is lacking in the literature.

The assessments that demonstrated poor reliability in our study were visual clarity (ICC=0.42), contrast sensitivity (ICC=0.43), and near-far quickness (ICC=0.28). These lower reliability values could be due to a multitude of factors, including aspects of the statistical design and conditions of the testing environment. For each of these assessments, the mean scores and standard deviations at each visit were similar (visual clarity: visit 1 = -0.1 ± 0.14, visit 2 = -0.09 ± 0.21; contrast sensitivity: visit 1 = 1.5 ± 0.26, visit 2 = 1.5 ± 0.26; near-far quickness: visit 1 = 21.2 ± 6.12, visit 2 = 23.7 ± 7.24). These mean scores are also similar to initial mean scores and retested scores from Fraser et al.[342] This shows that the scores on these assessments may be consistent, but do not meet absolute agreement when the systematic errors of the raters and random residual errors are included.[52] Furthermore, the lower ICC scores could be caused by a lack of variability among sampled participants or the pool of participants being too small, although this is less likely with a sample size of 100 participants. In regards to the testing environment, screen glare from other lights in the room reflecting off the glossy surface of the tablet may have affected the results on these assessments, especially since they were all performed at a distance of 10 feet. The other assessment performed on the tablet at a distance of 10 feet was depth perception, which requires the participant to wear 3D glasses that may have minimized the effect of reflected light. However, measures were taken to minimize the influence of screen glare in the windowless room by turning off all overhead lighting and screens in the line of sight of the sensory station. Lastly, Fraser et al. found that invalid scores on Senaptec Sensory Station assessments at initial visit may occur due to lack of effort, motivation, or attention,[342] which could have been present for our assessments with poor reliability.

There are numerous applications for the more reliable sensorimotor assessments, notably the go/no-go, multiple object tracking, eye-hand coordination, depth perception, and reaction time tests. The Senaptec Sensory Station used to complete these assessments has been marketed primarily for performance training purposes. The majority of prior evidence using computerized sensory stations have focused on predicting performance in sport and determining sensorimotor skill expertise by sport.[13,327,336] A study of 252 professional baseball players demonstrated sensorimotor assessments from the Nike SPARQ significantly predicted on-base percentage, walk rate, and strikeout rate.[13] A separate study by Burris et al. used assessments from the computerized sensory station to identify that athletes who play sports requiring high coordination of the whole body or parts of the body (e.g., baseball and tennis) exhibit better measures of visual clarity, contrast sensitivity, and reaction time.[327] Meanwhile, athletes from strategic sports requiring processing of complex information concurrently about the position and objective of teammates and opponents (e.g., soccer and basketball) have higher measures of spatial working memory. We calculated the MDC95 for each sensorimotor assessment of this computerized sensory station, which provides values for clinically meaningful changes in each skill. This allows clinicians to use these tests to measure additional performance improvements as an outcome of training. Considering that multiple-object tracking was not included in the Nike SPARQ, and that this skill is key to successful performance in sport through improved obstacle avoidance,[273-275] future research should examine the performance of this assessment.

The reliability data from this computerized sensory station may also be used for injury assessment, rehabilitation, and recovery evaluation. DeCicco et al. used the device to determine the relationship between neurovascular coupling (NVC) and sensorimotor performance in combat soldiers with and without concussion history.[46] They found that concussion history did not impact the relationship between NVC response and sensorimotor performance, suggesting that these measures may be utilized for performance and/or injury evaluation. A published abstract of 224 high school and college student-athletes found that depth perception is worse in those with concussion history, which suggests this sensorimotor skill may be compromised following SRC.[186] Considering this evidence in those with a concussion history, future research should examine sensorimotor skills acutely following SRC. The MDC95 values will help clinicians use these assessments to measure sensorimotor performance as an outcome of treatment/rehabilitation effectiveness and recovery from injury. For example, the MDC95 values could be used to assess clinically meaningful changes in go/no-go following SRC. This would help clinicians determine the athlete's ability to inhibit movement in response to stimuli, which may protect them from mistakes in sport and potential injury. Future research should consider examining effective intervention strategies to improve each sensorimotor assessment using the computerized sensory station protocol described in our methods.

This study is not without limitations. First, 40% of our sample had a history of concussion, but were not excluded unless their injury was sustained within 6 months of testing. While one previous study revealed no impact of concussion history,[46] another study found deficits in depth perception in those with a concussion history,[186] which may have influenced results in this assessment despite good reliability. The history of other injury types (e.g., musculoskeletal injury) was not captured as well. For example, a potential history of shoulder injury may have affected performance on eye-hand coordination and go/no-go assessments, as they require prolonged movement of the upper extremities that may result in fatigue. However, while participants reported they were healthy at the time of testing, we cannot conclude these results are representative of an injury-free population. Second, while the screening questionnaire on the device captures ocular correction and history of eye surgery, we did not exclude based on either of these variables. Therefore, results may differ slightly based on ocular correction used and should be examined in the future. Next, our sample was predominantly female (80%) and only college-aged individuals, which limits the generalizability of the findings to non-female, high school, and older adult populations. Lastly, screen glare from other lights in the room reflecting off the glossy surface of the tablet and television screen may have affected the results on the sensorimotor assessments, although steps were taken to minimize disturbances from the testing environment (i.e., turned off all lights in the windowless room).

3.6. Conclusion

The assessments of sensorimotor skills using the Senaptec Sensory Station demonstrated suitable reliability for assessing sensorimotor function, especially go/no-go, multiple object tracking, eye-hand coordination, depth perception, and reaction time, in a healthy, largely athletic, college-aged population. Meanwhile, assessments of visual skills, including visual clarity, contrast sensitivity, and near-far quickness demonstrated poor reliability in this population, and should be used with caution. Overall, this comprehensive computerized sensory station can be implemented in research and clinical practice for the evaluation of performance and assessment of injury, rehabilitation, and recovery.

CHAPTER 4: SENSORIMOTOR SKILLS THROUGHOUT RECOVERY FOLLOWING SPORT-RELATED CONCUSSION IN COLLEGIATE ATHLETES

4.1. Abstract

Background: Emerging evidence suggests that subtle sensorimotor deficits may be present following clinical recovery from sport-related concussion (SRC). These underlying impairments are hypothesized to contribute to heightened risk of subsequent injury upon return to play (RTP). However, there is limited research examining a battery of sensorimotor skills acutely, at medical clearance, and after RTP following SRC in collegiate athletes.

Purpose: The purpose of this study was to examine sensorimotor skill performance throughout recovery and after RTP following SRC in collegiate athletes compared to healthy matched controls.

Methods: A prospective cohort study of participants following SRC and healthy matched controls was performed in a university laboratory setting. Participants with SRC were included if they were between the ages of 18 and 30 years and received a diagnosis of SRC from a licensed healthcare provider within 5 days of enrollment, and were excluded if they had a neurological brain condition (e.g., epilepsy) or did not plan to return to organized sport. Controls were matched to participants with SRC on biologic sex, age, and sport, and excluded if they had a neurological brain condition (e.g., epilepsy) or had sustained an SRC in the past 6 months. Participants with SRC completed their acute visit within 5 days of injury, their second visit at the time of medical clearance (+3 days), and the third visit at least one-month post-RTP. Controls completed three visits according to the same schedule as their matched participant with SRC. At each visit, participants completed demographic, injury, medical history, and recovery information, along with the Sport Concussion Assessment Tool-5 (SCAT5) and 10 sensorimotor skill assessments on a computerized sensory station (Senaptec Sensory Station, Senaptec Inc.,

Beaverton, OR). Two-way mixed-effects analyses of variances (ANOVAs) were used to determine the effect of group (SRC vs. control), time (acute, medical clearance, $\geq$1 one-month post-RTP), and the interaction between these independent variables on sensorimotor performance. Statistical significance was set a priori at $p < 0.05$.

Results: A total of 40 participants completed the study, 25 following SRC (mean age = 21.4 ± 2.9; 56% female) and 15 controls (mean age = 21.1 ± 2.5; 40% female). No significant differences in demographic or medical history variables were found at the acute visit. The SRC group reported a significantly greater number and severity of symptoms compared to controls ($p < 0.001$) at the acute visit, but not at medical clearance ($p > 0.05$) or one-month post-RTP ($p > 0.05$). Sensorimotor performance across recovery demonstrated a significant group x time interaction for reaction time ($F_{(1.3, 48.8)} = 6.85$, $p = 0.007$, $\eta_p^2 = 0.15$). Reaction time was statistically significantly worse in the SRC group (54.13 ± 21.72 msec, $p = 0.017$) compared to the control group at the acute visit. In the SRC group, reaction time was statistically significantly decreased between acute and medical clearance time points (M = 45.7, SE = 14.71 msec, $p = 0.01$) and the acute and one-month post-RTP time points (M = 58.9, SE = 14.8 msec, $p = 0.002$). No other significant interactions were found, although there were significant main effects of time for go/no-go, eye-hand coordination, and multiple-object tracking.

Conclusion: An examination of sensorimotor skills in collegiate athletes following SRC revealed significantly slower reaction time acutely and throughout recovery compared to healthy matched controls. While go/no-go, eye-hand coordination, and multiple-object tracking significantly changed over time, no differences were noted between groups. These findings support extant evidence regarding the presence of persistent reaction time deficits in athletes after SRC, even beyond clinical recovery, and reflect the need for routine incorporation of reaction time assessment in SRC management.

4.2. Introduction

Sport-related concussion (SRC) has become a challenging issue facing collegiate athletes, coaches, and clinicians and researchers alike. Approximately 3.8 million SRCs occur annually in the United States, with an SRC rate of 4.13 per 10,000 athlete exposures (AEs) in collegiate athletes.[3,105] An SRC results in a variety of clinical signs and symptoms,[249] and represents a functional disturbance rather than a structural injury, therefore it cannot be observed through neuroimaging (e.g., X-ray, magnetic resonance imaging).[6] To address the complexity and heterogeneity of the injury, medical consensus supports a multifaceted approach to SRC management involving a variety of assessments (e.g., balance test, neurocognitive test).[1,9,162,322] While many tools have strong psychometric properties and have been effective in evaluating SRC, there is no "gold-standard" evaluation tool for diagnosis or assessment of recovery.[10] Due to this critical limitation, there is a need to identify evaluation tools that can advance the multifaceted SRC assessment approach and improve management of SRC.

A multitude of components of the sensorimotor system are affected following SRC. Acutely, deficits in vestibular (e.g., visual motion sensitivity, vestibular-ocular reflex) and oculomotor function (e.g., horizontal and vertical saccades) are common,[16-18] and can be assessed using the Vestibular-Ocular Motor Screening and King-Devick tests.[31,255] Postural stability deficits have been evaluated using the Balance Error Scoring System,[17,205] Sensory Organization Test,[17] and through single or dual-task gait analyses.[218,220] Neurocognitive deficits, often evaluated using the Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT) test,[189,191] are also common following SRC and result in slowed processing speed, poor memory, decreased task attention, and diminished decision-making capabilities.[19] These performance and functional deficits that arise acutely following SRC, along with accompanying symptoms such as headache, dizziness, confusion, and fatigue, inhibit sensorimotor skills, which involve the process of receiving sensory input and producing a motor output.[20-22] Assessments of specific sensorimotor skills, such as reaction time and go/no-go, have been measured using computer programs or clinic-friendly adaptations.[33] Even after clinical recovery from SRC, some studies have found lingering cognitive, ocular, perceptual, and motor dysfunction compared to healthy controls.[23-26,49,313] These persisting deficits in sensorimotor skills have been linked to increased risk of subsequent SRC and lower extremity musculoskeletal injury,[11,12,30,313] which becomes a major concern for athletes upon return to play (RTP).

While there are a range of assessments for sensorimotor function (e.g., vestibular, motor), the critical barrier is that these assessments only stress individual components of the sensorimotor system. This may not provide a detailed picture of the athlete's deficits or be efficient in a clinical setting if numerous sensorimotor assessments have to be conducted. Furthermore, experimental evidence has scarcely examined the wide array of sensorimotor skills (e.g., depth perception, perception span, multiple-object tracking) that are used in sport, which means clinicians may fail to identify persistent deficits that do not become apparent until the athlete RTP. Assessment tools that measure a comprehensive set of sensorimotor skills and can augment the sporting context, such as computerized sensory stations,[43] should be employed to obtain a thorough understanding of deficits following SRC. Incorporating this type of comprehensive device acutely will benefit athletes by providing a more robust assessment of sensorimotor skills that are affected immediately following SRC, which would allow for targeted treatment and rehabilitation moving forward in the management process. This comprehensive assessment may also be important at the time of medical clearance by confirming there are no underlying sensorimotor skill deficits, despite determination of clinical recovery, which would mitigate the concern of the athlete being ready to RTP. Lastly, it would be of value to obtain a comprehensive assessment of sensorimotor skills at least one month after the athlete RTP, a time at which acute and subacute effects of SRC are expected to have subsided but evidence has shown SRC-related decrements are still apparent.[49] This will inform clinicians of lingering deficits in sensorimotor skills that may contribute to subsequent injury in this at-risk population.

One such computerized sensory station (Senaptec Sensory Station, Senaptec Inc., Beaverton, OR) assesses 10 sensorimotor skills: visual clarity, contrast sensitivity, depth perception, near-far quickness, perception span, multiple-object tracking, reaction time, target capture, eye-hand coordination, and go/no-go. Extant literature has used computerized sensory stations to examine sensorimotor performance in combat soldiers with concussion history and to examine the relationship between sensorimotor performance and head impact biomechanics in sport.[44-46] However, computerized sensory stations have not been used to evaluate collegiate athletes at various stages of recovery following SRC. Therefore, the purpose of this study was to examine sensorimotor skill performance throughout recovery and after RTP following SRC in collegiate athletes compared to healthy matched controls. Based on evidence of widespread cognitive, motor, vestibular, and ocular deficits acutely,[16-19,220] we hypothesized that the SRC group will perform worse on all sensorimotor skills tested with the computerized sensory station when compared to healthy matched controls acutely. Based on evidence of persistent deficits in response inhibition and reaction time after clinical recovery from SRC,[48,49] we hypothesized that the SRC group will perform worse on go/no-go, eye-hand coordination, and reaction time assessment at the time of medical clearance and at least one-month post-RTP compared to controls.

4.3. Methodology

Design

Sensorimotor skills were compared between participants following SRC (SRC group) and healthy matched controls (Control group) using a prospective cohort design. This study was approved by the Michigan State University (MSU) Institutional Review Board for Human Subjects Research. All participants signed an informed consent prior to initiation of study procedures.

Participants

Participants were recruited from MSU and local colleges in Michigan through an established recruitment network of sports medicine clinicians (e.g., athletic trainers, team physicians). After a clinician diagnosed an athlete with an SRC, they would share information regarding the study with the athlete and then connect the interested athletes with the study team. Participants with SRC who agreed to participate were asked to refer a friend or teammate that may be interested and fit inclusion criteria to serve as a control participant. If a control was not identified, the study team utilized the recruitment network within the local MSU community for potential healthy participants. Participants with SRC were included if they were between the ages 18-30 years with an SRC diagnosis from a licensed healthcare provider within 5 days of enrollment. Participants with a neurological brain condition (e.g., epilepsy) or those that did not plan to return to organized sport were excluded. Controls were matched to participants with SRC on sex, age, and sport. Controls with a diagnosed SRC within the past 6 months or a neurological brain condition (e.g., epilepsy) were excluded.

Sample Size Estimation

The estimation for the study was based on a comparison of sensorimotor skills, specifically dual-task gait balance control deficits, after concussion in a group of adolescents and young adults with a control group.[344] This study indicated large eta-squared ($\eta^2 > 0.14$) and medium to large partial eta-squared ($\eta_p^2 > 0.06$) effect sizes were present for participants with concussion compared to controls. Using a large partial eta-squared effect size of 0.15, an acceptable power of (1-β) of 0.80, and a-priori alpha level of 0.05, we estimated that 37 participants per group were required to identify significant differences. For this dissertation, data collection was halted for analysis with 25 participants following SRC and 15 controls.

Procedures

Participants with SRC completed their acute visit within 5 days of injury, their second visit at the time of medical clearance (+3 days), and the third visit at least one-month post-RTP. Within 5 days was selected for the acute timepoint to make it feasible for the study team to collect data on injuries that were sustained over the weekend in sporting events. Additionally, while 72 hours is considered "acute" in the SRC literature,[345] acute pathophysiology of concussion can span up to 10 days.[64] At least one month from RTP was selected for the third timepoint because we expect the acute and subacute effects of SRC to have subsided but evidence has shown SRC-related deficits may still exist.[49] The study team attempted to test participants as close to one-month post-RTP as possible, but were often challenged by participant availability and interest to return. Controls completed three sessions according to the same schedule as their matched participant with SRC to minimize confounding variables.

At the acute visit, participants completed an intake form with demographic (e.g., age, sex), injury characteristics (e.g., loss of consciousness, continued play), and medical history questions (e.g., SRC history, ocular history), followed by the symptom inventory of the Sport Concussion Assessment Tool-5 (SCAT5).[168] Afterwards, participants completed sensorimotor assessments on a computerized sensory station. At the medical clearance visit, participants reported recovery information (e.g., date of symptom resolution, date of clearance) and completed the SCAT5 symptom inventory and sensorimotor assessment battery. At the one-month post-RTP visit, participants completed an intake form with questions addressing their experience in sport following RTP (e.g., return of symptoms or subsequent injury), the SCAT5 symptom inventory, and the sensorimotor assessment battery.

Sensorimotor Assessments

We used a computerized sensory station (Senaptec Sensory Station, Senaptec Inc., Beaverton, OR) to test 10 different sensorimotor skills. This device uses an adjustable television screen with a tablet mounted on top and an Android remote to complete 10 sensorimotor assessments at distances of 2 or 10 feet (**Figure 1**).[43] The description, procedures, and units for each sensorimotor assessment are described in detail in Fraser et al. and Gilrein et al.[337,342] The study team member conducting the testing session followed an established standard operating procedure. The participant began by completing an intake form on the device that captures data regarding their vision (e.g., eye exam, ocular corrections) and pertinent medical history (e.g., eye surgery, SRC history). Once completed, the participant was presented with a brief video demonstration on the device prior to the start of each test followed by a short and easy practice round. No coaching or further help was provided by the study team members other than the standardized instructions at this point. The participant then initiates the assessment using the remote when they are ready and understand the instructions.

A previous version of the current computerized sensory station, the Nike SPARQ, demonstrated repeatability and minimal learning effects across two visits.[47,337] Preliminary data of the reliability of device used in this study revealed moderate to good agreement on the majority of sensorimotor assessments.[346] While all 10 assessments were completed, to eliminate any reliability concerns, only those that demonstrated good or excellent reliability were included in the analyses. These assessments were the go/no-go (ICC=0.88), eye-hand coordination (ICC=0.85), multiple-object tracking (ICC=0.85), depth perception (ICC=0.81), and reaction time (ICC=0.81) tests. This conservative approach was chosen because established evidence recommends a minimum reliability threshold of 0.7 for clinical applicability.[53] The description, procedures, and units for each sensorimotor assessment used in analyses are provided in **Table 5**.

Table 5. Computerized Sensory Station Skills, Descriptions, Procedures, and Units of Assessments Demonstrating Good Reliability.

Assessment	Description	Procedures	Units
Depth Perception	How well can participant judge depth and distance	With 3D glasses on, swipe in the direction of the ring that appears closest	Arcsec (Lower is better)
Multiple-Object Tracking	How well participant can divide attention between moving objects and track them at various speeds	Select the dots that flashed red at the beginning of the tests once they are done rotating	Composite score (Higher is better)
Reaction Time	How rapidly participant can react in response to a visual stimulus	Remove the required index finger when the pattern turns red as quickly as possible	Msec (Lower is better)
Eye-Hand Coordination	How rapidly and accurately participant can respond to changing target	Touch the green dots that appear within the grid as quickly as possible	Msec (Lower is better)
Go/No-Go	How rapidly and accurately participant can decide about a target and respond to changes	Touch the green dots that appear within the grid as quickly as possible while not touching the red dots	Total score (Higher is better)

Abbreviations: LogMAR = Logarithm of the Minimum Angle of Resolution; LogCS = Logarithm of Contrast Sensitivity; Arcsec = Arcsecond; Msec = Millisecond

Statistical Analysis

Descriptive statistics were calculated for demographic, medical history, and recovery variables, injury characteristics, and SCAT5 symptoms at each visit for SRC and control groups. Data were normally distributed; therefore, independent samples t-tests were used to compare continuous data between groups, while chi-square tests were used to compare categorical data between groups. Data related to performance on the 5 sensorimotor assessments (go/no-go, eye-hand coordination, multiple-object tracking, depth perception, reaction time) across recovery were analyzed via separate two-way mixed-effects analyses of variances (ANOVAs) to determine the effect of group (SRC vs. control), time (acute, medical clearance, one-month post-

RTP), and the interaction between these independent variables. Greenhouse-Geisser epsilon corrections were applied when the sphericity assumption did not hold. Statistical significance for all omnibus tests was set a priori at $p < 0.05$. For significant interactions, univariate general linear models with least significant difference confidence interval adjustments were performed to calculate simple main effects of group and repeated measures general linear models were performed to calculate simple main effects of time. For main effects, follow-up pairwise comparisons were performed with the Bonferroni procedure to control family-wise type I error. Estimations of effect size for mean differences were reported as partial eta-squared (η_p^2) values and interpreted as small (0.01-0.08), medium (0.09-0.24), and large (>0.25).[347] All statistical analyses were performed using SPSS software (version 27.0; SPSS, Inc, Chicago, IL).

4.4. Results

Acute Visit

Overall, 40 participants completed the study protocol and were included in analyses, 25 (62.5%) following SRC and 15 (37.5%) controls. In the SRC group, the time to presentation to the acute visit was 3.4 ± 1.6 days. No differences were noted between SRC and control groups for demographic (**Table 6**) or medical history variables (**Table 7**). Injury characteristics for the SRC group are presented in **Table 8**. The SRC group reported a significantly greater total number of symptoms (SRC: 16.3 ± 7.2, Control: 3 ± 3.2, $p<0.001$) and symptom severity score (SRC: 35.1 ± 17.9, Control: 5.9 ± 8.1, $p<0.001$) on the SCAT5 compared to controls.

Table 6. Descriptive Statistics for Demographic Variables of Sport-Related Concussion and Healthy Matched Controls Groups.

Variable	SRC (n=25)	Control (n=15)	*p*-value
Age (years)	21.4 (2.9)	21.1 (2.5)	0.76
Sex			
Female	14 (56%)	6 (40%)	0.33
Male	11 (44%)	9 (60%)	
Race			
White	18 (72%)	10 (66.6%)	
Black	2 (8%)	1 (6.7%)	0.96
Other	4 (16%)	3 (20%)	
Asian	1 (4%)	1 (6.7%)	
Ethnicity			
Non-Hispanic	23 (92%)	12 (80%)	0.27
Hispanic	2 (8%)	3 (20%)	
Handedness			
Right	24 (96%)	12 (80%)	
Left	1 (4%)	2 (13.3%)	0.22
Both	0 (0%)	1 (6.7%)	
Year in School			
College Freshman	4 (16%)	3 (20%)	
College Sophomore	2 (8%)	1 (6.7%)	
College Junior	5 (20%)	3 (20%)	0.98
College Senior	5 (20%)	4 (26.6%)	
Graduate Student	6 (24%)	3 (20%)	
Other	3 (12%)	1 (6.7%)	
Sport			
Baseball	1 (4%)	1 (6.7%)	
Cross Country	1 (4%)	1 (6.7%)	
Figure Skating	1 (4%)	0 (0%)	
Football	5 (20%)	5 (33.3%)	
Ice Hockey	2 (8%)	1 (6.7%)	
Powerlifting	1 (4%)	0 (0%)	0.91
Rugby	5 (20%)	2 (13.3%)	
Soccer	3 (12%)	1 (6.7%)	
Softball	2 (8%)	2 (13.3%)	
Track & Field	1 (4%)	0 (0%)	
Volleyball	1 (4%)	0 (0%)	
Wrestling	2 (8%)	2 (13.3%)	

Table 6 (cont'd).

Level of Play			
College	**12 (48%)**	**12 (80%)**	**0.17**
Club	**7 (28%)**	**1 (6.7%)**	
Intramural	**1 (4%)**	**0 (0%)**	
Recreational	**3 (12%)**	**0 (0%)**	
Other	**2 (8%)**	**2 (13.3%)**	

Continuous data are presented as mean (SD) and categorical data are presented as n (%). SRC=Sport-Related Concussion Group; Control=Healthy Matched Control Group

Table 7. Descriptive Statistics for Medical History of Sport-Related Concussion and Healthy Matched Controls Groups.

Variable	SRC (n=25)	Control (n=15)	*p*-value
Prior Concussion History			
No	15 (60%)	11 (73.3%)	0.39
Yes	10 (40%)	4 (26.7%)	
Number of Prior Concussions	1.6 (0.97)	1.5 (1)	0.87
Headache/Migraine			
No	24 (96%)	14 (93.3%)	0.71
Yes	1 (4%)	1 (6.7%)	
Learning Disorder/Dyslexia			
No	22 (88%)	14 (93.3%)	0.59
Yes	3 (12%)	1 (6.7%)	
ADD/ADHD			
No	19 (76%)	11 (73.3%)	0.85
Yes	6 (24%)	4 (26.7%)	
Anxiety/Depression			
No	15 (60%)	12 (80%)	0.19
Yes	10 (40%)	3 (20%)	
Motion Sickness			
No	22 (88%)	14 (93.3%)	0.59
Yes	3 (12%)	1 (6.7%)	
Eye Exam Ever			
No	6 (24%)	2 (13.3%)	0.41
Yes	19 (76%)	13 (86.7%)	
Eye Exam Past Year			
No	14 (56%)	11 (73.3%)	0.27
Yes	11 (44%)	4 (26.7%)	
Eye Correction in Sport			
Contact Lenses	4 (44.4%)	4 (80%)	0.3
Glasses	3 (33.3%)	0 (0%)	
None	2 (22.2%)	1 (20%)	
Eye Surgery Ever			
No	24 (96%)	15 (100%)	0.43
Yes	1 (4%)	0 (0%)	

Continuous data are presented as mean (SD) and categorical data are presented as n (%). SRC=Sport-Related Concussion Group; Control=Healthy Matched Control Group

Table 8. Descriptive Statistics for Injury Characteristics and Acute Visit Data of the Sport-Related Concussion Group and Healthy Matched Controls Groups.

Variable	SRC (n=25)	Control (n=15)	*p*-value
Time to Presentation (days)	3.4 (1.6)	-	-
Loss of Consciousness		-	-
No	20 (80%)		
Yes	5 (20%)		
Anterograde Amnesia		-	-
No	5 (20%)		
Yes	20 (80%)		
Continued Play		-	-
No	11 (44%)		
Yes	14 (56%)		
Total Number of Symptoms	16.3 (7.2)	3 (3.2)	**<0.001**
Symptom Severity Score	35.1 (17.9)	5.9 (8.1)	**<0.001**

Continuous data are presented as mean (SD) and categorical data are presented as n (%). Significant p-values (<0.05) are bolded. SRC=Sport-Related Concussion Group; Control=Healthy Matched Control Group

Medical Clearance Visit

Recovery information for the SRC group, along with symptom scores for both groups, are reported in **Table 9**. The mean time between acute visit and the medical clearance visit was 11.9 ± 3.2 days for the SRC group and 12.2 ± 3.5 days for the control group.

Table 9. Descriptive Statistics for Medical Clearance Visit Data of the Sport-Related Concussion Group and Healthy Matched Controls Groups.

Variable	SRC (n=25)	Control (n=15)	*p*-value
Time to Symptom Resolution (days)	14.6 (14.7)	-	-
Time to RTP Protocol Start (days)	14.3 (15.6)	-	-
Time to First Practice (days)	17.1 (15.1)	-	-
Time to Clearance (days)	17.2 (14.3)	-	-
Total Number of Symptoms	1.8 (3.7)	1.6 (2.8)	0.89
Symptom Severity Score	2.6 (5.7)	3.6 (6.2)	0.59
Time from Acute Visit (days)	11.9 (3.2)	12.2 (3.5)	0.75

Continuous data are presented as mean (SD). Significant p-values (<0.05) are bolded. SRC=Sport-Related Concussion Group; Control=Healthy Matched Control Group; RTP=Return to play

One-Month Post-RTP Visit

At the one-month post-RTP visit, no differences were noted between groups for the total number of symptoms (SRC: 0.6 ± 1.8, Control: 0.2 ± 0.6, p = 0.42) or symptom severity scores (SRC: 1.4 ± 5.0, Control: 0.3 ± 0.7, p = 0.38) on the SCAT5. The mean time between medical clearance visit and the one-month post-RTP visit was 55.3 ± 26.7 days for the SRC group and 66.1 ± 26 days for the control group (p = 0.31). The mean time for the SRC group was lowered by the 10 additional participants included in the analyses.

Sensorimotor Skill Performance Across Recovery

Mean scores on reaction time, go/no-go, eye-hand coordination, multiple-object tracking, and depth perception assessments at each visit for the SRC and control groups are presented in **Table 10**.

Table 10. Mean Scores on Sensorimotor Assessments at Each Visit of the Sport-Related Concussion and Healthy Matched Controls Groups.

Reaction Time (Msec; lower is better)			
Group	**Acute**	**Medical Clearance**	**One-Month Post-RTP**
SRC (n=25)	368.4 (80.3)	322.7 (29.4)	309.5 (28.4)
Controls (n=15)	314.3 (31.02)	306.3 (21.5)	316.6 (29.9)
Go/No-Go (Total Score; higher is better)			
Group	**Acute**	**Medical Clearance**	**One-Month Post-RTP**
SRC (n=25)	5.2 (4.8)	9.5 (5.7)	11.8 (6.5)
Controls (n=15)	8.7 (3.9)	12.1 (5.1)	12.4 (4.7)
Eye-Hand Coordination (Msec; lower is better)			
Group	**Acute**	**Medical Clearance**	**One-Month Post-RTP**
SRC (n=25)	57762.3 (18039.2)	47674.6 (4396.5)	45661.9 (3653.8)
Controls (n=15)	49235.5 (2970.7)	46486.5 (3069.2)	45176.3 (2880.8)
Multiple-Object Tracking (Composite Score; higher is better)			
Group	**Acute**	**Medical Clearance**	**One-Month Post-RTP**
SRC (n=25)	1385.3 (511.8)	1647.1 (556.9)	1688.1 (543.9)
Controls (n=15)	1363.8 (410.7)	1639.7 (556.6)	1567.2 (618.7)

Table 10 (cont'd).

Depth Perception (Arcsec; lower is better)			
Group	**Acute**	**Medical Clearance**	**One-Month Post-RTP**
SRC (n=25)	168.2 (89.9)	146.12 (85.1)	154.04 (92.6)
Controls (n=15)	179.7 (81.3)	179.5 (71.3)	179.1 (83.5)

Continuous data are presented as mean (SD). SRC=Sport-Related Concussion Group; Control=Healthy Matched Control Group

Reaction Time

There was a statistically significant interaction between group and time on reaction time ($F_{(1.3, 48.8)} = 6.85$, $p = 0.007$, $\eta_p^2 = 0.15$) (**Figure 3**). Post-hoc analysis of simple main effects of group revealed a statistically significant difference in reaction time between the SRC and control group at the acute visit ($F_{(1, 38)} = 6.2$, $p = 0.017$, $\eta_p^2 = 0.14$). Reaction time was statistically significantly slower (i.e., worse) in the SRC group (54.13 ± 21.72 msec, $p = 0.017$) compared to the control group at the acute visit. No statistically significant differences in reaction time between the SRC and control group were found at medical clearance ($F_{(1, 38)} = 3.49$, $p = 0.069$, $\eta_p^2 = 0.08$) or one-month post-RTP ($F_{(1, 38)} = 0.57$, $p = 0.46$, $\eta_p^2 = 0.015$). Post-hoc analysis of simple main effects of time revealed a statistically significant effect of time on reaction time for the SRC group ($F_{(1.2, 29.6)} = 12.25$, $p = 0.001$, $\eta_p^2 = 0.34$), but not for the control group ($F_{(2, 28)} = 2.14$, $p = 0.14$, $\eta_p^2 = 0.13$). For the SRC group, reaction time statistically significantly decreased (i.e., improved) from acute to medical clearance time points (M = 45.7, SE = 14.71 msec, $p = 0.01$) and from acute to one-month post-RTP time points (M = 58.9, SE = 14.8 msec, $p = 0.002$), but was not statistically significantly different between medical clearance and one-month post-RTP (M = 13.2, SE = 5.75 msec, $p = 0.09$).

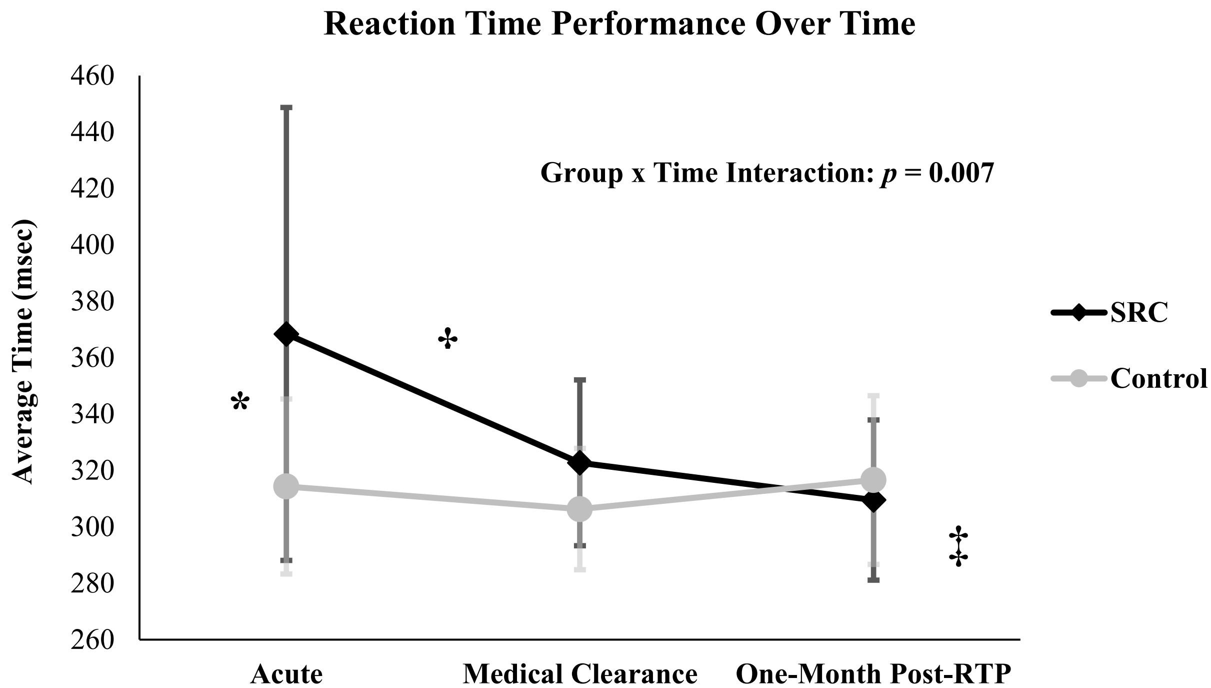

Figure 3. Mean ± SD reaction time performance scores across the acute, medical clearance, and one-month post-RTP visits for the SRC and Control groups. *Significant difference in reaction time between SRC and Control groups at the acute visits. †Significant difference in reaction time for the SRC group between acute and medical clearance visits. ‡Significant difference in reaction time for the SRC group between acute and one-month post-RTP visits.

Go/No-Go

There was no statistically significant interaction between group and time on go/no-go ($F_{(2, 76)} = 2.4$, $p = 0.09$, $\eta_p^2 = 0.06$), along with no statistically significant main effect of group ($F_{(1, 38)} = 2.15$, $p = 0.15$, $\eta_p^2 = 0.05$) (**Figure 4**). However, the main effect of time showed a statistically significant difference in mean go/no-go scores at the different time points ($F_{(2, 76)} = 30.9$, $p < 0.001$, $\eta_p^2 = 0.45$). Follow-up pairwise comparisons revealed that mean go/no-go scores statistically significantly increased (i.e., improved) from acute visit to medical clearance (M = 3.8, SE = 0.72, $p < 0.001$) and from acute visit to one-month post-RTP (M = 5.1, SE = 0.75, $p < 0.001$), but not from medical clearance to one-month post-RTP (M = 1.3, SE = 0.54, $p = 0.071$).

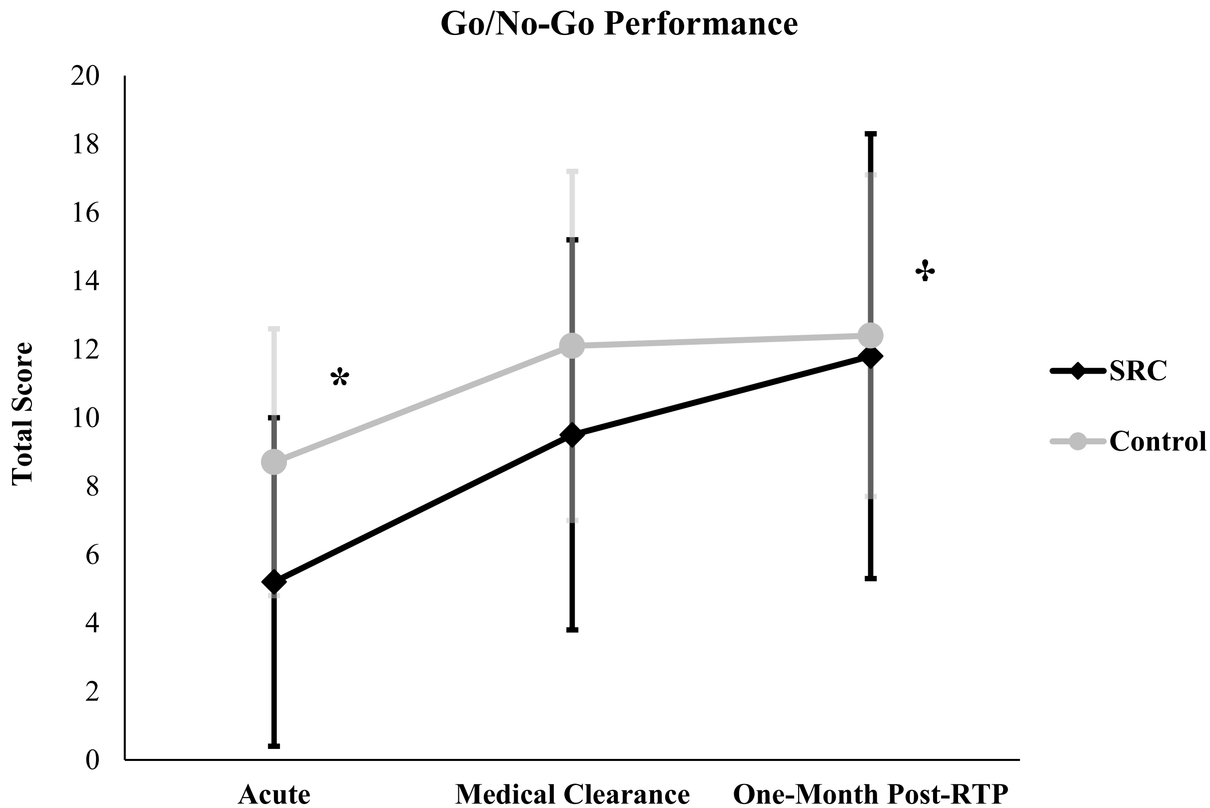

Figure 4. Mean ± SD go/no-go performance scores across the acute, medical clearance, and one-month post-RTP visits for the SRC and Control groups. *Significant increase in go/no-go scores between acute and medical clearance visits. †Significant increase in go/no-go scores between acute and one-month post-RTP visits.

Eye-Hand Coordination

There was no statistically significant interaction between group and time on eye-hand coordination ($F_{(1.1, 40.9)} = 2.8$, $p = 0.09$, $\eta_p^2 = 0.07$), along with no statistically significant main effect of group ($F_{(1, 38)} = 3.1$, $p = 0.09$, $\eta_p^2 = 0.08$) (**Figure 5**). However, the main effect of time showed a statistically significant difference in mean eye-hand coordination scores at the different time points ($F_{(1.1, 40.9)} = 10.4$, $p = 0.002$, $\eta_p^2 = 0.22$). Follow-up pairwise comparisons revealed that mean eye-hand coordination statistically significantly decreased (i.e., improved) from acute visit to medical clearance (M = 6418.3, SE = 2309.3 msec, $p = 0.025$), from acute visit to one-month post-RTP (M = 8079.8, SE = 2207.2 msec, $p = 0.002$), and from medical clearance to one-month post-RTP (M = 1661.5, SE = 514.9 msec, $p = 0.008$).

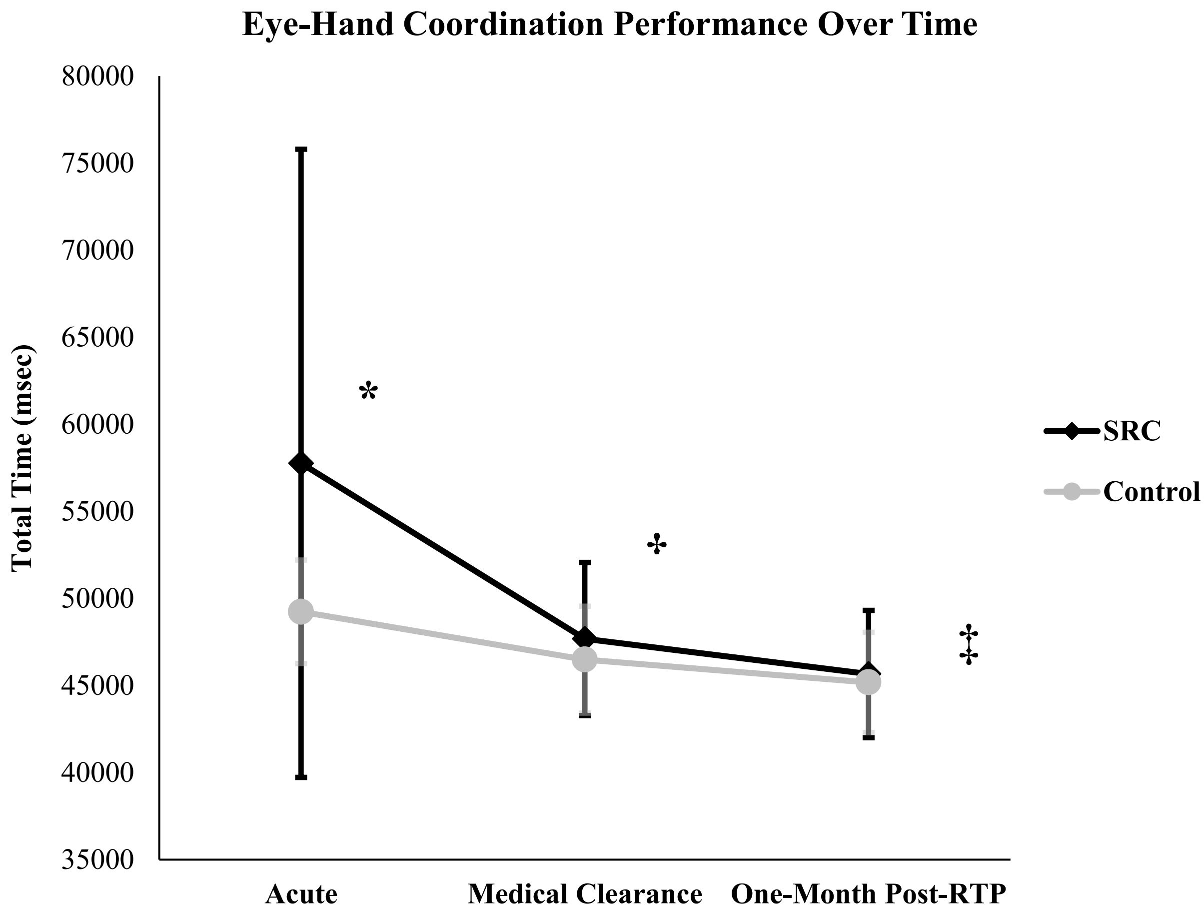

Figure 5. Mean ± SD eye-hand coordination performance scores across the acute, medical clearance, and one-month post-RTP visits for the SRC and Control groups. *Significant decrease in eye-hand coordination between acute and medical clearance visits. †Significant decrease in eye-hand coordination between medical clearance and one-month post-RTP visits. ‡ Significant decrease in eye-hand coordination between acute and one-month post-RTP visits.

Multiple-Object Tracking

There was no statistically significant interaction between group and time on multiple-object tracking ($F_{(2, 76)} = 0.29$, $p = 0.75$, $\eta_p^2 = 0.01$), along with no statistically significant main effect of group ($F_{(1, 38)} = 0.11$, $p = 0.74$, $\eta_p^2 = 0.003$) (**Figure 6**). However, the main effect of time showed a statistically significant difference in mean multiple-object tracking scores at the different time points ($F_{(2, 76)} = 7.02$, $p = 0.002$, $\eta_p^2 = 0.16$). Follow-up pairwise comparisons revealed that mean multiple-object tracking scores statistically significantly increased from acute visit to medical clearance (M = 268.9, SE = 78.9, $p = 0.005$) and from acute visit to one-month post-RTP (M = 253.06, SE = 83.7, $p = 0.013$), but not from medical clearance to one-month post-RTP (M = 15.8, SE = 78.9, $p = 0.99$).

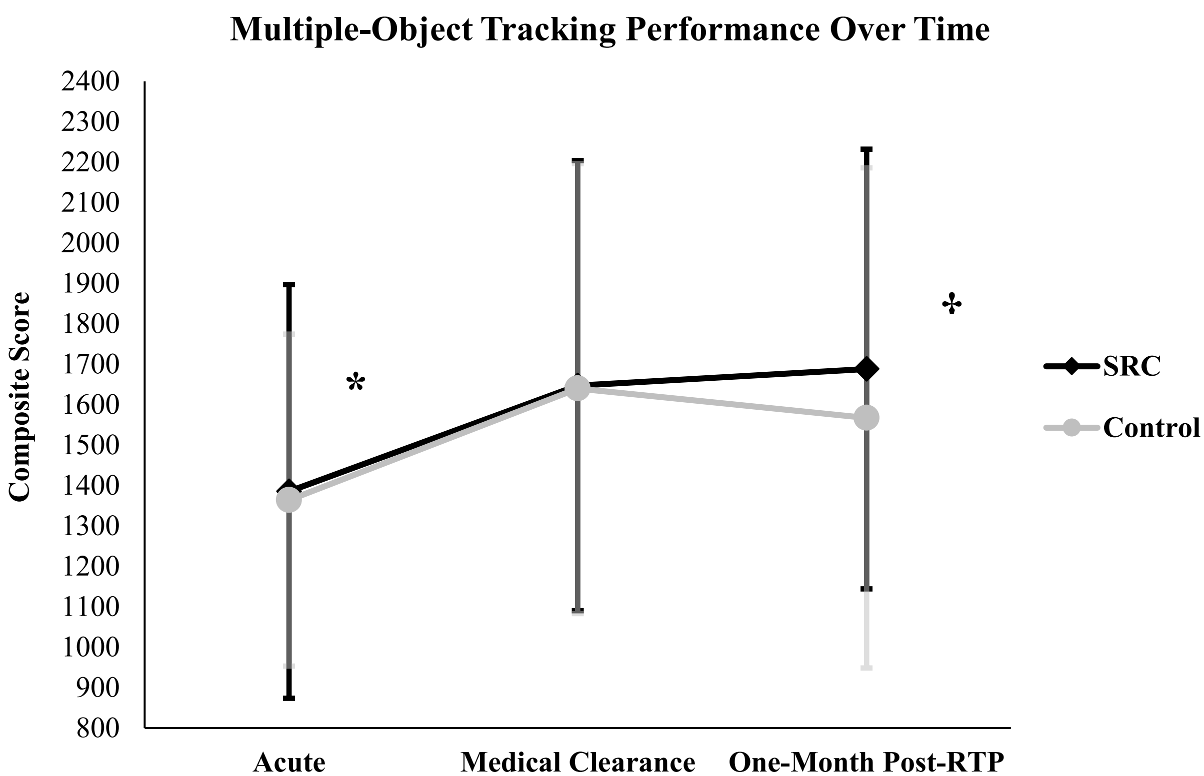

Figure 6. Mean ± SD multiple-object tracking performance scores across the acute, medical clearance, and one-month post-RTP visits for the SRC and Control groups. *Significant increase in multiple-object tracking between acute and medical clearance visits. †Significant increase in multiple-object tracking between acute and one-month post-RTP visits.

Depth Perception

There was no statistically significant interaction between group and time on depth perception ($F_{(2, 76)} = 0.47$, $p = 0.63$, $\eta_p^2 = 0.01$), along with no statistically significant main effects of time ($F_{(2, 76)} = 0.49$, $p = 0.61$, $\eta_p^2 = 0.01$) and group ($F_{(1, 38)} = 0.89$, $p = 0.35$, $\eta_p^2 = 0.02$). (**Figure 7**).

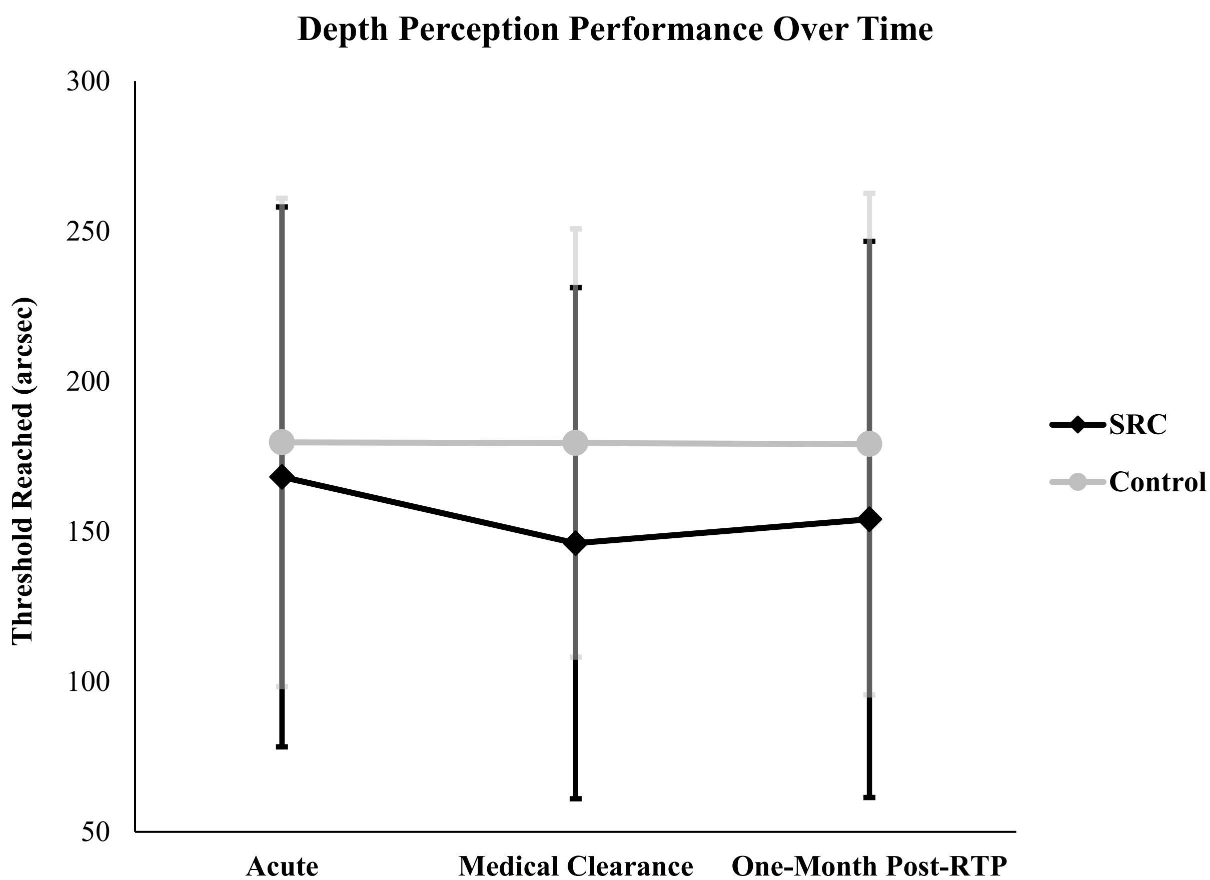

Figure 7. Mean ± SD depth perception performance scores across the acute, medical clearance, and one-month post-RTP visits for the SRC and Control groups.

4.5. Discussion

The current study compared sensorimotor skills in collegiate athletes following SRC to healthy matched controls. Results from this prospective cohort study revealed that collegiate athletes following SRC demonstrated significantly worse reaction time scores throughout recovery compared to healthy matched controls. More specifically, reaction time was significantly slower in athletes with SRC acutely and significantly improved to the time of medical clearance and one-month post-RTP. As a result, clinicians should be aware that collegiate athletes following SRC may demonstrate deficits in reaction time throughout recovery, and even after RTP, which could place them at risk for subsequent injury. Our findings support extant evidence regarding the presence of persistent reaction time deficits in athletes after SRC, even beyond clinical recovery, and reflect the need for routine incorporation of reaction time assessment in SRC management. While go/no-go, eye-hand coordination, and multiple-object tracking sensorimotor skills significantly changed throughout recovery, no differences were noted between groups. Furthermore, while scores on go/no-go and eye-hand coordination were consistently worse in athletes with SRC and improved throughout recovery compared to healthy matched controls, a significant interaction was not found for these sensorimotor skills assessments. This demonstrates that go/no-go, eye-hand coordination, multiple-object tracking, and depth perception assessments from this computerized sensory station do not appear to be sensitive to SRC across recovery and suggests that other sensorimotor assessment modalities may be better suited for the evaluation of SRC.

Reaction Time Throughout Recovery

Results from our study support previous evidence that demonstrates robust reaction time deficits following SRC that persist beyond medical clearance and clinical recovery.[48] A multitude of studies have found acute reaction time deficits post-SRC, independent of the study design and methodology.[33,34,48,348] Older, clinic-friendly tests of reaction time, involving grasping a falling measuring stick, have shown to be sensitive to concussion and distinguish between athletes with SRC, controls, and to baseline levels.[33,349] Now, computerized neurocognitive platforms are more popular for assessing reaction time following SRC, with simple measures (i.e., tasks requiring pressing a single computer button or trigger in response to a stimulus) demonstrating larger reaction time deficits following injury compared to mixed measures (i.e., composite score derived from subtests of ImPACT).[48] Howell et al. found significantly slower simple reaction times in a group of collegiate athletes with SRC (305.2 ± 32.4 msec) compared to controls (275.4 ± 22.1 msec) using a tablet-based neurocognitive evaluation.[350] Although the device and software was different, our results also showed the SRC group recorded slower simple reaction times than the healthy matched control group within 5 days of injury (368.4 ± 80.3 msec vs. 314.3 ± 31.02 msec, respectively). This supports a meta-analysis performed by Lempke et al.,[48] which demonstrated that reaction time deficits are present acutely regardless of the tool or device used. The computerized sensory station used in the current study adds to that body of literature of available sensorimotor assessments able to identify reaction time deficits acutely following SRC.

We also observed that reaction time deficits in the SRC group persisted beyond medical clearance, which is supported by previous evidence, although this research is still in its infancy. Lempke et al. revealed that significant reaction time deficits were still present during the intermediate term (21-59 days), but improved in the long-term (80-365 days) following concussion.[48] The intermediate term from their meta-analysis spans the average time from injury to the post-RTP visit in our study (58.7 days). As large-scale longitudinal and epidemiological studies have reported clinical recovery to occur for the vast majority of collegiate athletes within 28 days,[6,303,351] our findings support hypotheses that reaction time deficits may still be present at or beyond the time of clinical recovery.

While the reason for our finding related to reaction time is beyond the scope of the current study, there are a number of potential explanations, along with clinical implications, for the lingering deficits. The relatively small-sample size in our study may mask true effects, making it possible that group differences were observed at medical clearance and one-month post-RTP that may not be present. Alternatively, the type of reaction time assessment used in this study may be more challenging than other assessment types used in post-concussion evaluations, which elicits the lingering reaction time deficits. Research has shown attentional deficits are reflective of executive dysfunction, and these abilities may also require a longer period of recovery than what traditional computerized neurocognitive tests can identify.[24,308] Nevertheless, emerging research suggests that deficits in sensorimotor ability have been linked to increased risk of lower extremity musculoskeletal injury.[11,12,30,313] Studies have postulated that this association may be related to reaction time,[352] although a study of the ImPACT reaction time domain score and measuring stick drop did not significantly predict subsequent musculoskeletal injury.[353] Future research should investigate the performance of this sensory station's reaction time assessment and subsequent injury following SRC.

Eye-Hand Coordination and Go/No-Go Throughout Recovery

The eye-hand coordination and go/no-go assessments used in this study are difficult multimodal tasks that may more accurately reflect sensorimotor skills used by athletes in sport than standard SRC assessments, which speaks to the appeal of computerized sensory stations in identifying underlying deficits. Extant literature has demonstrated at length that impairments in cognitive functioning following SRC affects processing, eye-hand coordination, decision-making, and related skills that are used in these assessments.[19,187,188] One study in particular found that collegiate female soccer players following SRC performed significantly worse on decision-making, response inhibition (i.e., go/no-go), and planning compared to age-matched controls.[271] Despite what prior research has shown, our study revealed no significant interaction between the SRC and control group for the eye-hand coordination or go/no-go assessments.

While no significant interaction was found, eye-hand coordination scores were higher in the SRC group at each visit compared to controls. In both groups, eye-hand coordination scores were higher acutely and improved at each visit, as evidenced by the main effect of time. This may demonstrate a slight learning effect over time, even though the assessment demonstrated good reliability, or could be a result of improved effort and motivation. At baseline, Fraser et al. found that once athletes observed how their scores compared with others in their sport, level, and position, their attitudes and effort improved at a retest session.[342] This could be the case in our study as well, especially among the controls. It is also possible that with an increased sample size and even sample of controls, the interaction effect would change. While the eye-hand coordination assessment may be useful in determining deficits throughout recovery following SRC, further research is needed to support this. Therefore, it may not be a determining factor in management decisions at this time.

For the go/no-go assessment, scores were lower in the SRC group at each visit compared to controls, although no significant interaction was observed. Scores were lowest in both groups at the acute visit and improved significantly over time, as evidenced by the significant main effect for time. Again, these improvements may be the result of learning effects from better technique and greater effort and motivation.[342] Previous research has demonstrated deficits in inhibitory control (i.e., go/no-go) acutely (within 72 hours) and up to one-month following RTP in athletes following SRC compared to matched controls.[49] However, that study used a modified Flanker task on a laptop, which may have been easier for participants to complete than the go/no-go assessment on a large television screen that required greater motor responses. Similar to the eye-hand coordination assessment, it is possible that with an increased sample size and an even sample of controls, the interaction effect would change to significant and support this previous research.

Depth Perception and Multiple-Object Tracking Throughout Recovery

A published abstract using computerized sensory stations has identified worse depth perception in high school and collegiate athletes with a history of SRC compared to those without a history of SRC, suggesting the eyes' ability to work in tandem may be compromised following SRC.[186] A separate study of individuals following moderate TBI and SRC showed impaired stereopsis compared to controls, although using a virtual reality system at different positions of the visual field.[354] Nonetheless, this was not the case in our study in a sample of collegiate athletes following SRC compared to controls, where we found no significant group by time interaction. Scores on the depth perception assessment were lower in the SRC group at each visit compared to the controls. The reasoning behind these conflicting findings is unknown, as the SRC group did not differ significantly on any medical history variables, including history of SRC or ocular issues, compared to their counterparts. It is more likely that these differences are due to the difficulty of the assessment, as many participants reported that they were never able to see the target and made educated guesses throughout the test. This is supported by Fraser et al. who reported similar experiences in a study of collegiate athletes using the computerized sensory station during baseline testing for concussion.[342] Although preliminary evidence has shown this depth perception assessment to be reliable,[346] other assessment modalities of depth perception, such as virtual reality, may be better to elicit differences between athletes following SRC and controls.

Similar to depth perception, no significant interaction between groups and over time was identified for the multiple-object tracking assessment. Additionally, scores were higher in the

SRC group at each visit compared to controls and both groups scores improved over time, as demonstrated by the main effect of time. Once again, these findings conflict with extant evidence following concussion. A study of 15 participants with concussion and 20 controls revealed that the concussion group had greater deficits in their ability to maintain visual attention on tracking multiple moving objects, which was particularly hindered by increased tracking load and distraction.[355] Multiple-object tracking has also been used to predict post-concussion syndrome in adults <35 years old.[356] The multiple-object tracking assessment used in our study requires sustained attention and excellent peripheral vision to track several moving circles simultaneously. This results in participants often reaching a lower number of paired targets (i.e., 3 targets), but few successfully completing a higher number of paired targets (i.e., 6 targets), regardless of injury. Therefore, it is likely that results from our study are due to the assessment being too difficult to allow for differentiation between groups.

Clinical Implications

Our findings add relevant information to clinical knowledge regarding the presence of sensorimotor skill deficits acutely, throughout recovery, and after RTP in collegiate athletes following SRC. The presence of a significant interaction for reaction time supports nascent literature demonstrating persistent reaction time deficits beyond clinical recovery from SRC.[48,49] Clinicians should be aware of possible reaction time deficits in collegiate athletes following SRC and tailor their management plan accordingly. This may allow for improvement of these skills via visuomotor training or may allow clinicians to make more informed RTP decisions.[333] As reaction time is crucial in sport,[13,14] ensuring there are no underlying deficits at the time of medical clearance may help minimize the risk of subsequent injury.[11,12,30,313] Given evidence of other persistent deficits, including cognitive, ocular, perceptual, and motor, which all contribute to the sensorimotor system,[23-26,49,313] regular assessment of reaction time should be added to the multi-faceted concussion management approach. While some clinical practice guidelines encourage incorporation of sensorimotor assessment in management protocols,[357] future consensus statements should consider the evolving evidence.

Limitations

This study is not without limitations. First, the sample size in both groups did not meet the estimation and the sample size in the control group was 10 participants less than the SRC group, leaving the study underpowered. Therefore, evenly distributed groups that meet the sample size estimation for adequate power may result in different findings than those presented in this study. Second, the SRC and control groups only included collegiate athletes in the Mid-Michigan area, and were predominantly white and non-Hispanic. This may restrict generalizability of the findings to athletes of different ages, states, races and ethnicities. Additional data should be collected on participants of other ages, races, and ethnicities, as research has identified different recovery times between white and black athletes following SRC and younger athletes.[40,358] Next, only 5 of the 10 sensorimotor skills administered by the computerized sensory station were used in analyses to account for tests with poor (visual clarity, contrast sensitivity, and near-far quickness ICCs = 0.28-0.43) and moderate reliability (target capture and perception span ICCs = 0.51-0.63), which limits the applicability of the device as a comprehensive assessment of sensorimotor function. While the 5 sensorimotor assessments that were not used may still be useful, further reliability and validity studies need to be performed. Additionally, evidence at SRC baseline testing has demonstrated the possibility of invalid scores on the computerized sensory station due to lack of understanding, effort, and motivation,[342] which could have affected the results in our study, especially among the control group. However, this study only used reliable assessments and participants did not express any of those concerns to the study team.

4.6. Conclusion

An examination of sensorimotor skills in collegiate athletes following SRC revealed significantly worse reaction time acutely and throughout recovery compared to healthy matched controls. While go/no-go, eye-hand coordination, and multiple-object tracking significantly changed over time, no differences were noted between groups. These findings support extant evidence regarding the presence of persistent reaction time deficits in athletes after SRC, even beyond clinical recovery, and reflect the need for routine incorporation of reaction time assessment in SRC management. This will aid clinicians in curating individualized treatment plans, inform RTP decisions, and mitigate concerns regarding the risk of subsequent injury.

CHAPTER 5: THE RELATIONSHIP BETWEEN SYMPTOM FACTORS AND SENSORIMOTOR SKILLS FOLLOWING SPORT-RELATED CONCUSSION IN COLLEGIATE ATHLETES

5.1. Abstract

Background: As a result of the heterogeneous nature of sport-related concussion (SRC), clinicians and researchers have aggregated symptoms into groups, called factors, to better inform management of athletes with SRC. While the association between these symptom factors and neurocognitive performance has been studied, the association between symptom factors and performance on an array of sensorimotor skills is unknown. Additionally, it is unclear how symptom factors and sensorimotor skills are associated with recovery time following SRC in collegiate athletes.

Purpose: The primary purpose of this study was to examine the relationship between symptom factors and sensorimotor skills in collegiate athletes following SRC at the acute visit. The secondary purpose was to determine if symptom factors or sensorimotor skills were associated with recovery time.

Methods: A prospective cohort study of collegiate athletes following SRC was performed in a university laboratory setting. Participants with SRC were included if they were between the ages of 18 and 30 years and received a diagnosis of SRC from a licensed healthcare provider within 5 days of enrollment, and were excluded if they had a neurological brain condition (e.g., epilepsy). Participants with SRC completed an acute visit within 5 days of injury and a second visit at the time of medical clearance (+3 days). Participants completed an intake form with demographic, injury, medical history, and recovery information, along with the symptom inventory from the Sport Concussion Assessment Tool-5 (SCAT5) and 10 sensorimotor skill assessments on a computerized sensory station (Senaptec Sensory Station, Senaptec Inc., Beaverton, OR).

Symptoms were aggregated into a migraine-fatigue, affective, and cognitive ocular factor. Spearman's rank-order correlations were run to assess the relationship between each symptom factor and sensorimotor skill at the acute visit. A series of 8 linear multiple regressions were conducted with symptom factors and sensorimotor skills at the acute visit as independent variables and days to symptom resolution as the dependent variable. Statistical significance was set at a priori at $p < 0.05$.

Results: A total of 64 participants (mean age: 20.7 ± 2.5, 34 female, 30 male) following SRC completed the study. The average time to presentation was 3.7 ± 1.7 days and the sample presented as predominantly white (67.2%) and without a history of SRC (51.6%), headache/migraine (90.6%), ADD/ADHD (82.8%), or anxiety/depression (71.9%). The mean total number of symptoms was 11.9 ± 7.4 and mean severity was 25.8 ± 22.3. The migraine-fatigue factor had the greatest mean score (7.92 ± 5.9), followed by cognitive ocular (3.5 ± 4.4) and affective (3.14 ± 4.7). Statistically significant correlations were found between all three symptom factors with go/no-go, eye-hand coordination, and reaction time assessments ($p < 0.05$). None of the symptom factors or sensorimotor assessment scores were significantly associated with recovery time following SRC in collegiate athletes.

Conclusion: The cognitive-ocular, migraine-fatigue, and affective symptom factors from the SCAT5 were significantly correlated with performance on speed-based sensorimotor assessments, including go/no-go, eye-hand coordination, and reaction time, at the acute visit in collegiate athletes following SRC. However, none of the three symptom factors or 5 sensorimotor assessments were associated with recovery time while controlling for covariates. These findings further expand our knowledge of how specific symptom factors are related to

SRC assessments and recovery outcomes, which helps inform SRC management and clinical decision-making.

5.2. Introduction

Sport-related concussion (SRC) has become a major public health crisis with approximately 3.8 million SRCs occurring annually in the United States.[3] Collegiate athletes are particularly at risk, with an SRC rate of 4.13 per 10,000 AEs.[105] Since the injury does not present clinically in a consistent manner, medical consensus advocates for a multifaceted approach to SRC management involving a variety of assessments (e.g., symptom checklist, vestibular/oculomotor test).[1,9,162,322] One of the most valuable assessment tools in the clinical diagnosis of SRC is the self-reported symptom inventory, such as the Post-Concussion Symptom Scale (PCSS) and Sport Concussion Assessment Tool-5 (SCAT5) symptom scale.[55,168] Self-reported symptoms at the initial clinical presentation remain the strongest and most consistent predictor of SRC recovery.[15] Due to the heterogeneity of SRC symptom presentation, researchers have explored possible grouping of symptoms into meaningful categories (i.e., profiles, clusters, or factors). The establishment of SRC symptom factors can inform the types of assessments administered, along with targeted therapies and rehabilitation programs for athletes with SRC.

A widely used and popular factor structure for the PCSS was published in 2012 by Kontos et al.,[55] and included cognitive-fatigue-migraine, affective, somatic, and sleep factors. This led to the development of clinical profiles or trajectories following SRC that include cognitive/fatigue, vestibular, ocular, post-traumatic migraine, anxiety/mood, and cervical/sleep.[249] Given the clinical utility of identifying symptom factors, the recommended use of the SCAT5's symptom inventory for the acute assessment of SRC,[6] and the different symptoms ("pressure in the head," neck pain, blurred vision, "don't feel right," and confusion) compared to the PCSS, researchers developed symptom factors for the SCAT5 as well.[359,360] Recent research aggregated SCAT5 symptoms in adolescents following concussion into energy, mental health, migrainous, cognitive, and vestibulo-ocular factors.[359] Anderson et al. identified migraine-fatigue (5 symptoms: headache, "pressure in head", sensitivity to light, sensitivity to noise, and "don't feel right"), affective (4 symptoms: more emotional, irritability, sadness, nervous or anxious), and cognitive-ocular (4 symptoms: blurred vision, balance problems, difficulty remembering, confusion) symptom factors in high school and collegiate athletes with SRC.[360] The delineation of SCAT5 symptoms into different factor structures provides further validation for the presence of different concussion types.[249,260]

Since symptom inventories are part of a more comprehensive assessment approach, researchers have also attempted to determine the relationship between symptom factors and performance on other SRC assessment tools. Covassin et al. found that athletes with multiple prior SRCs exhibited deficits on neurocognitive measures of verbal memory and reaction time along with the cognitive-fatigue-migraine symptom cluster.[183] Cohen et al. found that higher scores on somatic symptom factors at initial visit following SRC predicted worse performance on vestibular/ocular screening components at second visit, but not neurocognitive performance.[51] Furthermore, none of the symptom factors were significantly associated with recovery time.[51] Identifying these associations early helps further determine concussion clinical profiles and guide treatment approaches, but evidence is lacking determining the relationship between symptom factors and sensorimotor assessments. This is a concern because emerging research demonstrates deficits in an array of sensorimotor skills, including reaction time, split attention, and response inhibition,[267,270-272] acutely following SRC and even beyond clinical recovery.[23-26,313] Guty et al. did examine symptom factors with sensorimotor function and found a significant association between headache symptoms and attention/processing speed impairment in collegiate student-athletes after SRC.[50] Lastly, although not specifically investigating symptom factors, a study of sensorimotor impairment across several domains, including oculomotor, near-point convergence, optokinetic nystagmus, vestibular-ocular reflex, positional tests, and postural stability, found the results collectively explained symptoms, such as dizziness, following concussion in adults.[26] Still, there is a paucity of studies investigating the relationship between symptom factors and sensorimotor skills following SRC.

With deficits across a multitude of sensorimotor skills acutely following SRC and beyond clinical recovery, it is important to determine their relationship with specific symptom factors. This will further help to inform the types of sensorimotor assessments administered, along with targeted therapies and rehabilitation programs for athletes with SRC. Therefore, the purpose of this study was to examine the correlation between symptom factors, using the SCAT5 symptom factors from Anderson et al.,[360] and sensorimotor skills, including go/no-go, eye-hand coordination, multiple-object tracking, depth perception, and reaction time, following SRC in collegiate athletes at their acute visit. Secondarily, we sought to examine the association between symptom factors, sensorimotor skills, and recovery time following SRC in collegiate athletes. As acute symptom burden and symptom factors have been associated with worse concussion assessment outcomes,[26,50,51] we hypothesized that higher cognitive-ocular, migraine-fatigue, and affective symptom factor scores would be associated with worse performance on go/no-go, eye-hand coordination, multiple-object tracking, depth perception, and reaction time assessments. As evidence has shown initial visit symptom factors are not associated with recovery time,[51] we hypothesized that scores on the three symptom factors would not be significantly associated with recovery time following SRC in collegiate athletes.

5.3. Methodology

Design

A prospective design was used to examine the association between symptom factors, sensorimotor skills, and recovery time following SRC. This study was approved by the Michigan State University (MSU) Institutional Review Board for Human Subjects Research. Trained research coordinators conducted consenting procedures and all participants signed an informed consent prior to the start of the study.

Participants

Participants were recruited from MSU and local colleges in Michigan through an established recruitment network. Participants with SRC were included if they were between the ages 18-30 years with an SRC diagnosis from a licensed healthcare provider within 5 days of enrollment and excluded if they had a neurological brain condition (e.g., epilepsy).

Sample Size Estimation

The estimation for the proposed study was based on prior evidence demonstrating a moderate correlation ($r_s = 0.38$) between SCAT5 symptoms and a concussion balance assessment.[361] This study was selected for sample size estimation since balance incorporates multiple aspects of the sensorimotor system and may be one of the best assessments of sensorimotor function and integration available at this time.[17,228] Using an acceptable power of ($1-\beta$) of 0.80 and a-priori alpha level of 0.05, we estimate that 52 participants with SRC will be required to identify a positive or negative relationship with a moderate association.

Procedures

Participants with SRC completed an acute visit within 5 days of injury and a second visit at the time of medical clearance (+3 days). While 72 hours is considered "acute" in the SRC literature,[345] acute pathophysiology of concussion can span up to 10 days[64]; therefore, 5 days was selected for the first time point to allow the study team to collect data on injuries that were sustained over the weekend in sporting events. At the acute visit, participants completed an intake form with demographic, injury characteristics, and medical history questions (e.g., prior concussion history), followed by the symptom inventory from the SCAT5.[168] Afterwards, participants completed sensorimotor assessments on a computerized sensory station. At the medical clearance session, participants reported recovery information, including days to symptom resolution and days to clearance to return to play (RTP), and completed the symptom inventory and the sensorimotor assessments.

Symptom Factors

The SCAT5 symptom inventory includes a list of 22 symptoms commonly reported after SRC and is designed to quantify the severity of post-concussion symptoms using a 7-point (0 = none to 6 = severe) Likert-type scale. This symptom inventory was used to create 3 new symptom factor variables: migraine-fatigue, affective, and cognitive-ocular.[360] The migraine-fatigue factor includes headache, "pressure in head", sensitivity to light, sensitivity to noise, and "don't feel right" symptoms. The affective symptom factor includes more emotional, irritability, sadness, and nervous or anxious symptoms. The cognitive-ocular factor includes blurred vision, balance problems, difficulty remembering, confusion. Neck pain, nausea or vomiting, and "feeling in a fog" did not meet primary loading criteria and dizziness, feeling slowed down, difficulty concentrating, fatigue or low energy, drowsiness, and trouble falling asleep were excluded due to high cross-loading by Anderson et al.[360] Symptom severity scores from individual symptoms that make up a factor were summed to create a new symptom severity score for each symptom factor.

Sensorimotor Assessments

The computerized sensory station (Senaptec Sensory Station, Senaptec Inc., Beaverton, OR) used in this study incorporates an adjustable television screen, mounted tablet, and an Android remote (**Figure 1**) to test 10 sensorimotor skills.[43] The sensorimotor assessment, description, procedures, and units for each sensorimotor assessment are explained in Fraser et al.[342] The computerized sensory station's 7-test previous version, the Nike SPARQ, demonstrated repeatability and minimal learning effects,[47] while preliminary data of the reliability of Senaptec has revealed moderate to good agreement on the majority of sensorimotor assessments.[346] While all 10 sensorimotor assessments were completed in the study procedures, only those demonstrating good reliability [go/no-go (ICC=0.88), eye-hand coordination (ICC=0.85), multiple-object tracking (ICC=0.85), depth perception (ICC=0.81), and reaction time (ICC=0.81)] were used in analyses. The description, procedures, and units for each sensorimotor assessment used in analyses are provided in **Table 5**.

Statistical Analysis

Descriptive statistics in the form of mean ± SD for continuous variables and frequency (%) for categorical variables were calculated for demographic and medical history information, injury characteristics, and symptoms for participants with SRC. Shapiro Wilk's tests were performed to assess normality. Due to not all variables being normally distributed, Spearman's rank-order correlations were run to assess the relationship between each symptom factor (migraine-fatigue, affective, and cognitive-ocular) and sensorimotor skills (go/no-go, eye-hand coordination, multiple-object tracking, depth perception, and reaction time) at the acute visit. The correlation coefficients (positive or negative) were interpreted as ≥ 0.7 = very strong, 0.40-0.69 = strong, 0.30-0.39 = moderate, 0.20-0.29 = weak, and 0.01-0.19 = negligible relationship.[362]

Eight separate multiple linear regression analyses were conducted with symptom factors (migraine-fatigue, affective, and cognitive-ocular) and sensorimotor skills (go/no-go, eye-hand coordination, multiple-object tracking, depth perception, and reaction time) as the independent variable and days to symptom resolution representing recovery time as the dependent variable. As prior evidence has recommended a minimum of ten participants for every variable included in the regression model,[363,364] it was decided a priori that a maximum of 5 covariates would also be included in the regression models. To determine which covariates were included, separate univariate linear regressions were performed with known variables that affect SRC recovery (e.g., acute symptom severity, SRC history, female sex).[15,42] Covariates with a significance level of $p < 0.05$ in univariate regression models were then entered into the multiple regression models. All variables were assessed for multicollinearity using Tolerance and Variance Inflation Factors. For the multiple regression models, the overall percent of explained variance of the model (R^2), regression coefficient (β), constant, 95% confidence intervals (95% CI), and *p*-values were calculated. Statistical significance was set a priori at $p < 0.05$. All statistical analyses were performed using SPSS software (version 27.0; SPSS, Inc, Chicago, IL).

5.4. Results

Participants

Overall, 64 participants (mean age: 20.7 ± 2.5, 34 female, 30 male) following SRC completed the study. The sample was predominantly white (67.2%), non-Hispanic (95.3%), right-handed (90.6%), and played football (25%) (**Table 11**). Among medical history variables, more of the sample had no history of SRC (51.6%), headache/migraine (90.6%), ADD/ADHD (82.8%), and anxiety/depression (71.9%). Additional medical history information is presented in **Table 12**. The average time to presentation was 3.7 ± 1.7 days. Twelve (18.8%) participants reported loss of consciousness, 14 (21.9%) could not remember their injury, and 27 (42.2%) continued to play following their SRC.

Table 11. Descriptive Statistics for Demographic Variables of Participants with Sport-Related Concussion.

Variable	Mean (SD) / N (%)
Age (years)	20.7 (2.5)
Sex	
Female	34 (53.1%)
Male	30 (46.9%)
Race	
White	43 (67.2%)
Black	14 (21.9%)
Other	5 (7.8%)
Asian	2 (3.1%)
Ethnicity	
Non-Hispanic	61 (95.3%)
Hispanic	2 (3.1%)
Other	1 (1.6%)
Handedness	
Right	58 (90.6%)
Left	5 (7.8%)
Both	1 (1.6%)
Year in School	
College Freshman	13 (20.3%)
College Sophomore	7 (10.9%)
College Junior	14 (21.9%)
College Senior	14 (21.9%)
College 5th Year	4 (6.3%)
Graduate Student	8 (12.5%)
Other	4 (6.3%)
Sport	
Cheerleading	4 (6.3%)
Football	16 (25%)
Gymnastics	2 (3.1%)
Ice Hockey	2 (3.1%)
Rugby	5 (7.8%)
Soccer	10 (15.6%)
Swimming & Diving	2 (3.1%)
Track & Field	2 (3.1%)
Volleyball	3 (4.7%)
Wrestling	3 (4.7%)
Other	15 (23.5%)

Table 11 (cont'd).

Level of Play	
College	**42 (65.6%)**
Club	**8 (12.5%)**
Intramural	**1 (1.6%)**
Recreational	**3 (4.7%)**
Other	**10 (15.6%)**

Continuous data are presented as mean (SD) and categorical data are presented as n (%).

Table 12. Descriptive Statistics for Medical History of Participants with Sport-Related Concussion.

Variable	**Mean (SD) / N (%)**
Prior Concussion History	
No	33 (51.6%)
Yes	31 (48.4%)
Number of Prior Concussions	1.77 (0.92)
Headache/Migraine	
No	58 (90.6%)
Yes	6 (9.4%)
Learning Disorder/Dyslexia	
No	59 (92.2%)
Yes	5 (7.8%)
ADD/ADHD	
No	53 (82.8%)
Yes	11 (17.2%)
Anxiety/Depression	
No	46 (71.9%)
Yes	18 (28.1%)
Motion Sickness	
No	60 (93.8%)
Yes	4 (6.3%)
Eye Exam Ever	
No	14 (21.9%)
Yes	50 (78.1%)
Eye Exam Past Year	
No	34 (53.2%)
Yes	30 (46.8%)

Table 12 (cont'd).

Eye Correction in Sport	
Contact Lenses	**8 (12.5%)**
Glasses	**7 (10.9%)**
None	**49 (76.6%)**
Eye Surgery Ever	
No	63 (98.4%)
Yes	1 (1.6%)

Continuous data are presented as mean (SD) and categorical data are presented as n (%).

Symptom Factors

Symptom information from the SCAT5, including calculated symptom factors, reported at the acute visit are presented in **Table 13**.

Table 13. Symptom Information of Participants with Sport-Related Concussion Reported at the Acute Visit.

Variable	**Mean (SD)**
Total Number of Symptoms	11.9 (7.4)
Symptom Severity Score	25.8 (22.3)
Migraine-Fatigue Factor Score	7.92 (5.9)
Cognitive-Ocular Factor Score	3.5 (4.4)
Affective Factor Score	3.14 (4.7)

Continuous data are presented as mean (SD).

Sensorimotor Assessments

Sensorimotor assessment scores from the acute and medical clearance visits are presented in **Table 14**.

Table 14. Sensorimotor Assessment Scores for Participants with Sport-Related Concussion at the Acute and Medical Clearance Visit.

Assessment	Acute Visit	Medical Clearance
Go/No-Go (Total Score; higher is better)	5.7 (5.5)	8.9 (6.2)
Eye-Hand Coordination (Msec; lower is better)	57003.9 (14813.9)	48550.6 (4633.9)
Multiple-Object Tracking (Composite Score; higher is better)	1399.3 (525.2)	1662.5 (580.6)
Depth Perception (Arcsec; lower is better)	168.4 (91.2)	164.6 (83.4)
Reaction Time (Msec; lower is better)	357.8 (64.5)	321.4 (30.7)

Continuous data are presented as mean (SD).

Correlation Between Symptom Factors and Sensorimotor Skills

There was a statistically significant moderate and negative correlation between go/no-go scores and the migraine-fatigue ($p < 0.05$) and cognitive-ocular ($p < 0.01$) factors, along with a weak negative correlation with the affective symptom factor ($p < 0.05$). There was also a statistically significant strong positive correlation between eye-hand coordination and the migraine-fatigue ($p < 0.01$) factor, along with moderate positive correlations with the cognitive-ocular ($p < 0.05$) and affective symptom factors ($p < 0.05$). Lastly, there was a statistically significant weak positive correlation between reaction time and the migraine-fatigue factor ($p < 0.05$), along with a moderate positive correlation with the cognitive-ocular factor ($p < 0.01$) and a strong positive correlation with the affective symptom factor ($p < 0.01$). Remaining correlations are presented in **Table 15**.

Table 15. Correlations Between Symptom Factors and Sensorimotor Skills for Participants with Sport-Related Concussion at the Acute Visit.

Assessment	Migraine-Fatigue	Cognitive-Ocular	Affective
Go/No-Go (Total Score; higher is better)	-0.31*	-0.34**	-0.29*
Eye-Hand Coordination (Msec; lower is better)	0.4**	0.32*	0.34*
Multiple-Object Tracking (Composite Score; higher is better)	-0.2	-0.23	-0.07
Depth Perception (Arcsec; lower is better)	0.08	0.09	0.15
Reaction Time (Msec; lower is better)	0.29*	0.38**	0.42**

*Statistically significant at $p < 0.05$ level. **Statistically significant at $p < 0.01$ level.

Relationship Between Symptom Factors and Recovery Time

Separate univariate linear regressions revealed that female sex, history of headache/migraine, continued play, total number of symptoms at the acute visit, and time to presentation were significantly associated with days to symptom resolution ($p < 0.05$). Since total number of symptoms at the acute visit had statistically significant strong positive correlations with the migraine-fatigue ($r = 0.81$, $p < 0.01$), cognitive-ocular ($r = 0.77$, $p < 0.01$), and affective ($r = 0.7$, $p < 0.01$) symptom factors individually, this variable was removed from the multiple regression models. Therefore, only female sex, history of headaches/migraine, continued play, and time to presentation were included as covariates in the multiple regression models.

The multiple regression results examining the relationship between the migraine-fatigue symptom factor and days to symptom resolution, while controlling for female sex, history of headache/migraine, continued play, and time to presentation, is presented in **Table 16**. The multiple regression model was statistically significant ($F_{(5, 50)} = 11.5$, $p < 0.001$, Adj. $R^2 = 0.5$), but the migraine-fatigue factor did not significantly add to the model ($B = 0.23$, $p = 0.13$).

Table 16. Multiple Regression Results for Days to Symptom Resolution with Migraine-Fatigue Factor as the Independent Variable.

	B	**95% CI for *B***	**β**	***p***
(Constant)	1.41	-3.15-5.98	-	0.54
Female Sex	1.37	-2.15-4.89	0.08	0.44
Headache/Migraine	14.98	9.3-20.67	0.53	**<0.01**
Continued Play	3.45	-0.06-6.95	0.21	0.05
Time to Presentation	1.4	0.4-2.41	0.29	**<0.01**
Migraine-Fatigue	0.23	-0.07-0.52	0.17	0.13

Significant *p*-values are bolded. *B* = Unstandardized regression coefficient; 95% CI = 95% Confidence interval; SE *B* = Standard error of the regression coefficient; β = Standardized coefficient

The multiple regression results examining the relationship between the cognitive-ocular symptom factor and days to symptom resolution, while controlling for female sex, history of headache/migraine, continued play, and time to presentation, is presented in **Table 17**. The multiple regression model was statistically significant ($F_{(5, 50)} = 10.5$, $p < 0.001$, Adj. $R^2 = 0.47$), but the cognitive-ocular factor did not significantly add to the model ($B = 0.11$, $p = 0.66$).

Table 17. Multiple Regression Results for Days to Symptom Resolution with Cognitive-Ocular Factor as the Independent Variable.

	B	**95% CI for *B***	**β**	***p***
(Constant)	2.93	-1.25-7.09	-	0.17
Female Sex	2.16	-1.38-5.69	0.13	0.23
Headache/Migraine	14.78	8.98-20.58	0.52	**<0.01**
Continued Play	4.11	0.51-7.71	0.25	**0.03**
Time to Presentation	1.23	0.23-2.22	0.25	**0.02**
Cognitive-Ocular	0.11	-0.38-0.59	0.05	0.66

Significant *p*-values are bolded. *B* = Unstandardized regression coefficient; 95% CI = 95% Confidence interval; SE *B* = Standard error of the regression coefficient; β = Standardized coefficient

The multiple regression results examining the relationship between the affective symptom factor and days to symptom resolution, while controlling for female sex, history of headache/migraine, continued play, and time to presentation, is presented in **Table 18**. The multiple regression model was statistically significant ($F_{(5, 50)} = 10.5$, $p < 0.001$, Adj. $R^2 = 0.46$), but the affective factor did not significantly add to the model ($B = -0.06$, $p = 0.78$).

Table 18. Multiple Regression Results for Days to Symptom Resolution with Affective Factor as the Independent Variable.

	B	95% CI for *B*	β	*p*
(Constant)	3.07	-1.08-7.22	-	0.14
Female Sex	2.56	-0.89-6.01	0.16	0.14
Headache/Migraine	14.99	9.02-20.96	0.53	**<0.01**
Continued Play	4.46	1.07-7.86	0.27	**0.01**
Time to Presentation	1.23	0.23-2.23	0.25	**0.02**
Affective	-0.06	-0.47-0.35	-0.03	0.78

Significant *p*-values are bolded. *B* = Unstandardized regression coefficient; 95% CI = 95% Confidence interval; SE *B* = Standard error of the regression coefficient; β = Standardized coefficient

Relationship Between Sensorimotor Skills and Recovery Time

Separate univariate analyses revealed that female sex, history of headache/migraine, continued play, time to presentation, and total number of symptoms at the acute visit were significantly associated with days to symptom resolution ($p < 0.05$). Therefore, these 5 variables were included in each multiple regression model as covariates.

The multiple regression results examining the relationship between depth perception and days to symptom resolution, while controlling for female sex, history of headache/migraine, continued play, time to presentation, and total number of symptoms at the acute visit, are presented in **Table 19**. The multiple regression model was statistically significant ($F_{(6, 49)} = 10.2$, $p < 0.001$, Adj. $R^2 = 0.5$), but depth perception did not significantly add to the model ($B = -0.003$, $p = 0.77$).

Table 19. Multiple Regression Results for Days to Symptom Resolution with Depth Perception as the Independent Variable.

	B	**95% CI for *B***	**β**	***p***
(Constant)	0.63	-5.14-6.39	-	0.83
Female Sex	0.81	-2.76-4.38	0.05	0.65
Headache/Migraine	14.61	8.98-20.24	0.51	**<0.01**
Continued Play	3.25	-0.21-6.71	0.19	0.07
Time to Presentation	1.39	0.42-2.38	0.29	**<0.01**
Number of Symptoms	0.31	0.03-0.58	0.24	**0.03**
Depth Perception	-0.003	-0.021-0.02	-0.03	0.77

Significant *p*-values are bolded. *B* = Unstandardized regression coefficient; 95% CI = 95% Confidence interval; SE *B* = Standard error of the regression coefficient; β = Standardized coefficient

The multiple regression results examining the relationship between multiple-object tracking and days to symptom resolution, while controlling for female sex, history of headache/migraine, continued play, time to presentation, and total number of symptoms at the acute visit, are presented in **Table 20**. The multiple regression model was statistically significant ($F_{(6, 49)} = 10.9$, $p < 0.001$, Adj. $R^2 = 0.52$), but multiple-object tracking did not significantly add to the model ($B = 0.002$, $p = 0.18$).

Table 20. Multiple Regression Results for Days to Symptom Resolution with Multiple-Object Tracking as the Independent Variable.

	B	95% CI for *B*	β	*p*
(Constant)	-3.10	-9.79-3.58	-	0.36
Female Sex	1.41	-2.07-4.89	0.09	0.42
Headache/Migraine	15.12	9.59-20.66	0.53	**<0.01**
Continued Play	3.57	0.16-6.98	0.22	**0.04**
Time to Presentation	1.39	0.44-2.36	0.28	**<0.01**
Number of Symptoms	0.29	0.03-0.56	0.24	**0.03**
Multiple-Object Tracking	0.002	-0.001-0.005	0.14	0.18

Significant *p*-values are bolded. *B* = Unstandardized regression coefficient; 95% CI = 95% Confidence interval; SE *B* = Standard error of the regression coefficient; β = Standardized coefficient

The multiple regression results examining the relationship between eye-hand coordination and days to symptom resolution, while controlling for female sex, history of headache/migraine, continued play, time to presentation, and total number of symptoms at the acute visit, are presented in **Table 21**. The multiple regression model was statistically significant ($F_{(6, 49)} = 10.23$, $p < 0.001$, Adj. $R^2 = 0.5$), but eye-hand coordination did not significantly add to the model ($B = 0.000013$, $p = 0.81$).

Table 21. Multiple Regression Results for Days to Symptom Resolution with Eye-Hand Coordination as the Independent Variable.

	B	**95% CI for *B***	**β**	***p***
(Constant)	-0.51	-7.82-6.82	-	0.89
Female Sex	0.94	-2.54-4.41	0.06	0.59
Headache/Migraine	14.79	9.14-20.44	0.52	**<0.01**
Continued Play	3.27	-0.23-6.76	0.19	0.07
Time to Presentation	1.42	0.44-2.39	0.29	**<0.01**
Number of Symptoms	0.29	-0.003-0.58	0.23	0.05
Eye-Hand Coordination	0.000013	0.000-0.000	0.03	0.81

Significant *p*-values are bolded. *B* = Unstandardized regression coefficient; 95% CI = 95% Confidence interval; SE *B* = Standard error of the regression coefficient; β = Standardized coefficient

The multiple regression results examining the relationship between go/no-go and days to symptom resolution, while controlling for female sex, history of headache/migraine, continued play, time to presentation, and total number of symptoms at the acute visit, are presented in **Table 22**. The multiple regression model was statistically significant ($F_{(6, 49)} = 11.61$, $p < 0.001$, Adj. $R^2 = 0.54$), but go/no-go did not significantly add to the model ($B = 0.31$, $p = 0.06$).

Table 22. Multiple Regression Results for Days to Symptom Resolution with Go/No-Go as the Independent Variable.

	B	95% CI for *B*	β	*p*
(Constant)	-2.47	-7.83-2.89	-	0.36
Female Sex	1.18	-2.18-4.54	0.07	0.48
Headache/Migraine	13.99	8.55-19.45	0.49	**<0.01**
Continued Play	2.11	-1.37-5.59	0.13	0.23
Time to Presentation	1.45	0.51-2.39	0.29	**<0.01**
Number of Symptoms	0.39	0.11-0.68	0.32	**<0.01**
Go/No-Go	0.31	-0.01-0.62	0.20	0.06

Significant *p*-values are bolded. *B* = Unstandardized regression coefficient; 95% CI = 95% Confidence interval; SE *B* = Standard error of the regression coefficient; β = Standardized coefficient

The multiple regression results examining the relationship between reaction time and days to symptom resolution, while controlling for female sex, history of headache/migraine, continued play, time to presentation, and total number of symptoms at the acute visit, are presented in **Table 23**. The multiple regression model was statistically significant ($F_{(6, 49)}$ = 10.46, $p < 0.001$, Adj. $R^2 = 0.51$), but reaction time did not significantly add to the model (*B* = -0.01, $p = 0.41$).

Table 23. Multiple Regression Results for Days to Symptom Resolution with Reaction Time as the Independent Variable.

	B	95% CI for *B*	β	*p*
(Constant)	3.46	-5.87-12.79	-	0.46
Female Sex	1.05	-2.42-4.51	0.06	0.55
Headache/Migraine	14.73	9.17-20.29	0.52	**<0.01**
Continued Play	2.77	-0.78-6.32	0.17	0.12
Time to Presentation	1.45	0.47-2.42	0.29	**<0.01**
Number of Symptoms	0.35	0.05-0.64	0.28	**0.02**
Reaction Time	-0.01	-0.04-0.02	-0.09	0.41

Significant *p*-values are bolded. *B* = Unstandardized regression coefficient; 95% CI = 95% Confidence interval; SE *B* = Standard error of the regression coefficient; β = Standardized coefficient

5.5. Discussion

The current study examined the relationship between SCAT5 symptom factors and sensorimotor skills at the acute visit following SRC in collegiate athletes, along with the association between symptom factors and sensorimotor skills with recovery time. Results from our study revealed that the cognitive-ocular, migraine-fatigue, and affective symptom factors were significantly correlated with performance on go/no-go, eye-hand coordination, and reaction time skills, but not with multiple-object tracking or depth perception skills. These findings partially supported our hypotheses, except the lack of association with multiple-object tracking and depth perception. Secondarily, none of the symptom factors at the acute visit were significantly associated with recovery time, which supported our hypothesis.

To our knowledge, this is the first study to examine the relationship between symptom factors and sensorimotor skills acutely following SRC. Sensorimotor function is becoming an important component of the multifaceted approach to SRC management, as emerging research demonstrates deficits in sensorimotor skills acutely,[267,270-272] and even after athletes return to play.[23-26,313] This is a concern to clinicians and healthcare professionals because underlying sensorimotor and neuromuscular control deficits have been linked with lower extremity musculoskeletal injury.[11,12,30,313] Therefore, distinguishing any specific effects of symptom groupings on sensorimotor skills becomes important, as this may better inform treatment plans and help mitigate these future concerns. Our results demonstrated that an increase in cognitive-ocular, migraine-fatigue, and affective symptom factors from the SCAT5 were significantly correlated with worse performance on go/no-go, eye-hand coordination, and reaction time skills. Given the frequent and recommended use of the SCAT5 for acute assessment of SRC,[6] these findings inform clinicians about three sensorimotor skills correlated to SCAT5 symptom factors. This is especially valuable due to the absence of a robust sensorimotor skill assessment tool in the acute phase. With this evolving knowledge of deficits to be expected given an athlete's symptom factors, clinicians can improve the individualized management of SRC. For example, identifying that an athlete has high loading into the cognitive-ocular factor at the acute visit may indicate congruent deficits in reaction time, eye-hand coordination, and go/no-go, and allow for early vestibular or visuomotor rehabilitation.[333,365]

The relationships identified in this study are supported, in part, by previous evidence. Research has demonstrated that headache symptoms, which load into the migraine-fatigue factor from the SCAT5,[360] are significantly related to poor overall neurocognitive performance following SRC.[50] In particular, headache symptoms were associated with worse attention/processing speed in collegiate student-athletes after SRC. As the go/no-go, eye-hand coordination, and reaction time assessments from our study all involve heavy attention/processing speed elements, this helps to explain the correlation between the migraine-fatigue factor and worse performance on these tests. Additional research has demonstrated that athletes who report visual symptoms, including fogginess, experience slowed reaction time and processing speed,[366] which supports the relationship in our study between the cognitive-ocular factor and performance on the go/no-go, eye-hand coordination, and reaction time assessments. The affective symptom factor is more often linked with endorsement on psychological inventories,[367] but post-injury somatization in athletes with loading into this factor may be a reason for the correlation with the sensorimotor assessments.[51]

While the strength and significance of relationships differed, our study adds to the literature that symptom factors from the SCAT5 are associated with processing speed-based sensorimotor skills acutely following SRC. This could be due to the salience of symptoms in the SCAT5 factors (e.g., headache, "pressure in head", blurred vision) when athletes are attempting to complete a demanding task, along with acute effects of cognitive dysfunction.[368,369] The lack of relationship between symptom factors and depth perception and multiple-object tracking scores supports this, as neither of these assessments require athletes to react to information quickly. Nonetheless, the lack of significant correlations was surprising, given that both assessments by nature interact with symptoms that load into the SCAT5 symptom factors. It is possible that they are significantly correlated with symptoms that were excluded due to cross-loading,[360] such as dizziness. Dizziness has been shown to predict worse performance on neurocognitive testing,[173] and may have been correlated with multiple-object tracking performance since the task requires athletes to track multiple objects at once as they rotate rapidly. On the other hand, we expected depth perception to be correlated with the cognitive-ocular factor at the least, as blurred vision loads onto this factor and is associated with ocular dysfunction following SRC.[329,330] The absence of significant correlations may also be due to participants guessing on the multiple-object tracking and depth perception assessments because they are too difficult,[342] which results in data that may not reflect true performance.

Our study also provided findings regarding the relationship between SCAT5 symptom factors, sensorimotor skills, and recovery time following SRC in collegiate athletes. To our knowledge, this is the first study to find that none of the symptom factors from the SCAT5 were significantly associated with recovery time in collegiate athletes. Although it is difficult to compare symptom factors from different inventories, our findings were not surprising as previous evidence using PCSS symptom factors also found no significant association between symptom factor scores at the acute visit and recovery time.[51] While the most consistent predictor of prolonged recovery is the severity of acute symptoms,[15,370] our findings combined with results from Cohen et al. demonstrate that unique symptom factors may not be as effective in differentiating prolonged recovery time acutely.[51] This may be due to the exclusion of symptoms in the SCAT5 symptom factors, such as dizziness, nausea, and fatigue, that are common following SRC and have been associated with longer recovery times.[173,360,371] Without the added severity of these symptoms and the overall symptom severity score, other risk factors, such as female sex, history of headaches/migraine, continued play, and time to presentation, which were included in our multiple regression models, contribute more to the association with prolonged recovery. Although symptom factors are useful, this suggests that additional information, including vestibular/ocular, neurocognitive, and sensorimotor impairments, are crucial at the acute visit to accurately determine injury prognosis.

Similar to symptom factors at the acute visit, performance on sensorimotor assessments was also not significantly associated with recovery time following SRC in collegiate athletes. This could be a result of the computerized sensory station used to complete the sensorimotor assessments, which has primarily been used for training purposes rather than diagnosis of SRC.[333,335] More sensitive and specific SRC assessments used at the acute visit, such as the Vestibular/Ocular Motor Screening tool and Immediate Post-Concussion Assessment and Cognitive Test, have been shown to predict recovery.[372] Alternatively, it could be because sensorimotor impairments do not manifest as clearly until the subacute phase of the SRC recovery timeline.[373] Several research studies have identified sensorimotor impairments beyond expected recovery timelines for adults following SRC, regardless of symptoms.[26,30,374] Therefore, while sensorimotor assessments from the acute visit may not predict recovery time, clinicians should consider patterns of performance on these tests, especially with the correlation to symptom factors and the ability to fluctuate over time.

This study is not without limitations. First, our sample only included collegiate athletes in the Mid-Michigan area, which may restrict generalizability. Therefore, further research should be conducted in youth and older athletes to elucidate any differences in findings and help with generalizability. Similarly, our sample was predominantly white and non-Hispanic. Additional data should be collected on participants of other races and ethnicities, as research has identified different recovery times between white and black athletes following SRC.[358] Second, as with all subjective self-report forms, participants may not have been completely honest or understood how to properly report SCAT5 symptoms. This may have impacted loading into symptom factors, which could alter our results. However, trained research coordinators worked with the athletes to improve understanding and answer any questions related to wording of the symptoms. Next, while the sensorimotor assessments used in this are reliable,[346] participants at baseline have reported issues with task competency,[342] which could have been true in our sample and affected the results. Future research should examine the relationship between SCAT5 symptom factors with other sensorimotor assessments to determine if similar correlations exist, and to determine if sensorimotor skills from other assessments predict recovery following SRC.

5.6. Conclusion

Among collegiate athletes following SRC, the cognitive-ocular, migraine-fatigue, and affective symptom factors from the SCAT5 were significantly correlated with performance on speed-based sensorimotor assessments, including go/no-go, eye-hand coordination, and reaction time, at the acute visit. However, none of the symptom factors from the SCAT5 or sensorimotor assessments were significantly associated with recovery time in collegiate athletes following SRC. These findings further expand our knowledge of how specific symptom factors are related to recovery and other SRC assessments, and in an area gaining importance in the literature. Overall, this improved understanding can inform more individualized treatment plans following SRC that target expected sensorimotor deficits and minimize future burden of collegiate athletes.

CHAPTER 6: SUMMARY AND CONCLUSIONS

6.1. Summary

The purpose of this dissertation was to determine the influence of SRC on sensorimotor skills in collegiate athletes. Specifically, this dissertation 1) determined the test-retest reliability of 10 sensorimotor skills assessed by a novel computerized sensory station, 2) examined sensorimotor skill performance throughout recovery and after RTP following SRC in collegiate athletes compared to healthy matched controls, and 3) examined the relationship between symptom factors and sensorimotor skills in collegiate athletes following SRC at the acute visit, along with their association with recovery time. For the first specific aim, participants completed 10 sensorimotor skills (visual clarity, contrast sensitivity, depth perception, near-far quickness, perception span, multiple-object tracking, reaction time, target capture, eye-hand coordination, and go/no-go) on a computerized sensory station at two visits one week apart (± 1 day). For the second specific aim, a prospective cohort study was conducted to compare sensorimotor skills between collegiate athletes following SRC and healthy matched controls at an acute visit (within 5 days of SRC), at medical clearance (+3 days), and at least one-month post-RTP. For the third specific aim, a prospective study of collegiate athletes following SRC was conducted to investigate the relationship between symptom factors from the SCAT5 and sensorimotor skills at an acute visit (within 5 days of SRC), along with their relationship with recovery time captured at a medical clearance visit (+3 days).

6.1.1. The Reliability of a Computerized Sensory Station for the Comprehensive Assessment of Sensorimotor Skills in College-Aged Individuals

Sensorimotor skills, which involve the brain receiving and processing sensory input from the environment and producing an appropriate motor output, play a pivotal role in sport.[13,14] To provide a complete picture of sensorimotor function, clinicians and researchers have begun to use commercial technology-aided assessments, such as computerized sensory stations, that can augment sporting contexts and test a multitude of skills at one time.[334,335] However, there is limited research examining the reliability of computerized sensory stations that measure a comprehensive battery of sensorimotor skills in college-aged individuals. This first study, using a sample of 100 participants (80 female, age=21.6 ± 2.8 years), found that go/no-go, multiple-object tracking, eye-hand coordination, depth perception, and reaction time sensorimotor assessments demonstrated good reliability (ICCs = 0.81-0.88), target capture and perception span demonstrated moderate reliability (ICCs = 0.51-0.63), and visual clarity, contrast sensitivity, and near-far quickness demonstrated poor reliability (ICCs = 0.28-0.43). Overall, results of this study of the dissertation implied that only some of the sensorimotor assessments of the computerized sensory station demonstrated clinically acceptable reliability for evaluation of performance improvements and injuries, such as SRC, in a clinical setting.

6.1.2. Sensorimotor Skills Throughout Recovery Following Sport-Related Concussion in Collegiate Athletes

Emerging evidence suggests that underlying deficits to sensorimotor skills, including reaction time and go/no-go, may be present following clinical recovery from SRC.[23-26,49,313] These underlying impairments are hypothesized to contribute to heightened risk of subsequent injury,[11,12,30,313] which becomes a major concern for athletes upon RTP and for clinicians making RTP decisions. However, there is currently a lack of evidence identifying deficits in sensorimotor skills across the recovery timeline in collegiate athletes following SRC. In the second study of this dissertation, collegiate athletes following SRC were compared on a battery of sensorimotor skill assessments to healthy matched controls acutely (within 5 days of injury), at the time of medical clearance (+3 days), and at least one month following their RTP. Using a sample of 25 participants following SRC (mean age = 21.4 ± 2.9; 56% female) and 15 controls (mean age = 21.1 ± 2.5; 40% female), results of this study identified a significant group x time interaction for reaction time ($F_{(1.3, 48.8)} = 6.85$, $p = 0.007$, $\eta_p^2 = 0.15$). Reaction time was statistically significantly slower in the SRC group (54.13 ± 21.72 msec, $p = 0.017$) compared to the control group at the acute visit, and improved between acute and medical clearance time points (M = 45.7, SE = 14.71 msec, $p = 0.01$) and the acute and one-month post-RTP time points (M = 58.9, SE = 14.8 msec, $p = 0.002$). These findings support extant evidence regarding the presence of persistent reaction time deficits in athletes after SRC, even beyond clinical recovery,[49] and reflect the need for routine incorporation of reaction time assessment in the multifaceted SRC approach. If clinicians can identify reaction time deficits early, they can develop individualized treatment plans, make informed RTP decisions, and hopefully mitigate the risk of subsequent injury.

6.1.3. The Association Between Symptom Clusters and Sensorimotor Skills Following Sport-Related Concussion

Clinicians and researchers have aggregated SRC symptoms into meaningful groups, called factors, to better inform management of athletes with SRC.[55,360] Determining the association between symptom factors and other SRC assessments further helps individualize management plans; however, the association between symptom factors and performance on an array of sensorimotor skills is unknown. Additionally, it is unclear how symptom factors and sensorimotor skills may be related to recovery time following SRC in collegiate athletes. In the third study of this dissertation with a sample of 64 participants (mean age: 20.7 ± 2.5, 34 female, 30 male) following SRC, statistically significant correlations were identified between cognitive-ocular, migraine-fatigue, and affective symptom factors from the SCAT5 with go/no-go, eye-hand coordination, and reaction time assessments ($p < 0.05$). However, neither symptom factors nor sensorimotor assessments were significantly associated with recovery time. These findings further expand our knowledge of how specific symptom factors are related to recovery and other SRC assessments, and help inform SRC management and clinical decision-making.

6.2. Limitations

The first study of this dissertation is limited primarily by characteristics of the sample collected. First, 80% of the sample was female, which limits the generalizability of the reliability results to other sexes. Second, this study only included college-aged individuals, which limits the generalizability as well to populations of different ages. Third, 40% of the sample had a history of SRC, which may have influenced reliability results,[186] despite the injuries being > 6 months from the time of testing. The history of other injury types, such as shoulder injuries, was not collected and could have altered results as well if participants experienced fatigue from the usage of their upper extremities. However, all participants did report they were healthy and injury-free at the time of testing. Other possible limitations could have arisen from conditions of the testing environment. Screen glare from lights in the room reflecting off the device could have affected the results on the sensorimotor assessments, although this is unlikely as steps were taken to minimize such disturbances.

The second study of this dissertation was also limited by characteristics of the sample collected. First, the sample size in both groups did not meet the estimation for the dissertation, and the sample size in the control group was 10 participants less than the SRC group. Even groups that meet the sample size estimation for adequate power may reflect different findings. Second, the SRC and control sample only included collegiate athletes in the Mid-Michigan area, which may restrict generalizability of the findings to athletes of different ages and different states. Similarly, both groups were predominantly white and non-Hispanic. Additional data should be collected on participants of other ages, races, and ethnicities, as research has identified different recovery times between white and black athletes following SRC and younger athletes.[40,358] Outside of the study population, the main limitations arose from the computerized sensory station administering the sensorimotor assessments. Only 5 of the 10 sensorimotor assessments administered by the computerized sensory station were used in analyses to account for reliability concerns, which limits the applicability of the device as a “comprehensive” tool. While the 5 sensorimotor assessments that were not used (target capture, perception span, visual clarity, contrast sensitivity, near-far quickness) may still be useful, further reliability and validity studies need to be performed. Additionally, evidence at concussion baseline testing has demonstrated the occurrence of invalid scores on the computerized sensory station due to lack of understanding, effort, and motivation.[342] While this study only used reliable assessments and participants did not express a lack of any of those factors, this could have affected the results, especially in the control group.

The third study of this dissertation shared the limitations that arose in study two related to population demographics and the computerized sensory station. Additionally, this study used the symptom inventory from the SCAT5, which is a subjective, self-report form.[166] As is true with all subjective self-report forms, participants may not have been completely honest or understood how to properly report their symptoms, which may have impacted loading into symptom factors, which could alter the results. However, trained research coordinators worked with the athletes to improve understanding and provide any clarification needed. Altogether, future research should confirm these findings by examining the relationship between SCAT5 symptom factors with other sensorimotor assessments, along with their relationship with recovery time following SRC.

6.3. Strengths

The first study of this dissertation was the first in the current body of evidence to determine the test-retest reliability of this computerized sensory station (Senaptec Sensory Station, Senaptec Inc., Beaverton, OR) in college-aged individuals. This provides clinicians and researchers with an understanding of which sensorimotor assessments demonstrated clinically acceptable reliability and can be used with confidence in a clinical setting. The MDC95 values that were calculated further benefit the scientific community, by providing benchmarks for clinically meaningful changes in scores on each of the sensorimotor assessments. This allows clinicians to use this device to determine objective performance improvements as an outcome of training, or as an outcome of treatment/rehabilitation effectiveness and recovery from injury. These findings also provide data related to what mean scores may look like initially in a large sample of 100 college-aged individuals. While the test-retest reliability and reliable change indices of previous computerized sensory stations have been determined,[47,337] the reliability of this novel device has not been studied.

The second study of this dissertation was the first in the literature to examine a comprehensive battery of sensorimotor skills throughout recovery from SRC in collegiate athletes compared to healthy matched controls. While studies have examined SRC assessment of skills individually, such as multiple-object tracking,[355] there is a paucity of evidence examining numerous skills at once. This study offers evidence of a comprehensive assessment of sensorimotor function across three time points, which may provide a more complete picture of deficits for clinicians and is more efficient in a clinical setting. The results demonstrating significantly worse reaction time acutely and beyond medical clearance in collegiate athletes following SRC adds to the nascent literature of deficits beyond clinical recovery from SRC.[48,49] This allows clinicians to be aware of possible reaction time deficits in collegiate athletes following SRC and will help them tailor their management plan accordingly. Even the lack of significant findings for go/no-go, eye-hand coordination, multiple-object tracking, and depth perception provide an understanding of what deficits clinicians may not need to be concerned with beyond clinical recovery, which was lacking in the literature. From a study design perspective, the prospective nature with rigorous matching criteria helps to reduce bias and reflects a higher level of evidence.

The third study of this dissertation was the first study to examine the relationship between symptom factors and sensorimotor skills acutely following SRC. While other studies have examined symptom factors with performance on neurocognitive and vestibular/ocular assessments of SRC,[51,372] results from this study speak to how symptom groupings and sensorimotor assessments are related during the acute phase of SRC. This informs clinicians about three sensorimotor skills that may need to be evaluated based on SCAT5 symptom factors, which is especially valuable due to the absence of a robust sensorimotor skill assessment tool in the acute phase. This study also fills a gap in the literature related to the association of SCAT5 symptom factors and sensorimotor performance acutely with recovery time following SRC. Most of the evidence of symptom factors has used the PCSS,[51,55,372] so this is the first study to find that none of the symptom factors from the SCAT5 were significantly associated with recovery time. This improved understanding can inform more individualized treatment plans following SRC.

6.4. Conclusions

Overall, based on the results of the three studies in this dissertation, sensorimotor skills are influenced by sport-related concussion in a population of collegiate athletes. The first study found that go/no-go, eye-hand coordination, multiple-object tracking, depth perception, and reaction time skills from a computerized sensory station are reliable and can be used to evaluate sensorimotor skill deficits throughout recovery from SRC. Using those reliable sensorimotor skill assessments, study two found that reaction time is significantly worse in collegiate athletes following SRC compared to a group of healthy matched controls acutely and even beyond the time of clinical recovery. Lastly, study three found that cognitive-ocular, migraine-fatigue, and affective symptom factors were significantly correlated with go/no-go, eye-hand coordination, and reaction time sensorimotor skill assessments at the acute visit in collegiate athletes following SRC. As a whole, this dissertation provides novel comprehensive data regarding sensorimotor skills following SRC that clinicians, researchers, and the medical community can use to develop targeted and individualized treatment plans, make informed RTP decisions, and mitigate the risk of subsequent injury to collegiate athletes.

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APPENDIX A: INSTITUTIONAL REVIEW BOARD (IRB) APPROVAL FORM

MICHIGAN STATE
UNIVERSITY

Initial Study APPROVAL
Revised Common Rule

August 18, 2020

To: Tracey Covassin

Re: **MSU Study ID:** STUDY00004889
IRB: Biomedical and Health Institutional Review Board
Principal Investigator: Tracey Covassin
Category: Expedited 4, 7
Submission: Initial Study STUDY00004889
Submission Approval Date: 8/17/2020
Effective Date: 8/17/2020
Study Expiration Date: **None; however modification and closure submissions are required (see below).**

Title: The Use of the Senaptec Sensory Station in High School and College Students with and without Concussion

This submission has been approved by the Michigan State University (MSU) Biomedical and Health Institutional Review Board. The submission was reviewed by the Institutional Review Board (IRB) through the Non-Committee Review procedure. The IRB has found that this study protects the rights and welfare of human subjects and meets the requirements of MSU's Federal Wide Assurance (FWA00004556) and the federal regulations for the protection of human subjects in research (e.g., 2018 45 CFR 46, 21 CFR 50, 56, other applicable regulations).

Institutional restrictions to in-person human subject research activities conducted by MSU employees, MSU students, or agents of MSU are in place, but MSU is phasing in human research that has the potential for in-person interactions with participants, using a Tier approach. Restrictions to in-person interactions with human research participants by MSU employees, MSU students, or agents of MSU are in place until the activity is permitted under a Tier and a Human Research Plan for a Safe Return is approved. Visit http://hrpp.msu.edu/COVID-19/index.html for the restrictions, Tiers, forms, and the process.

How to Access Final Documents
To access the study's final materials, including those approved by the IRB such as consent forms, recruitment materials, and the approved protocol, if applicable, please log into the Click™ Research Compliance System, open the study's workspace, and view the "Documents" tab. To obtain consent form(s) stamped with the IRB watermark, select the "Final" PDF version of your consent form(s) as applicable in the "Documents" tab. Please note that the consent form(s) stamped with the IRB watermark must typically be used.

Office of Regulatory Affairs
Human Research Protection Program

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APPENDIX B: CHAPTER 4 SCORES ON SENSORIMOTOR ASSESSMENTS WITH POOR AND MODERATE RELIABILITY

Table 24. Mean Scores on Sensorimotor Assessments with Poor and Moderate Reliability at Each Visit of the Sport-Related Concussion and Healthy Matched Controls Groups.

Perception Span (Total Score; higher is better)			
Group	**Acute**	**Medical Clearance**	**One-Month Post-RTP**
SRC (n=25)	41.2 (13.1)	49.04 (11.1)	48.8 (10.2)
Controls (n=15)	42.3 (11.9)	44.33 (11.3)	44.9 (11.7)
Target Capture (Msec; lower is better)			
Group	**Acute**	**Medical Clearance**	**One-Month Post-RTP**
SRC (n=25)	226 (65.5)	197 (45.8)	195 (54.9)
Controls (n=15)	200 (64.1)	193.3 (62.3)	188.3 (24.8)
Contrast Sensitivity (LogCS; higher is better)			
Group	**Acute**	**Medical Clearance**	**One-Month Post-RTP**
SRC (n=25)	1.48 (0.32)	1.49 (0.3)	1.48 (0.26)
Controls (n=15)	1.49 (0.33)	1.43 (0.26)	1.41 (0.37)
Visual Clarity (LogMAR; lower is better)			
Group	**Acute**	**Medical Clearance**	**One-Month Post-RTP**
SRC (n=25)	-0.09 (0.12)	-0.1 (0.15)	-0.11 (0.1)
Controls (n=15)	-0.13 (0.13)	-0.11 (0.14)	-0.06 (0.14)

Table 24 (cont'd).

Near-Far Quickness (# Correct; higher is better)			
Group	**Acute**	**Medical Clearance**	**One-Month Post-RTP**
SRC (n=25)	18.2 (5.3)	22.2 (6.2)	23.3 (7.5)
Controls (n=15)	21.5 (7.3)	21 (9.13)	25.8 (6.6)

Continuous data are presented as mean (SD). SRC=Sport-Related Concussion Group; Control=Healthy Matched Control Group