SEX-RELATED DIFFERENCES IN VISUOMOTOR SKILLS, COGNITION, AND EMOTIONALITY FOLLOWING CONCUSSIVE INJURY

CéAnn A. Marks

A Thesis Submitted to the Faculty Of Graduate Studies

In Partial Fulfilment of The Requirements For The Degree of

Master of Arts

Graduate Program in Psychology

York University

Toronto, Ontario

July 2024

Abstract

Sex-related differences are commonly overlooked in most biomedical fields including concussion research. Much of the current concussion literature focuses on the analyses of males or a combined approach, lacking the separation of sexes for analytical purposes. **Methods:** Data were collected from 299 university athletes with varying concussion histories. Kinematic visuomotor measures and emotional symptoms were assessed through a basic visuomotor task and SCAT self-report measures. **Results:** Visuomotor performance varied substantially with concussion history and sex, with multiple concussions being linked to better performance. Emotionality results revealed females with 2 or more concussions have higher odds of being irritable, while 21-22-year-old females have lower odds of being nervous/anxious compared to their younger counterparts. No significant emotionality results were discovered for males. **Conclusion:** This study underscores distinctive recovery metrics between sexes in emotional and visuomotor domains following concussive injury. Findings suggest the need for tailored diagnostics and treatment for athletes following injury.

Acknowledgements

I would like to express my deepest gratitude to everyone who has supported and guided me throughout this research and thesis writing process. First, I would like to thank my supervisor Dr. Lauren Sergio for her support during this process, this would not be possible without you. Your expertise, guidance and patience have both allowed me to become a better researcher. Thank you for supporting my research ideas and providing opportunities that would have not been possible without your help. Second, to my committee member Dr. Denise Henriques, thank you for providing valuable support and expertise, when most needed.

A special thank you also goes out to my lab members, especially Nicole and Anthony. Both of you were a truly important part of this process by answering my many, many, many questions and assisting me in developing my research skills.

I am also extremely grateful for the financial support from the Ontario Graduate Scholarship, Brain Canada, and York University, which have been instrumental in allowing me to focus on my studies.

Most importantly, to my family and friends, especially my Mom, Jade and Raja. Your unwavering support and encouragement through this process have been my much-needed support system. Thank you for listening to me, providing valuable feedback, and encouraging and supporting my research ideas. I love you all more than you can imagine.

Finally, I dedicate this thesis to my grandpa Levi, may your light continue to shine and inspire everything that I do.

Table of Contents

List of Tables

List of Figures

List of Equations

List of Abbreviations

%DR = Percentage of Direction Reversals

AE = Absolute Error

BRC = Brain Reserve Capacity

CHx = Concussion History

CI = Confidence Interval

CMI = Cognitive Motor Integration

DR = Direction Reversal

DV = Dependent Variable

fMRI = Functional Magnetic Resonance Imaging

IV = Independent Variable

MT = Movement Time

mTBI = Mild Traumatic Brain Injury

NCHx = No Concussion History

non-SRC = Non-Sport Related Concussion

#PC = Number of Previous Concussions

nPL = Normalized Path Length

PV = Peak Velocity

RT = Reaction Time

SCAT = Sport Concussion Assessment Tool

SRC = Sport-Related Concussion

SSR = Split Screen Reversal

TBI = Traumatic Brain Injury

VE = Variable Error

Chapter 1: Introduction

Concussions are clinically diagnosed mild traumatic brain injuries (mTBI) resulting from transmitted impulsive forces to the brain or rapid acceleration-deceleration of the head (Master et al., 2018; Mullally, 2017). Annually, millions of individuals sustain concussions, with some experiencing prolonged effects (Champagne et al., 2023; Master et al., 2018). While concussive injuries are often sport-related, other mechanisms include falls, motor vehicle accidents, work-related injuries and interpersonal conflict resulting from direct or indirect trauma. Acute concussion recovery is typically associated with few or no complications, with recovery in days to weeks (Master et al., 2018). For persons with persistent symptoms, for one month or longer, the complexities may vary. Concussions can produce a variety of emotional and cognitive symptoms including, anxiety, depression and chronic headaches, along with attention, concentration, and visuo-vestibular deficits (Master et al., 2018).

Relative to non-sport related concussive injury, sport-related concussions (SRC) have been extensively studied partially owing to the high incidence and visibility of concussions among athletic populations and particular implications for youth and young adults.

Again, much is known about the mechanisms surrounding concussions and their symptoms but scant research exists regarding the sex differences in the presentation of said symptoms. This research is potentially significant as it aims to address the gaps in literature surrounding these differences. Further, understanding and distinguishing the difference between sexes regarding concussive injury, whether an athlete or non-athlete, is fundamental in formulating appropriate diagnostic protocols and recovery strategies.

1.1 Objectives & Hypotheses

This study is a comprehensive follow-up to the preliminary findings of Pierias (2021), where it was identified that males and females with concussion history exhibited distinctive post-concussion outcomes, wherein females recovered more reliably on visuomotor skills and reported significantly greater emotionality symptoms than males. The main objectives of this research were to 1) investigate sex-related differences in visuomotor skills, cognition and emotionality in university athletes with and without concussion history, 2) examine the effect that concussion history has on participants' complex skilled performance and emotionality, and 3) determine the nature of deficits across the aforementioned domains. Based on previous literature, it is hypothesized that females will recover more favourably in the visuomotor performance domain and lower in emotionality, while males will recover more favourably in the emotionality domain, and lower in visuomotor performance. Additionally, an increasing number of concussions decrease performance, with increasing performance across all age groups. It is further posited that among participants with concussion history, a positive relationship between the number of months lived since concussive injury and kinematic performance will exist such that the time between a concussion and the date of assessment decreases, performance will increase.

Chapter 2: Literature Review

2.1 Clinical Presentation, Diagnosis and Assessment of Concussions

SRCs present with a broad spectrum of clinical symptoms, consistent with those observed in non-SRCs. This requires the need for a multidimensional approach to the assessment and diagnosis of SRC. Owing to differences in presentation between individuals, concussive symptoms can vary across emotional, cognitive, and physical domains. Common emotional and cognitive symptoms include but are not limited to amnesia, anxiety, irritability, fatigue, and mental fogginess, while physical symptoms commonly include postural stability or balance issues and headaches (Putukian & Johnson, 2011). Further, distinctions in prevalence rates between males and females are present with females reporting higher rates of concussion diagnoses than males (Black et al., 2017). Similarly, females report more symptoms and greater symptom severity scores on concussion diagnostic testing (Alsalaheen et al., 2021).

As this research focused on SRC history, it is imperative to address the sex-based disparities in concussion diagnoses among athletes. The lifetime prevalence of a SRC among adolescents is around 24.6% (Veliz et al., 2021), with up to a 19% likelihood of an athlete sustaining a concussive injury during a single season of contact sport participation (Goodwin et al., 2023). However, due to the heavy reliance on self-reported symptoms in concussion diagnostic protocols, prevalence rates vary substantially across athletic populations.

Together with disparities in prevalence, sex-based differences have been identified in the clinical presentation of symptoms. Select sports concussion literature finds that female athletes may report higher post-concussive symptoms than males during baseline assessments. In meta-analysis work by Brown et al. (2015), they found that females were 43% more likely to report any symptoms associated with concussion at baseline testing. Additionally, for high school and college athletes, they observed significantly higher total symptom scores for females, compared to males at baseline. Of the symptoms reported, females had a significantly higher rate of reporting difficulty concentrating, emotional symptoms, vision/hearing problems, headaches, and energy/sleep disturbances (Brown et al., 2015). Comparable findings indicate that female athletes report significantly higher numbers of mild baseline symptoms compared to male athletes (Covassin et al., 2006). Additional to the increased number of symptoms reported by females, they also have greater symptom severity of feeling slowed down, pressure in the head, fatigue, drowsiness, dizziness, sensitivity to light, and sensitivity to noise (Bunt et al., 2021).

Part of the challenge surrounding the diagnoses of concussion in athletic and non-athletic populations is due to proper education and understanding of when and how to identify relevant symptoms.

Current international protocols require athletes to be evaluated by a physician and meet baseline measurements of both cognitive and motor assessments separately prior to beginning return-to-sport progressions. However, these assessments are identical for males and females despite evidence indicating distinct neural, biological, cognitive, physical and emotional manifestations of the injury between sexes. There exist several diagnostic tools for diagnosing and monitoring sports-related concussions, including but not limited to Post-Concussion Symptom Scale (PCSS), the Standardized Assessment of Concussion (SAC), the Sport Concussion Assessment Tool (SCAT), and Immediate Post-Concussion Assessment and Cognitive Testing (ImPACT) (Dessy et al., 2017). All assessments are used to evaluate and monitor SRCs, while the ImPACT and PCSS are also used in clinical settings.

A concern with most, if not all current diagnostic tools, is the lack of considering sex-related information as diagnostic criteria using an evidence-based approach. Understanding the varying prevalence rates between sexes, in addition to nuances in the way males and females clinically present and recover from concussions, is crucial to developing sound and safe concussion protocol programs, designed to keep athletes and non-athletes safe.

2.2 Sex-Related Differences in Concussion

Sex-related differences are a component of research that has been overlooked in most biomedical fields, most notably in concussion research. Current literature often lacks separation of sexes for analytical purposes, focusing mainly on males or a combined approach. However, recent studies of cognition and brain networks have adjusted to include the comparison of, or separation of, the two. Some studies have shown differences in the prevalence of concussions in males and females, combined with differences in clinical presentation and recovery trajectories (Berz et al., 2013; V. C. Merritt et al., 2019; Ono et al., 2016). For instance, work from Black et al. (2017) identified a greater incidence of concussion in female athletes compared to a similar number of male athletes. Analogous findings from a self-report study of Canadians, also found that women reported higher rates of concussions than males (Champagne et al., 2023).

Notably, previous work from our lab examined the effect of previous concussions on visuomotor skill performance and emotionality among varsity athletes (Pierias, 2021). Participants were required to self-report their previous concussion history and perform a computerized cognitive-motor integration (CMI) visuomotor task with a standard and non-standard condition. Results indicated that concussion history significantly impacted male visuomotor performance and anxious symptoms, whereas concussion history did not display an effect on females in either domain.

2.3 Recovery from Concussive Injury

Between 80% to 90% of SRCs resolve within seven to ten days (Gouttebarge & Kerkhoffs, 2021; Putukian & Johnson, 2011). Regarding concussion recovery, mixed findings throughout literature have been reported. For instance, various findings have shown no sex differences in recovery among athletes relating to cognitive recovery and symptoms (Black et al., 2017; Hannah et al., 2021; Ono et al., 2016). In a study with collegiate athletes, no differences in return-to-sport recovery were found in athletes who played men's and women's sports (i.e., basketball, soccer, and lacrosse). However, athletes in women's sports (i.e., field hockey, gymnastics, and equestrian), experienced longer symptom durations and return-to-academics time than those in men's sports (i.e., football, wrestling, and golf) (Bretzin et al., 2022).

However, a study examining the effect of concussion history and the time since an athlete's concussion found no significant group differences between the concussed group and healthy controls regarding balance performance (Merritt et al., 2017). Further, they discovered no significant correlation between time since the most recent concussion and balance performance. Results suggest that time since an individual's concussion, or their recovery time, may not be sufficient by itself to modulate postural performance. Additional research on concussive head injuries highlights sex-related differences in incidence, symptoms, and recovery trajectory, suggesting neurobiological and hormonal influences (Berz et al., 2013; Henry et al., 2010).

2.4 Neural Differences in Visuomotor Performance and the Impact of Concussion

Visuomotor performance, or the coordination between visual perception and motor control, is essential for most, if not all activities across populations. This skill is expressly important for athletes as they are required to process multiplanar visual information and sensory input to express appropriate motor control or movements during gameplay. This skill is an integral part of spatial awareness, a skill necessary for all athletes. This complex relationship between vision and movement increases cognitive load, which can be unconsciously cognitively taxing for athletes, particularly post-concussive injury. The integration between visual and motor processes during tasks primarily involves the motor cortex and cerebellum, along with parietal and occipital lobes (Culham et al., 2006). Literature has extensively documented that visuomotor performance can be modulated by various factors including biological sex.

Sex-based differences in visuomotor performance are evident in behavioural outcomes. For instance, females tend to perform better on tasks involving fine motor manipulations, while males perform better on tasks requiring spatial awareness and motor control (Halpern, 2013; Nicholson & Kimura, 1996). Researchers have attributed these differences in performance to distinctions in brain structure and activation between sexes. For instance, an fMRI study examining structural activation during a visuospatial cognitive task found that men showed significantly stronger parietal activation whereas women showed significantly greater right frontal activation (Weiss et al., 2003). Conversely, additional research has shown that women exhibit greater bilateral activity or greater brain area recruitment during visuomotor tasks compared to males (Smeha et al., 2022; Sneider et al., 2011). This bilateral pattern of activation has been further observed during tasks not related to visuomotor control such as language processing (Shaywitz et al., 1995). Such findings may elucidate the differences in sex-based visuomotor performance. However, despite the general agreement that suggests differences exist between males and females, some studies have not observed a sex effect.

Along with biological sex, visuomotor performance can be further modulated by concussive injury. Symptoms individuals experience post-concussion can drastically impair coordination and reaction time, critical elements of visuomotor performance (Alsalaheen et al., 2021). Further, extant literature suggests females experience more severe and prolonged concussion-related symptoms compared to males, making them more vulnerable to poorer visuomotor performance outcomes (Koerte et al., 2020).

While it is recognized that neural distinctions greatly modulate concussive outcomes and post-concussive performance, hormonal and structural brain differences between sexes are also understood to play a role in modulating these outcomes. For instance, a study examining if concussions occurred at different stages of the female menstrual cycle, determined that 66.7% of concussions occurred during the late luteal phase and the first two days of menstruation (La Fountaine et al., 2019). This 9-day phase is significant because this window is when estrogen and progesterone are approaching or at their monthly low. This may be further compounded by the fact that motor learning performance is decreased during the luteal phase of the menstrual cycle (Ikarashi et al., 2020). Females also have less cerebral spinal fluid compared to males (Cosgrove et al., 2007), and exhibit greater head-neck segment peak angular acceleration and displacement, making them more susceptible to concussive injury compared to males (Tierney et al., 2005). Alternatively stated, females' heads accelerate quicker than males when subjected to a rotational force, further, their head and neck segments move further during said acceleration.

Visuomotor skills, or the integration between visual perception and motor skills, are seen as the ability to coordinate vision with bodily movements (Offit et al., 2013). Visuomotor deficits can be observed post-concussion in various populations. Recent work by Phillips et al. (2023), examined the impact of SRC in adolescence on two touchscreen visuomotor tasks. Findings showed that movement planning was impaired in concussion history (CHx) participants in the eye-hand decoupling condition, and concussion history patients had worse spatial movement planning, compared to controls. This suggests that prolonged deficits from a sport related concussion sustained in adolescence, may be observed up to four-years post-injury (Phillips et al., 2023).

Notable differences in measures such as reaction time between those with history of concussion and controls have been observed. Post-injury, previously concussed individuals display increased reaction time (a common measure in visuomotor tasks) during a broad array of tasks, including Immediate Post-Concussion Assessment and Cognitive Test (ImPACT; Covassin et al., 2012), and grasping a falling measuring stick (Eckner et al., 2014).

Behavioural sex-related differences have been noted in several aspects of cognition such as verbal, visual-spatial and perceptual tasks, and dexterity and bimanual skill in the motor control domain (Kimura, 2002; Li, 2014; Weiss et al., 2003). Such observations create a clearer picture that male and female brains do, in fact, control aspects of cognitive and motor behaviour differently. For instance, previous works from our group suggest that following concussion, males performed worse than females on a cognitive-motor integration task (CMI) (Rogojin et al., 2023; Smeha, 2021). Irrespective of sex differences, CMI performance was worsened in those with concussion history compared to those without (Dalecki et al., 2016; Hurtubise et al., 2016).

2.5 Cognitive Effects of Concussion

Cognition refers to any or all processes and activities involved in the explicit or conscious acquisition, storage, retrieval and processing of information (Bayne et al., 2019). Concussive injury has been found to impact various cognitive processes such as attention, memory, decision-making and neuropsychological performance. A longitudinal study by David et al. (2013), found that concussed adolescents had a significantly increased reaction time on an attentional test compared to controls. Findings suggest that concussed individuals have difficulty recovering executive function after injury and may require more time to achieve a full recovery (Mihalik & Wasserman, 2017).

Visual changes resulting from concussive injury are a common cognitive effect. Impairment in higher cortical saccadic tasks has been found in acutely concussed individuals (Gunasekaran et al., 2019). Further, those with post-concussive visual motion sensitivity had increased symptoms and considerably more ocular motor screening abnormalities while watching stimulating videos (Allen et al., 2021). Apart from notable differences visual sensitivity post-injury, those with a history of concussion respond more slowly to gaze depth perception tasks than those without a history of concussion (Mihalik & Wasserman, 2017).

An interesting concept put forth by Satz (1993), is the idea of brain reserve capacity (BRC). This theory suggests that the brain's ability to withstand damage while maintaining function varies among individuals. The theory further suggests that individuals with a higher BRC have a greater buffer to withstand injuries without impairment; the threshold at which impairments become evident differs amongst individuals (Oldenburg et al., 2016). For instance, under this theory, two individuals with different BRCs may exhibit different impairments or symptoms following the same injury, a concept noted within concussion literature. Specifically, in a study of youth athletes, those with concussion history but greater sport experience reached a performance level of their non-history peers quicker than the individuals with concussion history and less sport experience (Dalecki et al., 2019). The BRC theory further posits that individuals with increased BRC as a protective factor may still experience challenges based on task, causing them to fall below the threshold of functional impairment.

While this work supporting this theory primarily involves the study of degenerative diseases such as Alzheimer's and Parkinson's Disease, traumatic brain injuries have also been studied. For instance, in a study examining rehabilitation outcomes in moderate to severe TBI patients, it was discovered that longer educational exposure was associated with disability-free recovery. On similar note, another study discovered that greater brain volume and higher educational level, may reduce vulnerability to cognitive deficits (Kesler et al., 2003).

2.6 Emotional Impact of Concussion

Emotionality, or the variety of subjective feeling states that predictably influence observable behaviours and physiological responses for functional purposes (Decker & Cadenhead, 2011). Individuals who have sustained a concussive injury are at an increased risk of depression, anxiety, problems with emotional regulation and irritability (Lima Santos et al., 2023; Merritt et al., 2019; Thomson et al., 2020). Rabelo (2017) determined that the more concussions an athlete sustains, the more depressive symptoms they experience, demonstrating the critical need to mitigate concussive injury across all populations. Further, findings show that lower fractional anisotropy in white matter tracts associated with emotional regulation may be linked with persistent symptomology (Lima Santos et al., 2021). More simply put, connectivity issues in areas of the brain linked with the regulating emotions, may explain ongoing symptoms experienced by those with concussion history.

2.7 Brain Networks Implicated in Concussion

The default mode network has been found to have decreased between and within functional connectivity resulting from concussions (Chong et al., 2018; Healey et al., 2022a; Plourde et al., 2020; Zhu et al., 2015). Altered network connectivity, resulting from concussions, is known to effect visuomotor skills and contribute to depressive symptoms (Coutinho et al., 2016).

Consideration of injury recovery time is important in understanding the potential functional alterations the brain may experience resulting from concussive impact. For instance, Churchill et al. (2021) examined the local and global efficiency of concussed athletes at their acute injury stage, return to play (RTP), and one-year post RTP stage. At participants' acute stage, they showed no local efficiency alterations but had elevated global efficiency, which resolved at RTP. However, at one-year post-RTP, athletes had reduced global efficiency, suggesting long-term structural abnormalities for those with history of concussion (Churchill et al., 2021). Likewise, reduced brain network activation, reduced functional connectivity, and altered brain structures in the posterior internal capsule and right corona radiata, have been found post-concussive injury (Churchill et al., 2017; Healey et al., 2022b; Kontos et al., 2016; Messé et al., 2013). Connectivity issues, reduced functioning, and structural changes of the brain, all contribute to the disparity in cognitive deficits experienced post-injury. Concerningly the resolution of these deficits sometimes does not occur before return to play as seen by Churchill et al. (2017).

2.8 Compounding Effects of Multiple Concussions

Incurring multiple concussions has been associated with protracted recovery time, symptoms and an increased risk of future concussive injuries. Athletes with a history of more than 3 concussions take longer to recover than athletes with 1 or no concussions (Covassin et al., 2013). Specifically, after 8 days, athletes that had a history of 3 or more concussions did not recover on their reaction time and verbal memory performance. A similar study with collegiate football players found that a history of multiple concussions was associated with slowed recovery, with symptoms lasting longer than those with 1 concussion (Guskiewicz et al., 2003). Additionally, individuals with previous concussion history exhibit delayed recovery in neurological function. This relationship seems to be further mitigated by the concurrent presence of learning disorders. Athletes with learning disabilities who experience a concussion perform worse than their non-learning disability concussed counterparts on neuropsychological measures (Collins et al., 1999). This relationship has been attributed to the potential lack of cognitive reserve in persons with learning disabilities. This finding underscores the significance of cognitive reserve as a resilience factor in concussion recovery. Despite this, alternate literature suggests no differences exist between individuals with three or more concussions and individuals with concussions in postural control measures (Dierijck et al., 2018). Several other studies established that multiple concussions did not affect neuropsychological function among athletes (Brooks et al., 2016; Collins et al., 1999; Iverson et al., 2012; Macciocchi et al., 2001).

Interestingly, more recent work from Buckley and colleagues examined 45 athletes with distinctive concussion history and learning disabilities (Buckley et al., 2020). Participants were divided into groups of no prior concussion, ≥3 prior concussions, or acute concussion. Subjects performed 5 trials of a gate initiation task on 4 forceplates. It was found that those with acute concussions had substantial impairments compared to those with ≥3 prior concussions who showed moderate postural control impairments. The mixed findings throughout literature surrounding the effects of multiple concussions on neuropsychological and postural performance further underline the need to examine these relationships.

Chapter 3: Research Study

3.1 Background

The increasing prevalence of concussive injuries in sports has raised significant concerns about its long-term effects on health-related domains. Millions of individuals sustain concussions every year, with some experiencing prolonged effects (Champagne et al., 2023; Master et al., 2018) Two of these domains have become central to concussion and SRC literature. Emotionality and visuomotor performance are two health domains that impact every aspect of our daily functioning. The concern for the impact of concussions on emotionality and visuomotor performance becomes all the more critical when we look at developing populations such as children and young adults.

Concussions are a form of mTBI that most commonly occur during sport participation, where injury results from transmitted impulsive forces to the brain or rapid acceleration-deceleration of the head (Master et al., 2018; Mullally, 2017). Previous studies have suggested that males and females recover differently in emotionality and visuomotor performance post-concussive injury. Specifically, females recover better in visuomotor performance and worse in emotionality, whereas males recover more favourably in emotionality and worse in visuomotor performance (Pierias, 2021).

The objective of this study is to investigate the sex-related difference in kinematic visuomotor skill performance and emotionality after concussive injury. This study further examines findings from Pierias (2021) regarding the sex-based differences in emotionality and visuomotor domains. Based on previous studies, we hypothesize that females will recover better in visuomotor performance but worse in emotionality, while males will show the inverse relationship. Additionally, we hypothesize that an increase in concussions will decrease kinematic performance, but performance will increase with age. We further posit that for participants with concussion history, more time lived since concussion will correlate with improved kinematic performance.

3.2 Methods

3.2.1 Participants

Study participants included 299 York University varsity athletes (F = 148), aged 17 to 31 years, with a mean age of 19.71 ± 1.92 years. Participant data was collected from 3 varsity baseline testing years (2019, 2022 and 2023) and aggregated into one dataset. Descriptive statistics by CHx are summarized in **Table 1**, with descriptive stats by sex and CHx in **Table 2**. All CHx participants were asymptomatic at the time of testing, in keeping with current return-to-play guidelines. No exclusion criteria were required for this study. Athletes were not aware of the nature of analyses being conducted on their task performance or self-report measures, limiting their ability to be influenced in their answers or performance.

Table 1. *Descriptive statistics and frequencies of participants with and without a history of concussion based on exposure and outcome variables*. *Individuals without a history of concussion. *n* represents the number of non-missing observations for each variable. Some variables have missing data, which accounts for the differences in sample sizes.

	All (n=299)		Healthy* (n=202)		Concussion History (n=86)	
	Mean or *n*	**SD or %**	**Mean or *n***	**SD or %**	**Mean or *n***	**SD or %**
Age (years)	19.72	1.92	19.63	1.79	19.92	2.19
Sex						
Female	*148*	49.50%	*101*	50.00%	*44*	51.20%
Male	*151*	50.50%	*101*	50.00%	*42*	48.80%
Number of Previously Diagnosed Concussions						
0	*202*	70.10%	*202*	100%	-	-
1	*45*	15.60%	-	-	*45*	52.30%
2	*26*	9.00%	-	-	*26*	30.20%
3	*10*	3.50%	-	-	*10*	11.60%
4	*3*	1.00%	-	-	*3*	3.50%
5	*1*	0.30%	-	-	*1*	1.20%
6	*0*	0%	-	-	*0*	0%
7	*1*	0.30%	-	-	*1*	1.20%

Time lived without concussion (months)	176.55	96.48	239.86	20.98	40.60	33.94
Kinematic Variables for Direct Condition						
Reaction Time (ms)	296.54	105.45	305.32	115.10	282.12	81.09
Movement Time (ms)	460.10	151.75	455.62	159.29	470.33	140.76
Peak Velocity (normalized)	0.86	0.10	0.86	0.12	0.86	0.08
Variable Error (mm)	4.72	4.27	4.75	3.89	4.72	5.00
Absolute Error (mm)	24.26	14.57	23.08	14.53	25.75	14.54
Path Length (mm)	104.40	8.33	104.59	8.89	104.00	7.45
Kinematic Variables for SSR Condition						
Reaction Time (ms)	389.08	175.82	400.50	178.86	372.95	175.01
Movement Time (ms)	891.39	480.02	868.99	472.50	951.72	515.79
Peak Velocity	0.89	0.12	0.90	0.12	0.87	0.14
Variable Error (mm)	12.19	15.94	13.16	16.78	10.41	14.33
Absolute Error (mm)	22.69	16.24	23.72	16.01	18.94	16.44
Path Length (mm)	124.44	36.40	123.81	27.43	122.29	23.61
Direction Reversals (%)	17.75	18.20	16.76	17.27	20.55	20.92
Emotionality Variables						
More Emotional						
0 (None)	*228*	82.30%	*160*	83.30%	*68*	80.00%
1 (Mild)	*29*	10.50%	*20*	10.40%	*9*	10.60%
2 (Mild)	*13*	4.70%	*8*	4.20%	*5*	5.90%
3 (Moderate)	*3*	1.10%	*2*	1.00%	*1*	1.20%
4 (Moderate)	*3*	1.10%	*1*	0.50%	*2*	2.40%
5 (Severe)	*0*	0%	*0*	0%	*0*	0%
6 (Severe)	*1*	0.40%	*1*	0.50%	*0*	0%
Irritability						
0 (None)	*220*	79.40%	*157*	81.80%	*63*	74.10%
1 (Mild)	*35*	12.60%	*21*	10.90%	*14*	16.50%
2 (Mild)	*17*	6.10%	*12*	6.30%	*5*	5.90%
3 (Moderate)	*4*	1.40%	*1*	0.50%	*3*	3.50%
4 (Moderate)	*1*	0.40%	*1*	0.50%	*0*	0%
5 (Severe)	*0*	0%	*0*	0%	*0*	0%
6 (Severe)	*0*	0%	*0*	0%	*0*	0%
Sadness						
0 (None)	*235*	84.80%	*162*	84.40%	*73*	85.90%
1 (Mild)	*30*	10.80%	*21*	10.90%	*9*	10.60%
2 (Mild)	*6*	2.20%	*4*	2.10%	*2*	2.40%

3 (Moderate)	5	1.80%	4	2.10%	1	1.20%
4 (Moderate)	0	0%	0	0%	0	0%
5 (Severe)	0	0%	0	0%	0	0%
6 (Severe)	1	0.40%	1	0.50%	0	0%
Nervous or Anxious						
0 (None)	180	65.00%	125	65.10%	55	64.70%
1 (Mild)	44	15.90%	27	14.10%	17	20.00%
2 (Mild)	28	10.10%	22	11.50%	6	7.10%
3 (Moderate)	18	6.50%	15	7.80%	3	3.50%
4 (Moderate)	1	0.40%	0	0%	1	1.20%
5 (Severe)	5	1.80%	2	1.00%	3	3.50%
6 (Severe)	1	0.40%	1	0.50%	0	0%

3.2.2 Study Design

This study used a cross-sectional within-subject design. Subjects were recruited from the York University Athletic Therapy Clinic as part of standardized pre-season baseline testing. Baseline data collection was conducted in the York University Stadium Clinic. Written informed consent was obtained from participants prior to participation (**Appendix A & B**). Ethics approval was granted by the York University Research Ethics Board.

3.2.3 Procedures

3.2.3.1 Visuomotor Skill Assessment Task. Participants performed a cognitive-motor integration (CMI) task to evaluate visuomotor performance. Visuomotor performance was assessed using the Brain Dynamics Indicator ™ (BrDI) on Samsung Tab A tablets. This assessment required participants to slide the index finger of their dominant hand from a central target to one of four peripheral targets (up, down, left or right) as quickly and as accurately as possible. The BrDI task included two conditions (each containing 20 trials): direct – where the target viewed and the finger movements are coupled (**Figure 1a**); and SSR – where the target viewed and the finger movements are decoupled (**Figure 1b**). The latter condition contained two levels of decoupling: (i) plane change; in which participants looked

at the upper half of the tablet while moving on the lower half, and (ii) reversal; in which the feedback was rotated 180°. The target distance was 35mm with the target sequence for each condition being randomized between the four targets, each target appearing 5 times.
For the direct condition, subjects were instructed to look at the 8mm green ball (central target) and then move their finger as quickly and accurately as possible to the peripheral 10mm target. For the SSR condition, participants were instructed to look at the 8mm green ball (central target) and then move the 5mm white dot representing their finger position to the 10mm peripheral target.

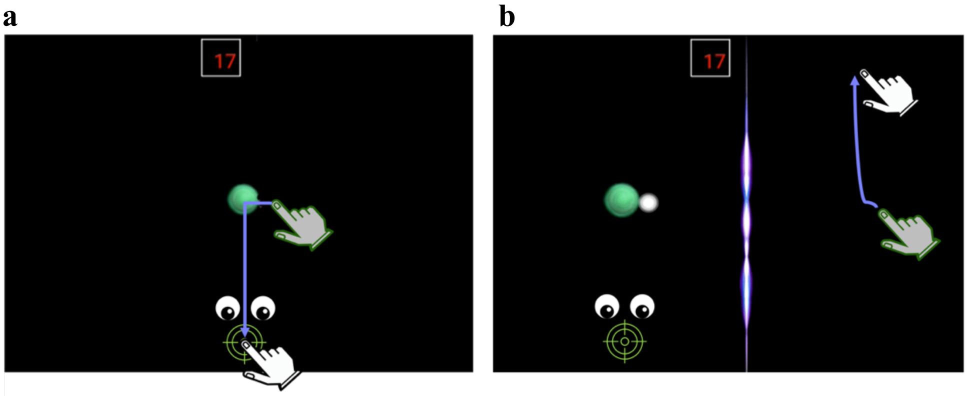


Figure 1. Diagram of the BrDI™ Visuomotor Task. **a)** Direct condition. Eye movements and finger movements are coupled when moving from the central target to the peripheral target. **b)** SSR condition. Movements occur on separate planes. Eye movements and finger movements are decoupled when moving from the central target to the peripheral target, while feedback is rotated 180°.

3.2.3.2 SCAT Emotionality Measures. The SCAT5 and the SCAT6 are standardized assessment tools for evaluating concussions, designed for use by healthcare professionals (Echemendia et al., 2023). SCAT5 symptoms have demonstrated high test-retest reliability (Hänninen et al., 2021), and since the SCAT6 uses the same symptom evaluation criteria, the reliability holds for this in theory as well. Under the “Symptom Evaluation” subheading of both assessment tool versions, there is a list of 22 identical symptoms. Athletes had to rate said symptoms on a scale from zero to six according to how they typically feel, with zero representing no symptoms, 1 and 2 – mild symptoms, 3 and 4 – moderate symptoms, and 5 and 6 – severe symptoms. For the purposes of this study, only the latter 4 symptom questions were extracted from each participants' SCAT. The four symptoms were more emotional, irritability, sadness, and nervous/anxious. These four symptoms were used to provide an understanding of individual emotionality levels.

3.2.4 Variables

Seven kinematic outcome variables were analyzed, specifically three time and four trajectory measures. Kinematic time measures include 1) reaction time (RT) – calculated as the time between the central target disappearing and movement onset, measured in milliseconds (ms), 2) movement time (MT) – calculated as time between movement onset and offset (comprised of full movement offset and ballistic or initial movement offset), measured in ms, and 3) peak velocity (PV) – the maximum velocity obtained for each trial, measured in mm/ms.

Trajectory measures include 1) normalized path length (nPL) – the distance from the starting point to the final destination of the entire motion, measured in millimetres (mm), 2) absolute error (AE) – average distance from each individual movement endpoint to the actual target location or end-point accuracy, measured in mm, and 3) variable error (VE) – the absolute distance between each individual movement endpoint from their mean movement or end-point precision, measured in mm. The seventh outcome measure, the percentage of direction reversals (%DR), is calculated as a deviation of greater than ±45° from a straight line between the center of the central and peripheral targets. This outcome measure is only applicable to the split-screen reversal (SSR) condition.

Four emotionality outcome variables will be analyzed per participants' SCAT 5 & 6 responses. The variables are more emotional, irritability, sadness, and nervous/anxious. Participants were required to respond to how they typically felt on a scale of 0 to 6 for each of the four aforementioned emotionality variables. The scale began with 0 representing no symptoms, 1 and 2 representing mild symptoms, 3 and 4 representing moderate symptoms, and 5 and 6 representing severe symptoms (see Appendices **C and D**, respectively).

Exposure variables for this study are defined as biological sex (male or female), age, concussion history (concussed = history of concussion or healthy = no history of concussion (NCHx)), number of previous concussions (#PC) and time lived since concussion. Time lived since concussion is a measure of the number of months that have passed between a participant's concussion and the assessment date. If a participant did not sustain a concussion, this value would be expressed as their age in months (or the time between their date of birth and the assessment date).

3.2.5 Behavioural Data Processing

Kinematic data, such as finger position, timing, and error metrics were collected for each trial and converted into a binary readable format using a custom C++ application. Failed trials were detected by the software and resulting in trial termination if the participant's finger left the target home too early (<2000ms), MT was too long (>10000ms), RT was too long (>8000ms) or RT was too short (<150ms). Trials coded as DRs were analyzed as separate variables from correct trials. A custom Matlab analysis program (MathWorks, Inc., USA) was used to generate a velocity profile for each trial, recording movement onset and end at 10% of the participant's peak velocity. Each profile was scored by performing visual inspections and making corrections where necessary. Finally, the scored data was processed to generate 7 different movement and trajectory outcome measures.

3.2.6 Statistical Analysis

3.2.6.1 Missing Data. Study data included missing variable data for *#PC* (n = 11), *CHx* (n = 11), *age* (n = 12), *time lived without concussion* (n = 85) and all SCAT variables (n = 22), due to study restrictions. Kinematic missing data for RT, MT, PV, VE, AE and nPL (n

= 6 *each*) resulted from data output errors. Further, DR analyses were conducted on 2022 and 2023 data as 2019 data was unavailable. All statistical analyses were conducted on completed cases, minimizing the adverse effect of missing data on statistical modelling. Descriptive statistics were calculated for continuous variables and frequency distributions for categorical variables.

Previous literature has found no differences between CHx and NCHx participants in direct task conditions (Dalecki et al., 2019), as a result only SSR kinematic variables were analyzed for multivariable linear regression analyses and analysis of variance (ANOVA). Further, in keeping with the objectives of this study, we wanted to determine the effect of CHx on complex skilled performance, hence using only SSR data.

3.2.6.2 Data Transformations. All peak velocity values were normalized to match the directionality of all other kinematic variables, as seen in (1). Consequently, peak velocity data are unitless, with values closer to 1 indicating poor performance, and values closer to 0 indicating inferior performance.

$$\mathrm{PV}_{\mathrm{transformed}} = 1 - \left(\frac{(\text{current PV} - \text{minimum PV})}{\text{maximum PV}}\right) \tag{1}$$

To conduct parametric testing on kinematic outcome variables, distributions required normality. Consequently, six of seven kinematic variables were transformed to meet normality assumptions. A reflective cube root transformation was performed on PV as seen in (2) due to its left-skewed distribution:

$$\sqrt[3]{(\text{maximum PV} - \text{current PV})} \tag{2}$$

Log_{10} transformations were applied to nPL, VE, and MT as seen in (3) considering their original right-skewness:

$$\log_{10}(\text{variable})$$

$$(3)$$

Square root transformations were applied to AE as seen in (4):

$$\sqrt{\mathrm{AE}} \tag{4}$$

Finally, cube root transformations were applied to %DR as seen in (5):

$$\sqrt[3]{(\%\mathrm{DR})} \tag{5}$$

No transformations were applied to RT as this variable met the assumptions of normality.

3.2.6.3 Variable Recoding. The variable *number of previous concussions* was recoded into 3 groups: 0 concussions (healthy), 1 concussion, and 2 or more concussions. Further, each SCAT emotionality variable was recoded individually, where all 0 values were reported as no emotion versus emotion, respective to their SCAT variable. Recoding resulted in the following binary SCAT variables: *no emotion – emotion*, *no irritability – irritability*, *no sadness – sadness,* and *not nervous/anxious – nervous/anxious.* Finally, age was recoded into four groups before analyses: 17 to 18 years, 19 to 20 years, 21 to 22 years, and 23 years and older.

3.2.6.4 Relationship between kinematic performance, sex and #PC. Two-way ANOVA was independently conducted for each transformed kinematic variable against the exposure variables *sex*, *#PC* to determine main and interaction effects. Post-hoc analyses were performed to determine significant pairwise differences between *#PC* groups.

Before, presenting ANOVA data, kinematic data were back-transformed for ease of interpretation and understanding. Tukey's mean difference values and Tukey's confidence intervals were back-transformed to their original values. Back-transformations were applied to PV (6), nPL, VE and MT (7), AE(8), %DR(9):

$$(\text{maximum PV} - \text{current PV})^3$$

(6)

$$10^{\text{variable}}$$

(7)

$$AE^2$$

(8)

$$\%DR^3$$

(9)

3.6.6.5 Association between kinematic performance, sex, #PC and age. Multivariable linear regression analyses were performed on non-transformed data to examine the effects of sex, number of previous concussions and age on each kinematic outcome variable.

3.6.6.6 Relationship between kinematic performance and time lived since concussion. Finally, Spearman's correlation analyses were performed to determine the relationship between *time lived since concussion* and all seven kinematic variables. The *time lived since concussion* variable was split to analyze CHx individuals and not their NCHx counterparts, aligning with the objectives of this research. Accordingly, all participants who sustained a concussion occurred in less than 150 months. For these analyses only 2019 and 2022 data were examined, as 2023 data was unavailable.

3.6.6.7 Relationship between emotionality, sex, and #PC. A chi-square test of independence and crosstabs were independently conducted to determine if significant associations existed between 1) emotionality variables and sex, and 2) emotionality variables and number of previous concussions.

3.6.6.8 Association between emotionality, #PC and age. Binary logistic regression analyses were performed separately for males and females to determine the odds of reporting *emotion* versus *no-emotion, irritability* versus *no-irritability*, *sadness* versus *no-sadness*, and *nervous/anxious* versus *not nervous/anxious*, based on number of concussions and age.

Statistical analyses were performed using IBM SPSS v29.0.2.0 (IBM Corp., Armonk, NY, USA), and plots were generated using the ggplot2 package using R (v4.2.3) software. The significance level for all statistical tests was set at an alpha level of .05 ($\alpha = 0.05$). All analyses met their respective statistical assumptions. All planned comparisons will include a stratified sex analysis.

3.3 Results

3.3.1 Descriptive Statistics

Descriptive statistics were calculated to determine and characterize the key continuous variables of interest among participants. The mean age of participants was 19.72 years (SD = 1.92), while the mean age of healthy and CHx participants was 19.63 (SD = 1.79) and 19.92 (SD = 2.19) years, respectively. Kinematic measures for both conditions showed standard performance metrics, in line with previous research. **Figure 2** shows sample kinematic task trajectories of male and female participants with CHx and NCHx. A further breakdown of descriptive statistics based on sex and CHx is presented in **Table 2**.

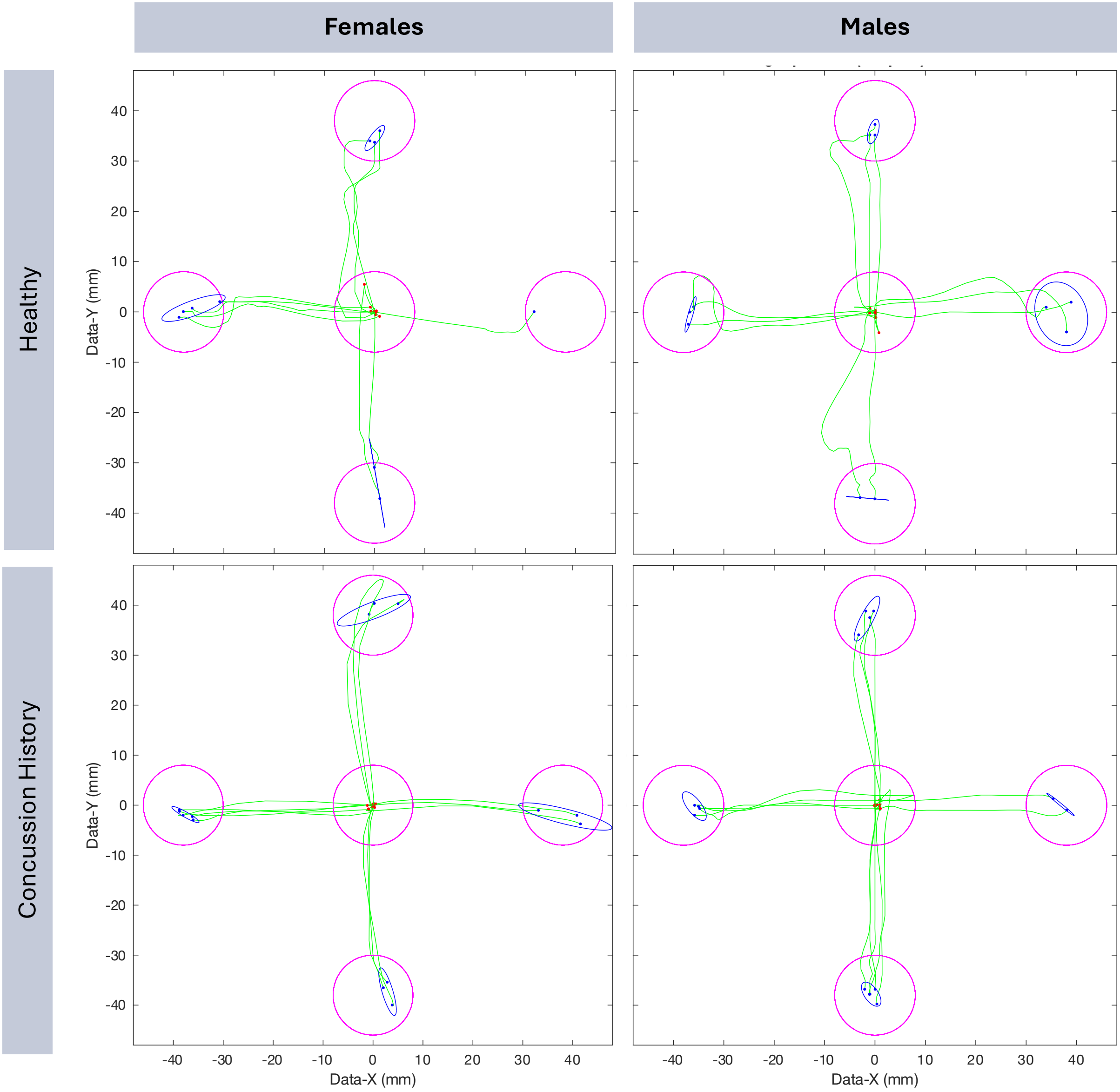


Figure 2. SSR kinematic task trajectories for healthy and concussed male and female participants. Example SSR trajectories from four male and female healthy and concussed participants. Peripheral pink circles represent end-point targets, while the middle pink circle represents the task starting position. Green lines show participants' paths, while endpoints are represented by blue dots with blue ellipses showing 95% confidence intervals.

Table 2. *Descriptive statistics and frequencies of participants by sex with and without a history of concussion based on exposure and outcome variables*. *Individuals without a history of concussion. n represents the number of non-missing observations for each variable. Some variables have missing data, which accounts for the differences in sample sizes.

	All Females (n=148)		All Males (n=151)		Healthy* Female (n=101)		Healthy* Male (n=101)		Concussion History Female (n=44)		Concussion History Male (n=42)	
	Mean or *n*	SD or %	Mean or *n*	SD or %	Mean or *n*	SD or %	Mean or *n*	SD or %	Mean or *n*	SD or %	Mean or *n*	SD or %
Age (years)	19.72	2.05	19.72	1.79	19.66	1.85	19.60	1.74	19.84	2.48	20.00	1.87
Number of previously diagnosed concussions												
0	*101*	69.70%	*101*	70.60%	101	100%	101	100%	-	-	-	-
1	*23*	15.90%	*22*	15.40%	-	-	-	-	*23*	52.30%	*22*	52.40%
2	*10*	6.90%	*16*	11.20%	-	-	-	-	*10*	22.70%	*16*	38.10%
3	*6*	4.10%	*4*	2.80%	-	-	-	-	*6*	13.60%	*4*	9.50%
4	*3*	2.10%	*0*	0%	-	-	-	-	*3*	6.80%	*0*	0%
5	*1*	0.70%	*0*	0%	-	-	-	-	*1*	2.30%	*0*	0%
6	*0*	0%	*0*	0%	-	-	-	-	*0*	0%	*0*	0%
7	*1*	0.70%	*0*	0%	-	-	-	-	*1*	2.30%	*0*	0%
Time lived without concussion (months)	179.19	96.51	173.17	96.87	240.60	20.99	238.89	21.11	41.43	39.85	39.61	25.80
Kinematic Variables for Direct Condition												
Reaction Time (ms)	278.30	87.99	314.29	117.64	287.33	92.52	323.13	131.82	260.92	76.68	304.33	80.48
Movement Time (ms)	478.73	171.99	441.96	127.01	475.72	192.52	435.71	115.09	485.84	121.35	454.09	158.44
Peak Velocity (normalized)	0.85	0.13	0.86	0.07	0.85	0.15	0.87	0.06	0.86	0.04	0.85	0.11
Variable Error (mm)	4.48	4.56	4.95	3.97	4.34	3.46	5.15	4.25	4.95	6.50	4.49	2.73
Absolute Error (mm)	26.61	13.92	21.98	14.88	24.18	14.39	22.00	14.66	31.66	11.73	19.56	14.73
Path Length (mm)	102.51	9.11	106.25	7.05	102.72	9.74	106.45	7.56	101.99	7.92	106.10	6.35
Kinematic Variables for SSR Condition												
Reaction Time (ms)	383.29	190.71	394.82	160.10	404.87	201.50	396.08	153.56	341.51	162.32	406.70	183.69
Movement Time (ms)	965.57	520.29	817.71	425.44	914.69	499.72	822.82	441.04	1103.14	556.56	789.22	416.41
Peak Velocity (normalized)	0.88	0.15	0.90	0.09	0.90	0.14	0.90	0.09	0.85	0.17	0.89	0.09
Variable Error (mm)	12.92	19.25	11.46	11.79	14.03	20.03	12.29	12.73	11.08	17.91	9.70	9.22
Absolute Error (mm)	22.47	18.25	22.90	14.03	23.18	17.84	24.28	13.99	20.36	19.53	17.41	12.36
Path Length (mm)	125.94	25.76	122.95	44.58	127.61	26.92	119.96	27.54	123.80	23.06	120.68	24.36

Direction Reversals (%)	23.00	19.38	12.04	14.97	22.21	17.86	11.30	14.93	24.48	22.29	14.36	17.29
Emotionality Variables												
More Emotional												
0 (None)	*111*	79.90%	*117*	84.80%	*80*	83.30%	*80*	83.30%	*31*	72.10%	*37*	88.10%
1 (Mild)	*15*	10.80%	*14*	10.10%	*8*	8.30%	*12*	12.50%	*7*	16.30%	*2*	4.80%
2 (Mild)	*8*	5.80%	*5*	3.60%	*4*	4.20%	*4*	4.20%	*4*	9.30%	*1*	2.40%
3 (Moderate)	*3*	2.20%	*0*	0%	*2*	2.10%	*0*	0%	*1*	2.30%	*0*	0%
4 (Moderate)	*1*	0.70%	*2*	1.40%	*1*	1.00%	*0*	0%	*0*	0%	*2*	4.80%
5 (Severe)	*0*	0.00%	*0*	0%	*0*	0%	*0*	0%	*0*	0%	*0*	0%
6 (Severe)	*1*	0.70%	*0*	0%	*1*	1.00%	*0*	0%	*0*	0%	*0*	0%
Irritability												
0 (None)	*110*	79.10%	*110*	79.70%	*81*	84.40%	*76*	79%	*29*	67.40%	*34*	81.00%
1 (Mild)	*18*	12.90%	*17*	12.30%	*7*	7.30%	*14*	15%	*11*	25.60%	*3*	7.10%
2 (Mild)	*8*	5.80%	*9*	6.50%	6	6.30%	6	6%	*2*	4.70%	*3*	7.10%
3 (Moderate)	*2*	1.40%	*2*	1.40%	*1*	1.00%	*0*	0%	*1*	2.30%	*2*	4.80%
4 (Moderate)	*1*	0.70%	*0*	0%	*1*	1.00%	*0*	0%	*0*	0%	*0*	0%
5 (Severe)	*0*	0%	*0*	0%	*0*	0%	*0*	0%	*0*	0%	*0*	0%
6 (Severe)	*0*	0%	*0*	0%	*0*	0%	*0*	0%	*0*	0%	*0*	0%
Sadness												
0 (None)	*117*	84.20%	*118*	85.50%	*81*	84.40%	*81*	84.40%	*36*	83.70%	*37*	88.10%
1 (Mild)	*12*	8.60%	*18*	13.00%	*7*	7.30%	*14*	14.60%	*5*	11.60%	*4*	9.50%
2 (Mild)	6	4.30%	*0*	0%	*4*	4.20%	*0*	0%	*2*	4.70%	*0*	0%
3 (Moderate)	*3*	2.20%	*2*	1.40%	*3*	3.10%	*1*	1.00%	*0*	0%	*1*	2.40%
4 (Moderate)	*0*	0%	*0*	0%	*0*	0%	*0*	0%	*0*	0%	*0*	0%
5 (Severe)	*0*	0%	*0*	0%	*0*	0%	*0*	0%	*0*	0%	*0*	0%
6 (Severe)	*1*	0.70%	*0*	0%	*1*	1.00%	*0*	0%	*0*	0%	*0*	0%
Nervous or Anxious												
0 (None)	*86*	61.90%	*94*	68.10%	*62*	64.60%	*63*	65.60%	*24*	55.80%	*31*	73.80%
1 (Mild)	*24*	17.30%	*20*	14.50%	*13*	13.50%	*14*	14.60%	*11*	25.60%	6	14.30%
2 (Mild)	*15*	10.80%	*13*	9.40%	*11*	11.50%	*11*	11.50%	*4*	9.30%	*2*	4.80%
3 (Moderate)	*9*	6.50%	*9*	6.50%	*7*	7.30%	*8*	8.30%	*2*	4.70%	*1*	2.40%
4 (Moderate)	*1*	0.70%	*0*	0%	*0*	0%	*0*	0%	*1*	2.30%	*0*	0%
5 (Severe)	*3*	2.20%	*2*	1.40%	*2*	2.10%	*0*	0%	*1*	2.30%	*2*	4.80%
6 (Severe)	*1*	0.70%	*0*	0%	*1*	1.00%	*0*	0%	*0*	0%	*0*	0%

3.3.2 Frequencies

Additional frequency characteristics were calculated to determine and characterize the key categorical variables of interest among participants. Frequency data are also presented in **Table 1**. For healthy and CHx groups, the percentage of males and females was approximately even within each group. **Table 3** highlights a breakdown of concussion history based on age groups. Most participants had zero previously diagnosed concussions (70.10%), with the second highest being having one previously diagnosed concussion (15.60%). For all SCAT emotionality measures, 0 was reported as the highest response.

Table 3. *Number of concussion history and no concussion history participants based on age group.* Table data reflects information from participants with recorded concussion history.

	17 – 18 years	19 – 20 years	21 – 22 years	23 years +
No Concussion History	71	66	49	15
Concussion History	25	32	23	6

3.3.3 Relationship between kinematic performance, sex and number of concussions

To examine any possible main effects and interactions as a function of group, we performed univariate ANOVA analyses on kinematic outcome variables. In general, we found that many of our movement control metrics were significantly related to the #PC (**Table 4**). Interestingly, AE was the only variable with a significant interaction effect between sex and #PC. Specifically, AE results were qualified by a significant interaction between sex and #PC ($F(2, 278) = 4.62$, $p = .011$, $\eta_p^2 = .032$) and a main effect of the #PC ($F(2, 278) = 4.05$, $p = .018$, $\eta_p^2 = .028$). Within the #PC group post-hoc analyses using Tukey's HSD (see **Table 5**) revealed a significant difference between the 0 – 2 or more group ($p = .028$), but no other concussion groups ($p<.05$). **Figure 3a** highlights these pairwise differences while highlighting the inverse relationship in accuracy between males and females. Despite sex not having a significant main effect ($p = .992$), visual distinctions are apparent between males and females with one previous concussion. Here, males have noticeably better accuracy than females, with this relationship shifting after 2 or more concussions.

Similarly, MT analyses revealed a main effect of sex ($F(1, 278) = 11.73$, $p = <.001$, $\eta_p^2 = .040$), and #PC ($F(2, 278) = 5.14$, $p = .006$, $\eta_p^2 = .036$). Within the #PC group, there were significant MT differences between the 0 – 2 or more ($p = .012$) and 1 – 2 or more ($p = .008$) concussion groups, and no other groups ($p<.05$). Across all #PC groups males performed better than females, however both sexes showed the similar trends between #PC groups (**Figure 3b**). Further, common to both sexes, 0 and 1 concussion groups had similar MT, with a noticeable change in MT occurring in the 2 or more concussions group. Despite these observations, a significant interaction effect between sex and #PC was not present ($p<.05$).

After analyzing RT, only a main effect of #PC emerged as significant ($F(2, 276) = 3.21$, $p = .042$, $\eta_p^2 = .023$), with further post-hoc analyses indicating significant RT differences between the 0 – 2 or more ($p = .024$) and 1 – 2 or more concussion groups ($p = .020$). This difference was not present in sex or through an interaction effect, or other post-hoc pairwise comparison groups ($p<.05$). Similar to MT, the trend in RT performance was similar between both sexes. However, **Figure 3c** shows that RT performance is better in females who have 1 and 2 or more previous concussions.

Similar to RT results, PV analyses revealed a main effect of #PC ($F(2, 278) = 5.31$, $p = .005$, $\eta_p^2 = .037$). Further pairwise group comparisons revealed significant differences between the 0 – 2 or more concussion groups ($p = .003$) but no other groups ($p<.05$). Sex and interaction effects were not observed ($p<.05$). Despite this, **Figure 3d** highlights the visual relationship between male and females with 2 or more concussions. Here males with 2 or more concussions perform noticeably better than their female counterparts.

Interestingly, similar to MT analyses, only DR had a significant group effect of sex. DR Analyses results revealed a main effect of sex ($F(1, 278) = 3.98$, $p = .048$, $\eta_p^2 = .026$). No additional group or interaction effects were observed ($p<.05$). This sex difference was observable within the 0 concussions and 2 or more concussions group, as seen in **Figure 3e**. Males NCHx had a noticeably lower %DR than females with NCHx, with the same relationship observable in participants with 2 or more concussions.

Finally, after analyses, VE and nPL results did not reveal significant main effects of sex, #PC, or interaction effects ($p<.05$). Despite these results, **Figure 3f** highlights the differences in sex-based nPL performance. For instance, in the 0 and 2 or more concussions group, males have a markedly higher nPL compared to females. This relationship is different from that observed in VE, where here, females with 2 or more concussions had observably better precision performance than males (**Figure 3g**).

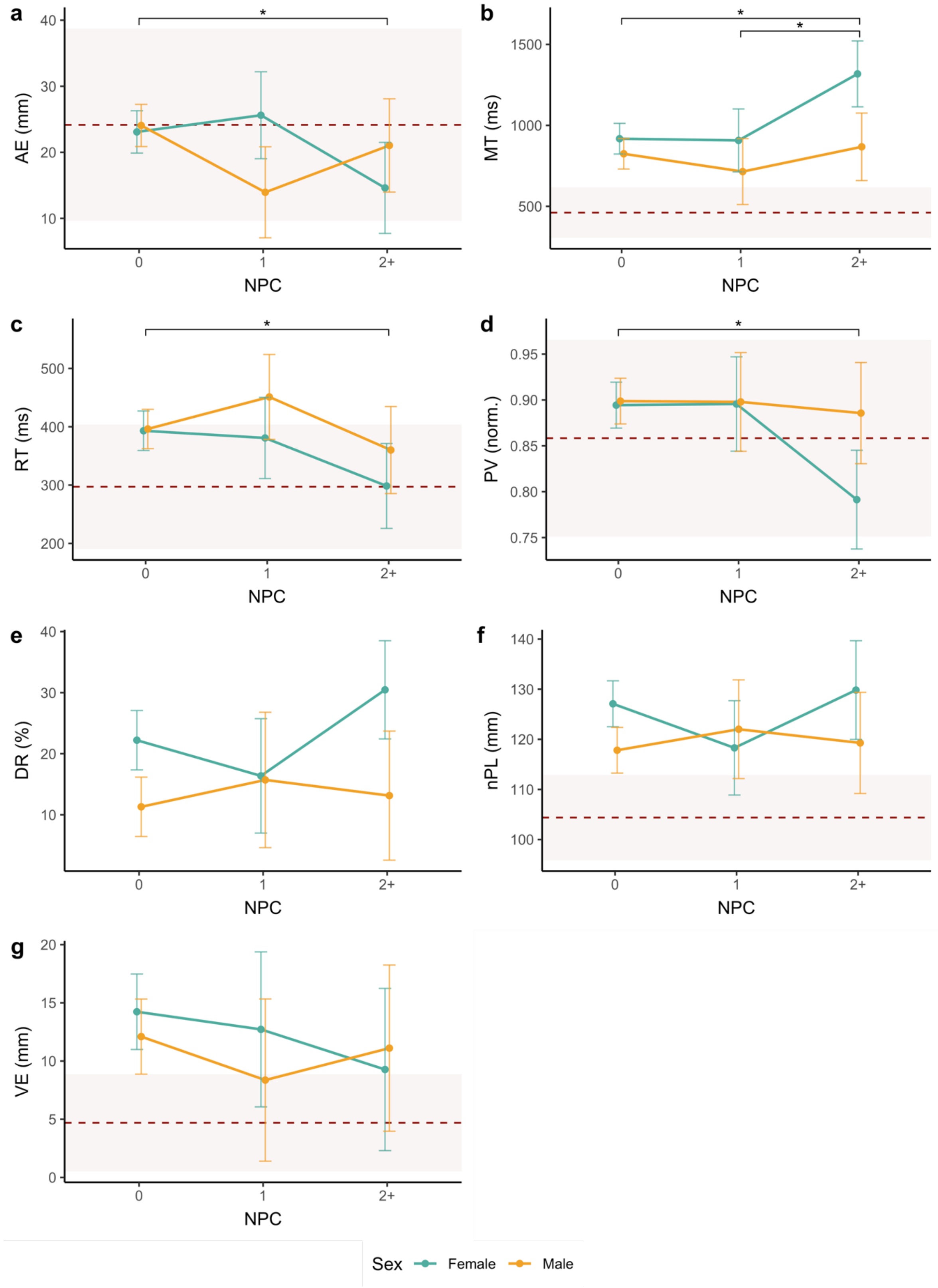


Figure 3. Estimated marginal means of SSR kinematic variables from two-way ANOVA analyses. Plots were all created using original (non-transformed) kinematic data. Red dashed lines represent direct condition mean values for each respective kinematic variable, with shaded areas representing one standard deviation above and below the mean. Error bars represent the 95% confidence intervals. **a.** RT estimated marginal means plot. **b.** MT estimated marginal means plot. **c.** PV estimated marginal means plot. **d.** VE estimated marginal means plot. **e.** AE estimated marginal means plot. **f.** nPL estimated marginal means plot. **g.** %DR estimated marginal means plot. * = p< .05.

Table 4. *Comparison of group means for all seven kinematic variables across sex and number of concussions exploring two-way interaction effects for SSR task condition.* †Reflective Cube Transformed Data. ‡Square Root Transformed Data. §Log_{10} Transformed Data. ▵Cube Root Transformed Data. Significance is indicated in boldface.

DV	Source	Sum of Squares	df	Mean Square	F	p-value	η^2
PV† (normalized)	Sex	0.02	1	0.02	0.88	0.350	0.00
	Number of Concussions	0.19	2	0.10	5.31	**0.005**	0.04
	Sex × Number of Concussions	0.09	2	0.04	2.41	0.092	0.02
	Error	5.04	278	0.02			
	Total	59.92	284				
nPL§ (mm)	Sex	0.01	1	0.01	2.36	0.126	0.01
	Number of Concussions	0.00	2	0.00	0.34	0.710	0.00
	Sex × Number of Concussions	0.02	2	0.01	1.62	0.199	0.01
	Error	1.62	277	0.01			
	Total	1227.77	283				
VE§ (mm)	Sex	0.22	1	0.22	1.20	0.274	0.00
	Number of Concussions	0.39	2	0.20	1.07	0.345	0.01
	Sex × Number of Concussions	0.54	2	0.27	1.47	0.232	0.01
	Error	51.03	278	0.18			
	Total	263.60	284				
AE‡ (mm)	Sex	0.00	1	0.00	0.00	0.992	0.00
	Number of Concussions	22.73	2	11.36	4.05	**0.018**	0.03
	Sex × Number of Concussions	25.88	2	12.94	4.62	**0.011**	0.03
	Error	779.49	278	2.80			
	Total	6331.02	284				
RT (ms)	Sex	88151.53	1	88151.53	3.09	.080	0.01
	Number of Concussions	183004.57	2	91502.28	3.21	**.042**	0.02
	Sex × Number of Concussions	57904.36	2	28952.18	1.02	.364	0.00
	Error	7871356.10	276	28519.41			
	Total	50553343.03	282				
MT§ (ms)	Sex	0.49	1	0.49	11.73	**<.001**	0.04
	Number of Concussions	0.43	2	0.21	5.14	**0.006**	0.04
	Sex × Number of Concussions	0.20	2	0.10	2.39	0.094	0.02
	Error	11.56	278	0.04			
	Total	2395.66	284				
DR▵ (%)	Sex	8.11	1	8.11	3.98	**0.048**	0.03
	Number of Concussions	1.20	2	0.60	0.29	0.746	0.00
	Sex × Number of Concussions	3.47	2	1.74	0.85	0.429	0.01
	Error	309.78	152	2.04			
	Total	903.84	158				

Table 5. *Tukey's post-hoc multiple comparisons of number of previously diagnosed concussions on peak velocity, absolute error, reaction time and movement time for SSR condition.* †Reflective cube transformed data. ‡Square root transformed data. §Log_{10} transformed data. △Values back-transformed from their original data transformations. Significance is indicated in boldface.

DV	Number of Concussions	Number of Concussions	Mean Difference△	Std. Error	p-value	95% CI Lower Bound△	95% CI Upper Bound△
PV† (normalized)	None	One	1.00	0.02	0.882	0.9999	1.000
		Two or more	1.00	0.02	**0.003**	1.000	1.002
	One	Two or more	1.00	0.03	0.066	1.000	1.002
AE‡ (mm)	None	One	0.20	0.28	0.241	0.04	1.23
		Two or more	0.55	0.29	**0.028**	0.00	2.01
	One	Two or more	0.08	0.36	0.703	0.32	1.32
RT (ms)	None	One	-20.16	28.16	.475	-75.60	35.27
		Two or more	65.64	28.99	**.024**	8.57	122.71
	One	Two or more	85.80	36.66	**.020**	13.64	157.97
MT§ (ms)	None	One	1.08	0.03	0.597	0.90	1.30
		Two or more	0.79	0.03	**0.012**	0.66	0.96
	One	Two or more	0.74	0.04	**0.008**	0.58	0.93

3.3.4 Relationship between emotionality, sex, and #PC

A chi-square test of independence was performed on all emotionality-related measures to determine a relationship between emotionality and sex, and emotionality and #PC. Results revealed no significant association between variables for any emotionality and sex analyses ($p<.05$) or emotionality and #PC analyses ($p<.05$). Despite this, 57.1% of females reported being emotional, whereas 51.3% of males reported not feeling emotional. Further crosstabulations revealed that among participants with NCHx, 83.3% reported not being emotional, 73.3% with one concussion reported not being emotional, and 82.9% of participants with 2 or more concussions reported not being emotional.

Crosstabulations of *irritability* indicated that approximately equal rates of males and females reported being irritable and not irritable. Further, among participants with no previous concussions, 81.8% reported not being irritable. Similarly, among those with one previous concussion, 75% reported not being irritable, while 73.2% of participants with 2 or more concussions reported not being irritable.

Males and females reported approximately equal rates of males and females reported being sad and not being sad. Further crosstabulations revealed that among participants with no previous concussions, 84.4% reported not being sad. Similarly, among those with one previous concussion, 84.1% reported not being sad, while 87.8% of participants with 2 or more concussions reported not being sad.

Similar to all other emotionality measures, 54.6% of females reported being nervous/anxious, whereas 52.2% of males reported not feeling nervous/anxious. Further, among participants with no previous concussions, 65.1% reported not being nervous/anxious. Similarly, among those with one previous concussion, 70.5% reported not being nervous/anxious, while 58.5% of participants with 2 or more concussions reported not being nervous/anxious.

3.3.5 Association between emotionality, #PC and age

Binary logistic regression analyses were performed on male and female participants separately to determine whether the #PC and age predicted the odds of more or less emotionality. Analyses of female participants showed that the overall model was not statistically significant in predicting the odds of females being irritable ($\chi^2(5) = 7.30$, $p = .199$). However, female participants with two or more concussions were approximately 208% more likely to be more irritable than those with NCHx [95% CI 1,08, 8.84]. All other predictors for females were non-significant (**Table 6**). A similar analysis was performed male participants. Here, the overall model was not statistically significant in predicting the odds of males being irritable ($\chi^2(5) = 4.12$, $p = .532$), with no predictors emerging as significant ($p<.05$).

Further analyses for nervousness/anxiousness in females found a non-statistically overall model ($\chi^2(5) = 7.29$, $p = .200$)**.** However, being 21 – 22 years old significantly predicted females being more nervous/anxious [95% CI .14, .99]. Specifically, 21 to 22-year-old females were 63% less likely to be more nervous/anxious compared to 17 and 18-year-olds. No other predictors were significant for females. A comparable analysis for males found a significant overall model in predicting the odds of being nervous/anxious, $\chi^2(5) = 12.77$, $p = .026$. Despite a significant overall model, no significant predictors emerged for males ($p<.05$).

A non-significant overall model was discovered for the odds of males ($\chi^2(5) = 6.67$, $p = .246$) and females ($\chi^2(5) = 3.37$, $p = .644$) being more emotional. No predictors emerged as significant for either sex in determining the odds of being emotional ($p<.05$).

Final analyses for males ($\chi^2(5) = 4.76$, $p = .446$) and females ($\chi^2(5) = 4.41$, $p = .492$) found a non-significant overall model in predicting the odds of being sad, with no significant predictors emerging for either sex ($p<.05$).

Table 6. *Association between participants' age, number of previously diagnosed concussions and four SCAT emotionality binary outcomes*. † Binary logistic regression. ‡ Data are presented as odds ratios using exponentiated beta values. Odds are representing being more emotional compared to not being more emotional, being more irritable compared to not being irritable, being sad compared to not being sad, and being nervous/anxious compared to not being nervous/anxious. △ Reference category = Zero previous concussions. §Reference Category = 17 to 18 year old. Significance is indicated in boldface.

		Females				Males			
			95% CI				95% CI		
	Variables†	OR‡	Lower Bound	Upper Bound	p-value	OR‡	Lower Bound	Upper Bound	p-value
More Emotional	**Number of Concussions**				0.296				0.757
	One△	2.28	0.80	6.52	0.124	0.95	0.24	3.74	0.943
	Two or More△	1.45	0.46	4.59	0.525	0.55	0.11	2.67	0.456
	Age				0.832				0.184
	19 to 20 yrs old§	1.41	0.53	3.80	0.493	1.66	0.58	4.80	0.347
	21 to 22 yrs old§	0.86	0.26	2.91	0.813	0.30	0.06	1.55	0.151
	23 yrs and older§	0.96	0.17	5.33	0.965	0.66	0.07	6.18	0.717
Irritability	**Number of Concussions**				0.087				0.756
	One△	2.01	0.67	6.02	0.214	1.26	0.41	3.95	0.687
	Two or More△	3.08	1.08	8.84	**0.036**	0.68	0.18	2.61	0.576
	Age				0.629				0.369
	19 to 20 yrs old§	1.29	0.49	3.41	0.601	1.21	0.46	3.18	0.705
	21 to 22 yrs old§	0.75	0.22	2.50	0.638	0.40	0.11	1.41	0.153
	23 yrs and older§	0.39	0.04	3.46	0.395	0.96	0.17	5.38	0.959
Sadness	**Number of Concussions**				0.917				0.848
	One△	1.24	0.36	4.26	0.738	0.94	0.24	3.70	0.931
	Two or More△	0.88	0.23	3.46	0.858	0.63	0.13	3.06	0.566
	Age				0.309				0.354
	19 to 20 yrs old§	0.69	0.25	1.93	0.483	0.94	0.32	2.79	0.914
	21 to 22 yrs old§	0.25	0.05	1.20	0.082	0.26	0.05	1.29	0.098
	23 yrs and older§	0.34	0.04	2.97	0.330	1.29	0.22	7.45	0.776
Nervous/Anxious	**Number of Concussions**				0.592				0.204
	One△	1.58	0.60	4.16	0.350	0.34	0.09	1.26	0.107
	Two or More△	1.35	0.50	3.63	0.550	1.32	0.47	3.69	0.597
	Age				0.118				0.067
	19 to 20 yrs old§	0.66	0.29	1.48	0.310	1.48	0.63	3.50	0.373
	21 to 22 yrs old§	0.37	0.14	1.00	**0.049**	0.37	0.12	1.08	0.069
	23 yrs and older§	0.23	0.04	1.17	0.076	0.58	0.10	3.19	0.527

3.3.6 Association between kinematic performance, sex, #PC and age

Multivariable linear regression analyses were performed to examine the relationship between sex, #PC, age, and kinematic outcome measures. The overall RT model was statistically significant, F(6, 274) = 2.63, p = .017 indicating the model explains a significant portion of the variance in RT (**Table 7**). The adjusted R^2 value of 0.034, further suggests that this model can account for approximately 3% of RT variability. The two or more concussion group (p = .019), and age groups 21 – 22 (p = .044) and 23 years and older (p = .018) emerged as significant predictors of RT. Specifically, having sustained two or more concussions was associated with a 68.17 ms decrease in RT compared to participants with no concussion history, indicating increased performance (**Figure 4a)**. Conversely, being 21– 22 was associated with a 53.31 ms increase and being 23 or older was associated with a 98.74 ms increase in RT compared to 17 – 18-year-olds, indicating decreased performance across all groups. **Figure 4a** shows the relationship between RT for all age groups. Conversely, sex, having sustained one concussion and ages 19-20 years were not significantly predictive of RT (p<.05).

MT analyses indicate the model explains a significant portion of the variance in MT, due to its overall significance (F(6, 276) = 3.30, p = .004). The adjusted R^2 value of 0.047, further suggests that this model can account for approximately 4.7% of MT variability. Sex (p = .008) and having sustained two or more concussions (p = .004) emerged as significant predictors of MT. Specifically, being female was associated with a 152.26 ms increase in MT compared to males (**Figure 4b**). Similarly, having two or more concussions was associated with a 239.90 ms increase in MT compared to no concussion history, indicating decreased performance. Having sustained one concussion and all age groups were not significantly predictive of MT (p<.05).

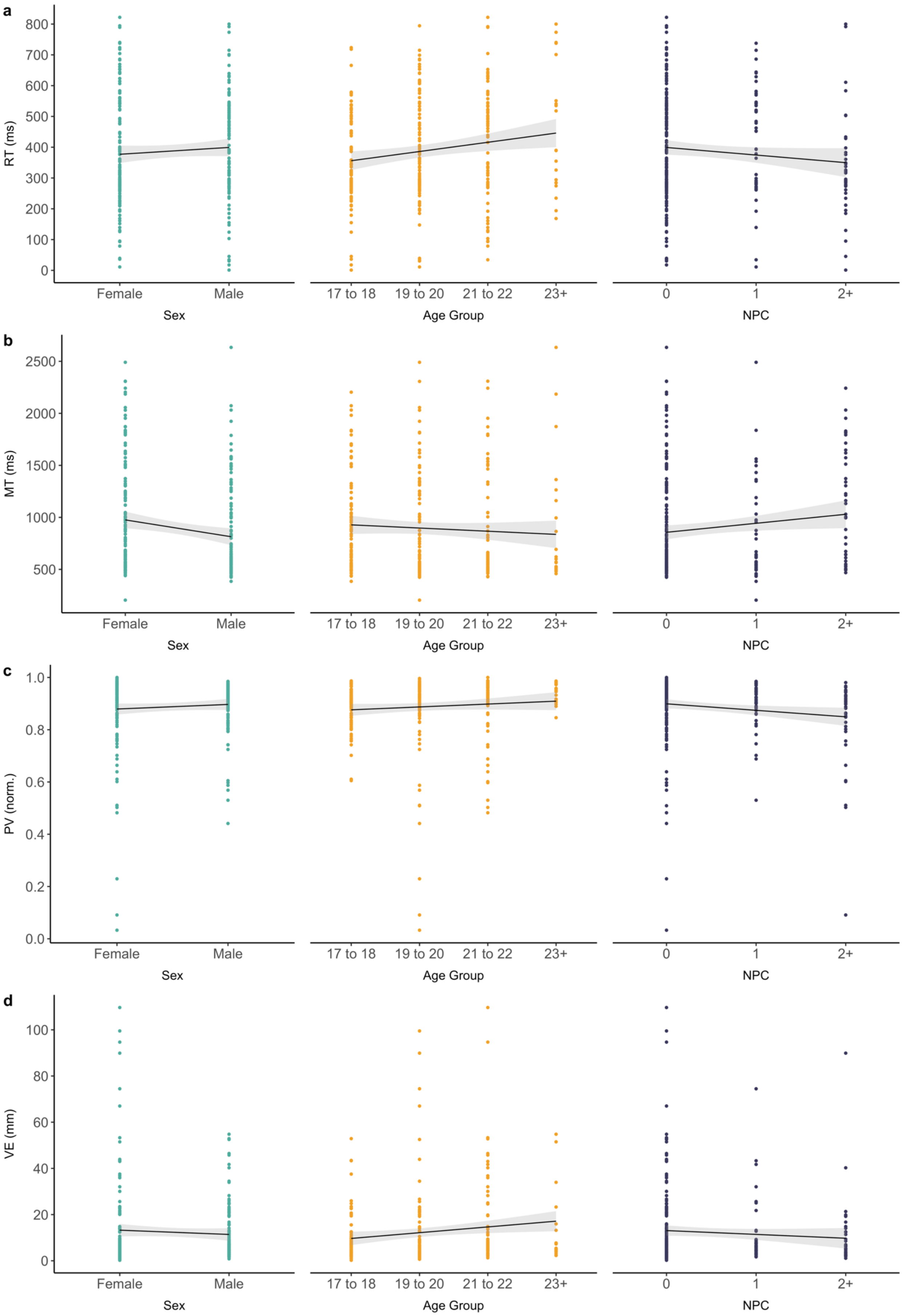
Results for PV suggested that the overall model was statistically significant, $F(6, 276) = 2.43$, $p = .027$, indicating the model explains a significant portion of the variance in PV. The adjusted R^2 value of .029, further suggests that this model can account for approximately 2.9% of PV variability. History of two more concussions was associated with a .06 decrease in PV compared to no concussion history ($p = .009$), indicating increased performance (**Figure 4c**). All other groups were not significant predictors of PV ($p>.05$).

The overall model for VE was not statistically significant, $F(6, 276) = 1.80$, $p = .100$, indicating the model does not explain a significant portion of the variance in VE. Despite this, the age group 21 – 22 years emerged as a significant predictor of VE ($p = .005$). Specifically, being 21 or 22 years old was associated with a 7.07 mm increase in end-point precision compared to 17 – 18 year olds, indicating decreased performance (**Figure 4d**). All other groups were not significant predictors of VE ($p>.05$).

Results for AE suggested that the overall model was not statistically significant, $F(6, 276) = .957$, $p = .455$, indicating the model does not explain a significant portion of the variance in VE. However, having sustained two or more concussions emerged as a significant predictor of AE ($p = .036$). Specifically, two or more concussions were associated with a 5.91 mm decrease in end-point accuracy compared to no concussion history, indicating increased performance. **Figure 4e** shows the relationship between concussion groups of significance. All other groups did not emerge as significant predictors of AE ($p<.05$).

The overall model for nPL was statistically significant, $f(6, 275) = 2.47$, $p = 0.024$, indicating that the model explains a substantial proportion of the variance in nPL. The adjusted R^2 value of .031, further suggests that this model can account for 3.1% of nPL variability. Sex ($p = 0.003$) and the age group 21 – 22 years ($p = 0.019$) emerged as significant predictors of nPL performance. Specifically, being female was associated with an nPL value 8.29 mm greater than males, indicating poorer performance. Further, being 21 – 22 years was associated with an 8.51 mm increase in nPL. No other significant predictors emerged ($p<.05$).

Finally, the %DR overall model was statistically significant, $F(6, 150) = 3.23$, $p = .005$. The adjusted R^2 value of .079, further suggests that this model can account for approximately 7.9% of DR variability. Sex emerged as a significant predictor of %DR ($p = <.001$)). Specifically, being female was associated with a 10.51% increase in DR compared to males, indicating decreased performance. **Figure 4g** highlights this visual relationship of significance. The performance of males compared to females is notably different from the age-based and #PC-based relationships for this variable. All other groups did not emerge as significant predictors of DR ($p>.05$).


a
b
c
d
RT (ms)
MT (ms)
PV (norm.)
VE (mm)
Female
Male
Sex
17 to 18
19 to 20
21 to 22
23+
Age Group
0
1
2+
NPC

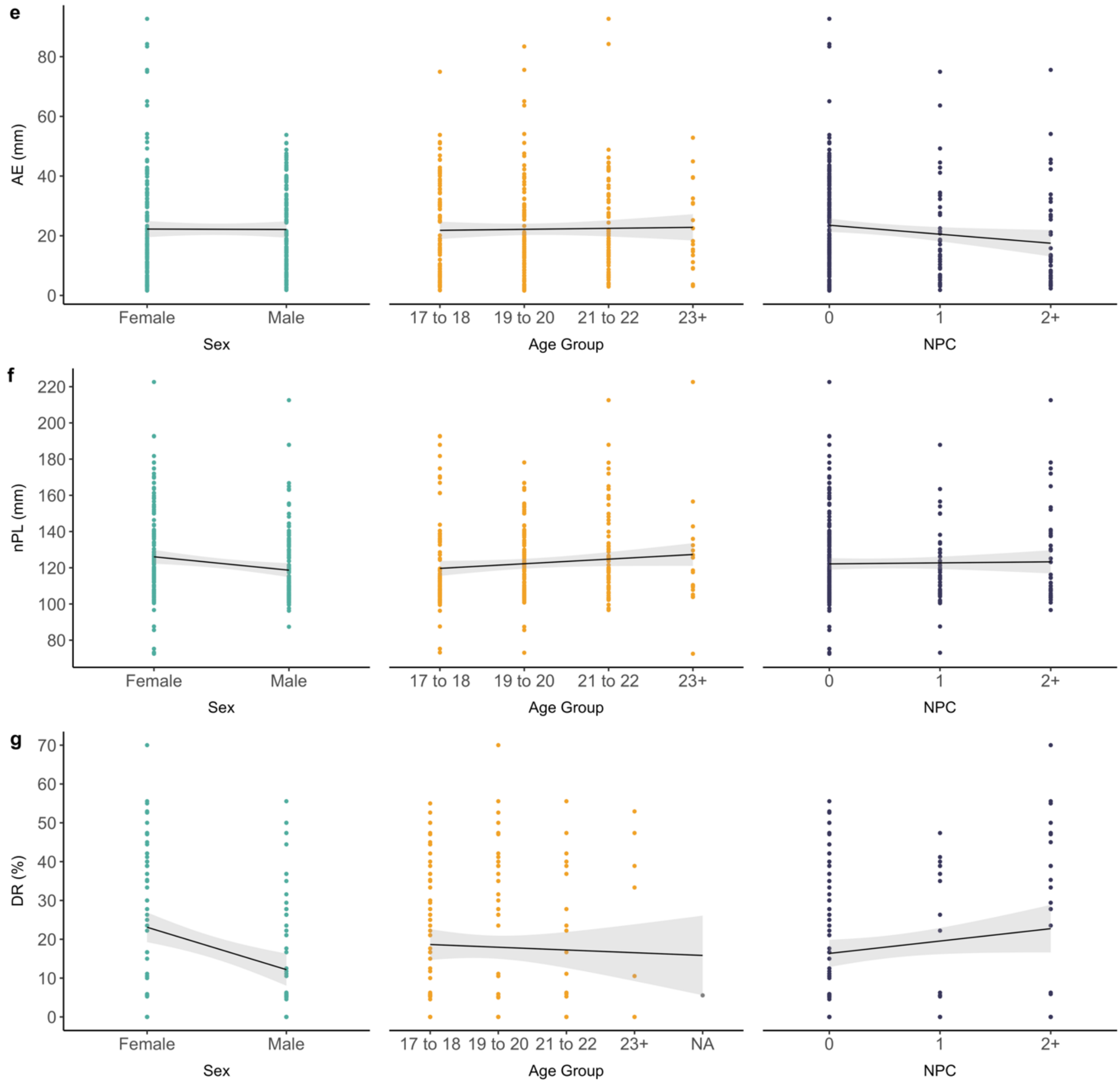


Figure 4. The effect of sex, age group, and number of previous concussions on kinematic performance. Linear regression analysis scatterplot for each kinematic variable visualized by sex, age group, and number of concussions. The regression line in black spans across or between groups with a shaded 95% CI. **a.** RT scatterplot. **b.** MT scatterplot. **c.** PV scatterplot. **d.** VE scatterplot. **e.** AE scatterplot. **f.** **n**PL scatterplot. **g.** %DR scatterplot.

Table 7. *Multivariable linear regression analyses predicting kinematic performance in SSR condition*. † Enter multiple regression analysis. ‡ Multivariate unstandardized linear regression coefficients. For each unit of the participants' characteristics there is an average β increase (+) or decrease (-) in respective kinematic variables. Negative RT, MT and PV β values indicate faster performance, while positive values indicate slower performance. [†]Reference Category = Males. [§]Reference Category = 17 to 18 yrs old. [‡]Reference category = Zero previous concussions. Significance is indicated in boldface.

DVs	IVs[†]	β[‡]	95% CI		p-value
			Lower Bound	Upper Bound	
PV	**Sex[†]**				
	Female	-0.02	-0.05	0.01	0.245
	Age[§]				
	19 to 20 yrs old	-0.01	-0.05	0.02	0.526
	21 to 22 yrs old	0.01	-0.03	0.04	0.774
	23 yrs and older	0.06	0.00	0.12	0.061
	Number of Previous Concussions[‡]				
	One	0.00	-0.04	0.04	0.949
	Two or more	-0.06	-0.10	-0.01	**0.009**
nPL (mm)	**Sex[†]**				
	Female	8.29	2.89	13.70	**0.003**
	Age[§]				
	19 to 20 yrs old	3.59	-3.01	10.19	0.285
	21 to 22 yrs old	8.51	1.38	15.63	**0.019**
	23 yrs and older	5.02	-5.92	15.95	0.367
	Number of Previous Concussions[‡]				
	One	-3.37	-10.92	4.18	0.381
	Two or more	1.55	-6.24	9.34	0.696
VE (mm)	**Sex[†]**				
	Female	1.97	-1.79	5.73	0.302
	Age[§]				
	19 to 20 yrs old	4.09	-0.50	8.67	0.081
	21 to 22 yrs old	7.07	2.12	12.01	**0.005**
	23 yrs and older	3.75	-3.86	11.36	0.333
	Number of Previous Concussions[‡]				
	One	-2.98	-8.24	2.27	0.265
	Two or more	-3.41	-8.83	2.02	0.218
AE (mm)	**Sex[†]**				
	Female	0.06	-3.75	3.88	0.974
	Age[§]				
	19 to 20 yrs old	0.16	-4.50	4.82	0.947
	21 to 22 yrs old	1.26	-3.77	6.29	0.622
	23 yrs and older	-0.63	-8.36	7.10	0.872

	Number of Previous Concussions‡				
	One	-3.64	-8.98	1.70	0.181
	Two or more	-5.91	-11.43	-0.40	**0.036**
RT (ms)	**Sex†**				
	Female	-20.98	-60.45	18.50	0.296
	Age§				
	19 to 20 yrs old	42.59	-5.60	90.78	0.083
	21 to 22 yrs old	53.31	1.46	105.16	**0.044**
	23 yrs and older	98.74	17.41	180.08	**0.018**
	Number of Previous Concussions‡				
	One	16.08	-39.07	71.22	0.566
	Two or more	-68.19	-125.11	-11.27	**0.019**
MT (ms)	**Sex†**				
	Female	152.26	40.74	263.78	**0.008**
	Age§				
	19 to 20 yrs old	-94.85	-231.03	41.33	0.171
	21 to 22 yrs old	-102.18	-249.11	44.74	0.172
	23 yrs and older	-22.21	-248.12	203.71	0.847
	Number of Previous Concussions‡				
	One	-50.01	-206.11	106.09	0.529
	Two or more	239.90	78.76	401.04	**0.004**
DR (%)	**Sex†**				
	Female	10.51	4.75	16.27	**<.001**
	Age§				
	19 to 20 yrs old	2.27	-4.30	8.84	0.495
	21 to 22 yrs old	-2.54	-10.62	5.53	0.535
	23 yrs and older	1.59	-10.95	14.13	0.802
	Number of Previous Concussions‡				
	One	-1.63	-9.68	6.41	0.689
	Two or more	5.71	-1.73	13.15	0.131

3.3.7 Relationship between kinematic performance and time lived since concussion

Spearman's rank-order correlation analyses were conducted to determine the relationships between the seven kinematic variables and the time lived since concussion separately for males and females. As seen in **Table 8**, none of the correlation analyses were statistically significant ($p<.05$). Although the correlation analyses were all insignificant, **Figure 5a** shows the interesting relationship between RT and time lived without concussion where both sexes show the same trend in RT performance. Specifically for individuals with 1 previous concussion, RT performance improves for individuals who sustained their injury closer to the assessment date. Conversely, for individuals with 2 or more concussions, performance decreases for individuals who sustained their concussion closer to the assessment date. nPL shows a different relationship between sexes as seen in **Figure 5b**. Performance for females with 1 concussion increases as the months lived without concussion decreases but decreases with 2 or more concussions. On the other hand, males show an inverse relationship with performance improving for those with 2 or more concussions but decreasing for 1 concussion as the months lived without concussion decrease.

Table 8. *Spearman's correlation results for SSR data and time lived without concussion.* The table shows Spearman correlation coefficients (r_s) along with p-values and sample sizes (N) for the relationships between kinematic variables and participants who had less than 150 months lived without a concussion.

	Female			Male		
Variables	r_s	p-value	N	r_s	p-value	N
PV & Time Lived Without Concussion (< 150 months)	0.23	0.182	36	0.02	0.921	31
nPL & Time Lived Without Concussion (< 150 months)	0.04	0.822	36	0.00	0.984	31
VE & Time Lived Without Concussion (< 150 months)	-0.02	0.891	36	-0.05	0.778	31
AE & Time Lived Without Concussion (< 150 months)	0.01	0.978	36	-0.12	0.520	31
RT & Time Lived Without Concussion (< 150 months)	0.22	0.199	36	0.00	0.996	31
MT & Time Lived Without Concussion (< 150 months)	-0.16	0.367	36	0.02	0.921	31
%DR & Time Lived Without Concussion (< 150 months)	0.01	0.946	26	-0.31	0.381	10

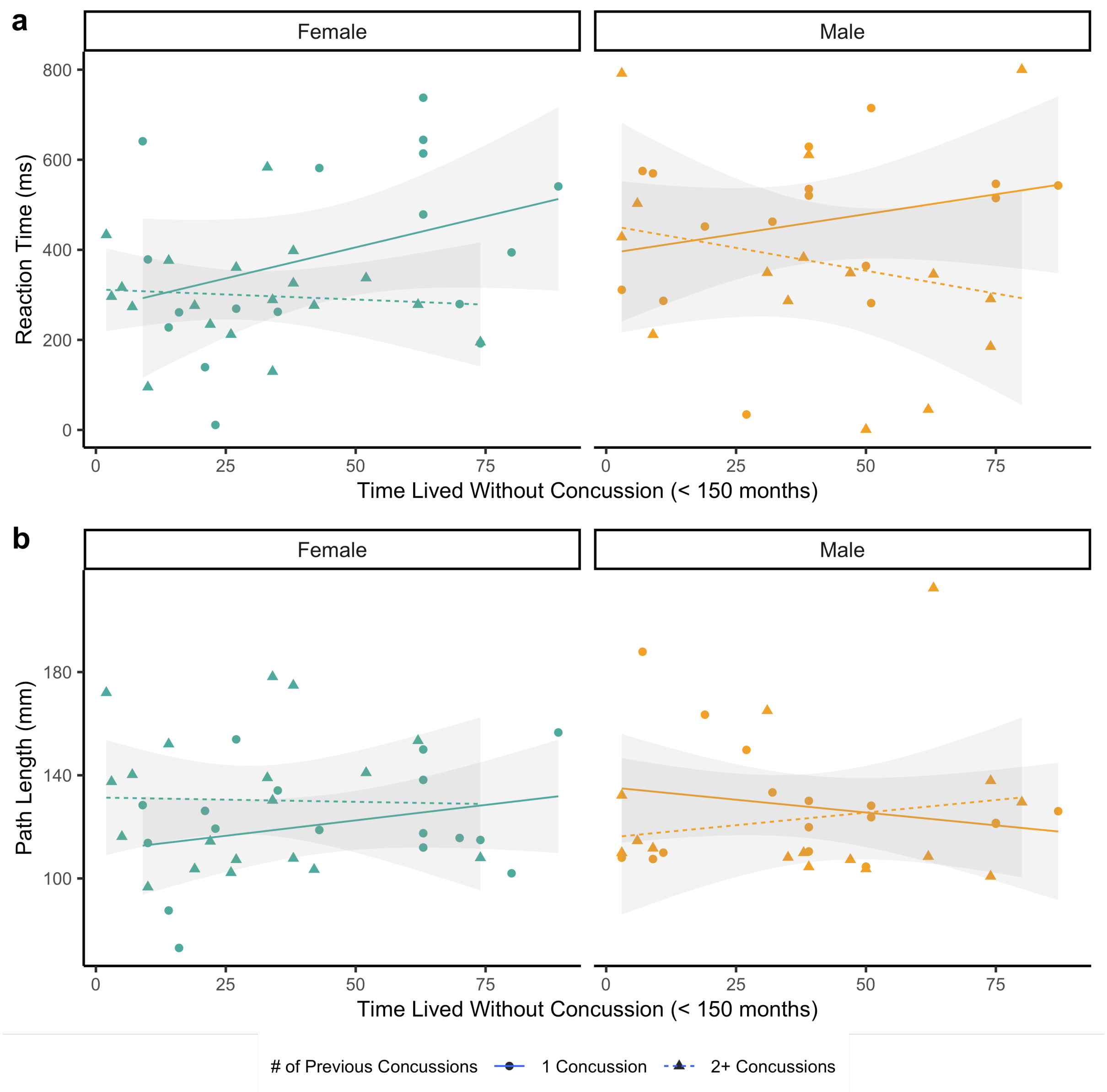


Figure 5. Impact of time lived since concussion on SSR variables by sex and number of concussions. All plots reflect SSR kinematic data based on sex and number of previous concussive injuries. Solid regression lines represent the trend in kinematic performance over time for participants with one previous concussion diagnosis. Dotted regression lines represent the trend in kinematic performance over time for participants with two or more previous concussion diagnoses. “0” months lived without a concussion represents the assessment date. **a.** RT correlation plot. **b.** nPL correlation plot.

Chapter 4: Discussion and Conclusion

The main goal of this study was to investigate the sex-related differences in kinematic performance and emotionality after concussive injury. The central findings of this study are 7-fold: 1) the effect of the number of previous concussions on participants' accuracy differed significantly by sex, 2) a history of 2 or more concussions was a significant predictor of improved PV, AE and RT performance and worse MT performance, 3) being female was a significant predictor of worse nPL, MT and DR performance, 4) being 21 years or older was a significant predictor of worse RT performance, 5) females with a CHx of 2 or more were 208% more likely to be irritable than those with NCHx , 6) 21-22-year-old females were 63% less likely to be nervous or anxious compared to 17-18-year-old females, and 7) females reported more emotionality symptoms than males irrespective of CHx. The findings of this study largely support the initial hypothesis, with significant evidence aligning with our expectations regarding emotionality and kinematic performance.

The relationship between multiple concussions and increased kinematic performance has been previously reported (Dalecki et al., 2019). Specifically, our findings noted two or more concussions as significant predictors of increased RT, PV and accuracy performance. This increase in performance after multiple concussive injuries may be attributed to a rise in brain resilience resulting from multiple years of sports experience. Dalecki et al. (2019) determined that youth with more years of eye-limb coordination sport experience were able to match the CMI performance of their peers more quickly than those with less sport experience. As CMI is particularly relevant for athletes, a more favourable recovery ensures a safe return to sport. Based on our analyses, our 2 or more concussion group may have higher brain resilience and motor skill reserve, causing significant group differences. Further, previously reported MT performance deficits in CHx individuals (Dalecki et al., 2019), are consistent with our findings of decreased MT performance for individuals with two or more concussions. Although much of our kinematic findings demonstrate improved performance after multiple concussions, our analyses do not allow further examination of potential modulators. For instance, a lack of information exists for individual differences in resilience. This information would allow a more comprehensive understanding of the factors influencing recovery and kinematic performance.

Animal model research has also discovered similar findings regarding physical exercise and brain reserve impact on post-TBI outcomes (Kopczynski et al., 2023). In this study, researchers divided rodents into three groups: a high-volume physical exercise, low-volume physical exercise, and sedentary. The high-volume group had free daily access to a running wheel, while the low-volume group only had access to the wheel intermittently, in 48-hour on-off intervals. The sedentary group never had access to the running as it was always locked. After TBI the mortality rate in the high and low exercise groups was around 20%, compared to 40% in the sedentary group. Further, engagement in physical activity prior to TBI sustained levels of pCREB and pro-BDNF. The findings suggest, that the pCREB-BDNF pathway formulates the neurological basis for neural reserves. This work aligns with our findings suggesting that physical activity may formulate the basis of cognitive reserve.

Enhanced recovery of CMI following concussive injury may further be linked to higher motor-skill reserve, developed through sport participation, facilitating behavioural recompensation. The presence of both increased motor skill reserve and brain resilience, mitigate the level of functional impairment experienced post-concussion. **Figure 6a** outlines the brain reserve capacity model for individuals with one concussion, adapted and modified from Satz (1993). Individuals with one previously sustained concussion fall into one category for domain-specific kinematic performance. For instance, a vulnerability factor sees that an individual has lower motor skill reserve and lower brain resilience, thus causing functional impairment. A protective factor posits that individuals with increased motor skill reserve and brain resilience will not experience functional impairment. This theory aligns with better female RT performance and male MT, precision, and accuracy performance, for individuals with one concussion compared to their counterparts. Based on this model, the aforesaid groups displayed a protective factor respective to their kinematic performance domains. A challenge factor, however, postulates that although individuals with increased motor skill reserve and brain resilience may perform well on certain tasks, they may still face challenges with other tasks or domains, resulting in impairments. This theory aligns with our data from male RT and female MT, precision and accuracy performance, for individuals with one concussion. Said groups presumably faced a domain-specific kinematic performance challenge causing impaired functional performance.

Similarly, **Figure 6b** outlines the BRC model for two or more concussions. Here the protective factor theory aligns with female RT, PV, precision and accuracy performance and male MT and nPL performance. Here, despite the history of multiple concussions, increased motor skill reserve and brain resilience serve as a buffer to mitigate the impact of cumulative concussive injury on kinematic performance. The challenge factor theory aligns with male RT, PV, precision, and accuracy performance and female MT and nPL performance. Brain resilience observed in females could be further attributed to bilateral activation in females during visuomotor control tasks (Smeha et al., 2022; Sneider et al., 2011), which further serves as a protective factor for functional impairment.

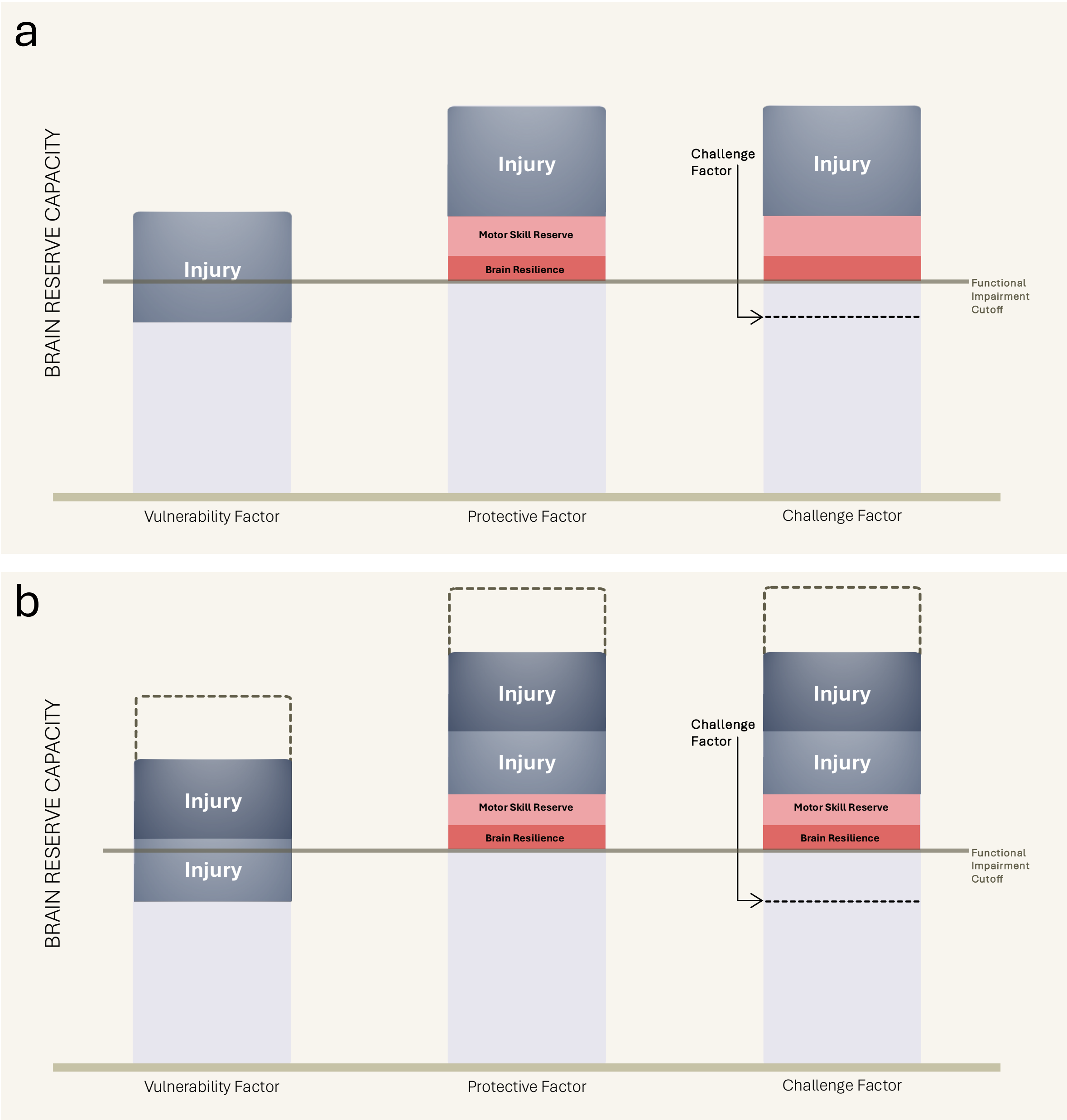


Figure 6. BRC functional impairment models for individuals with one or multiple SRCs. Vulnerability factor suggests that lower BRC allows for functional impairment after concussive injury. Protective factor suggests that increased BRC resulting from increased motor skill reserve and brain resilience does not allow for functional impairment after concussive injury. Challenge factory theory indicates that despite a higher BRC, the appropriate task or domain may challenge an individual with CHx, resulting in functional impairment. **a)** BRC model for one concussive injury. **b)** BRC model for two or more concussive injuries. Dotted boxes represent n number of additional injuries.

Contrary to our hypothesis, RT performance worsened with age. We expected to see an increase in RT performance with age, however the opposite was observed. In general, athletes have better kinematic performance than their non-athlete counterparts (Caramelli et al., 2020; Seidel & Ragert, 2019), however, within their group noteworthy differences are observed over a small number of years. It is plausible that poorer RT performance with age is attributed to cumulative sub-concussive impacts that become evident over time (Bailes et al., 2013; Caccese et al., 2019).

Study results revealed an interesting relationship between male and female DR performance. Here group mean differences for females were considerably worse than males. Historically, males have been found to have higher levels of impulsivity (Weafer & de Wit, 2014; Weinstein & Dannon, 2015), however, in a study of elite judo athletes females reported higher levels of impulsivity compared to males (Ferreira et al., 2017). Within our sample of athletes, although impulsivity was not explicitly measured, faster female RT and PV performance may be indirect indicators of impulsivity. This increase in RT and PV may cause females to start the task quickly, but make more corrective movements to compensate for incorrect initial movements. Simply put, sex differences in DR may be a function of impulsivity and not performance. Whereas slower male RT and PV may indicate a slower time to begin movements, but movements are completed correctly. This may further explain why males had marginally better precision performance overall compared to females; males are slower to begin movements because they are processing the correct movement.

In contrast to our initial hypothesis, time lived since concussion was not significantly correlated with kinematic performance in males or females. These findings contradict Dalecki (2019), where there was a significant relationship between the time since an individual's last concussion and CMI performance. Our findings may be potentially attributed to a lack of statistical power necessary to detect a significant correlation between said variables.

Alternatively, there lies the possibility that the #PC is a more robust modulator of kinematic performance than time in elite athletes. The results appear to suggest that the time lived since an individual's concussion does not correlate with their kinematic performance, but the presumed level of sport participation exposure plus CHx may effectively modulate kinematic performance.

Across all emotionality measures, results indicated that females reported experiencing more emotions than males. A point of interest is the potential influence of gender norms associated with symptom reporting (Alsalaheen et al., 2021; Brooks et al., 2018; Bunt et al., 2021). A study of 986 adolescent athletes noted that females had greater symptom severity and higher reporting frequency of concussive symptoms (Alsalaheen et al., 2021). Similar results were observed in a cohort of Japanese collegiate athletes, where females had a higher reporting frequency than males across all concussive symptoms (Tanaka et al., 2023). In a study looking at the gender norms in concussion reporting among college athletes, females had greater concussion knowledge and concussion reporting intention than males (Kroshus et al., 2017). Together this literature emphasizes the influence of gender norms on concussion reporting among athletes. This is particularly relevant to the results of our study due to its potential explanation of the lack of statistical significance for the male logistic regression analyses. In essence, the lack of significant findings in the male logistic regression analyses may be attributed to a lack of symptom reporting among males rather than a lack of fit within the regression model. Further, males were more likely not to report a concussion because they thought their coach would get mad (Wallace et al., 2017).

Interesting results emerged regarding females' irritability post-concussion. Again, the odds ratio was significantly higher for females with a history of 2 or more concussions, suggesting that the #PC increased the risk of becoming more irritable. Plausible explanations for these findings are two-fold: exposure to traumatic events poses a greater risk for irritability in females and pituitary dysfunction following concussion in female athletes leads to mood disruptions, including irritability. In a study with 7422 adolescents examining the effects of traumatic experience exposure on irritability, the odds ratio for females was significantly higher than males (Henriksen et al., 2021), findings consistent with our data. Specifically, females who experienced a serious accident had 45% greater odds of being irritable. Results suggest that experiencing trauma serves as a potential modulator of irritability in females. In another study with 133 female athletes, researchers explored the relationship between hormones and the presence of pituitary dysfunction post-mTBI (Eggertsdóttir Claessen et al., 2024). They found that 12.2% of female athletes with a history of mTBI had pituitary dysfunction (either hypopituitarism or hyperprolactinemia). Hypothalamic-pituitary-adrenal (HPA) axis dysfunction has been linked to mood and anxiety disorders (Mathew et al., 2001), which provides a basis for dysfunction if disturbed. These findings in conjunction with our results suggest that females' exposure to a traumatic event and pituitary dysfunction may cause increased irritability.

Additional unexpected results regarding nervousness and anxiousness between female age groups could be elucidated by situational factors. Again, our results found 21-22-year-old females had lower odds of being more nervous/anxious compared to 17 -18-year-old females. Situational factors may be modulating the relationship between nervousness/anxiousness in 17–18-year-olds due to immediate life stressors, rather than changes in age. For instance, compared to 21-22-year-olds, this age group is generally in the early years of their university education and varsity athlete participation. In contrast, 21-22-year-olds are generally in their final years of university education and varsity athlete participation, possibly resulting in reduced nervousness and anxiousness. These abrupt and significant life changes could exert an influence on overall levels of nervousness and anxiousness for 17–18-year-old female athletes.

4.1 Limitations

Despite several significant findings, this study is not without limitations. Firstly, although this study had a relatively high sample size, a larger sample size would have been helpful in increasing statistical significance for correlation analyses. Further, the distribution of concussion history participants across age groups was not uniform. This may introduce bias into the statistical model by giving disproportionate weight to larger groups due to their greater contribution to the model's overall fit. Including mental health history and the number of years of elite-level training among participants as variables could have further enhanced regression modelling by allowing for an evidence-based recovery metric and intervening variable to be incorporated. Another limitation of the present study is that emotionality measures relied solely on self-report measures. The use of self-report measures within research is common, yet there remains the risk of memory-related errors in reporting. Similarly, the potential for underreporting bias among male athletes exists, due to gender differences in reasoning and rates of reporting. Addressing this limitation may allow for a better statistical model fit for future studies, providing an accurate representation of objective emotionality between sexes.

4.2 Conclusions

This study investigates the sex differences in kinematic performance and emotionality after concussive injury. Our findings suggest that visuomotor tasks and self-report measures can detect sex-based behavioural and emotional changes after a concussion. We showed that across kinematic measures, sex, #PC and age were significant predictors of kinematic measure changes. Further, we showed that multiple concussions modulated irritability in female athletes. Our findings suggest that skill through sport experience enhances brain resilience thus mitigating the impact of multiple concussions on kinematic performance. Beyond this, the combination of enhanced motor skill reserve from high sport experience and enhanced brain resilience capacity may further serve as a protective factor for functional impairments among athletes. Future research could focus on determining the influence of concussion severity on visuomotor kinematic performance among athletes with multiple concussions or the impact of injury with age.

References

Allen, J. W., Trofimova, A., Ahluwalia, V., Smith, J. L., Abidi, S. A., Peters, M. A. K., Rajananda, S., Hurtado, J. E., & Gore, R. K. (2021). Altered Processing of Complex Visual Stimuli in Patients with Postconcussive Visual Motion Sensitivity. *AJNR. American Journal of Neuroradiology*, *42*(5), 930–937. https://doi.org/10.3174/AJNR.A7007

Alsalaheen, B., Almeida, A., Eckner, J., Freeman, J., Ichesco, I., Popovich, M., Streicher, N., & Lorincz, M. (2021). *Do male and female adolescents report symptoms differently after concussion?* https://doi.org/10.1080/02699052.2021.1896034

Bailes, J. E., Petraglia, A. L., Omalu, B. I., Nauman, E., & Talavage, T. (2013). Role of subconcussion in repetitive mild traumatic brain injury: A review. *Journal of Neurosurgery*, *119*(5), 1235–1245. https://doi.org/10.3171/2013.7.JNS121822

Bayne, T., Brainard, D., Byrne, R. W., Chittka, L., Clayton, N., Heyes, C., Mather, J., Ölveczky, B., Shadlen, M., Suddendorf, T., & Webb, B. (2019). What is cognition? *Current Biology*, *29*, R608–R615. https://doi.org/10.1016/j.cub.2019.05.044

Berz, K., Divine, J., Foss, K. B., Heyl, R., Ford, K. R., & Myer, G. D. (2013). Sex-specific differences in the severity of symptoms and recovery rate following sports-related concussion in young athletes. *Physician and Sportsmedicine*, *41*(2), 58–63. https://doi.org/10.3810/PSM.2013.05.2015

Black, A. M., Sergio, L. E., & MacPherson, A. K. (2017). The Epidemiology of Concussions: Number and nature of concussions and time to recovery among female and male canadian varsity athletes 2008 to 2011. *Clinical Journal of Sport Medicine*, *27*(1), 52–56. https://doi.org/10.1097/JSM.0000000000000308

Bretzin, A. C., Esopenko, C., D'Alonzo, B. A., & Wiebe, D. J. (2022). Clinical Recovery Timelines After Sport-Related Concussion in Men's and Women's Collegiate Sports. *Journal of Athletic Training*, *57*(7), 678–687. https://doi.org/10.4085/601-20

Brooks, B. L., Mannix, R., Maxwell, B., Zafonte, R., Berkner, P. D., & Iverson, G. L. (2016). Multiple Past Concussions in High School Football Players. *American Journal of Sports Medicine*, *44*(12), 3243–3251. https://doi.org/10.1177/0363546516655095/FORMAT/EPUB

Brooks, B. L., Silverberg, N., Maxwell, B., Mannix, R., Zafonte, R., Berkner, P. D., & Iverson, G. L. (2018). Investigating Effects of Sex Differences and Prior Concussions on Symptom Reporting and Cognition Among Adolescent Soccer Players. *American Journal of Sports Medicine*, *46*(4), 961–968. https://doi.org/10.1177/0363546517749588

Brown, D. A., Elsass, J. A., Miller, A. J., Reed, L. E., & Reneker, J. C. (2015). Differences in Symptom Reporting Between Males and Females at Baseline and After a Sports-Related Concussion: A Systematic Review and Meta-Analysis. *Sports Medicine*, *45*(7), 1027–1040. https://doi.org/10.1007/S40279-015-0335-6

Buckley, T. A., Munkasy, B. A., Krazeise, D. A., Oldham, J. R., Evans, K. M., & Clouse, B. (2020). Differential Effects of Acute and Multiple Concussions on Gait Initiation Performance. *Archives of Physical Medicine and Rehabilitation*, *101*(8), 1347–1354. https://doi.org/10.1016/j.apmr.2020.03.018

Bunt, S. C., Didehbani, N., Tarkenton, T., Rossetti, H., Hicks, C., Vargas, B., Silver, C., Nakonezny, P., Bell, K., Batjer, H., & Cullum, C. M. (2021). Sex Differences and Reporting of SCAT-5 Concussion Symptoms in Adolescent Athletes. *Clinical Journal of Sport Medicine*, *31*(5), E229–E234. https://doi.org/10.1097/JSM.0000000000000788

Caccese, J. B., Best, C., Lamond, L. C., Difabio, M., Kaminski, T. W., Watson, D. A. N., Getchell, N., & Buckley, T. A. (2019). Effects of Repetitive Head Impacts on a

Concussion Assessment Battery. *Medicine and Science in Sports and Exercise*, *51*(7), 1355–1361. https://doi.org/10.1249/MSS.0000000000001905

Caramelli, P., Lima, M. D. M., Palma, G. B., Furtado, C., Lasmar, R. P., & Rodrigues, A. C. O. (2020). Soccer heading and cognitive performance in professional soccer players: One-year longitudinal data. *Alzheimer's & Dementia*, *16*(S6). https://doi.org/10.1002/ALZ.046201

Champagne, A. S., Yao, X., McFaull, S. R., Saxena, S., Gordon, K. R., Babul, S., & Thompson, W. (2023). Self-reported concussions in Canada: A cross-sectional study. *Health Reports*, *34*(6), 17–28. https://doi.org/10.25318/82-003-x202300600002-eng

Chong, C. D., Todd, ;, & Schwedt, J. (2018). Research Imaging of Brain Structure and Function After Concussion. *Headache: The Journal of Head and Face Pain*, 827–835. https://doi.org/10.1111/head.13269

Churchill, N. W., Hutchison, M. G., Graham, S. J., & Schweizer, T. A. (2021). Long-term changes in the small-world organization of brain networks after concussion. *Scientific Reports*, *11*(1). https://doi.org/10.1038/S41598-021-85811-4

Churchill, N. W., Hutchison, M. G., Richards, D., Leung, G., Graham, S. J., & Schweizer, T. A. (2017). Neuroimaging of sport concussion: Persistent alterations in brain structure and function at medical clearance. *Scientific Reports*, *7*(1). https://doi.org/10.1038/S41598-017-07742-3

Collins, M. W., Grindel, S. H., Lovell, M. R., Dede, D. E., Moser, D. J., Phalin, B. R., Nogle, S., Wasik, M., Cordry, D., Daugherty, M. K., Sears, S. F., Nicolette, G., Indelicato, P., & McKeag, D. B. (1999). Relationship between concussion and neuropsychological performance in college football players. *JAMA*, *282*(10), 964–970. https://doi.org/10.1001/jama.282.10.964

Cosgrove, K. P., Mazure, C. M., & Staley, J. K. (2007). Evolving Knowledge of Sex Differences in Brain Structure, Function and Chemistry. *Biological Psychiatry*, *62*(8), 847. https://doi.org/10.1016/J.BIOPSYCH.2007.03.001

Coutinho, J. F., Fernandesl, S. V., Soares, J. M., Maia, L., Gonçalves, Ó. F., & Sampaio, A. (2016). Default mode network dissociation in depressive and anxiety states. *Brain Imaging and Behavior*, *10*(1), 147–157. https://doi.org/10.1007/S11682-015-9375-7

Covassin, T., Elbin, R. J., Harris, W., Parker, T., & Kontos, A. (2012). The role of age and sex in symptoms, neurocognitive performance, and postural stability in athletes after concussion. *American Journal of Sports Medicine*, *40*(6), 1303–1312. https://doi.org/10.1177/0363546512444554

Covassin, T., Moran, R., & Wilhelm, K. (2013). Concussion symptoms and neurocognitive performance of high school and college athletes who incur multiple concussions. *American Journal of Sports Medicine*, *41*(12), 2885–2889. https://doi.org/10.1177/0363546513499230/FORMAT/EPUB

Covassin, T., Swanik, C. B., Sachs, M., Kendrick, Z., Schatz, P., Zillmer, E., & Kaminaris, C. (2006). Sex differences in baseline neuropsychological function and concussion symptoms of collegiate athletes. *British Journal of Sports Medicine*, *40*(11), 923–927. https://doi.org/10.1136/BJSM.2006.029496

Culham, J. C., Valyear, K. F., Glimcher, P. W., & Kanwisher, N. (2006). Human parietal cortex in action This review comes from a themed issue on Cognitive neuroscience Edited. *Current Opinion in Neurobiology*, *16*, 205–212. https://doi.org/10.1016/j.conb.2006.03.005

Dalecki, M., Albines, D., Macpherson, A., & Sergio, L. E. (2016). Prolonged cognitive-motor impairments in children and adolescents with a history of concussion. *Concussion (London, England)*, *1*(3), CNC14. https://doi.org/10.2217/cnc-2016-0001

Dalecki, M., Gorbet, D. J., Macpherson, A., & Sergio, L. E. (2019). Sport experience is correlated with complex motor skill recovery in youth following concussion. *European Journal of Sport Science*, *19*(9), 1257–1266. https://doi.org/10.1080/17461391.2019.1584249

Decker, S. L., & Cadenhead, C. (2011). Emotionality. In *Encyclopedia of Clinical Neuropsychology* (pp. 946–947). Springer, New York, NY. https://doi.org/10.1007/978-0-387-79948-3_1454

Dessy, A. M., Yuk, F. J., Maniya, A. Y., Gometz, A., Rasouli, J. J., Lovell, M. R., & Choudhri, T. F. (2017). Review of Assessment Scales for Diagnosing and Monitoring Sports-related Concussion. *Cureus*, *9*(12). https://doi.org/10.7759/CUREUS.1922

Dierijck, J. K., Wright, A. D., Smirl, J. D., Bryk, K., & van Donkelaar, P. (2018). Sub-concussive trauma, acute concussion, and history of multiple concussions: Effects on quiet stance postural control stability. *International Journal of Psychophysiology*, *132*, 74–80. https://doi.org/10.1016/j.ijpsycho.2018.03.005

Echemendia, R. J., Brett, B. L., Broglio, S., Davis, G. A., Giza, C. C., Guskiewicz, K. M., Harmon, K. G., Herring, S., Howell, D. R., Master, C., McCrea, M., Naidu, D., Patricios, J. S., Putukian, M., Walton, S. R., Schneider, K. J., Burma, J. S., & Bruce, J. M. (2023). Sport concussion assessment tool™ - 6 (SCAT6). *British Journal of Sports Medicine*, *57*(11), 622–631. https://doi.org/10.1136/bjsports-2023-107036

Eckner, J. T., Kutcher, J. S., Broglio, S. P., & Richardson, J. K. (2014). Effect of sport-related concussion on clinically measured simple reaction time. *British Journal of Sports Medicine*, *48*(2), 112–118. https://doi.org/10.1136/BJSPORTS-2012-091579

Eggertsdóttir Claessen, L. Ó., Kristjánsdóttir, H., Jónsdóttir, M. K., Lund, S. H., Kristensen, I. U., & Sigurjónsdóttir, H. Á. (2024). Pituitary dysfunction following mild traumatic brain injury in female athletes. *Endocrine Connections*, *13*(2). https://doi.org/10.1530/EC-23-0363

Ferreira, T. V., Noce, F., Teoldo Da Costa, I., Vieira, M. M., & Da Costa, V. T. (2017). Is there a difference by sex in simple reaction time and impulsivity in Junior Brazilian Judo Team athletes? *Archives of Budo Science of Martial Arts And Extreme Sports*, *13*, 111–118. https://www.researchgate.net/publication/324112555

Goodwin, G. J., Salva, C. E., Rodrigues, J., Maietta, J., Kuwabara, H. C., Ross, S., Kinsora, T. F., & Allen, D. N. (2023). Characterizing the Network Structure of Post-Concussion Symptoms. *Archives of Clinical Neuropsychology*, *38*, 690–698. https://doi.org/10.1093/arclin/acad001

Gouttebarge, V., & Kerkhoffs, G. M. M. J. (2021). Sports career-related concussion and mental health symptoms in former elite athletes. *Neurochirurgie*, *67*(3), 280–282. https://doi.org/10.1016/J.NEUCHI.2020.01.001

Gunasekaran, P., Hodge, C., Rose, K., & Fraser, C. L. (2019). Persistent visual disturbances after concussion. *Australian Journal of General Practice*, *48*(8), 531–536. https://doi.org/10.31128/AJGP-03-19-4876

Guskiewicz, K. M., McCrea, M., Marshall, S. W., Cantu, R. C., Randolph, C., Barr, W., Onate, J. A., & Kelly, J. P. (2003). Cumulative Effects Associated with Recurrent Concussion in Collegiate Football Players: The NCAA Concussion Study. *JAMA*, *290*(19), 2549–2555. https://doi.org/10.1001/jama.290.19.2549

Halpern, D. F. (2013). Sex differences in cognitive abilities. In *Sex Differences in Cognitive Abilities, Fourth Edition* (4th ed.). Taylor and Francis. https://doi.org/10.4324/9780203816530

Hannah, T. C., Li, A. Y., Spiera, Z., Kuohn, L., Dai, J., McAuley, F., Ali, M., Durbin, J. R., Dreher, N., Marayati, N. F., Gometz, A., Lovell, M., & Choudhri, T. (2021). Sex-

Related Differences in the Incidence, Severity, and Recovery of Concussion in Adolescent Student-Athletes Between 2009 and 2019. *American Journal of Sports Medicine*, *49*(7), 1929–1937. https://doi.org/10.1177/03635465211008596

Healey, K., Fang, Z., Smith, A., Zemek, R., & Ledoux, A. A. (2022a). Adolescents with a concussion have altered brain network functional connectivity one month following injury when compared to adolescents with orthopedic injuries. *NeuroImage: Clinical*, *36*, 103211. https://doi.org/10.1016/J.NICL.2022.103211

Healey, K., Fang, Z., Smith, A., Zemek, R., & Ledoux, A. A. (2022b). Adolescents with a concussion have altered brain network functional connectivity one month following injury when compared to adolescents with orthopedic injuries. *NeuroImage: Clinical*, *36*. https://doi.org/10.1016/J.NICL.2022.103211

Henriksen, M., Skrove, M., Hoftun, G. B., Sund, E. R., Lydersen, S., Kalvin, C. B., & Sukhodolsky, D. G. (2021). Exposure to traumatic events poses greater risk for irritability in girls than in boys. *Journal of Affective Disorders Reports*, *6*. https://doi.org/10.1016/J.JADR.2021.100204

Henry, L. C., Bastien Tremblay, S., Boulanger, Y., Ellemberg, D., & Lassonde, M. (2010). Neurometabolic Changes in the Acute Phase after Sports Concussions Correlate with Symptom Severity. *Journal of Neurotrauma*, 65–76. https://doi.org/https://doi.org/10.1089/neu.2009.0962

Howell, D., Osternig, L., Van Donkelaar, P., Mayr, U., & Chou, L. S. (2013). Effects of concussion on attention and executive function in adolescents. *Medicine and Science in Sports and Exercise*, *45*(6), 1030–1037. https://doi.org/10.1249/MSS.0B013E3182814595

Hurtubise, J., Gorbet, D., Hamandi, Y., Macpherson, A., & Sergio, L. (2016). The effect of concussion history on cognitive-motor integration in elite hockey players. *Concussion (London, England)*, *1*(3), CNC17. https://doi.org/10.2217/cnc-2016-0006

Ikarashi, K., Sato, D., Iguchi, K., Baba, Y., & Yamashiro, K. (2020). Menstrual Cycle Modulates Motor Learning and Memory Consolidation in Humans. *Brain Sciences 2020, Vol. 10, Page 696*, *10*(10), 696. https://doi.org/10.3390/BRAINSCI10100696

Iverson, G. L., Echemendia, R. J., Lamarre, A. K., Brooks, B. L., & Gaetz, M. B. (2012). Possible lingering effects of multiple past concussions. *Rehabilitation Research and Practice*, *2012*, 316575. https://doi.org/10.1155/2012/316575

Kesler, S. R., Adams, H. F., Blasey, C. M., & Bigler, E. D. (2003). Premorbid intellectual functioning, education, and brain size in traumatic brain injury: an investigation of the cognitive reserve hypothesis. *Applied Neuropsychology*, *10*(3), 153–162. https://doi.org/10.1207/S15324826AN1003_04

Kimura, D. (2002). Sex Hormones Infl uence Human Cognitive Pattern. *Neuroendocrinology Letters Special Issue*, *23*, 231002–231009. www.nel.edu

Koerte, I. K., Schultz, V., Sydnor, V. J., Howell, D. R., Guenette, J. P., Dennis, E., Kochsiek, J., Kaufmann, D., Sollmann, N., Mondello, S., Shenton, M. E., & Lin, A. P. (2020). Sex-Related Differences in the Effects of Sports-Related Concussion: A Review. *Journal of Neuroimaging*, *30*(4), 387–409. https://doi.org/10.1111/jon.12726

Kontos, A. P., Reches, A., Elbin, R. J., Dickman, D., Laufer, I., Geva, A. B., Shacham, G., DeWolf, R., & Collins, M. W. (2016). Preliminary evidence of reduced brain network activation in patients with post-traumatic migraine following concussion. *Brain Imaging and Behavior*, *10*(2), 594–603. https://doi.org/10.1007/S11682-015-9412-6

Kopczynski, A., Carteri, R. B., Rodolphi, M. S., Oses, J. P., Portela, L. O., Geller, C. A., de Oliveira, V. G., De Bastiani, M. A., Strogulski, N. R., Smith, D. H., & Portela, L. V.

(2023). Lower and higher volumes of physical exercise build up brain reserves against memory deficits triggered by a head injury in mice. *Experimental Neurology*, *363*. https://doi.org/10.1016/j.expneurol.2023.114352

Kroshus, E., Baugh, C. M., Stein, C. J., Austin, S. B., & Calzo, J. P. (2017). Concussion reporting, sex, and conformity to traditional gender norms in young adults. *Journal of Adolescence*, *54*, 110–119. https://doi.org/10.1016/j.adolescence.2016.11.002

La Fountaine, M. F., Hill-Lombardi, V., Hohn, A. N., Leahy, C. L., & Testa, A. J. (2019). Preliminary evidence for a window of increased vulnerability to sustain a concussion in females: A brief report. *Frontiers in Neurology*, *10*(JUL). https://doi.org/10.3389/FNEUR.2019.00691/FULL

Li, R. (2014). Why women see differently from the way men see? A review of sex differences in cognition and sports. *Journal of Sport and Health Science*, *3*(3), 155–162. https://doi.org/10.1016/J.JSHS.2014.03.012

Lima Santos, J. P., Jia-Richards, M., Kontos, A. P., Collins, M. W., & Versace, A. (2023). Emotional Regulation and Adolescent Concussion: Overview and Role of Neuroimaging. *International Journal of Environmental Research and Public Health*, *20*(13), 6274. https://doi.org/10.3390/IJERPH20136274

Lima Santos, J. P., Kontos, A. P., Mailliard, S., Eagle, S. R., Holland, C. L., Suss, S. J., Abdul-waalee, H., Stiffler, R. S., Bitzer, H. B., Blaney, N. A., Colorito, A. T., Santucci, C. G., Brown, A., Kim, T., Iyengar, S., Skeba, A., Diler, R. S., Ladouceur, C. D., Phillips, M. L., … Versace, A. (2021). White Matter Abnormalities Associated With Prolonged Recovery in Adolescents Following Concussion. *Frontiers in Neurology*, *12*. https://doi.org/10.3389/FNEUR.2021.681467/FULL

Macciocchi, S. N., Barth, J. T., Littlefield, L., & Cantu, R. C. (2001). Multiple Concussions and Neuropsychological Functioning in Collegiate Football Players. *Journal of Athletic Training*, *36*(3), 303–306.

Master, C. L., Mayer, A. R., Quinn, D., & Grady, M. F. (2018). Concussion. *Annals of Internal Medicine*, *169*(1), ITC1. https://doi.org/10.7326/AITC201807030

Mathew, S. J., Coplan, J. D., Smith, E. L. P., Schoepp, D. D., Rosenblum, L. A., & Gorman, J. M. (2001). Glutamate-hypothalamic-pituitary-adrenal axis interactions: Implications for mood and anxiety disorders. *CNS Spectrums*, *6*(7), 555–564. https://doi.org/10.1017/S1092852900002091

Merritt, E. D., Brown, C. N., Queen, R. M., Simpson, K. J., & Schmidt, J. D. (2017). Concussion history and time since concussion do not influence static and dynamic balance in collegiate athletes. *Journal of Sport Rehabilitation*, *26*(6), 518–523. https://doi.org/10.1123/jsr.2016-0119

Merritt, V. C., Padgett, C. R., & Jak, A. J. (2019). A systematic review of sex differences in concussion outcome: What do we know? *Clinical Neuropsychologist*, *33*(6), 1016–1043. https://doi.org/10.1080/13854046.2018.1508616

Messé, A., Caplain, S., Pélégrini-Issac, M., Blancho, S., Lévy, R., Aghakhani, N., Montreuil, M., Benali, H., & Lehéricy, S. (2013). Specific and Evolving Resting-State Network Alterations in Post-Concussion Syndrome Following Mild Traumatic Brain Injury. *PLoS ONE*, *8*(6). https://doi.org/10.1371/JOURNAL.PONE.0065470

Mihalik, J. P., & Wasserman, E. B. (2017). Depth perception differences in athletes reporting a concussion history. *British Journal of Sports Medicine*, *51*(11), A3.2-A3. https://doi.org/10.1136/bjsports-2016-097270.7

Mullally, W. J. (2017). Concussion. *The American Journal of Medicine*, *130*, 885–892. https://doi.org/10.1016/j.amjmed.2017.04.016

Nicholson, K. G., & Kimura, D. (1996). Sex differences for speech and manual skill. *Perceptual and Motor Skills*, *82*(1), 3–13. https://doi.org/10.2466/PMS.1996.82.1.3

Offit, P. A., Snow, A., Fernandez, T., Cardona, L., Grigorenko, E. L., Doyle, C. A., McDougle, C. J., Bolling, D., Smith, E. G., Smith, J., Blackwell, A., Thibodeau, L., Tang, K., Wier, K., McDuffie, A., McDuffie, A., Poyau, S., Silverman, L. B., Dawson, M., … Mueller, V. T. (2013). Visual-Motor Function. *Encyclopedia of Autism Spectrum Disorders*, 3318–3319. https://doi.org/10.1007/978-1-4419-1698-3_758

Oldenburg, C., Lundin, A., Edman, G., Nygren-De Boussard, C., & Bartfai, A. (2016). Cognitive reserve and persistent post-concussion symptoms - A prospective mild traumatic brain injury (mTBI) cohort study. *Brain Injury*, *30*(2), 146–155. https://doi.org/10.3109/02699052.2015.1089598

Ono, K. E., Burns, T. G., Bearden, D. J., McManus, S. M., King, H., & Reisner, A. (2016). Sex-Based Differences as a Predictor of Recovery Trajectories in Young Athletes after a Sports-Related Concussion. *American Journal of Sports Medicine*, *44*(3), 748–752. https://doi.org/10.1177/0363546515617746

Phillips, B., Adkins, J. C., Jones, B. D., & Dalecki, M. (2023). Prolonged eye-hand decoupling deficits in young adults with a history of concussion from adolescence. *European Journal of Sport Science*, *23*(6), 1036–1046. https://doi.org/10.1080/17461391.2022.2085186

Pierias, A. E. (2021). *AN EXPLORATION OF SEX-AND HORMONE-RELATED DIFFERENCES IN COGNITIVE-MOTOR PERFORMANCE, BRAIN NETWORK INTEGRITY, AND RECOVERY METRICS FOLLOWING CONCUSSION.*

Plourde, V., Rohr, C. S., Virani, S., Bray, S., Yeates, K. O., & Brooks, B. L. (2020). Default mode network functional connectivity after multiple concussions in children and adolescents. *Archives of Clinical Neuropsychology*, *35*, 302–311. https://doi.org/10.1093/arclin/acz073

Putukian, M., & Johnson, R. W. (2011). The Acute Symptoms of Sport-Related Concussion: Diagnosis and On-field Management KEYWORDS Sport-related concussion Sideline management Concussion protocol Symptoms Diagnosis Mild traumatic brain injury Head injury Sports. *Clinics in Sports Medicine*, *30*, 49–61. https://doi.org/10.1016/j.csm.2010.09.005

Rabelo, J. L. (2017). *Sports-Related Concussions and Depression*. Alliant International University.

Rogojin, A., Gorbet, D. J., & Sergio, L. E. (2023). Sex differences in the neural underpinnings of unimanual and bimanual control in adults. *Experimental Brain Research*, *241*(3), 793–806. https://doi.org/10.1007/s00221-023-06561-5

Satz, P. (1993). Brain Reserve Capacity on Symptom Onset After Brain Injury: A Formulation and Review of Evidence for Threshold Theory. *Neuropsychology*, *7*(3), 273–295. https://doi.org/10.1037/0894-4105.7.3.273

Seidel, O., & Ragert, P. (2019). *Effects of Transcranial Direct Current Stimulation of Primary Motor Cortex on Reaction Time and Tapping Performance: A Comparison Between Athletes and Non-athletes - York University*. Frontiers in Human Neuroscience. https://doi.org/10.3389/fnhum.2019.00103

Shaywitz, B. A., Shaywltz, S. E., Pugh, K. R., Constable, R. T., Skudlarski, P., Fulbright, R. K., Bronen, R. A., Gore, J. C., Shankweiler, D. P., Katz, L., & Gore, J. C. (1995). Sex differences in the functional organization of the brain for language. *Nature*, *373*(6515), 607–609. https://doi.org/10.1038/373607a0

Smeha, N. (2021). *Sex-Related Differences in Visuomotor Skill Recovery Following Concussion in Working-Aged Adults*. http://hdl.handle.net/10315/38688

Smeha, N., Kalkat, R., Sergio, L. E., & Hynes, L. M. (2022). Sex-related differences in visuomotor skill recovery following concussion in working-aged adults. *BMC Sports Science, Medicine & Rehabilitation*, *14*(1), 72. https://doi.org/10.1186/s13102-022-00466-6

Sneider, J. T., Sava, S., Rogowska, J., & Yurgelun-Todd, D. A. (2011). A preliminary study of sex differences in brain activation during a spatial navigation task in healthy adults. *Perceptual and Motor Skills*, *113*(2), 461–480. https://doi.org/10.2466/04.22.24.27.PMS.113.5.461-480

Sport concussion assessment tool - 5th edition. (2017). *British Journal of Sports Medicine*, *51*(11), 851–858. https://doi.org/10.1136/BJSPORTS-2017-097506SCAT5

Tanaka, S., Sagisaka, R., Sone, E., & Tanaka, H. (2023). Sport level and sex differences in sport-related concussion among Japanese collegiate athletes: Epidemiology, knowledge, reporting behaviors, and reported symptoms. *Sports Medicine and Health Science*, *5*(3), 229–238. https://doi.org/10.1016/J.SMHS.2023.07.002

Thomson, R., Carabello, D., Mansell, J., & Russ, A. (2020). Depression Following Concussion in Retired Professional Football Players. *International Journal of Athletic Therapy and Training*, *25*(2), 54–56. https://doi.org/10.1123/IJATT.2019-0028

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

Veliz, P., McCabe, S. E., Eckner, J. T., & Schulenberg, J. E. (2021). Trends in the Prevalence of Concussion Reported by US Adolescents, 2016-2020. *JAMA*, *325*(17), 1789. https://doi.org/10.1001/JAMA.2021.1538

Wallace, J., Covassin, T., & Beidler, E. (2017). Sex differences in high school athletes' knowledge of sport-related concussion symptoms and reporting behaviors. *Journal of Athletic Training*, *52*(7), 682–688. https://doi.org/10.4085/1062-6050-52.3.06

Weafer, J., & de Wit, H. (2014). Sex differences in impulsive action and impulsive choice. *Addictive Behaviors*, *39*(11), 1573–1579. https://doi.org/10.1016/j.addbeh.2013.10.033

Weinstein, A., & Dannon, P. (2015). Is Impulsivity a Male Trait Rather than Female Trait? Exploring the Sex Difference in Impulsivity. *Current Behavioral Neuroscience Reports*, *2*(1), 9–14. https://doi.org/10.1007/S40473-015-0031-8

Weiss, E. M., Kemmler, G., Deisenhammer, E. A., Fleischhacker, W. W., & Delazer, M. (2003). Sex differences in cognitive functions. *Personality and Individual Differences*, *35*(4), 863–875. https://doi.org/10.1016/S0191-8869(02)00288-X

Weiss, E., Siedentopf, C. M., Hofer, A., Deisenhammer, E. A., Hoptman, M. J., Kremser, C., Golaszewski, S., Felber, S., Fleischhacker, W. W., & Delazer, M. (2003). Sex differences in brain activation pattern during a visuospatial cognitive task: a functional magnetic resonance imaging study in healthy volunteers. *Neuroscience Letters*, *344*(3), 169–172. https://doi.org/10.1016/S0304-3940(03)00406-3

Zhu, D. C., Covassin, T., Nogle, S., Doyle, S., Russell, D., Pearson, R. L., Monroe, J., Liszewski, C. M., DeMarco, J. K., & Kaufman, D. I. (2015). A potential biomarker in sports-related concussion: Brain functional connectivity alteration of the default-mode network measured with longitudinal resting-state fMRI over thirty days. *Journal of Neurotrauma*, *32*(5), 327–341. https://doi.org/10.1089/NEU.2014.3413

Appendix A. Informed Consent 1

INFORMED CONSENT

Date: July 2023

Study Name: **Varsity athlete data research analysis**

Lead Researcher: Dr. Lauren Sergio, School of Kinesiology and Health Science, Faculty of Health, 2032 Sherman Health Science Research Building, lsergio@yorku.ca, 416-736-2100x33641

Purpose of the Research: As part of your regular pre-season baseline testing prior to starting with your York University team, you are asked to do a number of tasks to ensure your safety during the season. Also, these measures can assist with optimal treatment by York's Sport Medicine team should you sustain an injury during the season. A team of faculty at York are interested in using these data for basic research purposes. The ultimate goal is to generate fundamental knowledge around injury history and performance, as well as to provide clinically practical information to the York University Sport Medicine team in the care and management of our varsity athletes. There will be absolutely no personal identifying information linked to these data. That is, your name will not be provided to the researchers, just the data when requested.

What You Will Be Asked to Do in the Research: *There is nothing that you will be asked to do beyond your normal participation in the required pre-season baseline measures. We simply want you to be aware of, and consent to, the use of your measures together with your fellow athlete's measures – again, not linked to you personally in any way – for research purposes.*

Risks and Discomforts: We do not foresee any risks or discomfort from agreeing to provide these data for research.

Benefits of the Research and Benefits to You: There are no direct benefits. Indirectly, information derived from this research may improve sport injury treatment at York University and elsewhere, and knowledge in the area of health and performance.

Voluntary Participation: Your participation in the study is completely voluntary and you may choose to not allow your data bto be part of the research database. They will still be used for your clinical management by the York University Athletic Therapy staff and physicians. Your decision not allow your data to be used for research will not influence the treatment you may receive from the sport injury clinic, your ongoing relationship with your team, coaches, and therapists, nor the nature of your relationship with York University either now, or in the future.

Withdrawal from the Study: You can decide to have your data to be included among those provided to researchs at any time, for any reason, if you so decide. Your decision to not allow your anonymized data to be used for research will not affect your relationship with the researchers, York University, or any other group associated with York Athletics. Your measures will still be used in the standard care done by the Sport Injury clinic.

Confidentiality: All information that you supply during your participation in York University athletics related to this research database will be held in confidence, and completely anonymized. Your data will be safely stored in a locked facility (the clinic) as well as a secure database maintained by York University UIT following the standards required for the storage of electronic personal health information (in line with the Personal Health Information Protection Act of Canada). Only clinic staff will have access to any information linking you to your measures, and only research staff will have access to the anonymized research data provided to them by the clinic director. The anonymized data will be stored indefinitely, archived following standard York University UIT secure server archiving protocols. Confidentiality will be provided to the fullest extent possible by law.

Questions About the Research? If you have questions about the research in general or about your role in the study, please feel free to contact Dr. Lauren Sergio either by telephone at (416) 736-2111, x33641 or by e-mail (lsergio@yorku.ca). You may also discuss any concerns with Clinic Director Andrea Prieur, CAT(C), (416)736-2100 x 77232, aprieur@yorku.ca. This research has received ethics review and approval by the Human Participants Review Sub-Committee, York University's Ethics Review Board and conforms to the standards of the Canadian Tri-Council Research Ethics guidelines. If you have any questions about this process, or about your rights as a participant in the study, please contact the Sr. Manager & Policy Advisor for the Office of Research Ethics, 5th Floor, Kaneff Tower, York University (telephone 416-736-5914 or e-mail ore@yorku.ca).
Legal Rights and Signatures:

I,_________________________,consent to participate in ***Varsity athlete data research analysis*** conducted by Dr. Lauren Sergio. I have understood the nature of this project and wish to participate. I am not waiving any of my legal rights by signing this form. My signature below indicates my consent.

Signature__________________________ **Date**_______________________
Participant

Signature__________________________ ____________________________
Principal Investigator

Appendix B. Informed Consent 2

INFORMED CONSENT

School of Kinesiology and Health Science, Faculty of Health
York University, Toronto, ON Canada
"Brain mechanisms for eye-hand coordination"

Date: December 1, 2021

Study Name: Brain mechanisms for skilled coordination

Researchers: Dr. Lauren E. Sergio, 2032 Sherman Health Science Building, 416-736-2100x33641, lsergio@yorku.ca

Purpose of the Research: Our research team is working to understand the control processes employed by the brain when interacting with one's environment to transform a visual or auditory signal into coordinated movement.

What You Will Be Asked to Do in the Research: You will be asked to perform up to four coordination tasks. To obtain these measures, we will ask you to move your finger along a touch sensitive screen or grasp a robotic handle placed in front of you. You may also be asked to touch targets on a wooden board or touch screen, and/or move your hand, stand, and take a few steps in front of a computer camera. In addition, you may asked to complete a questionnaire on your lifestyle, physical activity level, and computer experience. The questionnaire is either presented on our tablet computer or as an attachment to be completed and returned by email if participating remotely. In total, the study should take between 30 and 45 minutes to complete.

Risks and Discomforts: We do not foresee any risks or discomfort from your participation in the research. For one condition, you may be asked to wear a 68 gram soft headband for 5-10 minutes while performing the touchscreen task. Should this headband cause discomfort we will remove it immediately upon request.

Benefits of the Research and Benefits to You: The data from this study will benefit you indirectly by assessing your ability to perform skilled movement involving eye-hand coordination and balance maintenance during simple movements. This information will also be used to refine in-person and remote assessment tools of functional goal-directed movements.

Voluntary Participation and Withdrawal: Your participation in the study is completely voluntary and you may choose to stop participating at any time. Your decision not to volunteer, to stop participating, or to refuse to answer particular questions will not influence the nature of the ongoing relationship you may have with the researchers or study staff, nor the nature of your relationship with York University either now, or in the future. Should you wish to withdraw after the study, you will have the option to also withdraw your data up until the analysis is complete.

Confidentiality: All information you supply during the research will be held in confidence and unless you specifically indicate your consent, your name will not appear in any report or publication of the research. If you perform the task involving the computer camera, any captured images will be removed of identifying information shortly after the study by converting them into stick-figure representations. Your data will be safely stored in a locked facility equipped with an alarm, in a building with limited access. Only research staff/research team members will have access to this information. Any forms linking identity to the movement data will be destroyed within 11 years. Confidentiality will be provided to the fullest extent possible by law. The data collected in this research project may be used – in an anonymized form - by members of the research team in subsequent research investigations exploring similar lines of inquiry. Such projects will still undergo ethics review by the HPRC, our institutional REB. Any secondary use of anonymized data by the research team will be treated with the same degree of confidentiality and anonymity as in the original research project.

Because this project may employ e-based collection techniques, data may be subject to access by third parties as a result of various security legislation now in place in many countries and thus the confidentiality and privacy of data cannot be guaranteed during web-based transmission.

Questions About the Research? If you have questions about the research in general or about your role in the study, please feel free to contact Dr. Lauren Sergio either by telephone at (416) 736-2100, extension 33641 or by e-mail (lsergio@yorku.ca). This research has received ethics review and approval by the Human Participants Review Sub-Committee, York University's Ethics Review Board and conforms to the standards of the Canadian Tri-Council Research Ethics guidelines. If you have any questions about this process, or about your rights as a participant in the study, please contact the Sr. Manager & Policy Advisor for the Office of Research Ethics, 5th Floor, Kaneff Tower, York University (telephone 416-736-5914 or e-mail ore@yorku.ca).

Version 1.0 August 2020 ORE – Updated 2016

INFORMED CONSENT

School of Kinesiology and Health Science, Faculty of Health
York University, Toronto, ON Canada

"Brain mechanisms for eye-hand coordination"

Covid-19 Specific Consent Information

Research involving Face-to-Face Contact with Human Participants

COVID-19 has presented additional risks and challenges to conducting face-to-face research. Please see the attached COVID specific consent information prior to signing this document.

Covid-19 Specific Consent Information

Our laboratory at York University is under the jurisdiction of the city of Toronto public health. We are taking all safety precautions to reduce the risk of spread of COVID-19 and expect you to follow public health directives as well.

Only research involving participants considered "low risk" may proceed at this time. If you feel that you are from a vulnerable group with respect to COVID-19 effects (e.g., senior, immuno-compromised), please discuss your participation with the research team before consenting.

As always, regardless of your relation to the laboratory, you are under no obligation to participate and there will be no negative consequences if you change your mind about participating in the research. If at any time you feel pressured to participate, please contact the senior researcher, Dr. Lauren Sergio (lsergio@yorku.ca). Your safety and comfort are of paramount importance.

Because you are coming onto campus, the following safety protocols must be followed, as per Occupational Health and Safety:

- Screening – as per requirements for persons coming onto campus. Please use YU Screen, a new automated COVID-19 self-assessment screening tool that all faculty, staff, instructors, students, researchers and visitors must use before coming to campus to self-screen and confirm that they have not been exposed to COVID-19. Completing YU Screen before every trip to campus will be additional to complying with the University's vaccination requirement.

- Take appropriate precautions (e.g. face covering / cloth mask) if taking public transportation and entering public indoor spaces. If you don't have a mask, you will be provided with one to wear.

- Wash your hands upon coming onto campus / entrance to building. Hand sanitizer will be made available to you.

- Physical distancing will be maintained, at all times.

- We will be collecting personal contact information that we must retain in order to follow up with you and/or conduct contact tracing if you may have been exposed to COVID-19 in coming to the research site.

- Contact information will be kept separate from data collected through the research study to allow for de-identification of the research data (if applicable, as detailed in the protocol).

You maintain your right to withdraw from the study at any time, including research data (if applicable). If you do withdraw, we will continue to maintain your contact information and will only give it to Occupational Health if required for contact tracing.

We cannot guarantee anonymity as the personal contact information identifies you as a participant

INFORMED CONSENT

School of Kinesiology and Health Science, Faculty of Health
York University, Toronto, ON Canada
"Brain mechanisms for eye-hand coordination"

Legal Rights and Signatures:

I__________________, consent to participate in the "Brain Mechanisms for Skilled Movement" study conducted by Dr. Lauren Sergio and her research team. I have understood the nature of this project and wish to participate. I am not waiving any of my legal rights by signing this form. My signature or checkbox completion (if performing the study remotely) below indicates my consent.

Check here if you consent to participation in the study and are participating remotely ☐

Signature________________________ **Date**____________________
Participant

Signature________________________ **Date**____________________
Principal Investigator

Additional consent (where applicable)

You must seek additional consent by including check boxes or requesting additional signatures for the following:

1. **Video recording or use of photographs**

I ____________________ consent to the use of images of me (including photographs, video and other moving images), my environment and property in the following ways (please check all that apply):

In academic articles	☐ N	☐ Y
In print, digital and slide form	☐ N	☐ Y
In academic presentations	☐ N	☐ Y
In thesis materials	☐ N	☐ Y

Note that your moving and still images will be converted to stick figure representations and will be minimally identifiable.

Signature____________________ **Date**____________________

Participant Name:

2. **Consent to waive anonymity**

I, ______________________, consent to the use of my name in the publications arising from this research.

Signature____________________ **Date**____________________

Participant Name:

Version 1.0 August 2020 ORE – Updated 2016

Appendix C. Sport Concussion Assessment Tool 5 (SCAT5)

OFFICE OR OFF-FIELD ASSESSMENT

Please note that the neurocognitive assessment should be done in a distraction-free environment with the athlete in a resting state.

STEP 1: ATHLETE BACKGROUND

Sport / team / school: ______________________

Date / time of injury: ______________________

Years of education completed: ______________________

Age: ______________________

Gender: M / F / Other

Dominant hand: left / neither / right

How many diagnosed concussions has the athlete had in the past?: ______________________

When was the most recent concussion?: ______________________

How long was the recovery (time to being cleared to play) from the most recent concussion?: ______________________ (days)

Has the athlete ever been:

Hospitalized for a head injury?	Yes	No
Diagnosed / treated for headache disorder or migraines?	Yes	No
Diagnosed with a learning disability / dyslexia?	Yes	No
Diagnosed with ADD / ADHD?	Yes	No
Diagnosed with depression, anxiety or other psychiatric disorder?	Yes	No

Current medications? If yes, please list:

____

____

____

____

____

____

Name: ______________________

DOB: ______________________

Address: ______________________

ID number: ______________________

Examiner: ______________________

Date: ______________________

2

STEP 2: SYMPTOM EVALUATION

The athlete should be given the symptom form and asked to read this instruction paragraph out loud then complete the symptom scale. For the baseline assessment, the athlete should rate his/her symptoms based on how he/she typically feels and for the post injury assessment the athlete should rate their symptoms at this point in time.

Please Check: ☐ **Baseline** ☐ **Post-Injury**

Please hand the form to the athlete

	none	mild		moderate		severe	
Headache	0	1	2	3	4	5	6
"Pressure in head"	0	1	2	3	4	5	6
Neck Pain	0	1	2	3	4	5	6
Nausea or vomiting	0	1	2	3	4	5	6
Dizziness	0	1	2	3	4	5	6
Blurred vision	0	1	2	3	4	5	6
Balance problems	0	1	2	3	4	5	6
Sensitivity to light	0	1	2	3	4	5	6
Sensitivity to noise	0	1	2	3	4	5	6
Feeling slowed down	0	1	2	3	4	5	6
Feeling like "in a fog"	0	1	2	3	4	5	6
"Don't feel right"	0	1	2	3	4	5	6
Difficulty concentrating	0	1	2	3	4	5	6
Difficulty remembering	0	1	2	3	4	5	6
Fatigue or low energy	0	1	2	3	4	5	6
Confusion	0	1	2	3	4	5	6
Drowsiness	0	1	2	3	4	5	6
More emotional	0	1	2	3	4	5	6
Irritability	0	1	2	3	4	5	6
Sadness	0	1	2	3	4	5	6
Nervous or Anxious	0	1	2	3	4	5	6
Trouble falling asleep (if applicable)	0	1	2	3	4	5	6

Total number of symptoms:	of 22
Symptom severity score:	of 132
Do your symptoms get worse with physical activity?	Y N
Do your symptoms get worse with mental activity?	Y N
If 100% is feeling perfectly normal, what percent of normal do you feel?	

If not 100%, why?

____

____

____

Please hand form back to examiner

Davis GA, *et al. Br J Sports Med* 2017;**0**:1–8. doi:10.1136/bjsports-2017-097506SCAT5 3

Note. Page three of the SCAT5 where the symptom evaluation, 22-point symptom list is included. This research only requires the use of the bottom most symptoms: more emotional, irritability, sadness, and nervous or anxious ("Sport Concussion Assessment Tool - 5th Edition," 2017).

Appendix D. Sport Concussion Assessment Tool 6 (SCAT6)

Sport Concussion Assessment Tool 6 - SCAT6™

Off-Field Assessment

Please note that the cognitive assessment should be done in a distraction-free environment with the athlete in a resting state **after** completion of the Immediate Assessment/Neuro Screen.

Step 1: Athlete Background

Has the athlete ever been:

Hospitalised for head injury? (If yes, describe below)	Y	N
Diagnosed/treated for headache disorder or migraine?	Y	N
Diagnosed with a learning disability/dyslexia?	Y	N
Diagnosed with attention deficit hyperactivity disorder (ADHD)?	Y	N
Diagnosed with depression, anxiety, or other psychological disorder?	Y	N

Notes:

Current medications? If yes, please list:

Step 2: Symptom Evaluation

Baseline: ☐ **Suspected/Post-injury:** ☐ **Time elapsed since suspected injury:** ______ mins/hours/days

The athlete will complete the symptom scale (below) after you provide instructions. Please note that the instructions are different for baseline versus suspected/post-injury evaluations.

Baseline: Say ***"Please rate your symptoms below based on how you <u>typically</u> feel with "1" representing a very mild symptom and "6" representing a severe symptom."***

Suspected/Post-injury: Say ***"Please rate your symptoms below based on how you feel now with "1" representing a very mild symptom and "6" representing a severe symptom."***

PLEASE HAND THE FORM TO THE ATHLETE

Symptom	Rating
Headaches	0 1 2 3 4 5 6
Pressure in head	0 1 2 3 4 5 6
Neck pain	0 1 2 3 4 5 6
Nausea or vomiting	0 1 2 3 4 5 6
Dizziness	0 1 2 3 4 5 6
Blurred vision	0 1 2 3 4 5 6
Balance problems	0 1 2 3 4 5 6
Sensitivity to light	0 1 2 3 4 5 6
Sensitivity to noise	0 1 2 3 4 5 6
Feeling slowed down	0 1 2 3 4 5 6
Feeling like "in a fog"	0 1 2 3 4 5 6
"Don't feel right"	0 1 2 3 4 5 6
Difficulty concentrating	0 1 2 3 4 5 6
Difficulty remembering	0 1 2 3 4 5 6
Fatigue or low energy	0 1 2 3 4 5 6
Confusion	0 1 2 3 4 5 6
Drowsiness	0 1 2 3 4 5 6
More emotional	0 1 2 3 4 5 6
Irritability	0 1 2 3 4 5 6
Sadness	0 1 2 3 4 5 6
Nervous or anxious	0 1 2 3 4 5 6
Trouble falling asleep (if applicable)	0 1 2 3 4 5 6

Do your symptoms get worse with physical activity?	Y	N
Do your symptoms get worse with mental activity?	Y	N

If 100% is feeling perfectly normal, what percent of normal do you feel?

If not 100%, why?

PLEASE HAND THE FORM BACK TO THE EXAMINER

Once the athlete has completed answering all symptom items, it may be useful for the clinician to revisit items that were endorsed positively to gather more detail about each symptom.

Total number of symptoms: ______ **of 22** **Symptom severity score:** ______ **of 132**

For use by Health Care Professionals only

British Journal of Sports Medicine

Note. Page four of the SCAT6 where the symptom evaluation, 22-point symptom list is included. This research only requires the use of the bottom most symptoms: more emotional, irritability, sadness, and nervous or anxious (Echemendia et al., 2023).