DESCRIPTIVE ANALYSIS OF PRESEASON BASELINE DATA COLLECTED FROM UNIVERSITY VARSITY STUDENT-ATHLETES USING A COMPREHENSIVE CONCUSSION ASSESSMENT BATTERY

BEN MIGOTTO

A THESIS SUBMITTED TO THE FACULTY OF GRADUATE STUDIES
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

GRADUATE PROGRAM IN KINESIOLOGY AND HEALTH SCIENCE
YORK UNIVERSITY
TORONTO, ONTARIO

November 2022

ABSTRACT

The objectives of this study were to conduct a descriptive analysis of preseason baseline data collected from university varsity student-athletes using a comprehensive battery of assessments and to examine the effects of sex, concussion history and their interaction on variables. 325 student-athletes (165 males; 160 females) completed one or more of the following assessments: Sport Concussion Assessment Tool-5 (SCAT5); force plate postural sway; Doppler ultrasound cerebral blood flow; Brain Dynamic Indicator^{TM} (BrDI^{TM}); HurtSHynes^{TM} Test; oculomotor performance; Stroop Colour and Word Test. 140 student-athletes reported a history of concussion (RHOC) and 185 student-athletes had No RHOC. Significant effects of sex were observed for multiple variables within five assessments. A significant effect of concussion history was rarely observed. Significant interaction effects were found for variables in the BrDI^{TM} and HurtSHynes^{TM} Test. Considerable ceiling effects in scoring were observed across all student-athletes for the SCAT5 five-word immediate memory test. Overall, this study expands our understanding of the variability of results for varsity student-athletes across a variety of baseline assessments. Furthermore, the results support the need to develop sex-specific models of recovery following sports-related concussion.

ACKNOWLEDEMENTS

First and foremost, I would like to express my deepest gratitude to my thesis supervisor Dr. Loriann Hynes for encouraging me to utilize my passion for exploring the literature on the effects of sport-related concussion in a variety of domains and guiding me on how to concisely summarize my findings. The research experience that I have gained over the past two years would not have been the same without Dr. Hynes' unwavering support and mentorship.

Many thanks to my colleagues in the Whiplash and Head Injury Prevention/Rehabilitation Lab (Christina Amaral, Ravneet Kalkat and Michael Modica), Dr. George Mochizuki (and his students from the Dynamic Balance Lab), Dr. Lauren Sergio (and her students from the Motor Control Lab) and Andrea Prieur (and the York U Sports Medicine Team) for allowing me to analyze their preseason baseline data collected from university varsity student-athletes. With data comprised of baseline values for symptoms and various measures of neurocognitive functioning, postural control, cerebral blood flow volume, cognitive-motor integration and oculomotor performance, the comprehensiveness of this master's thesis would not have been possible without each of these sets of data and therefore I am grateful towards everyone involved in their collection. I would also like to thank my committee member Dr. Alison Macpherson for her guidance on the research design of my master's thesis and the constructive feedback that she provided in her review of the completed first draft.

Lastly, I want to acknowledge professor Dr. Trevor Cottrell from the Bachelor of Health Sciences degree program in Kinesiology and Health Promotion at Sheridan College. Not only was the experience in completing my capstone research project under his supervision vital in preparing me for writing and analyzing data for my master's thesis, Dr. Cottrell was a key motivator in helping me recognize the value of my research skills that I had personally overlooked for many years.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

Abbreviation	Complete Term
ACA	anterior cerebral artery
ADD	attention-deficit disorder
ADHD	attention-deficit/hyperactivity disorder
AE	absolute error
ANOVA	analysis of variance
AP	anteroposterior
AREA – CE	95 % confidence ellipse area
ASL	arterial spin labeling
BESS	Balance Error Scoring System
BFV	blood flow volume
BGC	brainstem gaze centres
BrDI	Brain Dynamic Indicator
CBF	cerebral blood flow
CCA	common carotid artery
CCHS	Canadian Community Health Survey
CISG	Concussion in Sport Group
cm	centimetres
CMI	cognitive-motor integration
CN	caudate nucleus
COP	centre of pressure
COPvel	center of pressure velocity
CPP	cerebral perfusion pressure
CSA	cross-sectional area
DLPC	dorsolateral prefrontal cortex
DU	Doppler ultrasound
EC	eyes closed
ECA	external carotid artery
ED	emergency department
EO	eyes open
GCS	Glasgow Coma Scale
g	grams
RHOC	reported history of concussion
ICA	internal carotid artery
ICP	intracranial cerebral pressure

Abbreviation	Complete Term
kg	kilograms
m	metres
MAP	mean arterial pressure
mBESS	modified Balance Error Scoring System
MCA	middle cerebral artery
mCHI	mild closed head injury
min	minutes
mL	millilitres
ML	mediolateral
mm	millimetres
MRI	magnetic resonance imaging
ms	milliseconds
MTb	ballistic movement time
mTBI	mild traumatic brain injury
NACRS	National Ambulatory Care Reporting System
NCAA	National Collegiate Athletics Association
NCAA ISP	National Collegiate Athletics Association Injury Surveillance Program
No RHOC	no reported history of concussion
P_aCO_2	partial pressure of arterial carbon dioxide
PCA	posterior cerebral artery
PCS	persisting concussion symptoms
PEF	parietal eye fields
PLfN	normalized path length
PV	peak velocity
Range	range of centre of pressure displacement
RMSdisp	root-mean-square of centre of pressure displacement
RT	reaction time
RTL	return to learn
RTS	return to sport
SAC	Standardized Assessment of Concussion
SC	superior colliculus
SCAT	Sport Concussion Assessment Tool
SCWT	Stroop Colour and Word Test
sec	seconds
SEF	supplementary eye fields
SNPR	substantia nigra pars reticulata

Abbreviation	**Complete Term**
SRC	sports-related concussion
TAMEAN	time-averaged mean velocity
TBI	traumatic brain injury
TCD	transcranial Doppler ultrasound
TMT	total movement time
V	Cramer’s V
VA	vertebral artery
VE	variable error
VADAR	Varsity Athlete Data Analysis Research
WHO	World Health Organization
$\chi 2$	Pearson’s chi-square

CHAPTER ONE: LITERATURE REVIEW AND INTRODUCTION

The Evolving Definition of Concussion

Concussion is a type of traumatic brain injury (TBI) that has been confusing physicians and neurosurgeons worldwide for centuries. Definitions of concussion have varied considerably as a result, with many conflicting or ambiguous in describing concussion and its mechanisms of injury.[1-9] 10th century Persian physician Rhazes was the first to provide a clear definition of concussion that was distinct from severe TBI, with the physician referring to concussion as a transient state of abnormal brain physiology.[1] In the centuries that followed, some physicians described concussion as a shaking of the brain against the skull following a low velocity blow to the head,[2-4] whereas others believed that a concussion was sustained only if the individual experienced an immediate loss of consciousness (LOC) following a head impact.[5-8] Conflicting interpretations and hypotheses on concussion continued to persist into the 20th century.[9-12] To establish a medical consensus, the Congress of Neurological Surgeons in 1966 defined concussion as a clinical syndrome of immediate and transient impairment of neural function induced by mechanical forces.[13] Despite its limitations, this definition was generally accepted by researchers and multiple professional associations of physicians.[14] Research interest in sports-related concussion (SRC) grew in the United States during the 1980s and 1990s, with a particular focus on characterizing concussion symptomology in athletes and developing methods and strategies for clinical assessment, management and return to sport (RTS).[15-24] This led to the first International Symposium on Concussion in Sport where the Concussion in Sport Group (CISG) addressed the need to develop a unifying model of concussion.[25] Since this inaugural meeting, the CISG have provided a consistent and thorough definition of SRC and its clinical features.[26-29] Their most recent consensus statement defined SRC as a TBI induced by biomechanical forces caused by either a direct impact to the head, neck or another body site with an impulsive force transmitted to the head-neck complex.[29] Additionally, the CISG definition states that a SRC involves a rapid onset of impaired neurological function that is then followed by a variety of acute signs and symptoms, which may or may not involve a LOC, that present within minutes to hours following the injury event.[29] These clinical signs and symptoms often describe a functional disturbance rather than a structural brain injury that can be visually observed on standard structural imaging techniques such as magnetic resonance imaging (MRI) and computerized tomography scans.[29,30] However, researchers using advanced neuroimaging techniques such as functional MRI, diffusion tensor imaging and MR spectroscopy have demonstrated evidence of neurometabolic, microstructural and functional alterations in the brain of concussed athletes during the acute, subacute and chronic stages of SRC.[30,31]

Concussion Pathophysiology

Most of our scientific knowledge on the pathophysiology of concussion is based on experimental animal model research.[32-34] Injurious acceleration and deceleration forces on the brain cause neuronal membrane disruption and axonal stretching, initiating a complex neurometabolic cascade (see Figure 1).[32-34] This cascade begins with a massive flux of ions through unregulated ion channels into intracellular and extracellular spaces, followed by rapid neuronal depolarization, an indiscriminate release and accumulation of the neurotransmitter glutamate, the binding of excess glutamate to ionotropic receptors and the subsequent opening of ion channels that permit calcium entry into cells.[32-34] The sequestering of excess calcium in the mitochondria as a temporary solution leads to mitochondrial dysfunction and impaired oxidative metabolism.[35-38] ATP-dependent sodium/potassium pumps are activated into overdrive to restore ionic and cellular homeostasis, which subsequently triggers an increase in glucose utilization to satisfy rising energy demands.[32-34,39] This scenario ultimately leads to a depletion of ATP stores and a buildup of lactate in the brain that can result in lactic acidosis, increased blood brain barrier permeability and cerebral edema.[32-34,39] The combination of increased glucose demand and injury-related reductions in cerebral blood flow (CBF) results in a mismatch between cerebral metabolic supply and energy requirements, leading to a deleterious neurometabolic crisis.[30-32] Sustaining a secondary concussive injury in close temporal proximity to the initial concussion may exacerbate this neurometabolic crisis and cause a more severe and potentially irreversible brain injury.[32,33,40-44]

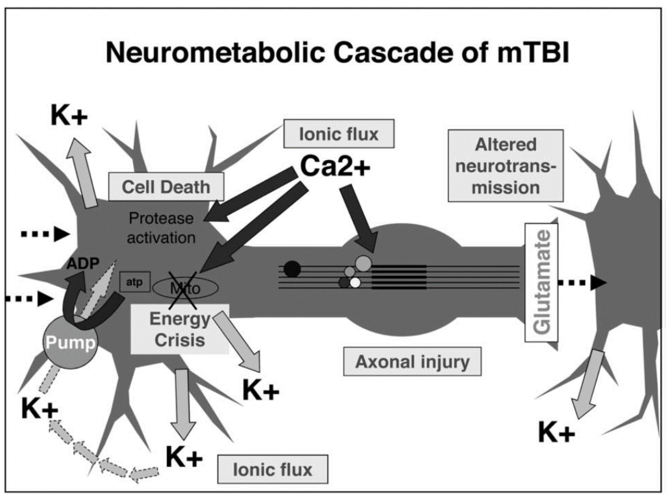

Figure 1. Diagram of the neurometabolic cascade and acute biological processes that occur after mild traumatic brain injury (mTBI). Diagram reprinted from Giza and Hovda[33] with permission from the publisher Wolters Kluwer Health, Inc. Please see Appendix A for license details and terms and conditions provided by Wolters Kluwer Health, Inc. and the Copyright Clearance Center.

Concussion and Traumatic Brain Injury Epidemiology

Referred to as a "silent epidemic", concussions and TBIs are a major public health concern around the world in both high and low- and middle-income countries.[45] Concussions and TBIs sustained in motor vehicle or motorcycle accidents,[45-49] during active military service[50-55] and from intimate partner violence[56-59] are some of the key areas of interest for researchers around the world examining the epidemiology of these brain injuries. A systematic review and meta-analysis conducted by Dewan et al[45] estimated that 69 million individuals worldwide, or 939 cases per 100,000 people, sustain a TBI from all-causes every year. In order to calculate the estimated incidence of TBI worldwide by severity, the team of academic researchers examined population-based studies that categorized the severity of TBI using Glasgow Coma Scale (GCS) scores for mild (score of 13 – 15), moderate (score of 9 – 12) and severe TBI (score of 3 – 8).[45] According to their results, mild TBI (mTBI) was estimated to affect 55.9 million people every year, followed by moderate and severe TBI with 7.62 million and 5.48 million people affected per year, respectively.[45] World Health Organization (WHO) regions with the highest estimated annual incidence of TBI were the Region of the Americas (United States and Canada) and the European Region with 1299 and 1012 TBI cases per 100,000 people, respectively.[45] WHO regions with the lowest estimated annual incidence of TBI were the African Region and the Eastern Mediterranean Region with 801 and 897 TBI cases per 100,000 people, respectively.[45]

It has been widely cited that an estimated 1.6 to 3.8 million sports-related TBI occur annually in the United States among individuals of all ages.[60] This estimate from Langois et al[60] was published in response to an estimate from the Injury Supplement to the 1991 National Health Interview Survey that exclusively focused on sports-related TBIs that resulted in a LOC and excluded TBIs that occurred without a LOC.[61] As studies published at the time revealed that a majority of SRCs did not result in a LOC,[62,63] the estimate from Langois et al[60] accounted for sports-related TBIs that occurred without a LOC and sports-related TBIs that were not observed by a physician or healthcare professional. Based on an analysis of 2010 - 2016 data from the National Electronic Information Surveillance System – All Injury Program, Sarmiento et al[64] determined that an estimated 283,000 children 18 years old and younger in the United States received treatment at an emergency department (ED) for a sports-related TBI per year. This study demonstrated that the annual incidence rates of ED visits for sports-related TBI increased with age, as children and adolescents 10 to 14 and 15 to 17 years old had higher rates of ED visits for sports-related TBI compared to children in younger age groups.[64] Based on sex, males had approximately twice the incidence rate of ED visits for sport-related TBI compared to females across all study years.[64] Football contributed to the highest annual estimates of ED visits for sport-related TBI in males ages 10 to 14 and 15 to 17 years old, whereas soccer and basketball contributed to the highest annual estimates of ED visits for sport-related TBI in females within these age groups.[64] In Canada, an analysis of Canadian Community Health Survey (CCHS) data collected from 2000-2001 to 2017-2018 revealed that the annual incidence rate of SRC or other sport-related brain injuries was consistently two-folds higher in males compared to females.[65] Additionally, this analysis of CCHS data demonstrated that the incidence rates of SRC in youth ages 12 to 14 and 15 to 19 years old greatly outnumbered the incidence rates in adults 20 years old and older.[65] Similar findings were observed in 2017-2018 National Ambulatory Care Reporting System (NACRS) data for Ontario and Alberta, as males and females ages 10 to 14 and 15 to 19 years old had the highest age-specific incidences rates of ED visits for SRC.[66] Ice hockey and football or rugby contributed to the highest incidence rates of ED visits for SRC in males ages 10 to 14 and 15 to 19 years old, whereas the incidence rates of ED visits for SRC in females within these age groups were the highest for rugby, other ball-related sports and ice hockey.[66]

The National Collegiate Athletics Association Injury Surveillance Program (NCAA ISP) in the United States provides clinicians and researchers with a comprehensive and updated analysis of SRC epidemiology in NCAA men's and women's sports.[67-69] The NCAA ISP has been very useful for evaluating the effectiveness of concussion policy and rule changes in NCAA collision and contact sports and for informing both clinical practice and concussion management guidelines.[67-69] It utilizes a convenience sample of certified athletic trainers at participating collegiate institutions that voluntarily provide detailed injury reports and athlete exposure data using their clinical electronic medical record systems.[70] Similar to SRC and sports-related TBI epidemiology in children and adolescents in the United States and Canada,[64-66] NCAA sports that consistently have the highest incidence rates of SRC are collision and contact sports consisting of men's football, men's and women's ice hockey, women's soccer and men's wrestling.[67-69] Men's and women's sports in the NCAA that typically have the lowest incidence rates of SRC are limited and non-contact sports including swimming and diving, cross-country, track and field and tennis.[67,69] Among sex-comparable sports, NCAA women's soccer and basketball consistently have higher incidence rates of SRC compared to men's soccer and basketball.[67-69] Player to player contact (ex. tackling or being tackled in football, body checking in ice hockey) is the most frequently reported mechanism of SRC in NCAA men's sports, while contact with sport equipment (ex. heading in soccer, blow to the head from spiking in volleyball) or an on-field apparatus are the most frequently reported mechanisms of SRC in NCAA women's sports.[67,69] In contrast to the NCAA ISP in the United States, Canadian universities and colleges lack a structured national software-based injury surveillance program for monitoring U Sports and Canadian Collegiate Athletic Association competitions and practices, student-athlete participation and both musculoskeletal injuries and SRCs sustained during the preseason, regular season and postseason. To our knowledge, the only sport injury surveillance program that was utilized on a large scale for Canadian university varsity or collegiate student-athletes was the Canadian Intercollegiate Sport Injury Registry during the 1990s for prospectively tracking sport injury rates and athlete exposures in university varsity student-athletes competing in the Canada West division of the Canadian Intercollegiate Athletic Union.[71-75] A majority of studies have examined SRC epidemiology in a single Canadian university varsity sport including men's football,[72,73] men's basketball[74] and men's and women's ice hockey.[75-77] Only two studies to our knowledge have examined SRC epidemiology in a variety of sports for both sexes at the Canadian university varsity level, with both studies exclusively comprised of York University varsity student-athletes.[78,79] Analyzing patient chart data collected during three to four school years, both studies reported that female varsity student-athletes had significantly more diagnosed SRCs compared to males.[78,79] Consistent with findings reported in studies examining NCAA ISP data, the sports with the highest incidence rates or total SRCs diagnosed were collision sports including women's rugby, men's football and both men's and women's ice hockey.[78,79] Overall, the published literature on SRC epidemiology in Canadian university varsity student-athletes is dated and limited by student-athlete population differences across studies and the use of varying data collection and statistical methodologies.[71-79]

Concussion Symptomatology and Recovery

Diagnosis and management of SRC can be a difficult task for clinicians due to the heterogenous presentation of symptoms and impairments that often have differential trajectories of resolution.[80-82] Symptoms typically present immediately following a SRC or progressively evolve over time within the first 24 hours post-concussion.[29,83] Clinicians often categorize SRC symptoms into symptom domains that include physical (ex. headache, neck pain), cognitive (ex. difficulties concentrating, retrograde/anterograde amnesia), emotional (ex. irritability, anxiety), sleep/wake (ex. sleeping more or less than usual), vestibular (ex. dizziness, balance disturbances) and ocular symptom domains (ex. double vision, sensitivity to light).[29,80,84,85]A number of symptoms of SRC are non-specific and can be observed in whiplash-related disorders or cervical spine injuries with or without a SRC diagnosis,[86-88] neurodevelopmental disorders and learning disabilities (ex. attention-deficit/hyperactivity disorder),[89-92] diagnosed mood disorders and psychiatric conditions[91-94] and in healthy non-concussed athletes and adults.[95,96] Female youth and collegiate student-athletes often report more symptoms and higher symptom severity scores following SRC[97-100] and at preseason baseline assessment[92,96,101-103] compared to male athletes matched by age and competitive level. However, some studies have observed similar symptom reporting between the sexes following SRC and at baseline assessment.[104,105] A majority of youth and collegiate student-athletes diagnosed with SRC typically recover within 7 to 14 days post-concussion.[106-108] However, a proportion of athletes will present with symptoms and impairments in specific clinical domains that persist beyond the expected time frame of clinical recovery (ex. four or more weeks post-concussion).[81, 88, 109,110]Although findings vary across studies, demographic groups and clinical variables associated with prolonged recovery following SRC include children and youth athletes,[109,110] female sex,[68,81,88,109,111] preinjury history of mood disorders or psychiatric conditions,[88,109,112,113] history of non-specific headaches or migraines,[88,108,113] previous history of diagnosed SRC,[109,112,115-117] post-traumatic amnesia[106,114,115,117,] and higher overall symptom burden following SRC.[106,114,117-119] Given the heterogeneous nature of SRC, utilizing a multifaceted, interdisciplinary and individualized assessment approach is essential for diagnosis, management and rehabilitation of SRC. This approach should be comprised of a comprehensive battery of paper or computerized assessment tools and non-invasive diagnostic procedures that evaluate SRC symptoms and various measures of neurocognitive functioning, postural control or balance, cerebral blood flow (CBF), cognitive-motor integration (CMI), vision and oculomotor function.

Concussion Assessment Tools

Force Plate Postural Sway

Postural control is defined as the ability to control the whole body's centre of mass within the base of support in order to maintain a specific posture during static or dynamic activities.[120,121] This requires the central nervous system to process and integrate afferent information from the somatosensory, visual and vestibular systems to send commands to the muscles of the lower extremities to generate the appropriate musculoskeletal contractions needed to maintain postural control.[121-123] Individuals with concussion or TBI can present with dysfunction in processing and integrating vestibular information, and if visual and somatosensory inputs are disrupted or are providing conflicting information, concussed individuals have to rely heavily on vision in order to maintain postural control.[121-126] Force plate platform technology has been utilized to examine objective and sensitive measures of quiet standing postural control with eyes open and eyes closed in a variety of populations diagnosed with concussion or TBI.[121,127-135] The amount of sway that an individual exhibits to maintain postural control during quiet standing tasks can be measured on a force plate platform by quantifying the movements of the centre of pressure (COP) in the anteroposterior (AP) and mediolateral (ML) directions independently.[136,137] COP is defined as the point of location of the vertical ground reaction forces under the feet and represents the weighted average of all the pressures applied over the supporting surface of the area in contact with the ground.[136,137] In a quiet stance position with feet shoulder-width apart, AP sway reflects ankle activity (plantar flexion and dorsiflexion), whereas ML sway represents loading and unloading mechanisms of the hips (abduction and adduction).[136,137] Conventional force plate COP measures include root-mean-square of COP displacement (RMSdisp), which represents the standard deviation from the mean COP displacement or distance, and mean COP velocity (COPvel).[138,139] Multiple studies have reported that collegiate and university varsity student-athletes diagnosed with SRC exhibit significantly faster COPvel in the AP and/or ML directions during quiet standing tasks performed with eyes closed compared to non-concussed sport-matched controls.[127,131,135] Some of these studies also examined RMSdisp in both directions and found that concussed athletes had significantly greater RMSdisp in the AP direction compared to healthy control athletes.[127,135] Interestingly, Murray et al[135] reported that concussed collegiate athletes who self-reported a previous history of multiple SRCs had significantly larger RMSdisp and faster COPvel in both AP and ML directions compared to healthy control athletes, concussed athletes with no prior SRC history and concussed athletes with a previous history of one SRC. Of the studies examining force plate COP measures beyond the acute phase of SRC, Powers et al[127] reported that COPvel in the AP direction remained elevated in concussed university varsity athletes when evaluated at RTS, while Pryhoda et al[131] determined that 60 percent of collegiate athletes at six months post-concussion continued to present with elevated COPvel in the ML direction beyond the proposed clinical thresholds when performing a double-leg stance task with eyes closed. In stark contrast to the collection of findings from these studies, Dierijck et al[120] assessed quiet stance postural control in concussed contact sport athletes at 72 hours, two weeks and one-month post-concussion and reported no significant differences in RMSdisp and COPvel at each assessment timepoint in both eyes open and eyes closed conditions between concussed athletes and healthy non-concussed athletes matched for sport, age, body mass index (BMI), and previous SRC history.

Sport Concussion Assessment Tool

The CISG developed the Sport Concussion Assessment Tool (SCAT) during the Second International Conference on Concussion in Sport to provide physicians with a standardized tool for sideline evaluation of SRC and to serve as an educational tool for patients.[26] The original SCAT was comprised of a combination of preexisting concussion assessment tools including the Post-Concussion Symptom Scale, Standardized Assessment of Concussion (SAC) cognitive screen tests,[140] modified Maddocks questions for assessing sport-specific orientation (ex. "What team did we play last?"),[21] a neurological screen and guidelines for a symptom-limited RTS program with stages of progression.[26] The SCAT was subsequently updated during the Third,[27] Fourth[28] and Fifth[29] International Consensus Conference on Concussion in Sport to produce the SCAT2, SCAT3 and SCAT5 editions, respectively. While major SCAT components have continued to be a part of each subsequent edition, limitations and ceiling effects in scoring on specific components have been addressed through revisions and improvements based on valuable insight gathered from systematic reviews of the literature,[141-143] CISG expert panel discussions and conference attendees.[27-29]

The most recent edition, the SCAT5, is an internationally recognized test battery developed specifically for licensed healthcare professionals to provide them with a multidimensional framework for evaluating individuals 13 years of age or older with a suspected or probable SRC.[29, 143, 144] The SCAT5 is comprised of an immediate/on-field assessment and a follow-up office/off-field assessment.[144] The immediate/on-field assessment consists of screening for red flags (ex. LOC, weakness or tingling in the arms or legs) and observable signs of SRC (ex. lying motionless on the playing field, disorientation or confusion), a memory assessment featuring Maddocks questions, the GCS for examining level of consciousness and a brief cervical spine assessment.[144] The office/off-field assessment includes a section to fill out information on athlete demographic characteristics and previous SRC history, a graded symptom evaluation checklist, SAC cognitive screen tests, the modified Balance Error Scoring System (mBESS) for postural control evaluation and a rapid neurological screen.[144] Multiple studies have demonstrated that female athletes report more symptoms and higher symptom severity scores on the SCAT graded symptom checklist compared to male athletes following SRC[81,97,145-147] and at preseason baseline assessment.[93,96,102,103,147] However, some studies have found no significant differences in symptom reporting between the sexes.[79,105] The graded symptom evaluation checklist in various editions of the SCAT has been shown to have some clinical utility in tracking symptom recovery within the first few days post-concussion and assisting in the planning and decision-making for gradual RTS.[106,114,118,142,148,149] Multiple studies have demonstrated that female athletes are symptomatic for longer periods of time post-concussion compared to males[81,146] whereas some studies have reported similar durations of concussion symptom presentation between sexes.[147] The SAC in the SCAT5 is comprised of cognitive tests evaluating orientation in time and place (ex. "What is the day of the week?"), five- or ten-word immediate memory and delayed recall, and concentration with months in reverse order and digits backwards tests.[144] Multiple studies have demonstrated that concussed athletes have significantly lower SAC performance scores immediately post-concussion and/or at 24 hours post-concussion compared to healthy non-concussed athletes.[103,148,150-154] While some of these studies have shown that scores on the SAC tests in concussed athletes return to baseline values when assessed at 48 hours post-concussion,[150,151,153] other studies have reported mild cognitive deficits in concussed athletes based on their test scores that persist for up to one-week post-concussion.[103,148,154] Studies have reported mixed findings regarding sex differences in baseline performance scores on the orientation test,[79,96,103,105,155,156] five-word immediate memory and delayed recall tests[102,103,156] and concentration tests.[105,155] An optional ten-word list was included in the SCAT5 for the immediate memory and delayed recall tests in order to minimize ceiling effects in scoring observed with the five-word list.[142,143] Multiple studies have demonstrated that the ten-word list eliminates ceiling effects in scoring when applied in a baseline assessment setting[96,105,155,156,157] and when differentiating between concussed and non-concussed athletes.[158] Many of these studies also observed similar baseline performance scores between male and female athletes for the ten-word immediate memory and delayed recall tests.[96,105,155] The mBESS test is a modified version of the Balance Error Scoring System (BESS), the latter of which was originally developed by researchers at the University of North Carolina to serve as a quick, cost-effective and easy-to-administer test for evaluating postural control.[144,160] The mBESS test is comprised of three 20 second (sec) trials that evaluate standing balance on a firm surface without shoes and eyes closed in a double leg stance, a single leg stance (standing on non-dominant foot) and a tandem stance in a heel-to-toe formation (non-dominant foot behind the dominant foot).[144] Trials are scored by an examiner counting the number of pre-defined errors made by the participant.[144] In contrast, the traditional BESS test evaluates postural control with two trials per stance, with one trial performed on a firm surface and one trial performed on a medium-density foam surface.[160] Multiple studies have demonstrated that the mBESS and BESS tests are most useful in detecting postural control impairments in acutely concussed athletes given the observation that total error scores for both tests typically return to baseline when assessed at three to five days post-concussion.[102,148,149,153, 159,161] A systematic review determined that the BESS test has moderate to high reliability and low to moderate sensitivity evidence supporting its use for evaluating postural control impairments in athletes with SRC.[162] More recently, the mBESS test has been shown to have poor test-retest reliability with low sensitivity and high specificity in identifying impaired postural control in concussed collegiate football athletes, thus suggesting that a lack of impairments observed with the mBESS test does not necessarily rule out a SRC being present.[163] Additionally, the mBESS and BESS tests are known to be limited as a measure of postural control due to examiner subjectivity in recording errors, susceptibility to practice or learning effects as a result of serial testing and fatigue effects when administered to athletes immediately following a SRC.[125,160,164] The rapid neurological screen is comprised of five tests that assess comprehension, range of pain-free passive cervical spine movement, double vision, timed tandem gait and finger-to-nose coordination.[144] The diagnostic utility of the rapid neurological screen is unknown given that the screen is a new addition within the SCAT5. Tandem gait speed has been reported to be significantly slower in collegiate student-athletes within 48 hours post-concussion compared to baseline performance.[165] This same study observed no significant differences between the total number of errors made in both the mBESS and BESS tests following SRC relative to baseline, thus suggesting that the tandem gait test may be a more sensitive test measure of postural control deficits following SRC.[165] A study utilizing the SCAT5 to differentiate concussed from non-concussed professional ice hockey athletes determined that athletes diagnosed with SRC were more likely to report double vision and present with tandem gait deficits compared to non-concussed athletes.[159] In contrast, one study observed adequate performance on each of the rapid neurological screen tests for a majority of male elite-level Rugby Union athletes participating in off-field concussion screening.[166] Overall, the literature demonstrates that the SCAT5 and previous SCAT editions are best suited to be administered as part of the screening evaluation during the acute stage of SRC, particularly within the initial three to five days post-concussion.[102,106,114,118,142,148-151,153,159,161]

Cerebral Blood Flow

The pathway of CBF to the brain begins at the aortic arch, which branches into the brachiocephalic artery, the left common carotid artery (CCA) and the left subclavian artery.[167]

The brachiocephalic artery bifurcates into the right CCA and the right subclavian artery (see Figure 2).[167] The left and right CCA ascend the neck and bifurcate into the left and right internal carotid arteries (ICA) and external carotid arteries (ECA) at approximately the fourth cervical vertebrae (C4).[168-170] While the ECA supply blood to the extracranial structures, the ICAs give rise to several arterial branches before bifurcating into the middle cerebral arteries (MCA) and the anterior cerebral arteries (ACA).[168-170] The largest of the two terminal branches of the ICA, the MCA runs laterally into the lateral sulcus where it branches into superior and inferior divisions to perfuse the lateral surface of the cerebral hemisphere including the lateral aspect of the frontal lobe, the superior and inferior partial lobe and the lateral aspect of the temporal lobes.[169,171] The subclavian arteries branch to form the left and right vertebral arteries (VA).[168-171] The VAs penetrate the transverse forminae of C6 through C1 before entering the skull cavity via the foramen magnum to travel along the ventral surface of the brainstem.[169,171] The main branches of the VAs supply blood to the spinal cord (anterior and posterior spinal arteries) and both the medulla and cerebellum (posterior inferior cerebellar artery).[169,171] The VAs merge with one another at the pontomedullary junction to form the basilar artery.[169,171] The basilar artery runs in the basilar sulcus on the ventral surface of the pons and ends at the midbrain where it bifurcates to form the left and right posterior cerebral arteries (PCA).[169,171] The left and right ICAs, ACAs, PCAs, posterior communicating arteries, the anterior communicating artery and the basilar artery connect with one another at the base of the brain to form the circle of Willis.[169-171,173] The circle of Willis is a vital structure as it allows for the distribution of blood flow to both cerebral hemispheres and acts as a safety mechanism if one of the connected arteries becomes blocked or narrowed.[169-172] With a change in pressure as a result of a blocked or narrowed artery, the anastomosis of the arteries contributing to the circle of Willis will permit the continued circulation of blood supply in a forward or backward direction in order to compensate for the disrupted blood flow in the affected artery.[169-171]

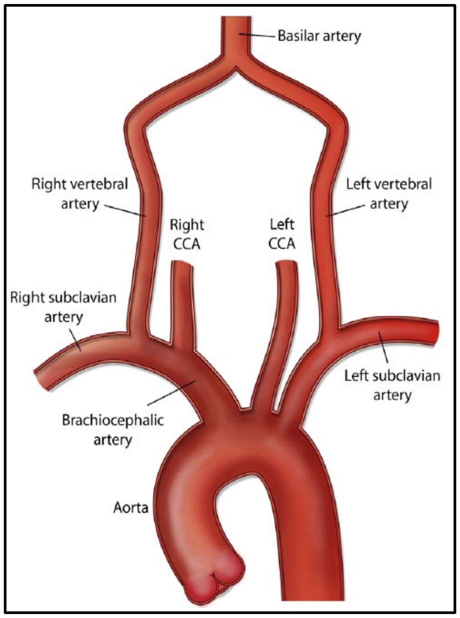

Figure 2. Schematic diagram illustrating the location of the aorta, brachiocephalic artery, left and right subclavian artery, left and right common carotid artery (CCA), left and right vertebral artery and the basilar artery. Diagram reprinted from Gunabushanam et al[167] with permission from the licensed content publisher Elsevier. See Appendix B for license details and terms and conditions provided by Elsevier and the Copyright Clearance Center.

CBF is generally defined as the volume of blood delivered to a defined unit mass of brain tissue per unit of time. The standard unit of measurement for CBF is milliliters (mL) of blood per 100 grams (g) of brain tissue per minute (min).[174] CBF can be assessed in a variety of ways depending on the diagnostic imaging techniques available and the goals of the researchers, particularly if they want to evaluate global or regional measures of CBF or both. For example, multiple studies have demonstrated in a variety of patient populations that CBF velocity in the MCA measured with transcranial Doppler ultrasound (TCD) is a valid and reliable index of regional CBF to specific areas of the brain supplied by the MCA.[175-180] Clinical researchers can directly quantify regional and global CBF volume with arterial spin labeling (ASL), a non-invasive and non-ionizing MRI technique that uses magnetic labelling of arterial blood water protons as an endogenous tracer for tissue perfusion imaging.[154,181-186] Researchers have also utilized Doppler ultrasound (DU) imaging techniques to estimate CBF within the cerebral arteries by measuring blood flow volumes (BFV) as a product of the angle-corrected, time-averaged flow velocity and the cross-sectional area of the artery.[187-193] Although ASL has its advantages, DU is a more readily available non-invasive imaging method that has a variety of benefits including low operational costs, accessibility for repeated measurements and its suitable for bedside monitoring.[190,191]

The control of CBF consists of a spectrum of overlapping regulatory mechanisms that facilitate optimal delivery of oxygenated blood and nutrients to the brain tissues and the removal of metabolic waste products and toxins.[171,194] A combination of mechanisms contribute to cerebral autoregulation, a complicated and often misinterpreted homeostatic process in the brain that minimizes the impact of the duration and magnitude of changes in mean arterial pressure (MAP) on CBF volume.[172,194,195] According to Neils Lassen's cerebral autoregulation curve presented in his influential review paper titled "Cerebral Blood Flow and Oxygen Consumption in Man"[196], CBF volume can remain constant (~50 ml/min/100 g brain mass) across a wide range of MAP values (~ 60–150 millimetres of mercury). Lassen's concept of cerebral autoregulation originated from averaged or adjusted CBF volume data and MAP measurements collected from seven studies that examined relationships between CBF volume and MAP in diverse participant populations including healthy human subjects administered highly vasoactive drugs and patients with systemic hypertension.[196] Multiple review papers have highlighted the erroneous assumption made in applying Lassen's traditional cerebral autoregulation framework, which was originally collected from scenarios involving slow, between-individual steady-state changes in MAP and physiological scenarios in which rapid, within-individual surges or fluctuations in

MAP were observed.[172,194,195] Contemporary research demonstrates that CBF regulation is much more pressure-passive than originally believed and it does not remain stable in all physiological and clinical conditions, especially in scenarios where there are rapid changes in MAP (ex. engaging in acute exercise).[172,195] For example, an individual who can tolerate large but steady changes in MAP without a significant change in CBF may experience a large reduction (or a large increase) in CBF in response to rapid changes in MAP.[172,195] While cerebral autoregulation is typically referred to as having static and dynamic components, this categorization is an experimental distinction rather than physiological one.[172,194.195,197] Static cerebral autoregulation aligns with the interpretations and conclusions of Lassen's work, referring to the steady-state relationship between CBF and MAP across several minutes to hours.[172,194.195,197] In contrast, dynamic cerebral autoregulation refers to the cerebral pressure-flow relationship observed during transient and rapid changes in MAP over a period of seconds or minutes (ex. during postural changes, engaging in acute exercise), whereby autoregulation reduces the impact of MAP changes by returning CBF towards baseline levels before full recovery of MAP.[172,194,195,197] CBF regulation in healthy humans is also believed to be mediated by a variety of sympathetic, parasympathetic, cerebral metabolic, myogenic and endothelium-dependent mechanisms working in unison.[172,194,197-198]

The pressure gradient driving CBF to the brain is cerebral perfusion pressure (CPP), which represents the difference between the MAP and the intracranial cerebral pressure (ICP), with ICP representing the pressure of the cerebrospinal fluid in the subarachnoid space.[172,200-202] Edema or intracranial hemorrhaging of the brain following moderate to severe TBI can cause elevations in ICP, leading to a disruption of CBF, a reduction in CPP and potentially a secondary ischemic insult.[194,202-204] Symptoms of elevated ICP can overlap with SRC symptoms including headaches, nausea and vision disturbances.[29,80,84,85] Although there is a limited amount of direct research evidence showing ICP changes in human subjects with concussion or mTBI,[205-208] findings from animal model studies suggest that ICP can remain elevated for several days following mTBI.[209-211]

CBF regulation is highly sensitive to changes in partial pressure of arterial carbon dioxide (P_aCO_2) and brain tissue levels of CO_2.[172,194,200] The entire cerebrovascular tree is sensitive to changes in $PaCO_2$ including the large cerebral arteries, pial arteries and arterioles and the parenchymal arterioles.[212-219] Interestingly, multiple studies have shown that the largest response to elevated P_aCO_2 (hypercapnia) occurs in the smaller arterioles based on vessel diameter changes relative to the baseline.[212,214,215,220,221] Hypercapnia leads to vasodilation of the arterioles in the downstream microvasculature bed, a reduction in cerebrovascular resistance and a resulting increase in CBF to clear out CO_2 from brain tissues.[194,200] In contrast, a reduction in $PaCO_2$ (hypocapnia) leads to vasoconstriction of the arterioles, an increase in cerebrovascular resistance and a subsequent decline in CBF that results in lower CO_2 clearance from the tissues.[194,200]

Measures of regional and global CBF volume have been investigated as biomarkers of neurophysiological recovery following SRC in youth and young adult athletes.[154,183-186] Multiple studies have found significantly reduced regional CBF volume in various lobes, cortices, gyri and other brain structures in concussed collegiate athletes compared to sex-, age- and sport-matched healthy control athletes, with concussed athletes presenting with variable and protracted recovery.[154,183,184] In university varsity student-athletes with acute SRC, Churchill et al[186] discovered that specific concussion symptom clusters had distinct patterns of altered regional CBF volume. This study reported that concussed athletes with high cognitive symptom scores on the SCAT3 graded symptom checklist had lower regional CBF volume in the frontal and subcortical areas relative to concussed athletes with high somatic symptom scores.[186] Interestingly, Barlow et al[185] reported that symptomatic children with mTBI had significantly higher global and regional measures of CBF volume (predominately bilateral inferior frontal and occipital regions) at 40 days post-injury compared to healthy controls of similar age and sex with no history of mTBI. This same study found that asymptomatic children that had clinically recovered from mTBI had significantly lower global and regional measures of CBF volume (predominately inferior temporal and parietal regions) at 40 days post-injury compared to healthy controls.[185]

Cognitive-Motor Integration

The concurrent application of thought and action is a process known as cognitive-motor integration (CMI).[222] CMI is essential for completing skilled activities, such as performing complex tasks at work or playing a sport, that are guided by non-standard visuomotor mappings where there is a decoupling of visual information from movement output and the integration of spatial and cognitive rules.[222] In contrast, standard visuomotor mappings guide simple tasks that involve direct interactions with a visual stimulus, whereby the stimulus itself guides the action and is the target of the action.[222] Elite athletes are highly skilled in their ability to utilize CMI within the context of sport-related rules, spatial information on the field of play and prior expertise in executing movements effectively and efficiently.[222] An example of a non-standard visuomotor task for an ice hockey athlete is passing the puck to a teammate on their right while looking and attempting to avoid a body check from an opponent to their left. In contrast, a standard visuomotor task is looking for a spare hockey stick on the bench rack and picking it up. It is hypothesized that concussion can cause deficits in rule-based skilled performance through disruptions within frontoparietal networks and communication between cortical and subcortical movement control brain regions that are responsible for planning and executing complex skilled movements that use CMI.[222-227] Most concussion assessment tools evaluate cognition and motor function separately and therefore lack the sensitivity to detect underlying functional impairments that could present when testing cognition and motor function concurrently through task paradigms that utilize task switching ("dual-tasking") and integration.[222] As a result, a touchscreen-based, eye–hand coordination assessment tool called the Brain Dynamic Indicator™ (BrDI™) was developed to evaluate CMI performance through a visuomotor task that incorporates two types of non-standard mapping: explicit rule integration (strategic control) and implicit spatial vision-to-hand-motion realignment (sensorimotor recalibration).[222] Multiple studies using the BrDI™ have demonstrated that young adult and youth athletes with a previous history of SRC have significantly pronounced CMI performance deficits compared to healthy age- and skill-matched athlete controls with no previous SRC history.[228-231] Interestingly, a majority of these athletes with a previous history of SRC were clinically asymptomatic and had long since returned to sport following their last SRC. Therefore, the results of these studies reveal that the lingering CMI performance deficits exhibited by these athletes had not been identified by standard concussion assessment tools.[228-231] A full body, sport-specific version of the BrDI™ known as the HurtSHynes™ Test has recently been piloted with the potential of being a more sensitive test metric of CMI performance for athletes returning to sport after recovering from a SRC.[232]

Vision and Oculomotor Function

Patients diagnosed with SRC may present with a variety of visual symptoms including intermittent blurred vision, double vision, motion sensitivity, eye strain and headaches.[88,233-235]

Many of these symptom complaints are often elicited or exacerbated by prolonged periods of reading, focusing or functioning within complex visuospatial environments.[88] Brain circuits involved in vision and oculomotor function are widely distributed in the frontal, parietal, cortical and subcortical structures, all of which are vulnerable to concussive brain trauma.[233,234] Many of these circuit pathways are responsible for coordinating saccades which are ballistic eye movements that rapidly shift foveation from one target stimulus to another.[233,234] Saccade generation involves complex cognitive processes including the assessment of the target stimulus and incorporating specific aspects of the target stimulus with goals and intentions.[233,234] Visuospatial information from the target stimulus is then relayed from the occipital lobe and processed in the posterior parietal cortex.[233,234] Saccades are initiated by signals transmitted from the frontal (FEF), parietal (PEF) or supplementary eye fields (SEF) to the superior colliculus (SC), which then project to the brainstem gaze centres (BGC) (see Figure 3).[233,234] The substantia nigra pars reticulata (SNPR) inhibits the SC to prevent saccade generation.[233,234] In order to deactivate this inhibitory mechanism, the FEFs are activated prior to a saccade, which then inhibits the SNPR via the caudate nucleus (CN).[233,234] The FEF generates voluntary or memory-guided saccades via direct connections to the BGC, the PEF produces reflexive saccades and the SEF generates saccades in coordination with body movements and successive saccades.[233,234] The dorsolateral prefrontal cortex (DLPC) is involved in the modulation of antisaccades.[233,234] Carrying a higher cognitive load than other saccades, antisaccades involve response inhibition of reflexive saccades to a target stimulus, followed by the generation of voluntary saccades in an equidistant and opposite direction of the target stimulus.[233,234] As the SCAT5 offers limited insight into the effects of SRC on vision and oculomotor function, oculomotor testing using eye tracking technology has been used to assess oculomotor function in athletes with acute SRC and persisting concussion symptoms (PCS).[88,236-239] Multiple studies have demonstrated that concussed collegiate and university varsity student-athletes exhibit significantly longer antisaccade reaction times or latencies and significantly higher percentage of directional errors for antisaccades at one-week post-concussion compared to healthy and physically active sex- and age-matched controls.[236,238] In contrast, Cochrane et al[239] reported that saccade latency was the most sensitive measure of oculomotor dysfunction in concussed collegiate student-athletes within 72 hours post-concussion compared to healthy age-matched collegiate student-athletes, whereas no significant differences were observed between concussed and healthy student-athletes in percentage of directional errors for antisaccades. Multiple studies have demonstrated that non-athlete patients with mild closed head injury (mCHI) have significantly impaired antisaccades and memory-guided saccades compared to matched healthy controls, with additional findings revealing increased saccadic latencies, higher directional errors and poorer spatial accuracy in mCHI patients.[240,241,242] In patients presenting with PCS following mCHI, Heitger et al[242] demonstrated that patients with PCS exhibited significantly more directional errors (antisaccades and memory-guided sequences of saccades) and significantly lower self-paced saccades on oculomotor tasks at three to five months post-injury compared to recovered mCHI patients. As concluded by Heitger et al[242], these oculomotor impairments observed in patients with PCS suggest prolonged dysfunction in response inhibition, short-term spatial memory, motor-sequencing programming and execution, visuospatial information processing and integration and visual attention under time pressure.

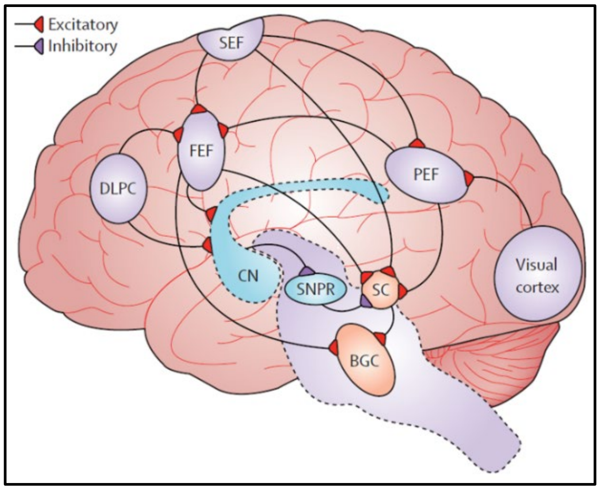

Figure 3. Major cortical areas involved in the control of eye movements and visual processing, with projections illustrating saccade generation. Diagram reprinted from Ventura et al[233] with permission from the licensed content publisher Elsevier. See Appendix C for license details and terms and conditions provided by Elsevier and the Copyright Clearance Center. Abbreviations: FEF, frontal eye fields; PEF, parietal eye fields; SEF, supplementary eye fields; SC, superior colliculus; BGC, brainstem gaze centres; SNPR, substantia nigra pars reticulata; CN, caudate nucleus; DLPC, dorsolateral prefrontal cortex.

Stroop Colour and Word Test

The Stroop Colour and Word Test (SCWT) is a neuropsychological assessment that examines a variety of executive functions including inhibition of cognitive interference, selective attention, cognitive flexibility and processing speed.[243,244] The test is comprised of three tasks performed in the following order: word task; colour task; and interference task.[243,245,246] The interference task involves colour-word pair items printed in an ink incongruent with the colour-word (ex. the word “blue” written in “yellow” ink). Performance on the interference task is dictated by the participant’s ability to activate the normally inhibited response of stating the ink colour of the colour-word as fast and accurately as possible while overcoming the cognitive interference associated with the more automatic or predominant response of stating the colour-word.[247] As a result, reaction times are typically slower for the interference task items compared to the word and colour task items. This phenomenon is known as the Stroop effect.[245] Neuroimaging studies examining brain activity of participants performing Stroop tasks have observed activation of brain structures within the fronto-parietal network, specifically the anterior cingulate cortex, dorsolateral prefrontal cortex, inferior frontal gyrus, inferior and superior parietal cortex and the insula.[226,248-250] Concussion-related dysfunction in the frontoparietal networks and interconnections between brain structures may be associated with poor performance on Stroop tasks.[223,224,226,251] For example, non-athlete adults with a current or previous history of concussion or TBI have been shown to have significantly higher Stroop error rates compared to healthy sex- and age-matched controls with no previous concussion history.[251,252] In contrast, some studies have reported no significant differences in SCWT errors across all three tasks between male athletes with a history of SRC and age-matched male athletes with no SRC history.[253,254]

CHAPTER TWO: THESIS PURPOSE, OBJECTIVES AND METHODS

Thesis Purpose and Objectives

The Varsity Athlete Data Analysis Research (VADAR) Consortium was established at York University as a long-term initiative to examine and compare the heterogenous features of SRC between male and female university varsity student-athletes using a comprehensive battery of both commonly administered concussion assessment tools and emerging tests or procedures. This battery consisted of SCAT5 tests, force plate COP measures of postural sway, DU measurements of cerebral BFV within the major cerebral arteries, both the BrDI™ and HurtSHynes™ Test for evaluating CMI performance, oculomotor tasks assessing saccades and antisaccdes and the SCWT to evaluate executive functions. The first action item of the VADAR Consortium was to collect preseason baseline values from a large sample of male and female varsity student-athletes at York University competing in a variety of collision, contact, limited and non-contact sports. This action item was pursued to optimize our assessment approach to SRC in the university varsity student-athlete population and to address the critical need for obtaining a normative dataset that can be used as a comparison to post-concussion data collected from student-athletes starting from the acute stage of SRC, at specific timepoints during their individualized recovery program and at return to sport (RTS) and return to learn (RTL). The objectives of this study were twofold. First, to conduct a descriptive analysis of preseason baseline data collected from university varsity student-athletes using a comprehensive battery of assessments, with data stratified by sex and concussion history for analysis. Second, to conduct two-way analysis of variance (ANOVA) statistics to examine the effects of sex, concussion history and the interaction effects between sex and concussion history on variables collected with each assessment.

Methods

Protocol

Baseline assessments were performed at York University's Goreman/Shore Sport Injury Clinic in August 2019 as part of the 2019-2020 preseason participation protocol organized as a joint effort between the VADAR consortium and the athletic therapy staff of the Athletics & Recreation Department. Upon arrival to the clinic, student-athletes were given consent forms and a demographic/medical information sheet to complete. Student-athletes were informed of the purpose, benefits and risks of each baseline assessment and were given the opportunity to ask questions regarding the study protocol.

Participants

The participant population consisted of York University varsity student-athletes who provided preseason baseline data for the 2019-2020 preseason participation protocol. Student-athletes were included in the study if they were 18 years of age or older, self-reported no history of concussion (No RHOC), or self-reported a previous history of diagnosed concussion (RHOC) and were asymptomatic at the time of preseason baseline data collection. Student-athletes were registered to compete in one of the following varsity sports: men's or women's ice hockey, basketball, soccer and volleyball; men's football; women's rugby; women's field hockey; co-ed teams of wrestling, tennis, cross-country and track and field. Student-athletes were excluded if they reported one or more of the following criteria on their preseason demographic/medical information sheet: recently diagnosed with a concussion and currently in concussion protocol; diagnosed with strabismus, colour blindness or had a history of visual epileptic seizures; history of neck pain within the previous two years; history of balance problems; recently sustained and/or rehabbing a musculoskeletal injury to the knee, hip or ankle; taking medications that may alter CBF. The study was carried out in accordance with the recommendations of the Declaration of Helsinki, with informed consent obtained from all student-athletes prior to study enrollment. Ethics approval was obtained from York University's Office of Research Ethics and Human Participants Review Committee.

Data Collection

Demographic Characteristics

The demographic/medical information sheet administered to each student-athlete was based on the SCAT5 athlete background section. Student-athletes provided information on their sex/gender, age and varsity sport in which they were registered to compete in for the 2019 – 2020 university varsity season. In addition, anthropometric measurements of body weight (kilograms;kg) and height (centimetres;cm) were collected. Student-athletes self-reported the number of previously diagnosed concussions that they had experienced in their lifetime, and if they had at least one previously diagnosed concussion, they disclosed the year in which their most recent concussion was sustained and the recovery time in days of their most recent concussion. For general medical history, student-athletes answered "yes" or "no" to the following questions: "Do you have a previous history of hospitalization for a head injury?"; "Have you been diagnosed or treated for a headache disorder or migraines?"; "Have you been diagnosed with a learning disability or dyslexia?"; "Have you been diagnosed with attention-deficit (ADD) or attention-deficit/hyperactivity disorder (ADHD)?".

Sport Concussion Assessment Tool 5

Student-athletes were administered the SCAT5 off-field assessment comprised of the graded symptom evaluation checklist, the Standardized Assessment of Concussion (SAC) cognitive tests, the modified Balance Error Scoring System (mBESS) for balance evaluation and the rapid neurological screen. For the graded symptom evaluation checklist, student-athletes self-rated 22 symptoms on a 7-point Likert scale ranging from 0 (none) to 6 (severe) based on how they generally felt in their day-to-day life. Ratings for 22 symptoms were summed to obtain a symptom severity score (maximum score = 132). The SAC cognitive tests evaluated orientation, five-word immediate memory, five-word delayed recall and concentration. The orientation test assessed awareness of the current day of the week, date, month, year and time (maximum score = 5). The immediate memory test was comprised of three trials that evaluated a student-athlete's ability to repeat as many words from a five-word list that they could remember being read to them by the test examiner. Each correct word was scored as one point. Scores for three trials were summed to obtain a five-word immediate memory total score (maximum score = 15). The delayed recall test was administered approximately five minutes after completing the immediate memory test to evaluate the number of words that could be accurately recalled from the same five-word list that was used for the immediate memory test (maximum score = 5). The concentration component of the SAC is comprised of the digits backwards test and months in reverse order test. The months in reverse order test assessed the ability of student-athletes to recite the 12 months of the year in reverse order beginning with December. One point was awarded for correctly reciting all 12 months in reverse order. A score of zero was given if any months were in the wrong order or were skipped. For the digits backwards test, the examiner read a string of numbers to student-athletes who were then asked to repeat them in reverse order. The test started with a string of three numbers (i.e., 4-9-3) and increased up to six numbers (i.e., 8-4-1-3-5-7) if each number string was answered correctly. One point was awarded for each string length answered correctly in reverse order (maximum score = 4). The digits backwards test was stopped if two consecutive answers were incorrect or if all four numbers strings were answered correctly in reverse order. Scores for the digits backwards and months in reverse order tests were summed to obtain the concentration total score (maximum score = 5). The mBESS test consisted of three 20 sec trials evaluating standing postural control on a firm surface without shoes in a double leg stance, a single leg stance (standing on non-dominant foot) and a tandem stance condition in a heel-to-toe formation (non-dominant foot behind the dominant foot). An examiner started timing each trial with a stopwatch when the student-athlete was in the proper position with hands on their hips and eyes closed. Each trial was scored by recording the number of errors, with one point allotted per error and a maximum number of 10 errors per trial. If the student-athlete committed multiple errors simultaneously, only one error was recorded. Errors on the mBESS test included the following: lifting hands off the iliac crest; opening eyes; any step, stumble or fall; moving hips into more than 30º of abduction; lifting the forefoot or heel; remaining out of the test position for more than five sec. Error scores for all three trials were summed to obtain a mBESS total error score (maximum error score = 30). For the rapid neurological screen, a normal/abnormal scoring system was used to assess comprehension (normal = athlete can read aloud and follow instructions without difficulty), pain-free passive cervical spine movement (normal = athlete has full range of pain-free passive cervical spine movement), eye movement without double vision (normal = athlete can look side-to-side and up-and-down without double vision), finger-to-nose coordination (normal = athlete can successfully perform five succussive finger-to-nose repetitions using their index finger as quickly and as accurately as possible) and tandem gait (normal = athlete can accurately and quickly walk in a forward direction with an alternating foot heel–to-toe gait without losing balance or having a separation between their heel and toe).

Force Plate Postural Sway Assessment

Force plate COP measures of postural sway were collected via 80 sec quiet standing tasks performed on a single ATMI AccuSway force plate (Advanced Mechanical Technology Inc., Watertown, MA, USA). Data was collected using AMTI NetForce data acquisition software. In a randomized order, student-athletes completed one quiet standing task in eyes open (EO) and eyes closed (EC) conditions. For both conditions, student-athletes were instructed to stand quietly with their arms at their sides and both feet shoeless on the force plate in a standardized foot position (long axis of the foot angled at 14°, heel centres 17 cm apart and positioned 10 cm from the back of the force plate).[255] In the EO condition, student-athletes were instructed to look straight ahead and fixate their eyes on a reference point located at eye level on the wall 2 m in front of them. Ground-reaction forces and moments from the force plate were sampled/digitized at 100 Hz and stored on a computer for processing. Centre of pressure data (COP) was processed in a custom code written in LabVIEW 2020 software (National Instruments, Austin, TX). The following force plate COP measures of postural sway were calculated in the anteroposterior (AP) and mediolateral (ML) directions in both EO and EC conditions: 95 % confidence ellipse area (AREA - CE) (measured in millimetres squared; mm^2); root-mean-square of COP displacement (RMSdisp) (measured in mm); mean COP velocity (COPvel) (measured in millimetres per second; mm/sec); range of COP displacement (measured in mm). AREA - CE is the ellipse area that encloses approximately 95 % of the points of the COP path.[138,139] AREA – CE measures in the AP and ML directions were calculated using the following formula from Preito et al[138]:

$$\text{AREA} - \text{CE} = \pi\, ab = 2\,\pi\, F_{.05\,[2,\, n-2]}\,[s^2_{AP}\, s^2_{ML} - s^2_{AP\,ML}]^{1/2}$$

$F_{.05\,[2,\, n-2]}$ represents the F statistic at a 95% confidence level for a bivariate distribution with n data points.[Prieto et al; 1996] s_{AP} and s_{ML} represent the standard deviations of the AP and ML time series, respectively, and $s_{AP\,ML}$ represents the covariance.[138] RMSdisp represents the deviations of sway from the mean COP location along the AP and ML time series.[138,139] RMSdisp measures in the AP and ML directions were calculated using the following formulas from Prieto et al[138]:

$$\text{RMSdisp AP} = \left[1/N \sum \text{AP}[n]^2\right]^{½}$$
$$\text{RMSdisp ML} = \left[1/N \sum \text{ML}[n]^2\right]^{½}$$

COPvel is the average velocity of the COP during the AP and ML time series.[138,139] COPvel measures in the AP and ML directions were calculated using the following formula from Preito et al[138]:

$$\text{COPvel} = \text{TOTEX/T}$$

TOTEX represents the total excursions or total length of the COP path and T denotes the time series sampling period. The range of COP displacement represents the maximum distance between any two points on the COP path during the time series sampling period.[138,139] Range measures for the AP and ML directions were calculated using the following formulas from Quijoux et al[139]:

$$\text{Range AP} = \max_{1 \leq n \leq m \leq N} \lceil \text{AP}_n - \text{AP}_m \lceil$$
$$\text{Range ML} = \max_{1 \leq n \leq m \leq N} \lceil \text{ML}_n - \text{ML}_m \lceil$$

Cerebral Blood Flow Volume Assessment

The DU methodology used in the current study for the cerebral blood flow volume (BFV) assessment has been validated in multiple studies that evaluated cerebral BFV in healthy adults using DU.[187-192] A portable LOGIQ™ *e* Ultrasound System (GE Healthcare, California, USA) equipped with a 12MHz linear array transducer was utilized to measure CBF velocities (cm/sec) and vessel diameters bilaterally for the common carotid artery (CCA), internal carotid artery (ICA) and the vertebral artery (VA).[193] Student-athletes were examined in a supine position on a therapy table with their heads slightly elevated and turned to the contralateral side by ~ 10º to measure CBF velocity in the CCA and VA and by 25° to 40° to measure CBF velocity in the ICA. Water soluble ultrasound transmission gel was applied to the surface of the transducer to serve as a coupling medium that allowed the ultrasound sound waves to be transmitted from the transducer to the targeted cerebral artery. The CCA was located in the transverse plane (Figure 4A) and imaged in the longitudinal plane (Figure 4B). The ICA was imaged at or slightly above (~1 cm) the level of the bifurcation of the CCA and was estimated to be between levels of the C2-C4 vertebrae to account for individual variability (Figure 4C). The VA was imaged at the level of the intertransverse segments of the vertebrae (Figure 4D). Angle-corrected CBF velocity measurements were collected across the entire vessel diameter with an insonation angle of 60º to ensure that measurements were as uniform as possible. Vessel diameter was measured three times across three cardiac cycles in order to obtain an average value for a single cardiac cycle. Cross-sectional area (CSA) (cm^2) of each vessel was calculated using the following formula: $(\text{vessel diameter} \div 2)^2 \times \boldsymbol{\pi}$. Time-averaged mean velocity (TAMEAN) (cm/sec) was recorded during end-diastolic phase of the cardiac cycle when the velocity profile was parabolic. Cerebral BFV measurements (millilitres per min; mL/min) were calculated bilaterally for the CCA, ICA and VA using the following formula: TAMEAN x vessel CSA x 60 sec (adjusting for a single cardiac cycle). Total cerebral BFV was calculated as the sum of the total ICA BFV and the total VA BFV.

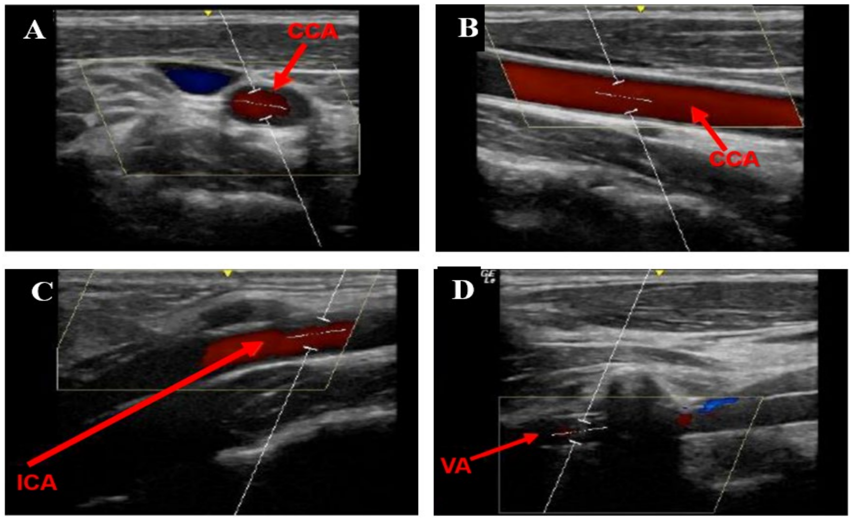

Figure 4. Doppler ultrasound imaging of **(A)** the common carotid artery (CCA) in the transverse plane, **(B)** the CCA in the longitudinal plane, (**C)** the internal carotid artery (ICA) at the level of bifurcation of the CCA and **(D)** the vertebral artery (VA) at the level of the intertransverse segments of the cervical vertebrae. Each image is reprinted from a master's thesis submitted by Ravneet Kalkat.[193]

Brain Dynamic Indicator™

The BrDI™ consists of a standard visuomotor mapping task (standard condition) and a non-standard visuomotor mapping task (CMI condition). Student-athletes performed each task by sliding the index finger of their dominant hand along a ASUS touchscreen tablet (ASUS Transformer Book T100TAF, Taipei City, TW) or an externally connected USB Keytec™ touchpad (Tyco Touch Inc., Richardson, TX) situated perpendicularly (horizontal plane) to the ASUS touchscreen located in the vertical plane. This setup ensured that the horizontally oriented touchpad was within a comfortable reach range of the student-athlete, while the vertically oriented touchscreen was located at or slightly below eye level. Each trial started with the student-athlete guiding a crosshair cursor to a yellow central target, which changed to green when reached. After the cursor was held in the green central target for 4000 milliseconds (ms), the central target disappeared and a red peripheral target (15 mm in diameter) appeared on the screen 55 mm in one of four peripheral directions (up, down, left, right) from the central target.

The central and peripheral targets were viewed on a black background to ensure good contrast. The emergence of the red peripheral target served as the ‘Go’ signal for the student-athlete to slide their index finger of their dominant hand along the touchscreen to move the cursor to the red peripheral target as quickly and accurately as possible. Once the cursor reached the target and was held for 500 ms, the red peripheral target disappeared and signaled the end of the trial. Following an inter-trial interval of 2000 ms, the yellow central target reappeared, signalling the student-athlete to return to the centre of the touchscreen for the next trial. In the standard condition, the spatial location of the red peripheral target on the touchscreen and the required hand movement were aligned (see Figure 5A). The CMI condition introduced two levels of decoupling, plane change and cue reversal (see Figure 5B). Plane change required implicit sensorimotor recalibration, with student-athletes instructed to maintain their gaze on the red peripheral target located on the vertically oriented touchscreen while moving the cursor on the horizontally oriented touchpad. Cue reversal required explicit rule integration with the motion of the cursor rotated 180° from the motion of the index finger. For example, to move the cursor to the left, the student-athlete had to slide their index finger to the right. In a randomized block design, student-athletes completed five trials in each of the four target directions (up, down, left, right) per condition. Therefore, student-athletes completed 20 trials in the standard condition and CMI condition, respectively. The total time to complete the BrDI™ assessment was approximately four to six minutes for each student-athlete.

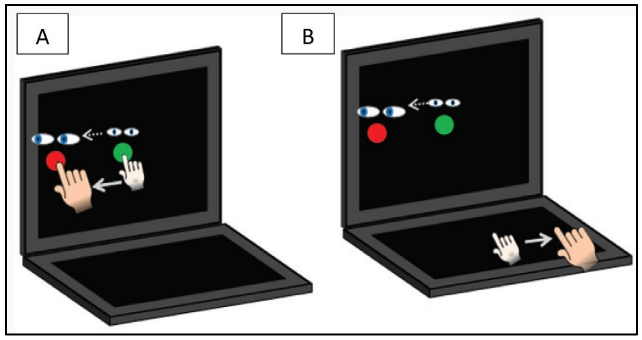

Figure 5. Illustration of the Brain Dynamic Indicator™. **(A)** Standard condition. (**B)** Cognitive-motor integration condition. Illustration reprinted from Smeha et al[256] with permission under the terms of the Creative Commons CC BY license (link: https://creativecommons.org/licenses/by/4.0/).

A custom-written analysis program (MATLAB®, Mathworks, Inc., Natick, MA) was used to process scored BrDI™ data to compute movement timing and movement execution variables. Kinematic variables for movement timing included movement time (MT), reaction time (RT) and peak velocity (PV). MT was calculated as the time interval (sec) between the movement onset and offset (reaching the peripheral target location) and was comprised of the ballistic movement time (MTb, initial movement offset) and the total movement time (MTf, full movement offset). RT was calculated as the time interval (sec) between the disappearance of the central target and the movement onset. PV represented the maximum velocity (mm/sec) obtained during the ballistic movement. Kinematic variables for movement execution were normalized path length (PLfN), absolute error (AE, accuracy) and variable error (VE, precision). PLfN was quantified as the percentage (%) of distance travelled between the start (movement onset) and end location (movement offset) of the entire movement. AE was calculated as the average distance (mm^2) between individual ballistic movement endpoints and the actual target location. VE was calculated as the average distance (mm^2) between the endpoints of the individual ballistic movements from their mean movements. The calculated outcomes for each variable were based on the average value for all correct trials in the standard and CMI condition.

HurtSHynes™ Test

The HurtSHynes™ Test evaluated the ability of student-athletes to execute movements in response to a series of visual directional cues while running a 26-metre (m) sprint.[232] The visual directional cues (up, down, left, right) were presented by an examiner holding a football to ensure the student-athlete could see the cues as they progressed through the test. Similar to the BrDI™, the HurtSHynes™ Test consists of a standard visuomotor mapping task (standard condition) and a non-standard mapping task (CMI condition). In the standard condition, the spatial location of the examiner's visual directional cues and the required movement responses of the student-athlete were matched. When the examiner extended their left arm holding the football, the correct response for the running student-athlete was to cut two steps laterally to the same side as the football (see Figure 6A). If the examiner raised the football over their head, the correct response for the student-athlete was to jump up with both hands in the air, plant their feet following the jump and then continue running (see Figure 6B). If the examiner lowered the football to the ground or below their waist, the student-athlete was required to drop down into a push-up stance, get back up and continue running. The CMI condition involved non-standard mappings of plane change and cue reversal, with the student-athlete performing movements in opposition to the visual directional cues presented by the examiner. For example, when the examiner extended their right arm, the correct response in the CMI condition for the running student-athlete was to cut two steps laterally to the opposite side of the football (see Figure 6C). When the examiner raised the football over their head, the correct response for the student-athlete was to drop down into a push-up stance (see Figure 6D), whereas lowering the football to the ground would require the student-athlete to jump up with both hands in the air.

Figure 6. Image examples of HurtSHynes Test™ visual directional cues and the corresponding athlete responses in the standard condition **(A and B)** and cognitive-motor integration condition **(C and D)**. Images are reprinted from a master's thesis submitted by Christina Amaral.[232]

The HurtSHynes™ Test was conducted on a leveled portion of grass. Student-athletes were instructed to run as fast as they could towards the finish line while responding to a visual directional cue administered every 5 m. Student-athletes were also reminded to keep their eyes focused on the football and maintain their running sprint following each response to a visual cue. Prior to starting the test, each student-athlete walked to a yellow soccer cone (20 cm x 20 cm x 5 cm) designated as the starting position. The examiner was located 26 m away at the test finish line marked by a yellow end cone. Each student-athlete was instructed to wait for the examiner to yell "3, 2, 1, Go!", with the word "Go" serving as the signal for the student-athlete to begin the test and start running. The entire HurtSHynes™ Test consisted of eight visual directional cues, with four cues in the standard condition and CMI condition, respectively. The order in which the examiner administered the four visual directional cues was randomized for each student-athlete for both conditions. To minimize potential learning effects, each student-athlete was randomly assigned to complete either the standard condition or the CMI condition first. Task completion time (ms) for the standard condition and CMI condition was recorded by the examiner using a manual stopwatch. Errors in response to visual directional cues were recorded by the examiner for each condition, with eight errors being the maximum number of errors a student-athlete could make for the entire test (maximum four errors per condition).

Oculomotor Assessment and Stroop Colour and Word Test

The oculomotor assessment, comprised of a saccade and antisaccade task, and the Stroop Color and Word Test were both administered using the NeuroFlex® vision software program (Saccade Analytics, Montreal, QC) delivered through a FOVE® Virtual Reality headset (FOVE, Inc., Chiyoda City, Tokyo) and a Dell™ G5 15 gaming laptop (Dell Inc., Round Rock, TX).[257] The saccade task consisted of a series of 12 small black targets displayed on a blue coloured screen, with targets appearing one at a time at 500 ms intervals at predetermined locations from the centre of the visual field (see Figure 7A). Student-athletes were instructed to direct their eyes to each target as fast as possible without moving their head and neck. Saccade latency (ms) was recorded for each eye movement during the saccade task. The antisaccade task began with student-athletes instructed to maintain a fixed gaze on a black target presented in the centre of the visual field. After a pre-set time of 250 – 500 ms, the black target disappeared and a red 'X' target appeared to the left or right periphery (see Figure 7B). Student-athletes were instructed to avoid looking at the red target and instead direct their eyes in an equidistant and opposite direction. Antisaccade reaction time (ms) was recorded for each eye movement during the antisaccade task. The SCWT consisted of a word task, a colour task and an interference task. Student-athletes were instructed to provide responses to as many items as possible within a 45 sec time period for each task. For the word task, student-athletes were instructed to verbally identify a colour *word* printed in white ink on a black screen (see Figure 8A). For the colour task, student-athletes were asked to state the *colour* of the items presented as five 'X' letter sequences ("XXXXX") (see Figure 8B). The interference task consisted of colour-word pairs printed in an ink incongruent with the words (ex. the word "blue" written in yellow ink). For this task, student-athletes were instructed to state the colour of the ink being shown (Figure 8C). The number of errors made by each student-athlete for the word, colour and interference tasks were recorded by the examiner and summed to obtain the total number of errors made on the entire SCWT.

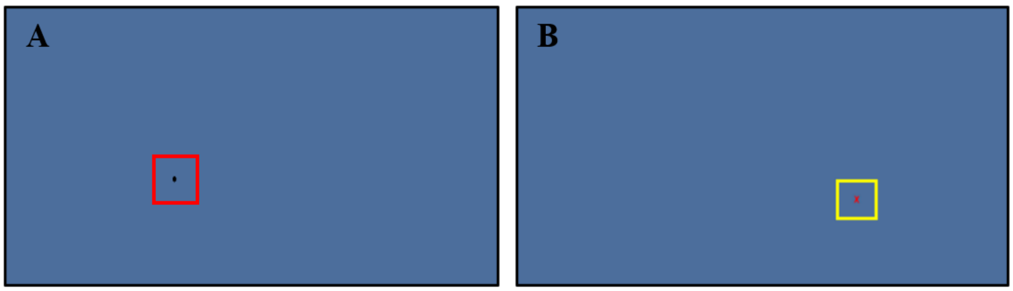

Figure 7. Images of the **(A)** saccade task and **(B)** antisaccade task. Images are reprinted from a master's thesis submitted by Michael Modica.[257]

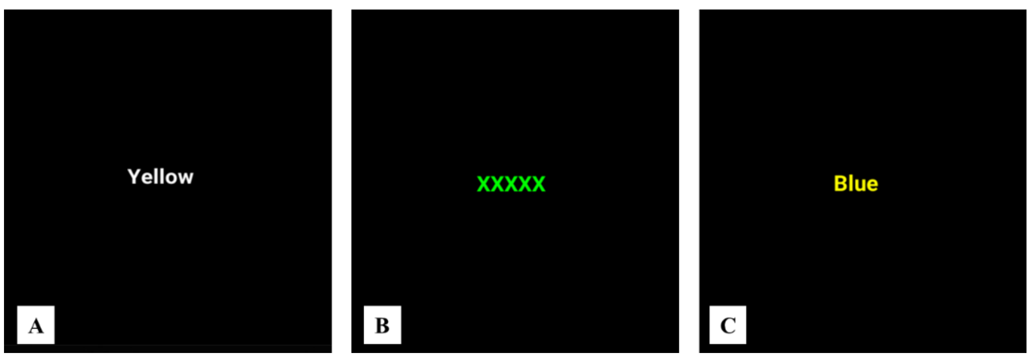

Figure 8. Image examples of the **(A)** word task, **(B)** colour task and **(C)** interference task of the Stroop Colour and Word Test. Images are reprinted from a master's thesis submitted by Michael Modica.[257]

Statistical Analysis

Statistical analyses were performed using IBM SPSS Statistics for Windows, version 27.0 (IBM Corp., Armonk, NY, USA) and Microsoft Excel 2019 (Microsoft Corp., Redmond, WA, USA). Demographic characteristics for university varsity student-athletes were stratified by sex for analysis. Means, standard deviations (SD) and ranges were calculated and reported for age, body weight, height, number of previously diagnosed concussions, recovery time (days) of most recent concussion and years since most recent concussion. For each of these characteristics, two-tailed independent t-tests were used to assess the significance level of the difference between means for male and female student-athletes. The number of previously diagnosed concussions (0, 1, 2, $\geq$ 3 concussions), recovery time of most recent concussion (0, 1 - 7, 8 - 14, 15 - 21, 22 - 28, > 28 days) and years since most recent concussion (0, 1, 2, 3, $\geq$ 4 years) were also compared between sexes using categorical data. Categorical data was used to compare the number and percentage of male and female student-athletes responding "yes" or "no" for each of the SCAT5 athlete background questions regarding general medical history. Student-athlete data on varsity sport participation for the 2019-2020 university varsity season was examined by sex and concussion history. Varsity sports were categorized as collision, contact and limited contact/non-contact sports. These categories were adapted from the American Academy of Pediatrics[258] and have been utilized in multiple studies involving NCAA student-athletes.[69,259-261] University varsity men's football, men's and women's ice hockey and women's rugby were categorized as collision sports due to the frequent and purposeful player contact (ex. tackling or body-checking) involved in each of these sports that is often delivered with high levels of force.[258] University varsity men's and women's soccer, men's and women's basketball, wrestling and women's field hockey were categorized as contact sports due to the routine player contact involved in these sports that is typically delivered with varying levels of force, in addition to contact with equipment or playing surfaces that can lead to SRC or a variety of musculoskeletal injuries.[258] University varsity men's and women's volleyball, track and field, cross-country and tennis were categorized as limited contact/non-contact sports due to the infrequent, accidental or the absence of player contact involved in these sports.[258] Preseason baseline data collected from each assessment was stratified by sex (male and female) and concussion history (No RHOC and RHOC) for descriptive analyses. For SCAT5 variables, means, SDs and ranges were calculated and reported for the total number of baseline symptoms and the total symptom severity scores from the graded symptom evaluation checklist, scores for tests in the SAC cognitive screen (orientation, five-word immediate memory, five-word delayed recall, digits backwards, concentration), errors for each mBESS stance (double leg, single leg and tandem stance) and mBESS total error scores. For the months in reverse order test within the concentration component of the SAC cognitive screen, means, SDs and the percentage of student-athletes with correct answers were calculated and reported. Bar charts were created to visualize the percentage distribution of scores or baseline symptoms for each SCAT5 test component (except rapid neurological screen tests), with one chart for student-athletes stratified by sex and one chart for student-athletes stratified by concussion history. For each of the rapid neurological screen tests, the percentage of student-athletes with normal results per the criteria described in the SCAT5 were calculated and reported. The number and percentage of student-athletes self-reporting specific baseline symptoms on the SCAT5 graded symptom evaluation checklist were calculated and reported based on sex, concussion history and for the total student-athlete population participating in this study. Clustered column charts were created to visualize and compare the percentage of student-athletes self-reporting specific baseline symptoms based on sex and concussion history. Pearson chi square (χ^2) tests with 2 × 2 contingency tables were conducted to determine if there were statistically significant associations between sex, or concussion history, and self-reporting specific baseline symptoms. Cramer's V effect size measures were calculated to assess the strength of the association between sex, or concussion history, and self-reporting specific baseline symptoms. The strength of associations were interpreted as negligible ($0.00 < V$

< 0.10), weak (0.10 < V < 0.20), moderate (0.20 < V < 0.40), relatively strong (0.40 < V < 0.60), strong (0.60 < V < 0.80) and very strong (0.80 < V < 1.00) based on criteria published by Rea and Parker.[262] A Fisher's exact test was used when one or more cells in the 2x2 contingency table had an expected frequency count of less than five. For the force plate postural sway assessment, means and SDs were calculated for AREA – CE in both EO and EC conditions, RMSdisp, COPvel and Range in AP and ML directions for both EO and EC conditions. For the cerebral BFV assessment, means and SDs were calculated for CCA, ICA and VA BFV bilaterally and total cerebral BFV. Within sexes, two-tailed independent t-tests were used to assess the significance level of the difference between left- and right-side BFV measurements for the CCA, ICA and VA. For the BrDI™ assessment, means and SDs were calculated for MTb, MTf, RT, PV, PLfN, AE and VE in the standard condition and CMI condition, respectively. For the HurtSHynes™ Test, means and SDs were calculated for completion time in the standard condition and the CMI condition, whereas means, SDs and ranges were calculated for total errors made in the standard condition and CMI condition. For the oculomotor assessment, means and SDs were calculated for saccade latency and antisaccade reaction time. For the SCWT, means, SDs and ranges were calculated for errors made in the word task, colour task, interference task and the entire SCWT. A two-way ANOVA was used to examine the significance of main effects of sex, concussion history and the interaction effects between sex and concussion history on each variable. Bar charts were created to visualize significant interaction effects between sex and concussion history for a specific variable. Statistical significance was accepted at $P < 0.05$ for all analyses.

CHAPTER THREE: RESULTS

Demographic Characteristics

Descriptive statistics for age, anthropometric measurements, number of previously diagnosed concussions, recovery time of most recent concussion and years since most recent concussion for male, female and total university varsity student-athletes are presented in Table 1. Preseason baseline data from a total of 325 university varsity student-athletes (male n = 165; female n = 160) was analyzed. Although male and female student-athletes were similar in age ($P = 0.095$; Table 1), males were significantly taller ($P < 0.001$; Table 1) and heavier ($P < 0.001$; Table 1) than females. A total of 140 student-athletes had a RHOC (male = 62 out of 165, 37.58%; female = 78 out of 160, 48.76%) and 185 student-athletes had No RHOC (male = 103 out of 165, 62.42%; female = 82 out of 160, 51.25%). Approximately 25% of all student-athletes (82 out of 325) reported one previously diagnosed concussion (male = 39 out of 165, 23.64%; female = 43 out of 160, 26.88 %), approximately 11% of all student-athletes (36 out of 325) reported two previously diagnosed concussions (male = 13 out of 165, 7.88%; female = 23 out of 160, 14.38%) and approximately 7% of all student-athletes (22 out of 325) reported three or more previously diagnosed concussions (male = 10 out of 165, 6.06%; female = 12 out of 160, 7.5%). While female student-athletes had a higher mean number of previously diagnosed concussions compared to males, the difference between sexes was not statistically significant ($P = 0.06$). The most common recovery time durations for the most recent concussion self-reported by student-athletes with a RHOC were durations of 28 days or more (male = 17 out of 62, 27.42%; female = 30 out of 78, 38.46%), between 1 to 7 days (male = 14 out of 62, 22.58%; female = 10 out of 78, 12.82%) and between 8 to 14 days (male = 9 out of 62, 14.52%; female = 13 out of 78, 16.67%).

Female student-athletes with a RHOC had significantly longer mean recovery time durations for their most recent concussion compared to male student-athletes with a RHOC ($P = 0.019$).

Table 1. Descriptive statistics for age, anthropometric measurements, number of previously diagnosed concussions, recovery time of most recent concussion and years since most recent concussion for male, female and total university varsity student-athletes.

Characteristic	Male (n = 165)	Female (n = 160)	Total (n = 325)
Age, mean ± SD (range) [a]	20.18 ± 1.82 (17 - 25)	19.84 ± 1.78 (17 - 31)	20.01 ± 1.80 (17 - 31)
Body weight (kg), mean ± SD (range) [b]	84.23 ± 19.69 (50 - 170) *	67.09 ± 12.13 (49 - 109)	75.96 ± 18.56 (49 - 170)
Height (cm), mean ± SD (range) [c]	183.50 ± 10.77 (118 - 205) *	170.40 ± 6.90 (150 - 193)	176.83 ± 11.13 (118 - 205)
Number of previously diagnosed concussions, n (%)			
0	103 (62.42)	82 (51.25)	185 (56.92)
1	39 (23.64)	43 (26.88)	82 (25.23)
2	13 (7.88)	23 (14.38)	36 (11.08)
≥ 3	10 (6.06)	12 (7.5)	22 (6.77)
Number of previously diagnosed concussions, mean ± SD (range)	0.59 ± 0.96 (0 - 6)	0.80 ± 1.01 (0 - 5)	0.70 ± 0.99 (0 - 6)
Recovery time of most recent concussion, n (% of athletes with a RHOC)			
0 days	3 (4.84)	1 (1.28)	4 (2.86)
1 - 7 days	14 (22.58)	10 (12.82)	24 (17.14)
8 - 14 days	9 (14.52)	13 (16.67)	22 (15.71)
15 - 21 days	3 (4.84)	4 (5.13)	7 (5)
22 - 28 days	2 (3.23)	2 (2.56)	4 (2.86)
> 28 days	17 (27.42)	30 (38.46)	47 (33.57)
Missing data	14 (22.58)	18 (23.08)	32 (22.86)
Recovery time of most recent concussion (days), mean ± SD (range)	22.79 ± 25.10 (0 - 120)	45.82 ± 63 (0 - 365) *	35.58 ± 50.97 (0 - 365)
Years since most recent concussion, n (% of athletes with a RHOC)			
0 years	6 (9.68)	16 (20.51)	22 (15.71)
1 years	12 (19.35)	18 (23.08)	30 (21.43)
2 years	9 (14.52)	19 (24.36)	28 (20.00)
3 years	13 (20.97)	11 (14.10)	24 (17.14)
≥ 4 years	19 (30.65)	12 (15.38)	31 (22.14)
Missing data	3 (4.84)	2 (2.56)	5 (3.57)
Years since most recent concussion, mean ± SD (range)	3.19 ± 2.63 (0 - 13)	2.28 ± 2.52 (0 - 14)	2.67 + 2.60 (0 – 14)

* Statistically significant difference ($P < 0.05$) between sexes.

Abbreviations: kg, kilograms; cm, centimetres; RHOC, reported history of concussion.

[a] Group sample sizes for age: male (n = 161); female (n = 160).

[b] Group sample sizes for body weight: male (n = 148); female (n = 138).

[c] Group sample sizes for height: male (n = 131); female (n = 136).

Table 2 presents data for the number of university varsity student-athletes participating in each varsity sport stratified by sex. The five varsity sports with the greatest number of male student-athletes participating in this study were men's ice hockey (34 out of 165, 20.61%), men's football (33 out of 165, 20%), men's soccer (24 out of 165; 14.55%), track and field (22 out of 165, 13.33%) and men's basketball (18 out 165, 10.91%). The five varsity sports with the greatest number of female student-athlete participating in this study were track and field (27 out of 160, 16.88%), women's soccer (25 out of 160, 15.63%), women's ice hockey (24 out of 160, 15%), women's rugby (24 out of 160, 15%) and women's field hockey (18 out of 160, 11.25%). When examined by sport contact level categories, collision sports had the greatest number of male student-athletes (67 out of 165, 40.61%), followed by contact sports (54 out of 165, 32.73%) and limited contact/non-contact sports (44 out of 165, 26.67%). In contrast, contact sports had the greatest number of female student-athletes (61 out of 160, 38.13%), followed by limited contact/non-contact sports (51 out of 160, 31.88%) and collision sports (48 out of 160, 30%). Table 3 presents data on the number of university varsity student-athletes participating in each varsity sport stratified by concussion history. Varsity sports with the greatest number of student-athletes with a RHOC were women's rugby (19 out of 140, 13.57%), men's football (17 out of 140, 12.14%), men's ice hockey (16 out of 140, 11.43%), women's soccer (12 out of 140, 8.57%) and women's field hockey (12 out of 140, 8.57%). The varsity sports with the lowest number of student-athletes with a RHOC were cross-country and tennis (4 out of 140, 2.86%), men's volleyball (5 out of 140, 3.57%), women's volleyball (7 out of 140, 5%), men's soccer (7 out of 140, 5%), men's basketball (7 out of 140, 5%) and wrestling (7 out of 140, 5%). Cross-country and tennis were combined for this analysis due to the low number of previously diagnosed concussions that had been self-reported by student-athletes competing in these sports.

The varsity sports with the greatest number of student-athletes with No RHOC were track and field (41 out of 185, 29.73%), men's ice hockey (18 out of 185, 9.73%), men's soccer (17 out of 185, 9.19%), men's football (18 out of 185, 8.65%) and both cross-country and tennis combined (14 out of 185, 7.57%). When examined by sport contact level categories, collision sports had the greatest number of student-athletes with a RHOC (63 out of 140, 45%), followed by contact sports (53 out 140, 37.86 %) and limited contact/non-contact sports (24 out of 140, 17 %). In contrast, limited contact/non-contact sports had the greatest number of student-athletes with No RHOC (71 out of 185, 38.38%), followed by contact sports (62 out of 185, 33.52%) and collision sports (52 out of 185, 28.11%).

Table 2. Number (%) of university varsity student-athletes participating in each varsity sport stratified by sex.

Sport	Male (n = 165)	Female (n = 160)
Collision sports		
Men's ice hockey	34 (20.61)	N/A
Women's ice hockey	N/A	24 (15)
Men's Football	16 (8.65)	N/A
Women's rugby	N/A	24 (15)
All collision sports	67 (40.61)	48 (30)
Contact sports		
Men's soccer	24 (14.55)	N/A
Women's soccer	N/A	25 (15.63)
Men's basketball	18 (10.91)	N/A
Women's basketball	N/A	13 (8.13)
Wrestling	12 (7.27)	5 (3.13)
Women's Field hockey	N/A	18 (11.25)
All contact sports	54 (32.73)	61 (38.13)
Limited contact/non-contact sports		
Men's volleyball	14 (8.48)	N/A
Women's volleyball	N/A	14 (8.75)
Track and field	22 (13.33)	27 (16.88)
Cross-country	3 (1.82)	6 (3.75)
Tennis	5 (3.03)	4 (2.5)
All limited contact/non-contact sports	44 (26.67)	51 (31.88)

Table 3. Number (%) of university varsity student-athletes participating in each sport stratified by concussion history.

Sport	No RHOC (n = 185)	RHOC (n = 140)
Collision sports		
Men's ice hockey	18 (9.73)	16 (11.43)
Women's ice hockey	13 (7.03)	11 (7.86)
Men's Football	16 (8.65)	17 (12.14)
Women's rugby	5 (2.70)	19 (13.57)
All collision sports	52 (28.11)	63 (45)
Contact sports		
Men's soccer	17 (9.19)	7 (5)
Women's soccer	13 (7.03)	12 (8.57)
Men's basketball	11 (5.95)	7 (5)
Women's basketball	5 (2.70)	8 (5.71)
Wrestling	10 (5.41)	7 (5)
Women's Field hockey	6 (3.24)	12 (8.57)
All contact sports	62 (33.52)	53 (37.86)
Limited contact/non-contact sports		
Men's volleyball	9 (4.86)	5 (3.57)
Women's volleyball	7 (3.78)	7 (5)
Track and field	41 (29.73)	8 (8.57)
Cross-country and tennis	14 (7.57)	4 (2.86)
All limited contact/non-contact sports	71 (38.38)	24 (17.14)

Abbreviations: No RHOC, no reported history of concussion; RHOC, reported history of concussion.

Table 4 presents the results for “yes” and “no” responses to Sport Concussion Assessment Tool (SCAT5) athlete background questions for male, female and total university varsity student-athletes. A majority of student-athletes reported that they did not have a history of hospitalization for a previous head injury, had not been diagnosed or received treatment for a headache disorder or migraines, had not been diagnosed with either a LD, ADD or ADHD and had not been diagnosed with depression, anxiety or other psychiatric disorder. However, a higher percentage of female student-athletes (15%, 24 out of 160) reported a diagnosis of depression, anxiety or other psychiatric disorder compared to males (5.45%, 9 out 165).

Table 4. Number (%) of "yes" and "no" responses to Sport Concussion Assessment Tool 5 athlete background questions on general medical history for male, female and total university varsity student-athletes.

Question	Male (n = 165)	Female (n = 160)	Total (n = 325)
Hospitalized for a prior head injury			
Yes	6 (3.64)	7 (4.38)	13 (4)
No	132 (80)	152 (95)	284 (87.38)
Missing data	27 (16.36)	1 (0.63)	28 (8.62)
Diagnosed or treated for headache disorder or migraines			
Yes	5 (3.03)	5 (3.13)	10 (3.08)
No	128 (77.58)	148 (92.5)	276 (84.92)
Missing data	32 (19.39)	7 (4.38)	39 (12)
Diagnosed with a learning disability or dyslexia			
Yes	4 (2.42)	8 (5)	12 (3.69)
No	129 (78.18)	143 (89.38)	272 (83.69)
Missing data	32 (19.39)	9 (5.63)	41 (12.62)
Diagnosed with attention-deficit or attention-deficit/hyperactivity disorder			
Yes	7 (4.24)	8 (5)	15 (4.62)
No	126 (76.36)	143 (89.38)	269 (82.77)
Missing data	32 (19.39)	9 (5.63)	41 (12.62)
Diagnosed with depression, anxiety, or other psychiatric disorder			
Yes	9 (5.45)	24 (15)	33 (10.15)
No	124 (75.15)	127 (79.38)	251 (77.23)
Missing data	32 (19.39)	9 (5.63)	41 (12.62)

Sport Concussion Assessment Tool 5

Table 5 summarizes descriptive statistics for SCAT5 variables within the graded symptom evaluation checklist, SAC cognitive screen, mBESS test and rapid neurological screen stratified by sex and concussion history. Group sample sizes varied for each SCAT 5 test component (see Table 5). Table 6 describes the statistical outcomes of a two-way ANOVA examining the effects of sex, concussion history and the interaction between sex and concussion history on SCAT5 variables within the graded symptom evaluation checklist, SAC cognitive screen and the mBESS test.

Table 5. Descriptive statistics for Sport Concussion Assessment Tool 5 variables in the graded symptom evaluation checklist, Standard of Assessment of Concussion (SAC) cognitive screen, modified Balance Error Scoring System (mBESS) test and rapid neurological screen tests in university varsity student-athletes stratified by sex and concussion history.

	Sex		Concussion History	
Variable	Male	Female	No RHOC	RHOC
Graded symptom evaluation checklist [a]				
Total number of baseline symptoms (out of 22 symptoms), mean ± SD (range)	2.14 ± 3.67 (0 - 22)	2.97 ± 3.78 (0 - 18)	2.00 ± 3.18 (0 - 19)	3.23 ± 4.26 (0 - 22)
Total symptom severity score (out of 132), mean ± SD (range)	3.59 ± 7.61 (0 - 56)	5.06 ± 7.98 (0 - 53)	3.29 ± 6.80 (0 - 53)	5.61 ± 8.79 (0 - 56)
SAC cognitive screen				
Orientation score (out of 5), mean ± SD (range) [b]	4.89 ± 0.34 (3 - 5)	4.91 ± 0.28 (4 - 5)	4.93 ± 0.25 (4 - 5)	4.86 ± 0.37 (3 - 5)
Five-word immediate memory total score (out of 15), mean ± SD (range) [c]	14.35 ± 1.17 (8 - 15)	14.66 ± 0.65 (12 - 15)	14.43 ± 1.08 (8 - 15)	14.60 ± 0.77 (11 - 15)
Five-word delayed recall score (out of 5), mean ± SD (range) [d]	3.07 ± 1.39 (0 - 5)	3.50 ± 1.40 (0 - 5)	3.40 ± 1.40 (0 - 5)	3.14 ± 1.41 (0 - 5)
Concentration component [e]				
Digits backwards score (out of 4), mean ± SD (range)	2.19 ± 1.06 (0 - 4)	2.44 ± 1.07 (0 - 4)	2.25 ± 1.10 (0 - 4)	2.40 ± 1.03 (0 - 4)
Months in reverse order score (out of 1), mean ± SD (% correct)	0.86 ± 0.35 (85.71)	0.92 ± 0.27 (92.05)	0.90 ± 0.30 (89.76)	0.88 ± 0.33 (87.88)
Concentration total score (out of 5), mean ± SD (range)	3.05 ± 1.13 (1 - 5)	3.36 ± 1.15 (1 - 5)	3.14 ± 1.15 (1 - 5)	3.28 ± 1.15 (1 - 5)
mBESS test [f]				
Double leg stance errors, mean ± SD (range)	0.06 ± 0.31 (0 - 2)	0 ± 0 (0)	0.01 ± 0.11 (0 - 1)	0.05 ± 0.30 (0 - 2)
Single leg stance errors, mean ± SD (range)	3.34 ± 2.7 (0 - 10)	2.17 ± 2.03 (0 - 9)	2.87 ± 2.66 (0 - 10)	2.58 ± 2.16 (0 - 8)
Tandem stance errors, mean ± SD (range)	1.44 ± 1.85 (0 - 10)	0.68 ± 1.35 (0 - 10)	1.10 ± 1.61 (0 - 10)	0.99 ± 1.72 (0 - 10)
mBESS total error score (out of 30), mean ± SD (range)	4.84 ± 3.99 (0 - 17)	2.85 ± 2.77 (0 - 15)	3.99 ± 3.64 (0 - 16)	3.62 ± 3.46 (0 - 17)
Rapid neurological screen tests				
Comprehension, % normal [g]	98.52	100	99.37	99.19
Pain-free passive cervical spine movement, % normal [h]	91.16	98.63	97.55	91.54
Eye movement without double vision, % normal [i]	93.2	95.97	95.73	93.18
Finger-to-nose coordination, % normal [j]	98.61	98.65	98.76	98.46
Tandem gait, % normal [k]	97.1	100	98.13	99.2

Abbreviations: No RHOC, no reported history of concussion; RHOC, reported history of concussion.

[a] Group sample sizes for graded symptom evaluation checklist: male (n = 159); female (n = 152); No RHOC (n = 174); RHOC (n = 137).

[b] Group sample sizes for orientation score: male (n = 145); female (n = 149); No RHOC (n = 164); RHOC (n = 130).

[c] Group sample sizes for five-word immediate memory total score: male (n = 150); female (n = 152); No RHOC (n = 168); RHOC (n = 134).

[d] Group sample sizes for five-word delayed recall: male (n = 148); female (n = 151); No RHOC (n = 166); RHOC (n = 133).

[e] Group sample sizes for concentration component: male (n = 147); female (n = 151); No RHOC (n = 166); RHOC (n = 132).

[f] Group sample sizes for mBESS test: male (n = 145); female (n = 151); No RHOC (n = 165); RHOC (n = 131).

[g] Group sample sizes for comprehension: male (n = 135); female (n = 147); No RHOC (n = 158); RHOC (n = 124).

[h] Group sample sizes for pain-free passive cervical spine movement: male (n = 147); female (n = 146); No RHOC (n = 163); RHOC (n = 130).

[i] Group sample sizes for eye movement without double vision: male (n = 147); female (n = 149); No RHOC (n = 164); RHOC (n = 132).

[j] Group sample sizes for finger-to-nose coordination: male (n = 144); female (n = 148); No RHOC (n = 162); RHOC (n = 130).

[k] Group sample sizes for tandem gait: male (n = 138); female (n = 147); No RHOC (n = 160); RHOC (n = 125).

Table 6. Statistical outcomes of a two-way ANOVA examining the effects of sex, concussion history and the interaction between sex and concussion history on Sport Concussion Assessment Tool 5 variables in the graded symptom evaluation checklist, Standard of Assessment of Concussion (SAC) cognitive screen and the modified Balance Error Scoring System (mBESS) test.

	Sex	Concussion History	Sex x Concussion History
Variable	*P* Value	*P* Value	*P* Value
Graded symptom evaluation checklist			
Total number of baseline symptoms	0.109	0.007	0.791
Total symptom severity score	0.207	0.015	0.386
SAC cognitive screen			
Orientation score	0.431	0.044	0.564
Five-word immediate memory total score	0.008	0.217	0.869
Five-word delayed recall score	0.006	0.062	0.236
Concentration component			
Digits backwards score	0.05	0.323	0.339
Months in reverse order score	0.074	0.48	0.968
Concentration total score	0.02	0.465	0.377
mBESS test			
Double leg stance errors	0.11	0.094	0.094
Single leg stance errors	< 0.001	0.543	0.507
Tandem stance errors	< 0.001	0.930	0.296
mBESS total error score	< 0.001	0.719	0.892

On the graded symptom checklist, approximately 42% of all student-athletes (130 out of 311) self-reported no baseline symptoms and had a total symptom severity score of zero. Stratified by sex, a higher percentage of male student-athletes (46.54 %, 74 out of 159) self-reported no baseline symptoms and had a total symptom severity score of zero compared to female student-athletes (36.84 %, 56 out 152) (see Figure 9A and Figure 9B). A similar percentage of male (3.14%, 5 out of 159) and female student-athletes (4.61%, 7 out of 152) had a total symptom severity score of 20 or greater (see Figure 9B). Stratified by concussion history, a higher percentage of student-athletes with No RHOC (47.70%, 83 out of 174) self-reported no baseline symptoms and had a total symptom severity score of zero compared to student-athletes with a RHOC (34.31%, 47 out of 137) (see Figure 10A and Figure 10B). A higher percentage of student-athletes with a RHOC (5.84%, 8 out of 137) had a total symptom severity score of 20 or greater compared to student-athletes with No RHOC (2.30%, 4 out of 174) (see Figure 10B). The two-way ANOVA demonstrated a significant main effect of concussion history for the total number of baseline symptoms (P = 0.007; Table 6) and the total symptom severity score (P = 0.015; Table 6). Student-athletes with a RHOC self-reported a significantly higher total number of baseline symptoms and significantly higher mean total symptom severity scores compared to student-athletes with No RHOC (Table 5). There no significant effects of sex and interaction between sex and concussion history observed for both the total number of baseline symptoms and the total symptom severity score.

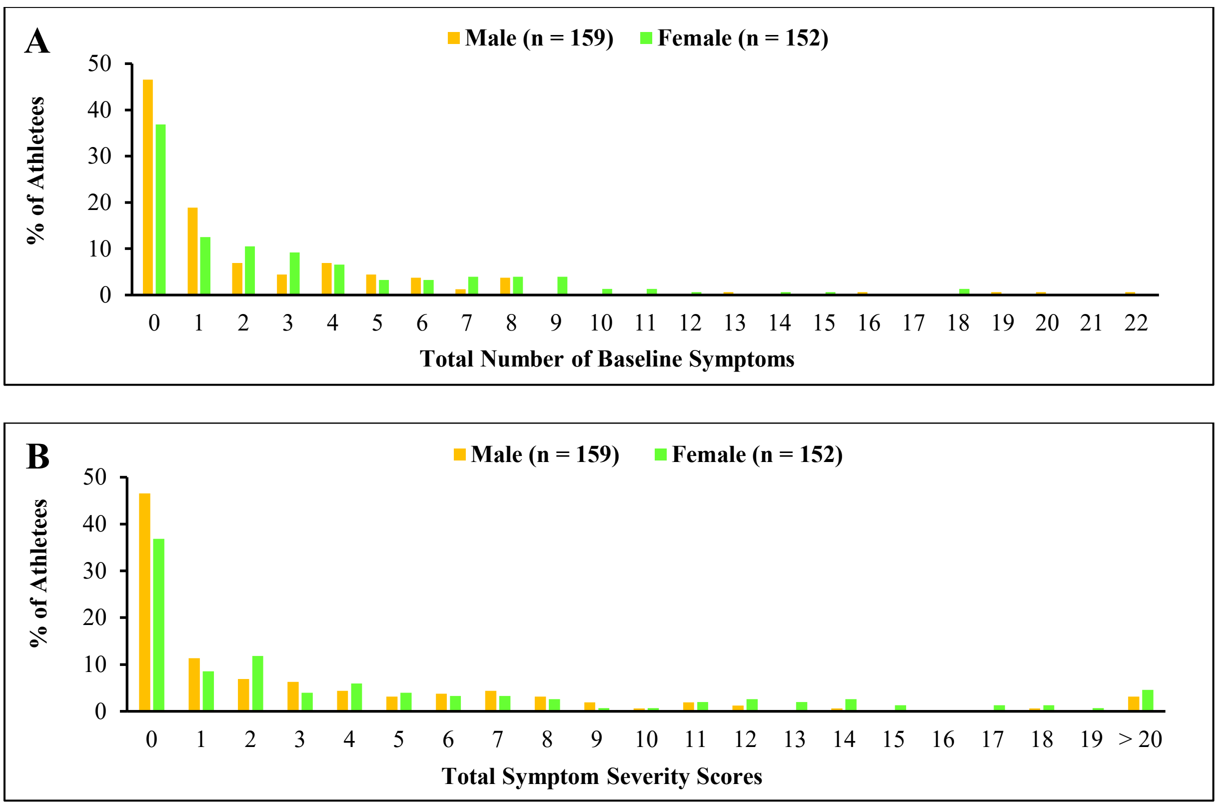

Figure 9. Percentage (%) distribution of the **(A)** total number of baseline symptoms self-reported and the **(B)** total symptom severity scores in university varsity student-athletes stratified by sex.

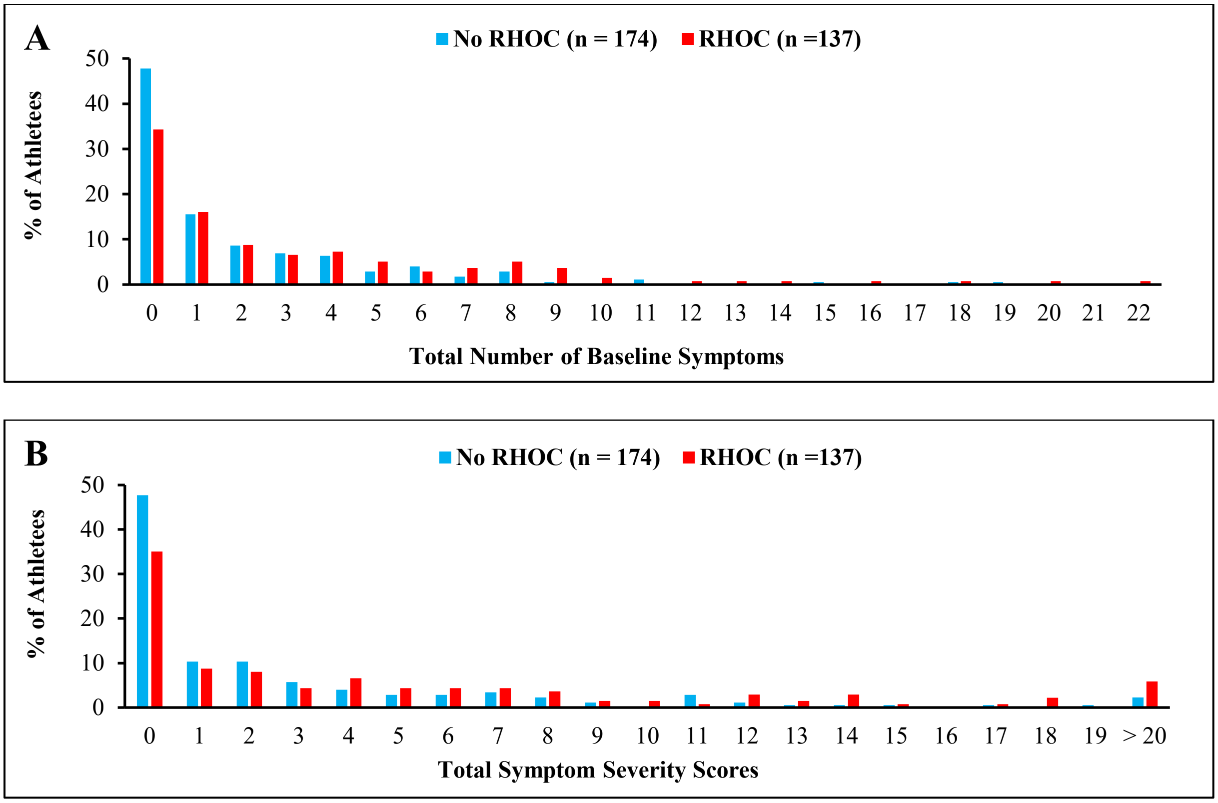

Figure 10. Percentage (%) distribution of the **(A)** total number of baseline symptoms self-reported and the **(B)** total symptom severity scores in university varsity student-athletes stratified by concussion history. Abbreviations: No RHOC, no reported history of concussion; RHOC, reported history of concussion.

Table 7 presents data on baseline symptoms self-reported by university varsity student-athletes on the Sport Concussion Assessment Tool 5 graded symptom checklist. The most common baseline symptoms self-reported by student-athletes were fatigue or low energy (98 out of 310, 31.61%), troubles falling asleep (66 out of 310, 21.29%), feeling nervous or anxious (58 out of 311, 18.65%), neck pain (55 out of 310, 17.74%), difficulties remembering (47 out of 311, 15.11%) and difficulties concentrating (46 out of 311, 14.79%). Table 8 presents data on specific baseline symptoms self-reported by university varsity student-athletes stratified by sex. The most common baseline symptoms self-reported by male student-athletes were fatigue or low energy (43 out of 159, 27.04%), troubles falling asleep (31 out of 159, 19.50%), feeling nervous or anxious (21 out of 159, 13.21%), neck pain (18 out of 159, 11.32%), headache (17 out of 159, 10.69%) and difficulties concentrating (17 out of 159, 10.69%). The most common baseline symptoms self-reported by female student-athletes were fatigue or low energy (55 out of 151, 36.42%), neck pain (37 out of 151, 24.50%), feeling nervous or anxious (37 out of 152, 24.34%), troubles falling asleep (35 out of 151, 23.18%), difficulties remembering (33 out of 152, 21.71%) and difficulties concentrating (29 out of 152, 19.08%). Sex was significantly associated with self-reporting neck pain (χ^2 (1, n = 310) = 9.222, P = 0.002; V = 0.172; Table 8), balance problems (χ^2 (1, n = 311) = 6.726, P = 0.01; V = 0.147; Table 8), difficulties remembering (χ^2 (1, n = 311) = 10.089, P = 0.001; V = 0.180; Table 8), difficulties concentrating (χ^2 (1, n = 311) = 4.337, P = 0.037; V = 0.118; Table 8) and feeling nervous or anxious (χ^2 (1, n = 311) = 6.350, P = 0.012; V = 0.143; Table 8). Compared to male student-athletes, female student-athletes were more likely to self-report symptoms of neck pain (female = 24.5% vs male = 11.32%; Table 8), balance problems (female = 14.47% vs male = 5.66%; Table 8), difficulties remembering (female = 21.71% vs male = 8.81%; Table 8), difficulties concentrating (female = 19.08% vs male = 10.69%; Table 8) and feeling nervous or anxious (female = 24.34% vs male = 13.21%; Table 8). Table 9 presents data on specific baseline symptoms self-reported by university varsity student-athletes stratified by concussion history. The most common baseline symptoms self-reported by student-athletes with No RHOC were fatigue or low energy (51 out of 174, 29.31%), troubles falling asleep (26 out of 173, 15.03%), neck pain (25 out of 174, 14.37%), difficulties concentrating (24 out of 174, 13.79%), feeling nervous or anxious (23 out of 174, 13.22%) and difficulties remembering (21 out of 174, 12.07%). The most common baseline symptoms self-reported by student-athletes with a RHOC were fatigue or low energy (47 out of 136, 34.56%), troubles falling asleep (40 out of 137, 29.20%), feeling nervous or anxious (35 out of 137, 25.55%), neck pain (30 out of 136, 22.06%), difficulties remembering (26 out of 137, 18.98%)

and headache (24 out of 137, 17.52%). Concussion history was significantly associated with self-reporting troubles falling asleep (χ^2 (1, n = 310) = 9.158, *P* = 0.002; V = 0.172; Table 9), feeling nervous or anxious (χ^2 (1, n = 311) = 7.680, *P* = 0.006; V = 0.157; Table 9), sensitivity to noise (χ^2 (1, n = 311) = 8.307, *P* = 0.004; V = 0.163; Table 9), sensitivity to light (χ^2 (1, n = 311) = 4.213, *P* = 0.04; V = 0.116; Table 9), feeling like "in a fog" (χ^2 (1, n = 310) = 5.334, *P* = 0.021; V = 0.131; Table 9), experiencing nausea or vomiting (Fisher's exact test *P* = 0.047; Table 9) and dizziness (χ^2 (1, n = 311) = 4.175, *P* = 0.041; V = 0.041; Table 9). Compared to student-athletes with No RHOC, student-athletes with a RHOC were more likely to self-report troubles falling asleep (RHOC = 29.20 % vs No RHOC = 15.03%; Table 9), feeling nervous or anxious (RHOC = 25.55% vs No RHOC = 13.22%; Table 9), sensitivity to noise (RHOC = 10.95% vs No RHOC = 2.87%; Table 9), sensitivity to light (RHOC = 13.14% vs No RHOC = 6.32%; Table 9), feeling like "in a fog" (RHOC = 12.50% vs No RHOC = 5.17%; Table 9), experiencing nausea or vomiting (RHOC = 4.38% vs No RHOC = 0.57%; Table 9) and dizziness (RHOC = 8.03% vs No RHOC = 2.87%; Table 9).

Table 7. Number (%) of university varsity student-athletes self-reporting specific baseline symptoms on the Sport Concussion Assessment Tool 5 graded symptom checklist.

Symptom	Athletes Reporting Symptom
Fatigue or low energy	98 out of 310 (31.61)
Trouble falling asleep	66 out of 310 (21.29)
Nervous or anxious	58 out of 311 (18.65)
Neck pain	55 out of 310 (17.74)
Difficulty remembering	47 out of 311 (15.11)
Difficulty concentrating	46 out of 311 (14.79)
Headache	43 out of 311 (13.38)
Irritability	39 out of 311 (12.54)
Feeling slowed down	38 out of 311 (12.22)
"Pressure in head"	33 out of 311 (10.61)
Balance problems	31 out of 311 (9.97)

(Continued)

Table 7. (Continued)

Symptom	Athletes Reporting Symptom
More emotional	31 out of 311 (9.97)
Drowsiness	30 out of 311 (9.65)
Sensitivity to light	29 out of 311 (9.32)
"Don't feel right"	27 out of 310 (8.71)
Feeling like "in a fog"	26 out of 310 (8.39)
Sadness	21 out of 311 (6.75)
Sensitivity to noise	20 out of 311 (6.43)
Dizziness	16 out of 311 (5.14)
Blurred vision	16 out of 311 (5.14)
Confusion	14 out of 311 (4.50)
Nausea or vomiting	7 out of 311 (2.25)

Table 8. Number (%) of university varsity student-athletes self-reporting specific baseline symptoms on the Sport Concussion Assessment Tool 5 graded symptom checklist stratified by sex.

Symptom	Sex	Athletes Reporting Symptom	χ^2 (df = 1)	*P* Value	V
Headache	Male (n = 159) Female (n = 152)	17 (10.69) 26 (17.11)	2.683	0.101	0.093
"Pressure in head"	Male (n = 159) Female (n = 152)	16 (10.06) 17 (11.18)	0.103	0.748	0.018
Neck pain	Male (n = 159) Female (n = 151)	18 (11.32) 37 (24.50)	9.222	0.002	0.172
Nausea or vomiting	Male (n = 159) Female (n = 152)	3 (1.89) 4 (2.63)	-	0.718†	-
Dizziness	Male (n = 159) Female (n = 152)	11 (6.92) 5 (3.29)	2.097	0.148	0.082
Blurred vision	Male (n = 159) Female (n = 152)	8 (5.03) 8 (5.26)	0.009	0.926	0.005
Balance problems	Male (n = 159) Female (n = 152)	9 (5.66) 22 (14.47)	6.726	0.01	0.147
Sensitivity to noise	Male (n = 159) Female (n = 152)	11 (6.92) 9 (5.92)	0.128	0.72	0.020
Sensitivity to light	Male (n = 159) Female (n = 152)	15 (9.43) 14 (9.21)	0.005	0.946	0.004
Feeling slowed down	Male (n = 159) Female (n = 152)	17 (10.69) 21 (13.82)	0.707	0.40	0.048
Feeling like "in a fog"	Male (n = 159) Female (n = 151)	13 (8.18) 13 (8.61)	0.019	0.891	0.008
"Don't feel right"	Male (n = 158) Female (n = 152)	15 (9.49) 12 (7.89)	0.249	0.618	0.028
Difficulty concentrating	Male (n = 159) Female (n = 152)	17 (10.69) 29 (19.08)	4.337	0.037	0.118
Difficulty remembering	Male (n = 159) Female (n = 152)	14 (8.81) 33 (21.71)	10.089	0.001	0.180

(Continued)

Table 8. (Continued)

Symptom	Sex	Athletes Reporting Symptom	χ^2 (df = 1)	*P* Value	V
Fatigue or low energy	Male (n = 159) Female (n = 151)	43 (27.04) 55 (36.42)	3.152	0.076	0.101
Confusion	Male (n = 159) Female (n = 152)	8 (5.03) 6 (3.95)	0.212	0.645	0.026
Drowsiness	Male (n = 159) Female (n = 152)	16 (10.06) 14 (9.21)	0.065	0.799	0.014
More emotional	Male (n = 159) Female (n = 152)	15 (9.43) 16 (10.53)	0.103	0.748	0.018
Difficulty remembering	Male (n = 159) Female (n = 152)	14 (8.81) 33 (21.71)	10.089	0.001	0.180
Fatigue or low energy	Male (n = 159) Female (n = 151)	43 (27.04) 55 (36.42)	3.152	0.076	0.101
Confusion	Male (n = 159) Female (n = 152)	8 (5.03) 6 (3.95)	0.212	0.645	0.026
Drowsiness	Male (n = 159) Female (n = 152)	16 (10.06) 14 (9.21)	0.065	0.799	0.014
More emotional	Male (n = 159) Female (n = 152)	15 (9.43) 16 (10.53)	0.103	0.748	0.018
Irritability	Male (n = 159) Female (n = 152)	15 (9.43) 24 (15.79)	2.862	0.091	0.096
Sadness	Male (n = 159) Female (n = 152)	7 (4.40) 14 (9.21)	2.853	0.091	0.096
Nervous or anxious	Male (n = 159) Female (n = 152)	21 (13.21) 37 (24.34)	6.350	0.012	0.143
Trouble falling asleep	Male (n = 159) Female (n = 151)	31 (19.50) 35 (23.18)	0.627	0.429	0.045

Abbreviations: χ2, Pearson's chi-square test; V; Cramer's V effect size.

† *P* value calculated with Fisher's exact test.

Table 9. Number (%) of university varsity student-athletes self-reporting specific baseline symptoms on the Sport Concussion Assessment Tool 5 graded symptom checklist stratified by concussion history.

Symptom	Concussion History	Athletes Reporting Symptom	χ^2 (df = 1)	*P* Value	V
Headache	No RHOC (n = 174) RHOC (n = 137)	19 (10.92) 24 (17.52)	2.801	0.094	0.095
"Pressure in head"	No RHOC (n = 174) RHOC (n = 137)	14 (8.05) 19 (13.87)	2.740	0.098	0.094
Neck pain	No RHOC (n = 174) RHOC (n = 136)	25 (14.37) 30 (22.06)	3.094	0.079	0.100
Nausea or vomiting	No RHOC (n = 174) RHOC (n = 137)	1 (0.57) 6 (4.38)	-	0.047†	-
Dizziness	No RHOC (n = 174) RHOC (n = 137)	5 (2.87) 11 (8.03)	4.175	0.041	0.116
Blurred vision	No RHOC (n = 174) RHOC (n = 137)	9 (5.17) 7 (5.11)	0.001	0.98	0.001
Balance problems	No RHOC (n = 174) RHOC (n = 137)	15 (8.62) 16 (11.68)	0.799	0.371	0.051

(Continued)

Table 9. (Continued)

Symptom	Concussion History	Athletes Reporting Symptom	χ^2 (df = 1)	*P* Value	V
Sensitivity to noise	No RHOC (n = 174)	5 (2.87)	8.307	0.004	0.163
	RHOC (n = 137)	15 (10.95)			
Sensitivity to light	No RHOC (n = 174)	11 (6.32)	4.213	0.04	0.116
	RHOC (n = 137)	18 (13.14)			
Feeling slowed down	No RHOC (n = 174)	16 (9.20)	3.366	0.067	0.104
	RHOC (n = 137)	22 (16.06)			
Feeling like "in a fog"	No RHOC (n = 174)	24 (13.79)	0.312	0.576	0.032
	RHOC (n = 137)	22 (16.06)			
"Don't feel right"	No RHOC (n = 174)	21 (12.07)	2.852	0.091	0.096
	RHOC (n = 137)	26 (18.98)			
Difficulty concentrating	No RHOC (n = 174)	24 (13.79)	0.312	0.576	0.032
	RHOC (n = 137)	22 (16.06)			
Difficulty remembering	No RHOC (n = 174)	21 (12.07)	2.852	0.091	0.096
	RHOC (n = 137)	26 (18.98)			
Fatigue or low energy	No RHOC (n = 174)	51 (29.31)	0.973	0.324	0.056
	RHOC (n = 136)	47 (34.56)			
Confusion	No RHOC (n = 174)	5 (2.87)	2.435	0.119	0.088
	RHOC (n = 137)	9 (6.57)			
Drowsiness	No RHOC (n = 174)	14 (8.05)	1.161	0.281	0.061
	RHOC (n = 137)	16 (11.68)			
More emotional	No RHOC (n = 174)	16 (9.20)	0.263	0.608	0.029
	RHOC (n = 137)	15 (10.95)			
Irritability	No RHOC (n = 174)	17 (9.77)	2.764	0.096	0.094
	RHOC (n = 137)	22 (16.06)			
Sadness	No RHOC (n = 174)	9 (5.17)	1.566	0.211	0.071
	RHOC (n = 137)	12 (8.76)			
Nervous or anxious	No RHOC (n = 174)	23 (13.22)	7.680	0.006	0.157
	RHOC (n = 137)	35 (25.55)			
Trouble falling asleep	No RHOC (n = 173)	26 (15.03)	9.158	0.002	0.172
	RHOC (n = 137)	40 (29.20)			

Abbreviations: No RHOC, no reported history of concussion; RHOC, reported history of concussion; $\chi2$, Pearson's chi-square test; V; Cramer's V effect size.

† *P* value calculated with Fisher's exact test.

For the orientation test in the SAC cognitive screen, approximately 90.5% of all student-athletes (266 out of 294) achieved an orientation score of five out of five. Stratified by sex, a similar percentage of male (89.66%, 130 out of 145) and female student-athletes (91.28%, 136 out of 149) achieved an orientation score of five out of five (see Figure 11A). Stratified by concussion history, a higher percentage of student-athletes with No RHOC (93.29%, 153 out of 164) achieved an orientation score of five out of five compared to student-athletes with a RHOC (86.92%, 113 out of 130) (see Figure 11B). The two-way ANOVA demonstrated a significant main effect of concussion history for orientation score ($P = 0.044$; Table 6), whereas no significant effect of sex and interaction between sex and concussion history were observed. Student-athletes with No RHOC had significantly higher mean orientation scores compared to student-athletes with a RHOC (Table 5). For the five-word immediate memory test, approximately 69% (208 out of 302) of all student-athletes achieved a five-word immediate memory total score of 15 out of 15. Stratified by sex, a higher percentage of female student-athletes (75%, 114 out of 152) achieved a five-word immediate memory total score of 15 out of 15 compared to male student-athletes (62.67%, 94 out of 150) (see Figure 12A). Stratified by concussion history, a slightly higher percentage of student-athletes with a RHOC (72.39%, 97 out of 134) achieved a five-word immediate memory total score of 15 out of 15 compared to student-athletes with No RHOC (66.07%, 111 out of 168) (see Figure 12B). The two-way ANOVA revealed a significant main effect of sex for five-word immediate memory total score ($P = 0.008$; Table 6), whereas no significant effect of concussion history and interaction between sex and concussion history were observed. Female student-athletes had significantly higher mean five-word immediate memory total scores compared to male student-athletes (Table 5). For the five-word delayed recall test, approximately 23% of all student-athletes (68 out of 299) achieved a five-word delayed recall score of five out of five. Stratified by sex, a higher percentage of female student-athletes (30.46%, 46 out of 151) achieved a five-word delayed recall score of five out of five compared to male student-athletes (14.86%, 22 out of 148) (see Figure 13A). Stratified by concussion history, a slightly higher percentage of student-athletes with No RHOC (25.30%, 42 out of 166) achieved a five-word delayed recall score of five out of five compared to student-athletes with a RHOC (19.55%, 26 out of 133) (see Figure 13B). The two-way ANOVA revealed a significant main effect of sex for five-word delayed recall score ($P = 0.006$;

Table 6), whereas no significant effect of concussion history and interaction between sex and concussion history were observed. Female student-athletes had significantly higher mean five-word delayed recall scores compared to male student-athletes (Table 5). For the digits backwards test within the SAC concentration component, approximately 18% of all student-athletes (54 out of 298) scored four out of four on the test by reciting all six digits backwards. The percentages of student-athletes scoring four out of four on the digits backwards test were low across study groups when stratified by sex (male = 14.29%, 21 out of 147; female = 21.85%, 33 out of 151; see Figure 14A) and concussion history (No RHOC = 16.87%, 28 out of 166; RHOC = 19.7%, 26 out of 132; see Figure 14B). No significant effects of sex, concussion history and interaction between sex and concussion history were observed for digits backwards score (Table 6). For the months in reverse order test within the SAC concentration component, approximately 89% of all student-athletes (265 out of 298) answered the test correctly. Stratified by sex, a slightly higher percentage of female student-athletes (92.05%, 139 out of 151) answered the months in reverse order test correctly compared to male student-athletes (85.71%, 126 out of 147) (see Figure 15A). Stratified by concussion history, a comparable percentage of student-athletes with No RHOC (89.76%, 149 out of 166) and student-athletes with a RHOC (87.88%, 116 out of 132) answered the months in reverse order test correctly (see Figure 15B). No significant effects of sex, concussion history and interaction between sex and concussion history were observed for months in reverse order score (Table 6). Approximately 17% (52 out of 298) of all student-athletes achieved a concentration total score of five out of five. Stratified by sex, a higher percentage of female student-athletes (21.85%, n = 33 out of 151) had a concentration total score of five out of five compared to male student-athletes (12.93%, n = 19 out of 147) (see Figure 16A). Stratified by concussion history, a comparable percentage of student-athletes with No

RHOC (15.66%, 26 out of 166) and with a RHOC (19.70%, 26 out of 132) had a concentration total score of five out of five (see Figure 16B). The two-way ANOVA demonstrated a significant main effect of sex for concentration total score ($P = 0.02$; Table 6), whereas no significant effects of concussion history and interaction between sex and concussion history were observed. Female student-athletes had significantly higher mean concentration total scores compared to male student-athletes (Table 5).

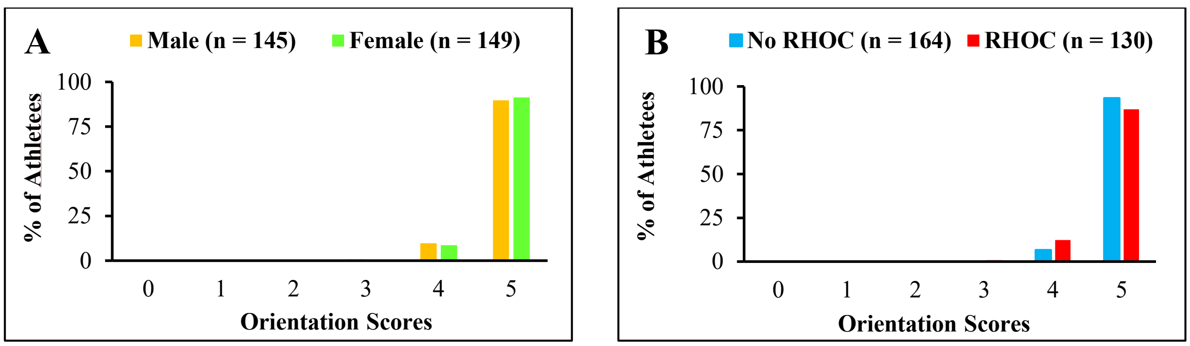

Figure 11. Percentage (%) distribution of orientation scores in university varsity student-athletes stratified by **(A)** sex and **(B)** concussion history. Abbreviations: No RHOC, no reported history of concussion; RHOC, reported history of concussion.

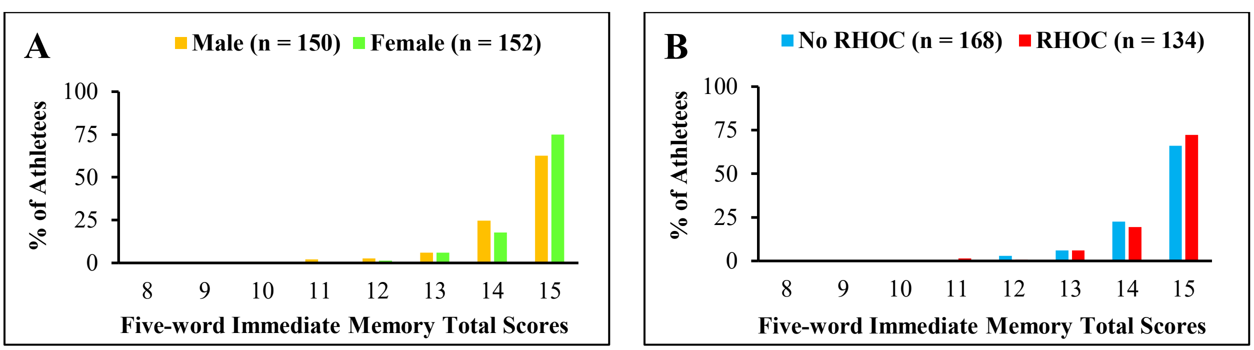

Figure 12. Percentage (%) distribution of five-word immediate memory total scores in university varsity student-athletes stratified by **(A)** sex and **(B)** concussion history. Abbreviations: No RHOC, no reported history of concussion; RHOC, reported history of concussion.

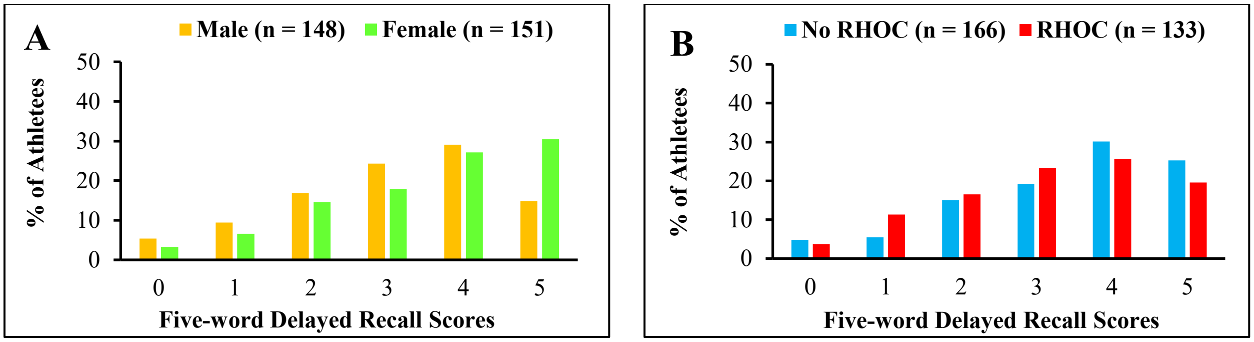

Figure 13. Percentage (%) distribution of five-word delayed recall scores in university varsity student-athletes stratified by **(A)** sex and **(B)** concussion history. Abbreviations: No RHOC, no reported history of concussion; RHOC, reported history of concussion.

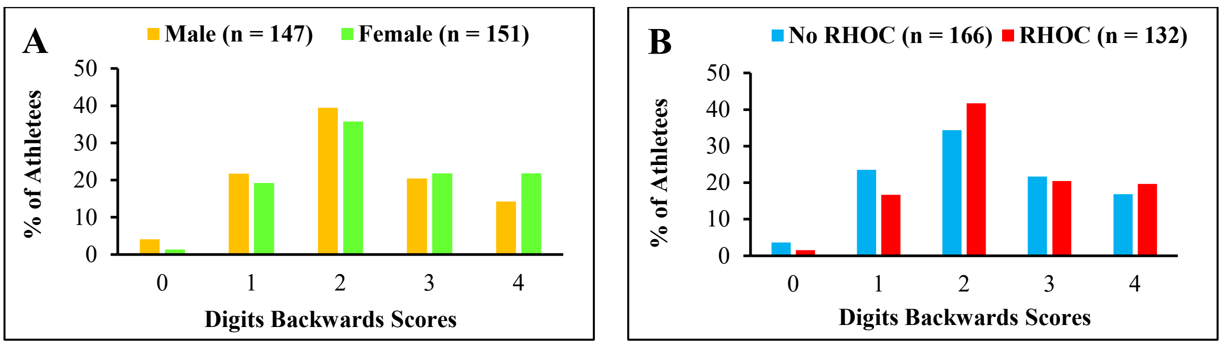

Figure 14. Percentage (%) distribution of digits backwards scores in university varsity student-athletes stratified by **(A)** sex and **(B)** concussion history. Abbreviations: No RHOC, no reported history of concussion; RHOC, reported history of concussion.

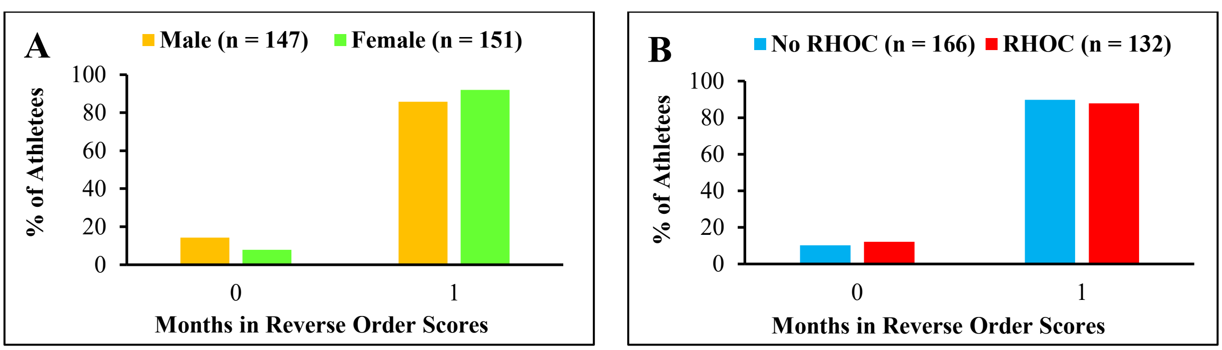

Figure 15. Percentage (%) distribution of months in reverse order scores in university varsity student-athletes stratified by **(A)** sex and **(B)** concussion history. Abbreviations: No RHOC, no reported history of concussion; RHOC, reported history of concussion.

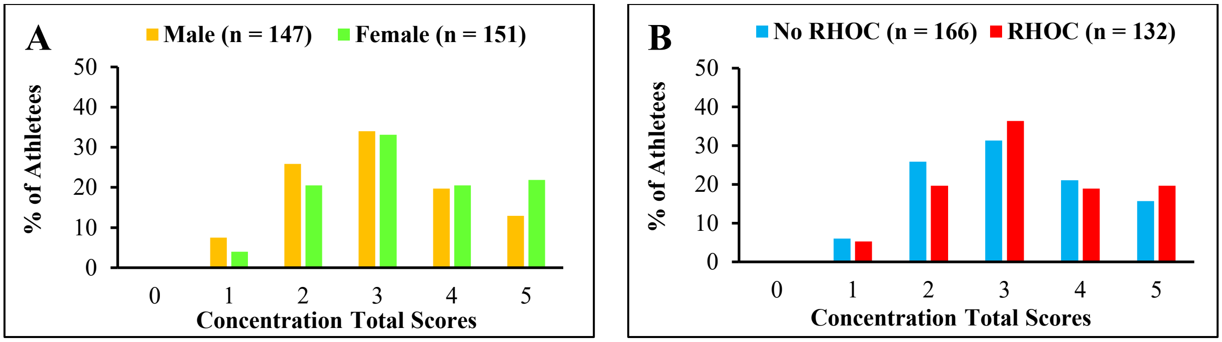

Figure 16. Percentage (%) distribution of concentration total scores in university varsity student athletes stratified by **(A)** sex and **(B)** concussion history. Abbreviations: No RHOC, no reported history of concussion; RHOC, reported history of concussion.

For the mBESS test, approximately 98% of all student-athletes (291 out of 296) made zero errors in the double leg stance trial, whereas approximately 20% (59 out of 296) and 54% of all student-athletes (160 out of 296) made zero errors in the single leg stance and tandem stance trials, respectively. The percentage of student-athletes that made zero errors in the double leg stance trial were similar when stratified by sex (male = 96.55%, 140 out of 145; female = 100%, n = 151 out of 151; see Figure 17A) and by concussion history (No RHOC = 98.79%, 163 out of 165; RHOC = 97.71%, 128 out of 131; see Figure 17B). While a similar percentage of male (19.31%, 28 out of 145) and female student-athletes (20.53%, 31 out of 151) made zero errors in the single leg stance trial, a higher percentage of female student-athletes (27.81 %, n = 42 out of 151) made one error in the single leg stance trial compared to male student-athletes (11.03%, 16 out of 145) (see Figure 18A). A higher percentage of male student-athletes (69.66 %, 101 out of 145) made two or more errors in the single leg stance trial compared to female student-athletes (51.66 %, 78 out of 151) (see Figure 18A). Stratified by concussion history, a similar percentage of student athletes with No RHOC and student athletes with a RHOC made zero errors (No RHOC = 19.39%, 32 out of 165; RHOC = 20.61%, 27 out of 131; see Figure 18B), one error (No RHOC = 20.61%, 34 out of 165; RHOC = 18.32%, 24 out of 131; see Figure 18B) and two or more errors (No RHOC = 60%, 99 out of 165; RHOC = 61.07%, 80 out of 131; see Figure 18B) in the single leg stance trial. For the tandem stance trial, a higher percentage of female student-athletes (66.89%, 101 out of 151) made zero errors compared to male student-athletes (40.69%, n = 59 out of 145), whereas a higher percentage of male student-athletes (59.31%, 86 out of 145) made one or more errors in the tandem stance trial compared to female student-athletes (33.31%, n = 50 out of 151) (see Figure 19A). When stratified by concussion history, a higher percentage of student-athletes with a RHOC (60.31%, 79 out of 131) made zero errors in the tandem stance trial compared to student-athletes with No RHOC (49.09%, 81 out of 165), whereas a higher percentage of student-athletes with No RHOC (50.91%, 84 out of 165) made one or more errors in the tandem stance trial compared to student-athletes with a RHOC (39.69%, 52 out of 131) (see Figure 19B). For the mBESS total error score, approximately 15.5% of all student-athletes (46 out of 296) completed the mBESS without making a single error. Stratified by sex, a higher percentage of female student-athletes (70.86%, 107 out of 151) had an mBESS total error score between zero and three compared to male student-athletes (45.52%, n = 66 out of 145), whereas a higher percentage of male student-athletes (54.48%, n = 79 out of 145) had an mBESS total error score of four or greater compared to female student-athletes (29.14%, n = 44 out of 151) (see Figure 20A). Stratified by concussion history, a similar percentage of student athletes with No RHOC and student-athletes with a RHOC had an mBESS total error score between zero and three (No RHOC = 58.18%, 96 out of 165; RHOC = 58.78%, 77 out of 131; see Figure 20B) and four or greater (No RHOC = 41.82%, 69 out of 165; RHOC = 41.22%, 54 out of 131; see Figure 20B). The two-way ANOVA demonstrated a significant main effect of sex for single leg stance errors ($P < 0.001$; Table 6), tandem stance errors ($P < 0.001$; Table 6) and mBESS total error score ($P < 0.001$; Table 6). Compared to female student-athletes, male student-athletes made significantly more errors in the single leg stance and the tandem stance and had significantly higher mean mBESS total error scores (Table 5). No significant effects of concussion history and interaction between sex and concussion history were observed for any mBESS variable.

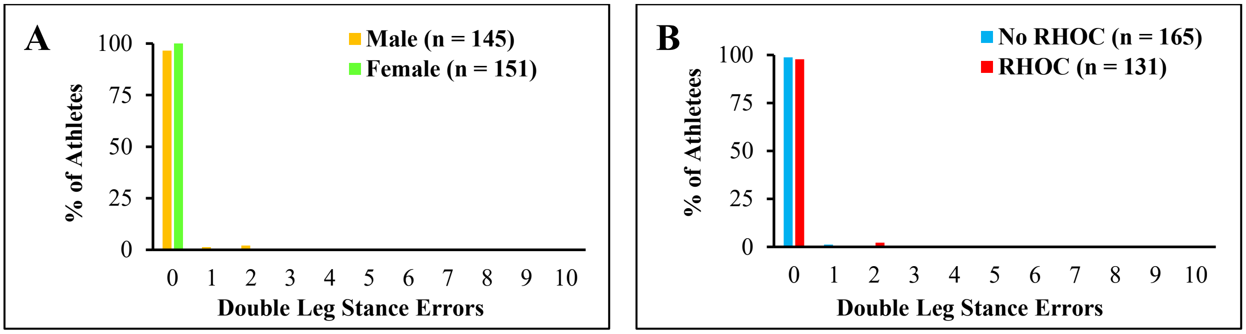

Figure 17. Percentage (%) distribution of modified Balance Error Scoring System (mBESS) double leg stance errors in university varsity student athletes stratified by **(A)** sex and **(B)** concussion history. Abbreviations: No RHOC, no reported history of concussion; RHOC, reported history of concussion.

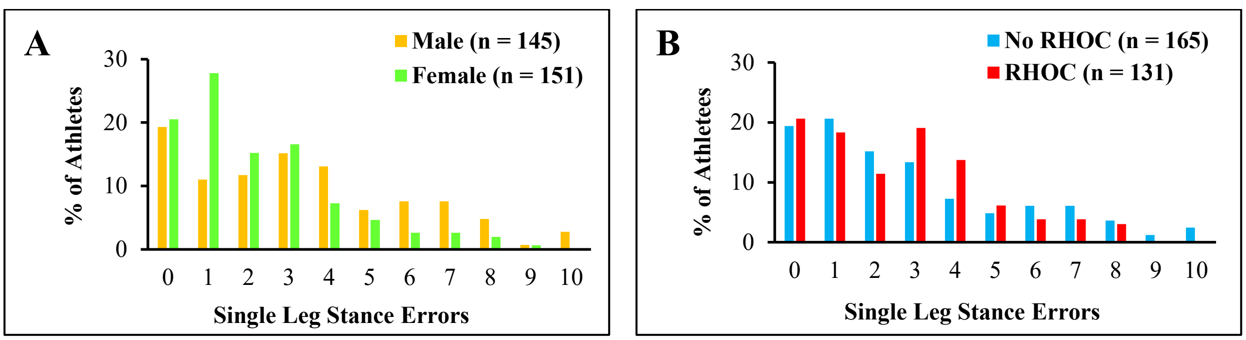

Figure 18. Percentage (%) distribution of modified Balance Error Scoring System (mBESS) single leg stance errors in university varsity student athletes stratified by **(A)** sex and **(B)** concussion history. Abbreviations: No RHOC, no reported history of concussion; RHOC, reported history of concussion.

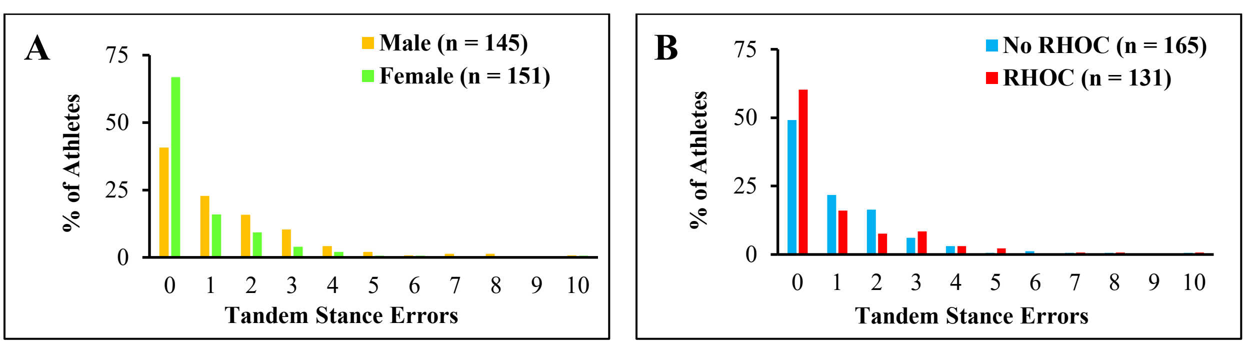

Figure 19. Percentage (%) distribution of modified Balance Error Scoring System (mBESS) tandem leg stance errors in university varsity student athletes stratified by **(A)** sex and **(B)** concussion history. Abbreviations: No RHOC, no reported history of concussion; RHOC, reported history of concussion.

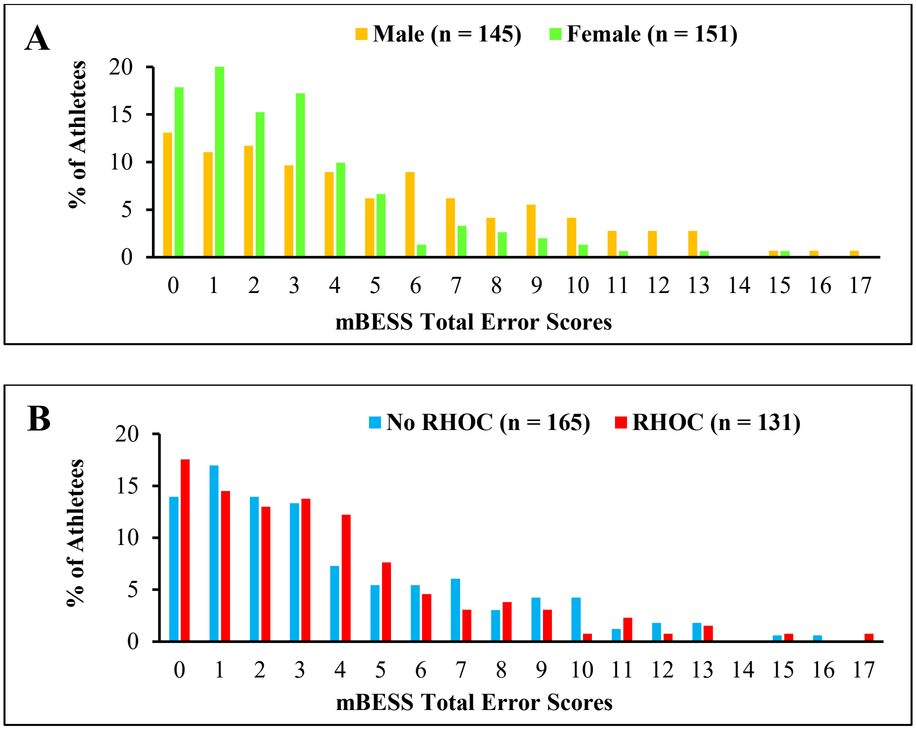

Figure 20. Percentage (%) distribution of modified Balance Error Scoring System (mBESS) total error scores in university varsity student athletes stratified by **(A)** sex and **(B)** concussion history. Abbreviations: No RHOC, no reported history of concussion; RHOC, reported history of concussion.

Results for the rapid neurological screen tests were normal for a majority of student-athletes when stratified by sex and concussion history (Table 5). However, a higher percentage of male student-athletes (8.84%, 13 out of 147) experienced pain on the passive cervical spine movement test compared to female student-athletes (1.37%, 2 out of 146) (Table 5). When stratified by concussion history, a higher percentage of student-athletes with a RHOC (8.46%, 11 out of 130; 9 males and 2 females) experienced pain on the passive cervical spine movement test compared to student-athletes with No RHOC (2.45%, 4 out of 163; 4 males) (Table 5).

Force Plate Postural Sway Assessment

A total of 286 student-athletes completed the force plate postural sway assessment (stratified by sex: male n = 149; female n = 137; stratified by concussion history: No RHOC n = 160; RHOC n = 126). Table 10 summarizes descriptive statistics for force plate COP measures of postural sway examined in EO and EC conditions stratified by sex and concussion history. Table 11 describes the statistical outcomes of a two-way ANOVA examining the effects of sex, concussion history and the interaction between sex and concussion history on force plate COP measures of postural sway examined in EO and EC conditions. The two-way ANOVA demonstrated significant main effects of sex for multiple force plate COP measures of postural sway in EO and EC conditions, whereas no significant effects of concussion history and interaction between sex and concussion history were observed for any measures. In the EO condition, male student-athletes had significantly higher mean values compared to female student-athletes for AREA – CE ($P = 0.032$; Table 11), RMSdisp AP ($P = 0.009$; Table 11), COPvel AP ($P = 0.013$; Table 11), Range AP ($P = 0.026$; Table 11) and Range ML ($P = 0.045$; Table 11). While male student-athletes presented with larger RMSdisp ML and faster COPvel ML compared to female student-athletes, the two-way ANOVA revealed no significant main effects of sex for RMSdisp ML and COPvel ML. In the EC condition, male student-athletes had significantly higher mean values compared to female student-athletes for AREA – CE ($P = 0.001$; Table 11), RMSdisp AP ($P < 0.001$; Table 11), COPvel AP ($P < 0.001$; Table 11), Range AP ($P = 0.002$; Table 11), RMSdisp ML ($P = 0.006$; Table 11), COPvel ML ($P = 0.007$; Table 10) and Range ML ($P = 0.016$; Table 11).

Table 10. Descriptive statistics for force plate centre of pressure (COP) measures of postural sway examined in eyes open (EO) and eyes closed (EC) conditions in university varsity student-athletes stratified by sex and concussion history.

	Sex		Concussion History	
Measures	Male (n = 149)	Female (n = 137)	No RHOC (n = 160)	RHOC (n = 126)
EO condition				
AREA – CE (mm^2)	615.63 ± 333.00	529.74 ± 339.26	564.63 ± 317.03	587.01 ± 364.15
RMSdisp AP (mm)	5.07 ± 1.65	4.62 ± 1.46	4.75 ± 1.49	4.99 ± 1.66
COPvel AP (mm/sec)	4.09 ± 1.41	3.74 ± 1.22	3.83 ± 1.25	4.04 ± 1.43
Range AP (mm)	26.90 ± 7.57	24.97 ± 7.57	25.62 ± 7.07	26.42 ± 8.27
RMSdisp ML (mm)	6.54 ± 2.29	6.01 ± 2.18	6.34 ± 2.38	6.22 ± 2.08
COPvel ML (mm/sec)	5.33 ± 2.01	4.85 ± 1.79	5.16 ± 2.04	5.03 ± 1.92
Range ML (mm)	32.41 ± 9.48	29.93 ± 10.20	31.14 ± 9.91	31.33 ± 9.90
EC condition				
AREA – CE (mm^2)	876.82 ± 527.28	685.23 ± 477.67	776.71 ± 477.88	795.64 ± 554.71
RMSdisp AP (mm)	6.33 ± 1.96	5.51 ± 1.96	5.88 ± 1.83	6.01 ± 2.20
COPvel AP (mm/sec)	5.04 ± 1.60	4.38 ± 1.58	4.68 ± 1.44	4.78 ± 1.83
Range AP (mm)	35.79 ± 11.26	31.65 ± 11.34	34.99 ± 11.58	33.58 ± 11.37
RMSdisp ML (mm)	7.09 ± 2.55	6.31 ± 2.22	6.76 ± 2.42	6.67 ± 2.45
COPvel ML (mm/sec)	5.68 ± 2.13	5.05 ± 1.84	5.40 ± 1.99	5.35 ± 2.06
Range ML (mm)	38.76 ± 13.03	35.07 ± 11.76	37.50 ± 12.94	36.34 ± 12.07

Values presented as mean ± SD.

Abbreviations: No RHOC, no reported history of concussion; RHOC, reported history of concussion; AREA – CE, 95 % confidence ellipse area; mm^2, millimetres squared; RMSdisp, root-mean-square displacement; AP, anteroposterior; mm, millimetres; COPvel, mean COP velocity; mm/sec, millimetres per second; ML, mediolateral.

Table 11. Statistical outcomes of a two-way ANOVA examining the effects of sex, concussion history and the interaction between sex and concussion history on force plate centre of pressure (COP) measures of postural sway examined in eyes open (EO) and eyes closed (EC) conditions in university varsity student-athletes.

	Sex	Concussion History	Sex x Concussion History
Measures	*P* Value	*P* Value	*P* Value
EO condition			
AREA – CE (mm^2)	0.032	0.387	0.470
RMSdisp AP (mm)	0.009	0.099	0.954
COPvel AP (mm/sec)	0.013	0.093	0.991
Range AP (mm)	0.026	0.235	0.734
RMSdisp ML (mm)	0.077	0.892	0.185
COPvel ML (mm/sec)	0.053	0.787	0.212
Range ML (mm)	0.045	0.634	0.181
EC condition			
AREA – CE (mm^2)	0.001	0.453	0.636
RMSdisp AP (mm)	< 0.001	0.297	0.603
COPvel AP (mm/sec)	< 0.001	0.334	0.508
Range AP (mm)	0.002	0.904	0.943

(Continued)

Table 11. (Continued)

	Sex	Concussion History	Sex x Concussion History
Measures	*P* Value	*P* Value	*P* Value
EC condition			
RMSdisp ML (mm)	0.006	0.948	0.499
COPvel ML (mm/sec)	0.007	0.898	0.459
Range ML (mm)	0.016	0.653	0.876

Abbreviations: AREA – CE, 95 % confidence ellipse area; mm^2, millimetres squared; RMSdisp, root-mean-square displacement; AP, anteroposterior; mm, millimetres; COPvel, mean COP velocity; mm/sec, millimetres per second; ML, mediolateral.

Cerebral Blood Flow Volume Assessment

A total of 79 student-athletes completed the DU cerebral BFV assessment (stratified by sex: male n = 38; female n = 41; stratified by concussion history: No RHOC n = 38; RHOC n = 41). Table 12 summarizes descriptive statistics for DU measurements of cerebral BFV within the CCA, ICA, VA and the total cerebral BFV stratified by sex and concussion history. Table 13 describes the statistical outcomes of a two-way ANOVA examining the effects of sex, concussion history and the interaction between sex and concussion history on DU measurements of cerebral BFV within the CCA, ICA, VA and the total cerebral BFV. The two-way ANOVA demonstrated a significant main effect of sex for left ($P < 0.001$; Table 13), right ($P = 0.003$; Table 13) and total CCA BFV ($P < 0.001$; Table 13). Male student-athletes had significantly higher mean left, right and total CCA BFV compared to female student-athletes (see Table 12). Within sexes, there were no significant mean differences between left and right CCA BFV for both male ($P = 0.113$; Table 12) and female student-athletes ($P = 0.115$; Table 12). The two-way ANOVA demonstrated a significant main effect of concussion history for right CCA BFV ($P = 0.032$; Table 13). Student-athletes with a RHOC had significantly lower mean right CCA BFV compared to student-athletes with No RHOC (Table 12). There were no significant effects of concussion history observed for left and right ICA and VA BFV measurements. The two-way

ANOVA demonstrated a significant main effect of sex for left (*P* = 0.023; Table 13), right (*P* = 0.001; Table 13) and total ICA BFV (*P* = 0.001; Table 13). Male student-athletes had significantly higher mean left, right and total ICA BFV compared to female student-athletes (Table 12). Within sexes, female student-athletes had significantly higher mean left ICA BFV compared to mean right ICA BFV (*P* = 0.023; Table 12), whereas male student-athletes did not have significant differences between mean left and right ICA BFV (*P* = 0.468; Table 12). The two-way ANOVA demonstrated a significant main effect of sex for left VA BFV (*P* = 0.032; Table 13), whereas no significant main effects of sex were observed for right and total VA BFV. Female student-athletes had significantly higher mean left VA BFV compared to male student-athletes (Table 12). Within sexes, mean left VA BFV was significantly higher compared to mean right VA BFV for both male (*P* = 0.039; Table 12) and female student-athletes (*P* = 0.001; Table 12). The two-way ANOVA demonstrated a significant main effect of sex for total cerebral BFV (*P* = 0.034; Table 13). Male student-athletes had significantly higher mean total cerebral BFV compared to female student-athletes (Table 12). There were no significant interaction effects between sex and concussion history observed for any cerebral BFV measurements.

Table 12. Descriptive statistics for Doppler ultrasound measurements of cerebral blood flow volume (BFV) within the common carotid artery (CCA), internal carotid artery (ICA), the vertebral artery (VA) and total cerebral BFV in university varsity student-athletes stratified by sex and concussion history**.**

	Sex		Concussion History	
Measurement	Male (n = 38)	Female (n = 41)	No RHOC (n = 38)	RHOC (n = 41)
CCA BFV (mL/min)				
Left CCA	694.65 ± 127.25	599.44 ± 99.56	658.89 ± 114.27	632.58 ± 130.15
Right CCA	649.36 ± 119.07	564.39 ± 99.76	640.42 ± 119.12	572.67 ± 106.01
Total	1344.00 ± 190.28	1163.83 ± 164	1299.32 ± 182.88	1205.24 ± 202.71
ICA BFV (mL/min)				
Left ICA	506.20 ± 116.42	453.37 ± 104.36 *	467.52 ± 115.12	489.22 ± 110.97
Right ICA	487.02 ± 112.81	403.79 ± 87.87	466.12 ± 115.96	423.16 ± 97.78
Total	993.22 ± 191.43	857.16 ± 161.39	933.65 ± 203.27	912.38 ± 175.00

(Continued)

Table 12. (Continued)

	Sex		Concussion History	
Measurement	Male (n = 38)	Female (n = 41)	No RHOC (n = 38)	RHOC (n = 41)
VA BFV (mL/min)				
Left VA	126.95 + 55.09 *	150.59 + 51.14 *	145 + 55.02	133.86 + 53.26
Right VA	104.48 + 36.07	108.74 + 53.55	109.55 + 48.18	104.04 + 43.79
Total	231.43 + 63.49	259.33 + 76.82	254.55 + 73.91	237.90 + 69.46
Total cerebral BFV † (mL/min)	1224.66 + 221.28	1116.49 + 197.16	1188.20 + 234.82	1150.28 + 195.50

Values are presented as mean + SD.

Abbreviations: No RHOC, no reported history of concussion; RHOC, reported history of concussion; mL/min, millilitres per minute.

* Statistically significant within-sex difference ($P < 0.05$) between mean left- and right-side BFV for the specific artery.

† Total cerebral BFV calculated as the sum of the total ICA BFV and the total VA BFV.

Table 13. Statistical outcomes of a two-way ANOVA examining the effects of sex, concussion history and the interaction between sex and concussion history on Doppler ultrasound measurements of cerebral blood flow volume (BFV) within the common carotid artery (CCA), internal carotid artery (ICA), the vertebral artery (VA) and total cerebral BFV in university varsity student-athletes.

	Sex	Concussion History	Sex x Concussion History
Measurement	*P* Value	*P* Value	*P* Value
CCA BFV (mL/min)			
Left CCA	< 0.001	0.771	0.116
Right CCA	0.003	0.032	0.792
Total	< 0.001	0.132	0.392
ICA BFV (mL/min)			
Left ICA	0.023	0.192	0.474
Right ICA	0.001	0.214	0.336
Total	0.001	0.914	0.920
VA BFV (mL/min)			
Left VA	0.032	0.187	0.872
Right VA	0.597	0.550	0.572
Total	0.050	0.167	0.802
Total cerebral BFV (mL/min) †	0.034	0.710	0.999

Abbreviations: mL/min. millilitres per minute.

† Total cerebral BFV calculated as the sum of the total ICA BFV and the total VA BFV.

Brain Dynamic Indicator ^{TM}

A total of 121 student-athletes completed the BrDI^{TM} assessment (stratified by sex: male n = 70; female n = 58; stratified by concussion history: No RHOC n = 89; RHOC n = 39). Table 14 summarizes descriptive statistics for BrDI^{TM} variables measured in the standard condition and CMI condition stratified by sex and concussion history. Table 15 describes the statistical outcomes of a two-way ANOVA examining the effects of sex, concussion history and the interaction between sex and history of concussion on BrDI^{TM} variables measured in the standard condition and CMI condition. The two-way ANOVA demonstrated a significant main effect of sex for PV in the standard condition ($P = 0.002$; Table 15), whereas no significant effects of concussion history and interaction between sex and concussion history were observed. Male student-athletes exhibited significantly higher mean PV in the standard condition compared to female student-athletes (Table 14). For VE in the standard condition, the two-way ANOVA demonstrated a significant main effect of sex ($P = 0.049$; Table 15) and a significant interaction effect between sex and concussion history ($P = 0.022$; Table 15), whereas no significant effect of concussion history was observed. For the significant main effect of sex on VE in the standard condition, female student-athletes exhibited significantly larger mean VE, indicating reduced precision, in the standard condition compared to male student-athletes (Table 14). For the significant interaction effect between sex and concussion history on VE in the standard condition, female student-athletes with a RHOC exhibited significantly larger mean VE in the standard condition compared to male student-athletes with a RHOC (see Figure 21). The two-way ANOVA demonstrated a significant main effect of sex for MTf in the CMI condition ($P = 0.002$; Table 15), whereas no significant effect of concussion history and interaction between sex and concussion history were observed. Female student-athletes exhibited significantly longer mean MTf in the CMI condition compared to male student-athletes (Table 14). The two-way ANOVA demonstrated a significant main effect of sex for PV in the CMI condition (*P* < 0.001; Table 15), whereas no significant effect of concussion history and interaction between sex and concussion history were observed. Male student-athletes had significantly higher mean PV in the CMI condition compared to female student-athletes (Table 14). No significant effects of sex, concussion history and interaction between sex and concussion history were observed for the following BrDI™ variables in the standard and/or CMI condition: MTb in both the standard and CMI condition; MTf in the standard condition; RT in both the standard and CMI condition; PLfN in both the standard and CMI condition; AE in both the standard and CMI condition (Table 15).

Table 14. Descriptive statistics for Brain Dynamic Indicator™ variables measured in the standard condition and cognitive-motor integration (CMI) condition in university varsity student-athletes stratified by sex and concussion history.

	Sex		Concussion History	
Variable	Male (n = 70)	Female (n = 58)	No RHOC (n = 89)	RHOC (n = 39)
Standard condition				
MTb (sec)	3.26 ± 0.38	3.38 ± 0.28	3.32 ± 0.34	3.28 ± 0.36
MTf (sec)	3.84 ± 0.32	3.94 ± 0.29	3.90 ± 0.33	3.87 ± 0.27
RT (sec)	0.36 ± 0.06	0.37 ± 0.06	0.37 ± 0.06	0.36 ± 0.07
PV (mm/sec)	1058.27 ± 310.96	859.80 ± 275.25	927.54 ± 312.54	1061.44 ± 288.27
PLfN (%)	109.03 ± 8.03	106.39 ± 5.73	107.40 ± 6.76	108.83 ± 8.06
AE (mm^2)	12.24 ± 3.89	12.64 ± 4.83	12.23 ± 4.23	12.85 ± 4.58
VE (mm^2)	6.03 ± 3.94	6.89 ± 5.94	6.21 ± 4.18	6.90 ± 6.40
CMI condition				
MTb (sec)	4.11 ± 0.39	4.04 ± 0.38	4.05 ± 0.39	4.15 ± 0.37
MTf (sec)	5.13 ± 0.53	5.58 ± 0.71	5.38 ± 0.71	5.24 ± 0.52
RT (sec)	0.48 ± 0.17	0.50 ± 0.28	0.48 ± 0.23	0.50 ± 0.20
PV (mm/sec)	719.45 ± 332.46	471.69 ± 274.68	574.46 ± 321.77	681.85 ± 342.20
PLfN (%)	129.75 ± 32.43	135.92 ± 22.01	132.47 ± 30.24	132.72 ± 23.47
AE (mm^2)	23.43 ± 10.75	28.59 ± 19.07	26.29 ± 16.06	24.59 ± 13.36
VE (mm^2)	17.92 ± 14.96	23.59 ± 25.62	21.42 ± 21.45	18.37 ± 18.59

Values are presented as mean ± SD.

Abbreviations: No RHOC, no reported history of concussion; RHOC, reported history of concussion; MTb, ballistic movement time; sec, seconds; MTf, full movement time; RT, reaction time; PV, peak velocity; mm/sec, millimetres per second; PLfN, normalized path length; AE, absolute error; mm^2, millimetres squared; VE, variable error.

Table 15. Statistical outcomes of a two-way ANOVA examining the effects of sex, concussion history and the interaction between sex and concussion history on Brain Dynamic Indicator™ variables measured in the standard condition and cognitive-motor integration (CMI) condition in university varsity student-athletes.

	Sex	Concussion History	Sex x Concussion History
Variable	*P* Value	*P* Value	*P* Value
Standard condition			
MTb (sec)	0.162	0.580	0.465
MTf (sec)	0.088	0.882	0.804
RT (sec)	0.441	0.649	0.447
PV (mm/sec)	0.002	0.064	0.975
PLfN (%)	0.066	0.458	0.879
AE (mm^2)	0.206	0.254	0.102
VE (mm^2)	0.049	0.188	0.022
CMI condition			
MTb (sec)	0.324	0.300	0.654
MTf (sec)	0.002	0.385	0.280
RT (sec)	0.365	0.477	0.194
PV (mm/sec)	< 0.001	0.186	0.634
PLfN (%)	0.252	0.833	0.945
AE (mm^2)	0.095	0.739	0.991
VE (mm^2)	0.235	0.528	0.754

Abbreviations: MTb, ballistic movement time; sec, seconds; MTf, full movement time; RT, reaction time; PV, peak velocity; mm/sec, millimetres per second; PLfN, normalized path length; AE, absolute error; mm^2, millimetres squared; VE, variable error.

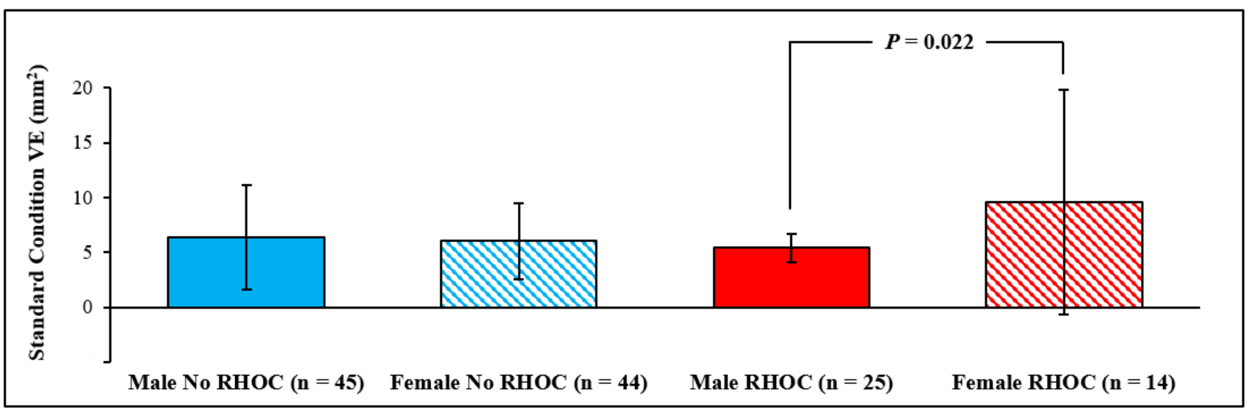

Figure 21. Mean variable error (VE) in the standard condition of the Brain Dynamic Indicator™ for male student-athletes with no reported history of concussion (No RHOC), female student-athletes with No RHOC, male student-athletes with a reported history of concussion (RHOC) and female student-athletes with a RHOC. The two-way ANOVA demonstrated a statistically significant interaction effect between sex and concussion history for mean VE in the standard condition (*P* = 0.022). Female student-athletes with a RHOC had significantly larger mean VE in the standard condition compared to male student-athletes with a RHOC.

HurtSHynes^{TM} Test

A total of 227 student-athletes completed the HurtSHynes^{TM} Test (stratified by sex: male n = 114; female n = 113; stratified by concussion history: No RHOC n = 114; RHOC n = 113). Table 16 summarizes descriptive statistics for HurtSHynes^{TM} Test variables, completion time and total errors, in the standard condition and the CMI condition stratified by sex and concussion history. Table 17 describes the statistical outcomes of a two-way ANOVA examining the effects of sex, concussion history and the interaction between sex and concussion history for completion time and total errors in the standard condition and the CMI condition of the HurtSHynes^{TM} Test. The two-way ANOVA demonstrated a significant interaction effect between sex and concussion history for completion time in the standard condition ($P = 0.001$; Table 17), whereas no significant effect of sex and concussion history were observed. Female student-athletes with No RHOC had significantly longer mean completion time in the standard condition compared to male student-athletes with No RHOC (see Figure 22). The two-way ANOVA demonstrated a significant main effect of sex ($P = 0.031$; Table 17) and a significant interaction effect between sex and concussion history ($P = 0.018$; Table 17) for total errors in the CMI condition, whereas a significant effect of concussion history was not observed. For the significant main effect of sex, male student-athletes had significantly higher mean total errors in the CMI condition compared to female student-athletes (Table 16). For the significant interaction effect between sex and concussion history, male student-athletes with No RHOC had significantly higher mean errors in the CMI condition compared to female student-athletes with No RHOC (Figure 23). There were no significant effects of sex, concussion history and interaction between sex and concussion history observed for total errors in the standard condition and completion time in the CMI condition (Table 17).

Table 16. Descriptive statistics for HurtSHynes^{TM} Test completion time and total errors in the standard condition and the cognitive-motor integration (CMI) condition in university varsity student-athletes stratified by sex and concussion history.

	Sex		Concussion History	
Variable	Male (n = 114)	Female (n = 113)	No RHOC (n = 114)	RHOC (n = 113)
Standard condition				
Completion time (sec), mean ± SD	10.20 ± 1.89	10.57 ± 1.30	10.31 ± 1.40	10.47 ± 1.84
Total errors, mean ± SD (range)	0.10 ± 0.30 (0 - 1)	0.10 ± 0.30 (0 - 1)	0.08 ± 0.27 (0 - 1)	0.12 ± 0.32 (0 - 1)
CMI condition				
Completion time (sec), mean ± SD	10.68 ± 1.93	11.07 ± 1.32	10.92 ± 1.73	10.82 ± 1.60
Total errors mean ± SD (range)	0.76 ± 0.85 (0 - 4)	0.50 ± 0.79 (0 - 3)	0.71 ± 0.83 (0 - 4)	0.56 ± 0.82 (0 - 3)

Abbreviations: No RHOC, no reported history of concussion; RHOC, reported history of concussion; sec, seconds.

Table 17. Statistical outcomes of a two-way ANOVA examining the effects of sex, concussion history and the interaction between sex and concussion history on HurtSHynes^{TM} Test completion time and total errors in the standard condition and cognitive-motor integration (CMI) condition in university varsity student-athletes.

	Sex	Concussion History	Sex x Concussion History
Variable	*P* Value	*P* Value	*P* Value
Standard condition			
Completion time (sec)	0.11	0.653	0.001
Total errors	0.879	0.355	0.676
CMI condition			
Completion time (sec)	0.061	0.42	0.241
Total errors	0.031	0.329	0.018

Abbreviations: sec, seconds.

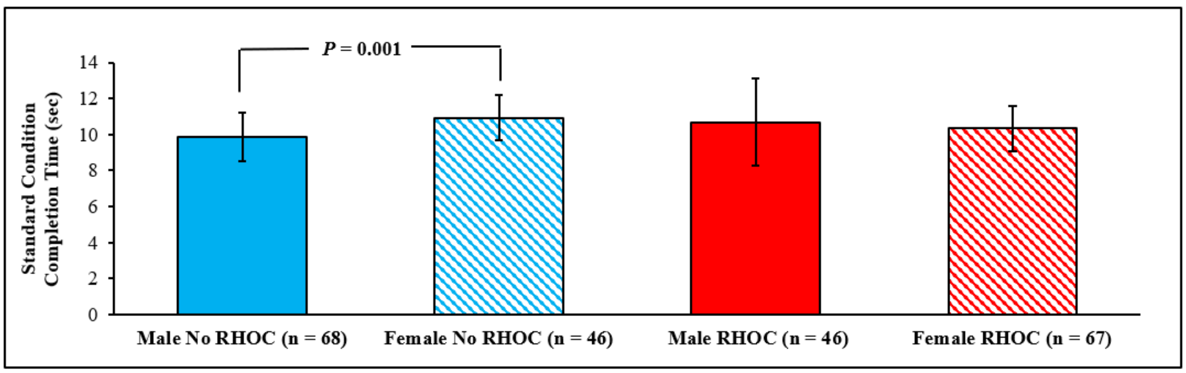

Figure 22. Mean completion time in the standard condition of the HurtSHynes^{TM} Test for male student-athletes with no reported history of concussion (No RHOC), female student-athletes with No RHOC, male student-athletes with a reported history of concussion (RHOC) and female student-athletes with a RHOC. The two-way ANOVA demonstrated a statistically significant interaction effect between sex and concussion history for mean completion time in the standard condition of the HurtSHynes^{TM} Test (P = 0.001). Female student-athletes with No RHOC had significantly longer mean completion time in the standard condition of the HurtSHynes^{TM} Test compared to male student-athletes with No RHOC.

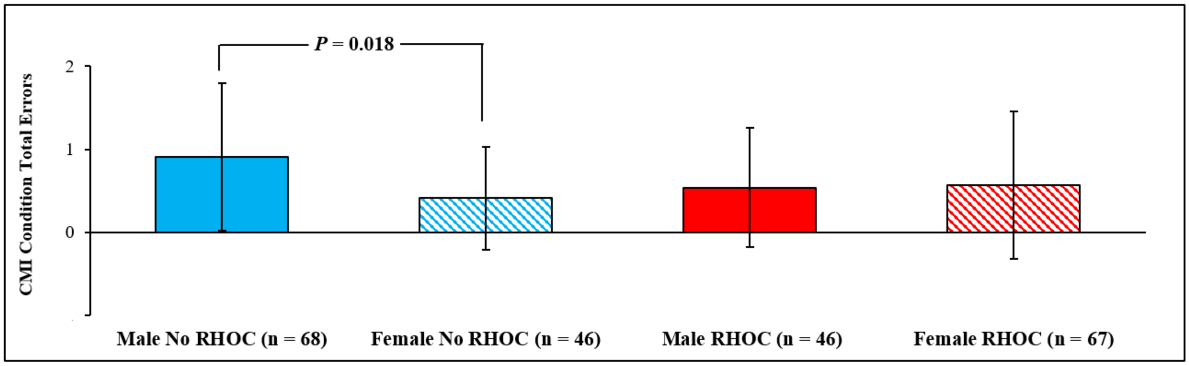

Figure 23. Mean total errors in the cognitive-motor integration (CMI) condition of the HurtSHynes^{TM} Test for male student-athletes with no reported history of concussion (No RHOC), female student-athletes with No RHOC, male student-athletes with a reported history of concussion (RHOC) and female student-athletes with a RHOC. The two-way ANOVA demonstrated a statistically significant interaction effect between sex and concussion history for mean total errors in the CMI condition of the HurtSHynes Test^{TM} (P = 0.018). Male student-athletes with No RHOC had significantly higher mean total errors in the CMI condition of the HurtSHynes^{TM} Test compared to female student-athletes with No RHOC.

Oculomotor Assessment and Stroop Colour and Word Test

A total of 161 student-athletes completed the oculomotor assessment (stratified by sex: male n = 87; female n = 74; stratified by concussion history: No RHOC n = 84; RHOC n = 77). 160 student-athletes athletes completed the SCWT (stratified by sex: male n = 87; female n = 73; stratified by concussion history: No RHOC n = 83; RHOC n = 77). Table 18 summarizes descriptive statistics for oculomotor assessment measures and SCWT error variables stratified by sex and concussion history. Table 19 describes the statistical outcomes of a two-way ANOVA examining the effects of sex, concussion history and the interaction between sex and concussion history on oculomotor assessment measures and SCWT error variables. For the oculomotor assessment, there were no significant effects of sex, concussion history and interaction between sex and concussion history observed for saccade latency and antisaccade reaction time. For the SCWT, there were no significant effects of sex, concussion history and interaction between sex and concussion history observed for word task errors, colour task errors, interference task errors and SCWT total errors.

Table 18. Descriptive statistics for oculomotor assessment variables and Stroop Colour and Word Test (SCWT) error variables in university varsity student-athletes stratified by sex and concussion history.

	Sex		Concussion History	
Variable	Male	Female	No RHOC	RHOC
Oculomotor assessment [a]				
Saccade latency (ms), mean ± SD	0.21 ± 0.04	0.20 ± 0.02	0.21 ± 0.04	0.20 ± 0.02
Antisaccade reaction time (ms), mean ± SD	0.47 ± 0.11	0.47 ± 0.12	0.47 ± 0.12	0.47 ± 0.11
SCWT [b]				
Word task errors, mean ± SD (range)	0.03 ± 0.18 (0 - 1)	0.01 ± 0.12 (0 - 1)	0.02 ± 0.15 (0 - 1)	0.03 ± 0.16 (0 - 1)
Colour task errors, mean ± SD (range)	0.31 ± 0.62 (0 - 3)	0.33 ± 0.67 (0 - 3)	0.29 ± 0.51 (0 - 2)	0.35 ± 0.76 (0 - 3)
Interference task errors, mean ± SD (range)	1.03 + 1.20 (0 - 5)	0.71 ± 0.81 (0 - 3)	0.99 ± 1.09 (0 - 5)	0.78 ± 1.00 (0 - 5)
Total SCWT errors, mean ± SD (range)	1.38 ± 1.44 (0 - 5)	1.05 ± 1.12 (0 - 4)	1.30 ± 1.36 (0 - 5)	1.16 ± 1.26 (0 - 5)

[a] Group sample sizes for oculomotor assessment: male (n = 87); female (n = 74); No RHOC (n = 84); RHOC (n = 77).

[b] Group sample sizes for SCWT: male (n = 87); female (n = 73); No RHOC (n = 83); RHOC (n = 77).

Abbreviations: No RHOC, no reported history of concussion; RHOC, reported history of concussion; ms, milliseconds.

Table 19. Statistical outcomes of a two-way ANOVA examining the effects of sex, concussion history and the interaction between sex and concussion history on oculomotor assessment variables and Stroop Colour and Word Test (SCWT) error variables in university varsity student-athletes.

	Sex	Concussion History	Sex x Concussion History
Variable	*P* Value	*P* Value	*P* Value
Oculomotor assessment			
Saccade latency (ms)	0.232	0.22	0.74
Antisaccade reaction time (ms)	0.689	0.895	0.292
SCWT			
Word task errors	0.385	0.941	0.202
Colour task errors	0.929	0.620	0.266
Interference task errors	0.069	0.263	0.298
Total SCWT errors	0.130	0.523	0.126

Summary of Significant Results

Table 20 provides a summary of the results on the significant effects of sex and concussion history on assessment variables. Table 21 provides a summary of the results on the significant interaction effects that were observed on specific BrDI™ and HurtSHynes™ Test variables.

Table 20. Results summary for the significant effects of sex and concussion history observed on assessment variables in university varsity student-athletes.

	Sex		**Concussion History**	
Variable	**Male**	**Female**	**RHOC**	**No RHOC**
SCAT5				
Total number of baseline symptoms			↑	
Total symptom severity score			↑	
Orientation score				↑
Five-word immediate memory score		↑		
Five-word delayed recall score		↑		
Concentration total score		↑		
mBESS errors	↑ Single leg errors Tandem errors Total errors			
Force Plate Postural Sway				
AREA – CE (mm^2)	↑ EO and EC			
RMSdisp AP (mm)	↑ EO and EC			
COPvel AP (mm/sec)	↑ EO and EC			
Range AP (mm)	↑ EO and EC			
RMSdisp ML (mm)	↑ EC			
COPvel ML (mm/sec)	↑ EC			
Range ML (mm)	↑ EO and EC			
Cerebral BFV Assessment				
CCA BFV (mL/min)	↑ Left and right CCA		↓ Right CCA	
ICA BFV (mL/min)	↑ Left and right ICA			
VA BFV (mL/min)		↑ Left VA		
Total cerebral BFV (mL/min) †	↑			
BrDI™				
PV (mm/sec)	↑ Standard and CMI Conditions			
VE (mm^2)		↑ Standard Condition		
MTf (sec)		↑ CMI Condition		

(Continued)

Table 20. (Continued)

	Sex		Concussion History	
Variable	**Male**	**Female**	**RHOC**	**No RHOC**
HurtSHynes™ Test				
Completion time (sec)				
Total errors	↑ CMI Condition			

RHOC, reported history of concussion; No RHOC, no reported history of concussion; SCAT5, Sport Concussion Assessment Tool 5; mBESS, modified Balance Error Scoring System; AP, anteroposterior; ML, mediolateral; EO, eyes open; EC, eyes closed; AREA – CE, 95 % confidence ellipse area; mm, millimetres; RMSdisp, root-mean-square displacement; COPvel, mean COP velocity; mm/sec, millimetres per second; BFV, blood flow volume; CCA, common carotid artery; ICA, internal carotid artery; VA, vertebral artery; mL/min. millilitres per minute; BrDI™, Brain Dynamic Indicator™; PV, peak velocity; VE, variable error; MTf, full movement time; sec, seconds; CMI, cognitive-motor integration.

↑ Mean value significantly higher in student-athletes with a RHOC compared to student-athletes with No RHOC.

↑ Mean value significantly higher in student-athletes with No RHOC compared to student-athletes with a RHOC.

↑ Mean value significantly higher in male student-athletes compared to female student-athletes.

↑ Mean value significantly higher in female student-athletes compared to male student-athletes.

↓ Mean value significantly lower in student-athletes with a RHOC compared to student-athletes with No RHOC.

† Total cerebral BFV calculated as the sum of the total ICA BFV and the total VA BFV.

Table 21. Results summary for the significant interaction effects observed on assessment variables in university varsity student-athletes.

Variable	**Sex x Concussion History Interaction Effects**
BrDI™	
VE (mm^2)	Females with a RHOC had significantly larger VE in standard condition compared to males with a RHOC.
HurtSHynes™ Test	
Completion time (sec)	Females with No RHOC had significantly longer completion times in standard condition compared to males with No RHOC.
Total errors	Males with No RHOC made significantly more errors in the CMI condition compared to females with No RHOC.

RHOC, reported history of concussion; No RHOC, no reported history of concussion; BrDI™, Brain Dynamic Indicator™; VE, variable error; mm^2, millimetres squared; sec, seconds; CMI, cognitive-motor integration.

CHAPTER 4: DISCUSSION

To the author's knowledge, this is the largest study of its kind to analyze preseason baseline data collected from a population of Canadian male and female university varsity student-athletes using a comprehensive battery of validated assessment tools and non-invasive diagnostic procedures. Significant main effects of sex were observed for multiple test variables within the SCAT5. For the mBESS test, male student-athletes made significantly more errors in the single leg stance and tandem stance trials and had significantly higher mBESS total error scores compared to female student-athletes. On the other hand, female student-athletes performed better than male student-athletes on SAC cognitive screen tests, as female student-athletes achieved significantly higher scores on both the five-word immediate memory and delayed recall tests as well as the concentration total score. Significant main effects of concussion history were observed for the total number of baseline symptoms reported and total symptom severity scores, as student-athletes with a RHOC self-reported significantly more baseline symptoms and had significantly higher total symptom severity scores compared to student-athletes with No RHOC. Significant main effects of sex were observed for a majority of force plate COP measures of postural sway, whereas neither significant effects of concussion history nor interaction were present for any force plate COP measures. In both EO and EC conditions, male student-athletes exhibited significantly larger mean AREA-CE of sway, mean RMSdisp and mean COP range and faster mean COPvel compared to female student-athletes. Significant main effects of sex were also observed for multiple DU measurements of cerebral BFV. Compared to female student-athletes, male student-athletes presented with significantly higher mean CCA BFV and ICA BFV bilaterally and significantly higher mean total cerebral BFV. In contrast, female student-athletes had significantly higher mean BFV in the left VA compared to male student-athletes. A significant main effect of concussion history was only observed for right CCA BFV, as student-athletes with a RHOC had significantly lower mean right CCA BFV compared to student-athletes with No RHOC. Surprisingly, this study found no significant main effects of concussion history for any variable examined with the BrDI™ assessment and the HurtSHynes™ Test. For the BrDI™, significant main effects of sex were observed for PV and VE in the standard condition and PV and MTf in the CMI condition. Male student-athletes attained substantially higher mean PV compared to female student-athletes in both the standard condition and the CMI condition, whereas female student-athletes exhibited significantly larger VE in the standard condition and significantly longer MTf in the CMI condition compared to male student-athletes. For the HurtSHynes™ Test, male student-athletes made significantly more errors in the CMI condition compared to female student-athletes. Significant interaction effects between sex and concussion history were found for completion time in the standard condition and total errors in the CMI condition of the HurtSHynes™ Test, however, these interaction effects were observed between male and female student athletes with No RHOC. No significant effects of sex, concussion history and interaction between sex and concussion history were observed for oculomotor assessment variables and SCWT error variables.

Sport Concussion Assessment Tool 5

The most common baseline symptoms self-reported by university varsity student-athletes on the SCAT5 graded symptom checklist were fatigue or low energy, troubles falling asleep, feeling nervous or anxious, neck pain, difficulties remembering, difficulties concentrating and headaches. The frequent self-reporting of these specific symptoms amongst university varsity student-athletes at baseline is consistent with the findings of multiple studies that examined baseline symptom reporting in university or collegiate student-athletes and high school athletes using the SCAT graded symptom checklist.[96,101,102,104,105,263-265] As multiple studies have demonstrated that these same athlete populations often receive an insufficient amount of sleep and experience poor sleep quality,[266-270] the author of the current study speculates that sleep deprivation may have played a role in the higher frequency of self-reported fatigue or low energy, troubles falling asleep and headaches in this cohort of university varsity student-athletes evaluated at baseline. The current study found that student-athletes with a RHOC had significantly higher mean total number of baseline symptoms and mean symptom severity scores compared to student-athletes with No RHOC. These results are consistent with findings across multiple studies published over the past 20 years that have demonstrated that collegiate, university varsity and high school student-athletes with a history of one or multiple SRCs self-report significantly more concussion-like symptoms at baseline compared to athletes with no history of SRC.[102,104,271-273] Based on $\chi 2$ tests, concussion history was significantly associated with self-reporting troubles falling asleep, feeling nervous or anxious, sensitivity to noise, sensitivity to light, feeling like "in a fog", experiencing nausea or vomiting and dizziness, with student-athletes with a RHOC found to be more likely to report each of these symptoms compared to student-athletes with No RHOC. However, it needs to be acknowledged that the strength of the associations were weak ($0.10 < V < 0.20$) based on the calculated Cramer's V effect sizes. While a significant main effect of sex was not observed for total number of baseline symptoms and total symptom severity scores, female student-athletes self-reported more baseline symptoms and had higher mean symptom severity scores compared to male student-athletes. Multiple studies have demonstrated in various athlete populations that female athletes self-report significantly more symptoms and higher total symptom severity scores at baseline on the SCAT graded symptom checklist or a similar concussion symptom scale compared to their male athlete counterparts.[96,101,103,104,155,269] Based on $\chi 2$ tests, sex was significantly associated with self-reporting baseline symptoms of neck pain, feeling nervous or anxious, difficulties concentrating, difficulties remembering and balance problems on the graded symptom checklist. Although Cramer's V effect sizes were weak for each of these significant associations, female student-athletes were shown to be more likely to self-report each of these symptoms at baseline compared to male student athletes. These results align with the major findings from a meta-analysis[274] on sex-related differences in baseline symptom reporting amongst high school and collegiate student-athletes, along with previous studies that evaluated collegiate or university varsity student-athletes[101,102] and elite rugby athletes.[155] Symptoms of neck pain, difficulties concentrating and feeling nervous or anxious, in addition to other symptoms including fatigue or low energy and irritability, may be associated with premenstrual syndrome and estrogen fluctuations during the female menstrual cycle.[274-276] However, data regarding the stage of menses in female student-athletes at the time of preseason baseline testing and information on the typical symptoms that they experience during menses were not collected for the current study. For the orientation test, similar mean orientation scores were observed between male and female student-athletes in the current study, which is consistent with the findings across multiple studies involving high school and collegiate student-athletes undergoing baseline testing with the SCAT.[96,103,105,156] However, some studies have reported significantly higher mean orientation scores in female athletes at baseline compared to male athletes.[79,155] When analyzed by concussion history, the current study found significantly higher mean orientation scores in student-athletes with No RHOC compared to student-athletes with a RHOC. This result has not been observed in previous studies. As student-athletes with a RHOC still scored well on the orientation test overall, it is entirely possible that this statistically significant finding was the result of a higher percentage of student-athletes with a RHOC scoring four out of five on the orientation test compared to student-athletes with No RHOC. Considerable ceiling effects in scoring were observed for the five-word immediate memory test, with nearly 70% of all student-athletes scoring 15 out of 15. This is consistent with multiple studies that found ceiling effects in baseline five-word immediate memory total scores in youth athletes and collegiate or university varsity student-athletes.[79,102,103,277] Female student-athletes had significantly higher mean five-word mean immediate memory total scores compared to male student-athletes. This result aligns with the findings of Jinguji et al[156] which determined that female high school athletes had significantly higher five-word mean immediate memory total scores at baseline compared to their male counterparts, but contrast with Shehata et al[102] which reported similar baseline scores between male and female university varsity student-athletes. However, both of these previous studies[102,156] had a much smaller sample size of female athletes compared to male athletes, whereas the sample size of student-athletes that completed the five-word immediate memory test in the current study consisted of a fairly equal representation of 150 male and 152 female student-athletes. For the five-word delayed recall test, the current study observed significantly higher mean delayed recall scores in female student-athletes compared to male student-athletes. This result aligns with the findings reported by Chin et al[103] which determined in a large study population of high school and collegiate student-athletes competing in collision and contact sports that female athletes had significantly higher five-word delayed recall scores at baseline compared to male athletes. The higher percentage of female student-athletes in the current study that scored five out of five on the five-word delayed recall test compared to male student-athletes aligns with findings reported by Shehata et al[102] in university varsity collision sport student-athletes. However, the study by Shehata et al[102] was comprised of an uneven sample size of 189 male and 60 female student-athletes, whereas the current study had a relatively balanced sample of 148 male and 151 female student-athletes that completed the five-word delayed recall test. When analyzed by concussion history, the current study found that student-athletes with No RHOC had higher mean five-word delayed recall scores compared to student-athletes with a RHOC. However, the effect of concussion history was not statistically significant for five-word delayed recall score. The optional ten-word list provided in the SCAT5 for the immediate memory and delayed recall tests has been shown to eliminate ceiling effects in baseline scores in various athlete populations.[96,105,155,157,158] Many of these studies observed similar ten-word immediate memory and delayed recall scores between sexes and between athletes with a history of SRC and athletes with no history of SRC.[96,105,155] To the author's knowledge, only Norheim et al[158] reported significant sex differences in baseline scores for the ten-word immediate memory and delayed recall tests in a population of collegiate student-athletes. Therefore, the ten-word list for the immediate memory and delayed recall tests should be administered to university varsity student-athletes in future preseason baseline testing protocols in order to eliminate ceiling effects in scoring and to obtain an accurate representation of baseline performance on both tests that can be compared to scores immediately following SRC and at subsequent post-concussion testing timepoints. The months in reverse order test in the concentration component of the SAC was an easy test for a majority of student-athletes participating in this study. This is consistent with the results of previous studies that examined baseline performance on the months in reverse order test in university varsity student-athletes[102] and high school rugby athletes.[96] For the digits backwards test, approximately 18% of 298 student-athletes in the current study received a digits backwards score of four out of four by reciting all six digits backwards. These results contrast with the findings of Shehata et al[102] which demonstrated that 51% of all university varsity student-athletes participating in their study were able to recite all six digits backwards at baseline. However, the findings reported by Shehata et al[102] were limited to male and female student-athletes competing in university varsity ice hockey, football and wrestling. In contrast, the current study was comprised of university varsity student-athletes from a variety of collision sports, contact and limited contact/non-contact sports. When the scores for months and reverse order and digits backwards tests were summed to obtain the total concentration score, female student-athletes in the current study had significantly higher mean concentration total scores compared to male student-athletes. This result aligns with Tucker et al[155] which reported that elite women's rugby athletes had significantly higher concentration total scores at baseline compared to elite men's rugby athletes. However, the results of the current study contrast with the findings reported by Petit et al,[105] which in a large study population of NCAA collegiate student-athletes from a variety of sports observed no significant differences in concentration total scores between male and female student-athletes. The major effects of sex on baseline mBESS performance in the current study, with male student-athletes performing worse compared to female student-athletes, is consistent with the findings across multiple studies that evaluated baseline mBESS performance in a variety of athlete populations including collegiate student-athletes.[96,103,155,156] However, our results for the mBESS test contrast with Petit et al[105] which found no significant differences between male and female NCAA collegiate student-athletes in single leg stance errors, tandem stance errors and mBESS total error scores. The absence of a significant effect of concussion history on mBESS variables at baseline in the current study is consistent with findings across multiple studies that evaluated high school and collegiate student-athletes and found no significant associations of concussion history, or differences between athletes with a concussion history and athletes with no concussion history, in errors made at baseline in each of the three mBESS stances and mBESS total error scores.[96,103,105,126] A majority of student-athletes in the current study had normal results for each of the SCAT5 rapid neurological screen tests. This is consistent with the findings reported by Black et al[96] in high school rugby athletes evaluated at preseason baseline testing. Interestingly, 13 male student-athletes in the current study experienced pain on the passive cervical spine movement test, whereas only two female student-athletes experienced pain when performing this test. These observations may be associated with a previous history of concussion, as 11 student-athletes with a RHOC, nine of which were males, experienced pain on the passive cervical spine movement test compared to four student-athletes with No RHOC. Studies that involved professional male ice hockey athletes[159] and male elite-level rugby athletes[166] undergoing concussion screening within one day of a suspected concussion found that a small subset of athletes experienced pain on the passive cervical spine movement test regardless of whether they were diagnosed with a concussion or not.

Force Plate Postural Sway Assessment

The significantly larger RMSdisp and faster COPvel observed in male student-athletes for the force plate postural sway assessment is consistent with previous studies which demonstrated that male athletes within various age groups exhibit significantly higher force plate COP measures of postural sway during 20 sec quiet standing tasks performed at baseline compared to age-matched female athletes.[134,278,279] The mechanisms underlying the significant effects of sex on force plate COP measures of postural sway are likely multifactorial and complex. Male student-athletes in the current study were significantly taller and heavier than female student-athletes, which may have contributed to males having greater difficulty in maintaining their posture on the force plate while standing in the upright position with EO and EC. In addition, females benefit anatomically from having a wider pelvis and shorter or smaller bone structure compared to males, which automatically lowers their centre of gravity closer to the ground (base of support) and provides them with better postural control and stability compared to males. Outside of sex-related anatomical factors, female student-athletes in the current study may have had more competitive experience in artistic sports (ex. gymnastics, figure skating and cheerleading) that require high quality postural control and fluidity between static and dynamic postural states.[134,278,280] Howell et al[278] reported that female athletes who competed in gymnastics, dance, and figure skating demonstrated significantly higher overall postural control ratings in all three mBESS stance conditions performed on a video-force plate system compared to both female and male athletes who participated in other sports (ex. soccer, basketball, lacrosse). Therefore, the significant differences between sexes in force plate COP measures of postural sway in the current study may have been influenced by a distinct training effect rather than solely sex-related anatomical characteristics. The absence of significant effects of concussion history for any force plate COP measures of postural sway in the current study is consistent with the findings reported by Dierijck et al[120], which demonstrated no discernable baseline differences in RMSdisp and COPvel between young adult male athletes with a history of three or more previous SRCs and matched athletes with no history of SRC assessed in 60 sec quiet stance trials performed in EO and EC conditions. Multiple studies have examined the effects of acute concussion on force plate COP measures of postural sway in university varsity or collegiate student-athletes.[127,131] Powers et al[127] demonstrated that concussed university varsity football athletes had significantly larger RMSdisp AP and faster COPvel AP in EC conditions compared to non-concussed teammates, with COPvel AP still elevated in concussed athletes when assessed at RTS (26.44 $\pm$ 14.03 days post-concussion). Pryhoda et al[131] reported that COPvel ML quantified in a double leg stance performed on a hard surface in EC conditions differentiated concussed collegiate student-athletes from non-concussed student-athletes at three days post-concussion. When collegiate student-athletes were assessed at six months post-concussion after having received medical clearance to RTS several months prior, Pryhoda et al[131] found that 60% of student-athletes (nine out of 15 athletes) had not recovered within the proposed clinical thresholds for COPvel ML (6.2 mm/sec) quantified in the double leg stance on a hard surface. In contrast to these studies, Dierijck et al[120] assessed quiet stance postural control in a cohort of concussed ice hockey and football athletes at 72 hours, two weeks and one-month post-concussion and found no significant differences in RMSdisp and COPvel measures in both EO and EC conditions between concussed athletes and healthy non-concussed athletes matched for sport, age, BMI, and previous SRC history. Outside of the collegiate and university student-athlete population, Rochefort et al[128] demonstrated that adolescents assessed at one-month post-concussion exhibited significantly larger AREA-CE of sway compared to healthy adolescent controls during two-minute double-leg stance standing trials performed in EO, EC and dual-task conditions on a Nintendo Wii Balance Board. In addition, Rochefort et al[128] reported that the original BESS test failed to differentiate balance performance between concussed adolescents and healthy controls. As a whole, the collection of findings across studies provides supporting evidence for objectively evaluating postural control and sway in concussed athletes in a longitudinal manner using force plate methods in order to detect impairments that are not identified by the mBESS or BESS tests following the initial three to five days post-concussion when errors scores for these tests typically return to baseline values.[102,148,149,153, 159,161]

Cerebral Blood Flow Volume Assessment

The significant effects of sex observed in the current study on DU measurements of CCA and ICA BFV bilaterally and total cerebral BFV contrast with findings reported in multiple DU studies which demonstrated no significant role of sex for each of these measurements in healthy adult participants.[187-192] However, student-athletes in the current study were exclusively young adult males and females, whereas the previous studies examined cerebral BFV in healthy adult male and female participants from various age cohorts throughout the lifespan (ex. 20 – 39, 40 – 59, 60 – 85 years old).[187-192] Therefore, it is difficult to make comparisons with the significant sex-related results in the current study for CCA, ICA and total cerebral BFV. For example, Scheel et al[189] (39 males, mean age, 51.8 $\pm$ 19.4 years old; 39 women, mean age, 51.9 $\pm$ 19.1 years old) and Albayrak et al[190] (90 males, mean age, 49.8 $\pm$ 17.4 years old; 90 females, mean age 49.5 $\pm$ 17.5 years old) examined cerebral BFV measurements primarily in healthy middle-aged adults. The result of significantly higher left VA BFV in female student-athletes compared to male student-athletes partially aligns with the non-significant results from Albayrak et al[190] which demonstrated that healthy adult female participants between the ages of 20 to 39 years old had higher mean BFV in the left and right VA compared to healthy males within the same age group. Within sexes, both male and female student-athletes had significantly higher mean BFV in the left VA compared to the right VA, which is consistent with previous research that evaluated BFV differences between the left and right VA in healthy adults using DU.[187,190,192] There are multiple working hypotheses that could explain the isolated significant main effect of concussion history on right CCA BFV demonstrated in the current study, with student-athletes with a RHOC presenting with significantly lower mean BFV in the right CCA compared to student-athletes with No RHOC. It is possible that some of the student-athletes with a RHOC may have sustained a concussion within the year prior to their preseason baseline data collection date and thus may have had some lingering deficits in BFV within the right CCA. Unfortunately, the descriptive statistics for time in years since last concussion were calculated and reported for all university varsity student-athletes with a RHOC. The calculation of the mean time in years since last concussion was not performed for student-athletes providing data for each individual baseline assessment, including the DU cerebral BFV assessment, as this was beyond the scope of this study. The sex of student-athletes in the RHOC and No RHOC groups may have also played a contributing factor in this outcome for right CCA BFV. Mean right CCA BFV for both female student-athletes with a RHOC (n = 25; 545.94 ± 109.28) and male student-athletes with a RHOC (n = 16; 614.42 ± 90.31) were noticeably lower compared to their same-sex counterparts of female student-athletes with No RHOC (n = 16; 593.20 ± 79.55) and male student-athletes with No RHOC (n = 22; 674.76 ± 132.47). At the same time, however, a significant interaction effect between sex and concussion history was not observed for right CCA BFV. It is also possible that student-athletes with a RHOC may have presented with less BFV in the right CCA as a result of the anatomical origins of the artery in addition to the effects of concussion. The right CCA originates from the brachiocephalic artery which also branches into the right subclavian artery.[169,170] In contrast, the left CCA branches directly off the aortic arch.[169,170] Given these differences in anatomical origin, the author of the current study speculates that the left CCA may receive a greater supply of blood flow compared to the right CCA.

A majority of studies that have investigated the effects of SRC on global and regional measurements of CBF volume have primarily focused on the acute and sub-acute stages of SRC and limited their statistical analyses to comparing CBF volume differences between concussed athletes and healthy athlete controls matched by sex, age and sport.[154,183-186] For example, multiple studies have found significantly reduced regional CBF volume in various lobes, cortices, gyri and other brain structures in concussed collegiate athletes compared to sex-, age- and sport-matched healthy athletes.[154,183,184] Unfortunately, there is a scarcity of long-term studies that have examined sex-related differences in global and regional CBF volume measurements in athletes with a history of SRC and athletes with no history of SRC. To the author's knowledge, only Hamer et al[281] pursued this research question using ASL techniques by recruiting 122 university varsity student-athletes from a variety of sports and dividing them into four cohorts based on sex and previous history of SRC. Hamer et al[281] demonstrated that male student-athletes with a history of SRC had significantly lower bilateral CBF volume, predominately in the temporal lobes, compared to male student-athletes with no history of SRC. While Hamer et al[281] found no significant differences in CBF volume between female student-athletes with a history of SRC and female student-athletes with no history of SRC, they observed that female student-athletes with a history of SRC had significantly greater variability in temporal CBF volume distribution compared to male student-athletes with a history of SRC. As there were no significant differences in temporal CBF volume variability observed between male and female student-athletes with no history of SRC, this suggests that the significantly greater CBF volume variability observed in female student-athletes with a history of SRC relative to males with a history of SRC was unlikely influenced by sex-related hormonal differences at the time of ASL imaging. Therefore, the major findings from Hamer et al[281] and the results of the current study provide strong justification to prioritize research in sex-specific models of neurophysiological recovery following SRC.

Brain Dynamic Indicator™ and HurtSHynes™ Test

The significant main effects of sex observed for specific BrDI™ variables in the current study contrast with findings reported in previous studies that examined performance in standard and non-standard visuomotor mapping tasks in university varsity student-athletes[228] and youth athletes.[230,231] Each of these studies demonstrated no significant effects of sex for any movement timing and movement execution variables.[228,230,231] The author of the current study speculates that the significantly higher mean PV observed in male student-athletes compared to female student-athletes in both the standard and CMI condition may be associated with male student-athletes having more competitive experience in sports that frequently involve non-standard visuomotor mapping tasks during competition and in-game scenarios. Over time they developed and honed their skills in using CMI in these scenarios and the ability to execute fast movements effectively and efficiently. The current study observed no significant effects of concussion history for any movement timing and movement execution variables measured in the standard condition and the CMI condition. This was surprising to the author of the current study, particularly for the CMI condition. The CMI condition of the BrDI™ is a non-standard visuomotor mapping task that has a greater level of task complexity with two levels of vision and motor decoupling (explicit rule integration and sensorimotor recalibration) that is specifically designed to draw out lingering neurological deficits in athletes or individuals with a previous history of concussion that would not be identified with less sensitive standard visuomotor mapping tasks that test cognition and motor function seperately.[222] Based on the results of the current study, however, it can be concluded that student-athletes with a RHOC had no any lingering deficits in CMI performance. The absence of a significant effect of concussion history on PV in the current study is consistent with findings reported in previous studies.[229,231]

Interestingly, student-athletes with a RHOC exhibited higher mean PV in their limb movements in both the standard and CMI condition compared to student-athletes with No RHOC, although this was not statistically significant. This observation contrasts with findings from previous studies that observed similar or higher mean PV in athletes with no history of SRC compared to athletes with a history of SRC.[229,231] The non-significant but higher mean PV exhibited by student-athletes with a RHOC in the current study may have been confounded by the larger proportion of male student-athletes in the RHOC group (n = 25) compared to female student-athletes with a RHOC (n = 14). As previously described, male student-athletes with a RHOC may have benefited from prior competitive sport experience and a highly developed CMI skillset in the context of their particular sport that was transferred to the BrDI™. Mean RT in both the standard and CMI condition were very similar between student-athletes with a RHOC and student-athletes with No RHOC. This was an unexpected result, as Hurtubise et al[229] demonstrated that asymptomatic professional ice hockey draft prospects with a history of SRC had significant performance deficits in RT in the CMI condition compared to age- and skill-matched prospects with no history of SRC. The author of the current study is uncertain as to what could be the reason(s) for this discrepancy between studies, and therefore recommends that it should be explored further in future studies with more comparable participant sample sizes of athletes with a history of SRC and well-matched athletes with no history of SRC. The lack of a significant effect of concussion history on AE in the current study in both the standard and CMI conditions aligns with findings previously reported by Brown et al[228] in university varsity student-athletes. In contrast, Hurtubise et al[229] demonstrated that asymptomatic professional ice hockey draft prospects with a history of SRC had significantly larger AE, indicating reduced accuracy, compared to age and skill-matched draft prospects with No RHOC. On the other hand, Dalecki et al[231] showed that asymptomatic youth athletes with a history of SRC had significantly smaller AE and thus greater movement accuracy in both the vertical (standard) and horizontal rotated (CMI) conditions compared to age-matched athletes with no history of SRC. The discrepancies in findings across studies for AE could be explained by the recovery status of athletes following their most recent SRC.[228,229,231] For example, the ice hockey draft prospects with a history of SRC in the study by Hurtubise et al[229] had persisting performance deficits in AE due to not having achieved complete neurological recovery from their most recent SRC. No significant effects of concussion history on VE in the standard condition and CMI condition were observed in the current study, which is consistent with findings reported in previous studies.[228,229,231] However, both a significant main effect of sex and a significant interaction effect between sex and concussion history were observed for VE in the standard condition. Female student-athletes had significantly larger VE in the standard condition compared to male student-athletes, indicating reduced precision in this condition for female student-athletes. For the significant interaction effect on VE in the standard condition, female student-athletes with a RHOC exhibited significantly larger VE in the standard condition compared to male student-athletes with a RHOC. As this significant interaction effect on VE in the standard condition was not observed between male and female student-athletes with No RHOC, it appears that female student-athletes with a RHOC were less precise in their arm movement end points in the standard condition. However, it has to be acknowledged that only 14 female student-athletes that completed the BrDI™ assessment had a RHOC, and therefore this small sample of female student-athletes with a RHOC may have impacted the significance level of this interaction effect. Similar to the results for the BrDI™ assessment, no significant effects of concussion history were observed for HurtSHynes™ Test variables. A significant main effect of sex was only observed for total errors in the CMI condition, as male student-athletes made significantly more errors in the CMI condition compared to female student-athletes. A significant interaction effect between sex and concussion history was also observed for total errors in the CMI condition, as male student-athletes with No RHOC made significantly more errors in the CMI condition compared to female student-athletes with No RHOC. Interestingly, mean total errors in the CMI condition were comparable between male and female student-athletes with a RHOC. A significant interaction effect between sex and concussion history was observed for completion time in the standard condition. Again, the significant interaction effect was present between male and female student-athletes with No RHOC, as female student-athletes with No RHOC had significantly longer competition times in standard condition compared to male student-athletes with No RHOC. In summary, the absence of a significant effect of concussion history for completion time and total errors in both the standard and CMI conditions of the HurtSHynes™ Test, in addition to the significant interaction effects isolated between male and female student-athletes with No RHOC, provides supporting evidence that student-athletes with a RHOC in this study had neurologically recovered from their previous concussions.

Oculomotor Assessment

The current study found no significant effects of sex, concussion history and interaction between sex and concussion history for saccade latency and antisaccade reaction time in university varsity student-athletes. Multiple studies have evaluated impairments in oculomotor performance in young adult athletes diagnosed with SRC and adults with mild closed head injury (mCHI) using computerized oculomotor tasks and longitudinally monitored the resolution of oculomotor impairments and overall clinical recovery.[236-238,241] These studies examined various measures of oculomotor performance including antisaccade latency or reaction time, percentage of directional errors in antisaccades (ex. performing a saccade instead of an instructed antisaccade) and memory-guided sequences of saccades and the number of self-paced saccades generated within a 30 sec time period. Johnson et al[236] and Webb et al[238] demonstrated that young adult athletes with SRC exhibited significantly longer antisaccade latencies or reaction times and significantly higher percentage of directional errors for antisaccades at one-week post-concussion compared to healthy physically active controls matched by sex and age. Johnson et al[236] also found that concussed athletes generated significantly fewer self-paced saccades in 30 secs and made significantly more directional errors in memory-guided sequences of saccades at one-week post-concussion compared to healthy matched controls. Similar to these studies, Heitger et al[241] determined that adult patients diagnosed with mCHI exhibited significantly longer antisaccade latencies and significantly more directional errors in memory-guided sequences at one-week post-injury compared to healthy sex- and age-matched controls with no history of head injury. Johnson et al[237] and Webb et al[238] evaluated concussed athletes with follow-up oculomotor assessments performed at 30 days post-concussion and 14 – 20 days following the initial assessment, respectively. While both studies demonstrated that the percentage of directional errors in antisaccades were still significantly higher in concussed athletes compared to healthy matched controls, antisaccade latencies or reaction times were not significantly different between groups at follow-up assessments.[237,238] Additionally, Johnson et al[237] reported that concussed athletes at 30 days post-concussion continued to present with deficits in self-paced saccades and memory-guided sequences of saccades, although some improvements were observed in these measures compared to values at one-week post-concussion. Heitger et al[241] continued to evaluate mCHI patients at three, six and 12 months post-injury. Compared to healthy sex- and age-matched controls with no history of head injury, mCHI patients exhibited less deficits in antisaccade latency and significantly more directional errors in memory-guided sequences of saccades at 3 months post-injury.[241] When evaluated at six and 12 months post-injury, no abnormalities in antisaccade latency and memory-guided sequences of saccades were observed in this cohort of mCHI patients.[241] The lack of a significant effect of concussion history on saccade latency and antisaccade reaction time in the current study is therefore not surprising given the fact that a majority of student-athletes with a RHOC had sustained their most recent concussion beyond one year prior to participating in the preseason baseline testing protocol. Based on the findings from previous studies,[88,237,238,241] university varsity student-athletes with SRC that present with oculomotor symptoms should be evaluated longitudinally using computerized oculomotor tasks in order to examine the presence of residual oculomotor impairments and to monitor their resolution.

Stroop Colour and Word Test

To the author's knowledge, this is the largest dataset of baseline values for errors made in each SCWT task collected from a population of adult male and female athletes. The current study demonstrated no significant main effects of sex, concussion history or interaction effects between sex and concussion history on errors made in the word task, colour task and interferences task and total errors for the entire SCWT. The absence of a significant effect of concussion history on SCWT errors in the current study expands on the findings of previous studies[253,254] that examined SCWT performance in exclusively adult male athlete populations with smaller sample sizes compared to the current study. For example, Moore et al[253] compared SCWT performance between university varsity soccer athletes with a history of SRC (27.3 ± 3.6 months since last SRC) and regular exposure to sub-concussive head impacts, university varsity soccer athletes who regularly sustained sub-concussive head impacts but self-reported no history of SRC and non-contact sport university athletes matched to soccer athletes by BMI, age, education and years of sport participation. Using a series of repeated measures ANOVAs, Moore et al[253] demonstrated no significant main effects of group for errors made in the word, colour and interference task of the SCWT. Clough et al[254] demonstrated no significant differences in SCWT performance between male amateur Australian rules football athletes with a history of SRC (greater than six months since last SRC) and sex- and age-matched athletes with no history of neurotrauma or participation in collision sports. In contrast to the results of the current study and previous research,[253,254] Caffey and Dalecki[251] demonstrated that non-athlete college students with a history of SRC from adolescence (45.30 ± 23.45 months since last SRC) had a significantly higher Stroop error rate on a computerized SCWT compared to sex- and age-matched non-athlete college students with no history of SRC. Caffey and Dalecki[251] also found that students with a history of SRC had a significantly higher error rate in the Stroop incongruent task condition (equivalent of the interference task in the current study) compared to the college students with no history of SRC. To the surprise of the author of the current study, student-athletes with a RHOC had comparable mean errors in the interference task to student-athletes with No RHOC. Therefore, it can be concluded that student-athletes with a RHOC did not experience greater difficulties on the interference task compared to their No RHOC counterparts in having to activate the commonly inhibited response of stating the ink colour of the colour-word and subduing the cognitive interference associated with the predominant response of stating the colour-word. It has been hypothesized that injury-induced dysfunction and alterations within the frontoparietal networks and interconnections between brain structures may be a contributing factor in poor performance on the SCWT for individuals with a previous history of concussion or TBI.[223,224,226,251] However, the results of the current study for the SCWT demonstrate that a history of SRC has no long-term effects on executive cognitive functioning in young adult athletes competing at the university varsity level.

Strengths and Limitations

As previously stated, this is the largest study of its type to analyze preseason baseline data collected from Canadian male and female university varsity student-athletes using a variety of validated baseline assessments. Comparable sample sizes of male and female student-athletes provided baseline data for each assessment. Additionally, preseason baseline data was collected from male and female student-athletes from a variety of collision sports, contact sports and limited contact/non-contact sports. Therefore, the results of this study can be generalized to male and female university varsity student-athletes at other Canadian universities competing in the same sports within the U Sports governing body. However, this study has some limitations that need to be addressed. A healthy survivor effect may be present in the subset of student-athletes with a RHOC. Some athletes may have retired from their sport during adolescence due to their history of one or multiple SRCs and therefore they did not reach the competitive university varsity level. As a result, there may be a cohort of former athletes that present with impairments or deficits in some of the baseline assessments used in this study. Concussion history data may have been influenced by recall bias. Student-athletes self-reported the number of previously diagnosed concussions that they had experienced, and if they had at least one previously diagnosed concussion, they also self-reported the recovery time of their most recent concussion and the number of years since their most recent concussion. As concussion non-disclosure amongst young adult and youth athletes is still a prominent issue, there may have been some student-athletes that avoided reporting a recent history of SRC (especially if they were actively playing their sport(s) in the summer or offseason) on their demographic information sheet in order to start their season or training camp on time without delay. Common reasons or factors that athletes often describe for not disclosing a possible SRC or a recent history of SRC include the following: they do not want to be removed from a game or competition; fears related to losing future playing time or a roster spot; they believe that the concussion and the symptoms that they are experiencing are not serious or severe; they face immense pressure from coaches, teammates and/or parents to “tough it out” and continue playing in order to avoid “letting their team down”.[113,282-286] There was substantial variation in the sample sizes of student-athletes providing data for each assessment. For example, the SCAT5 and force plate postural sway assessments were well attended by student-athletes and thus received a comprehensive dataset for the descriptive analyses. However, less student-athletes participated in the BrDI™ and DU cerebral BFV assessments given that these assessments were longer in duration. For future preseason baseline testing protocols, we hope to have a more evenly distributed allocation of student-athletes for each baseline assessment in order to obtain a more thorough dataset of normative baseline values for the university varsity student-athlete population. Demographic characteristics including anthropometric measurements and concussion history data (ex. number of previous diagnosed concussions, years since last concussion) were analyzed based on the entire university varsity student-athlete population that participated in the study, rather than analyzing demographic characteristics of student-athletes providing data for each individual assessment. The inter- and intra-rater reliability of measuring cerebral BFV using DU was not addressed in this study. As DU is an operator-dependent procedure, a single sonographer was responsible for collecting cerebral BFV measurements in order to avoid operator bias. Nevertheless, DU is a valuable non-invasive diagnostic tool that can be utilized for assessing changes in cerebral BFV following SRC longitudinally, given its low operational costs, accessibility for repeated measurements and its suitability for bedside monitoring.[190,191] The reporting of errors for each task in the SCWT were performed manually by a single examiner due to the novel methodology used with the application of the VR goggles. For future preseason baseline testing protocols, it is recommended that error reporting should be automated within the NeuroFlex® vision software system in order to enhance the reliability and accuracy of error reporting.

Future Directions

This dataset of normative baseline values collected from university varsity student-athletes can be utilized as a foundation for the development of a longitudinal study whereby concussed student-athletes are evaluated at the acute stage of SRC, throughout the recovery process and up to being cleared for RTS and RTL. With a larger sample size of student-athletes, future studies could examine differences in assessment variables between athletes in similar (ex. men's football vs woman's rugby) or dissimilar sports (ex. track and field vs men's and women's hockey combined) or make statistical comparisons between student-athletes grouped by participation in collision, contact and limited/non-contact sports. The author of the current study recommends that assessments that require an examiner to subjectively evaluate a student-athlete's performance in a specific metric should be paired with an objective assessment for a similar metric, when possible, in future preseason baseline testing sessions and/or at post-concussion and recovery time points. The mBESS test for example can be paired with the force plate postural sway assessment to evaluate postural control deficits in concussed student-athletes during the initial three to five days post-concussion. If the student-athlete's performance on the mBESS returns to their baseline values during or after this period, the force plate postural sway assessment can continue to be administered longitudinally through the remainder of the acute stage of SRC and at scheduled timepoints during the athlete's recovery up to RTS and RTL in order to determine if RMSdisp and COPvel measures have returned to baseline values. For the evaluation of CMI, the BrDI™ should be used during the acute stage of SRC to objectively assess deficits in movement timing and movement execution variables in both the standard and CMI condition. The HurtSHynes™ Test can be paired with the BrDI™ during the RTS and RTL progressions when the athlete has been medically cleared to engage in sport-specific exercise and participate in non-contact or full contact practice with their team. To address the potential link between concussion symptom presentation in female student-athletes with premenstrual syndrome and estrogen fluctuations during menses, menstrual cycle data should be collected from female student-athletes at future preseason baseline testing sessions, during the acute stage of SRC and at subsequent time points during their recovery. Female student-athletes could be asked to describe the symptoms that they typically experience during their menstrual cycle along with the severity of symptoms. This data would benefit researchers and athletic therapists in clinically differentiating symptoms related to menses and symptoms experienced following SRC.

Conclusions

This study revealed that university varsity student-athletes with a RHOC had no deficits or impairments in a majority of baseline assessment variables compared to student-athletes with No RHOC. These results provide supporting evidence that a majority of athletes recover from their previous SRCs. Sex-related differences in this study were most pronounced in DU measurements of cerebral BFV, mBESS test errors and force plate COP measures of postural sway. In response, we need to direct our focus towards developing sex-specific models of recovery for these metrics in order to enhance our understanding of the differences between sexes. Overall, this study expands our understanding of the variability of results for university varsity student-athletes across a variety of baseline assessments.

REFERENCES

1. Rhazes A. *Opera Medica Varia*. Venice: Bonetus Locctellus, 1497.
2. da Carpi B. *Isogogae Brevis*. Bononie: Benedictum Hectorus, 1523.
3. Lanfrancus. *A Most Excellent and Learned Worke of Chirurgery Called Chirurgia Por Va Lanfranci*. London: T Marshe, 1565.
4. Paré A. The works of that famous chirurgion Ambrose Parey. Translated out of Latin and compared with the French. 1st English ed. London: Cotes & Young, 1579.
5. Pott P. Observations on the nature and consequences of those injuries to which the head is liable from external violence. London: L Hawes, W Clarke, R Collins, 1768.
6. Petit J. *Traite des maladies chirurgicales et des operations que leur con vennent*. Paris: PF Didot le jeune, 1774.
7. Bell B. *A System of Surgery*. Edinburgh: Charles Elliott, 1786.
8. Kirkland T. A commentary on apoplectic and paralytic affections and on diseases connected with the subject. London: William Dawson, 1792.
9. Martland HS. Punch Drunk. *J Am Med Assoc*. 1928; 91(15):1103-1107. doi:10.1001/jama.1928.02700150029009
10. Denny-Brown D. Cerebral concussion. *Physiol Rev.*1945; 25 (2):296-325. doi:10.1152/physrev.1945.25.2.296
11. Saucier J. Concussion: A Misnomer. *Can Med Assoc J*. 1955;72(11):816-820.
12. Gurdjian ES, Webster JE, Lissner HR. Observations on the mechanism of brain concussion, contusion, and laceration. *Surg Gynecol Obstet*. 1955;101(6):680-690.
13. Congress of Neurological Surgeons. Committee on head injury nomenclature: glossary of head injury. *Clin Neurosurg.* 1966; 12:386–394.
14. American Medical Association. Subcommittee on classification of sports injuries: standard nomenclature of athletic injuries. Chicago: American Medical Association, 1966.
15. Hugenholtz H, Richard MT. Return to athletic competition following concussion. *Can Med Assoc J.* 1982;127(9):827-829.
16. Nelson WE, Jane JA, Gieck JH. Minor head injury in sports: a new system of classification and management. *Phys Sportsmed*.1984;12(3):103-107. doi:10.1080/00913847.1984.11701798
17. Cantu RC. Guidelines for return to contact sports after a cerebral concussion. *Phys Sportsmed*. 1986;14(10):75-83. doi:10.1080/00913847.1986.11709197
18. Barth JT, Alves WM, Ryan TV, et al. Chapter 17: Mild head injury in sports - neuropsychological sequelae and recovery of function. In: Levin HM, Eisenberg HM, Benton AL, eds. *Mild Head Injury*. Oxford University Press; 1989:257-275.
19. Kelly JP, Nichols JS, Filley CM, Lillehei KO, Rubinstein D, Kleinschmidt-DeMasters BK. Concussion in sports. Guidelines for the prevention of catastrophic outcome. JAMA. 1991;266(20):2867-2869. doi:10.1001/jama.266.20.2867
20. Cantu RC. Cerebral concussion in sport. Management and prevention. *Sports Med.* 1992;14(1):64-74. doi:10.2165/00007256-199214010-00005
21. Maddocks DL, Dicker GD, Saling MM. The assessment of orientation following concussion in athletes. *Clin J Sport Med.* 1995;5(1):32-35. doi:10.1097/00042752-199501000-00006
22. Kelly JP, Rosenberg JH. Diagnosis and management of concussion in sports. *Neurology.* 1997;48(3):575-580. doi:10.1212/wnl.48.3.575

23. McCrory PR. Were you knocked out? A team physician's approach to initial concussion management. *Med Sci Sports Exerc*.1997;29(7 Suppl): S207-212. doi:10.1097/00005768-199707001-00002
24. Cantu RC. Return to play guidelines after a head injury. *Clin Sports Med.* 1998;17(1):45-60. doi:10.1016/s0278-5919(05)70060-0
25. Aubry M, Cantu R, Dvorak J, et al. Summary and agreement statement of the first International Conference on Concussion in Sport, Vienna 2001. *Br J Sports Med.* 2002;36(1):6-7. doi:10.1136/bjsm.36.1.6
26. McCrory P, Johnston K, Meeuwisse W, et al. Summary and agreement statement of the 2nd International Conference on Concussion in Sport, Prague 2004. *Br J Sports Med.* 2005;39(4):196-204. doi:10.1136/bjsm.2005.018614
27. McCrory P, Meeuwisse W, Johnston K, et al. Consensus statement on concussion in sport: the 3rd International Conference on Concussion in Sport held in Zurich, November 2008. *J Athl Train.* 2009;44(4):434-448. doi:10.4085/1062-6050-44.4.434
28. McCrory P, Meeuwisse WH, Aubry M, et al. Consensus statement on concussion in sport: the 4th International Conference on Concussion in Sport held in Zurich, November 2012. *Br J Sports Med.* 2013;47(5):250-258. doi:10.1136/bjsports-2013-092313
29. McCrory P, Meeuwisse W, Dvorak J, et al. Consensus statement on concussion in sport—the 5th international conference on concussion in sport held in Berlin, October 2016. *Br J Sports Med.* 2017;51(11):838-847. doi:10.1136/bjsports-2017-097699
30. Chamard E, Lichtenstein JD. A systematic review of neuroimaging findings in children and adolescents with sports-related concussion. *Brain Inj*. 2018;32(7):816-831. doi:10.1080/02699052.2018.1463106
31. Slobounov SM, Sebastianelli WJ, Walter AE. Introduction: current understanding from basic brain science to clinical research. In: Slobounov SM; Sebastianelli WJ, eds. *Concussion in Athletics: From Brain to Behaviour*. 2nd ed. Springer; 2021: xi – xxvi.
32. Giza CC, Hovda DA. The neurometabolic cascade of concussion. *J Athl Train.* 2001;36(3):228-235.
33. Giza CC, Hovda DA. The new neurometabolic cascade of concussion. *Neurosurgery.* 2014;75(0 4):S24-S33. doi:10.1227/NEU.0000000000000505
34. Barkhoudarian G, Hovda DA, Giza CC. The molecular pathophysiology of concussive brain injury - an update. *Phys Med Rehabil Clin N Am.* 2016;27(2):373-393. doi:10.1016/j.pmr.2016.01.003
35. Verweij BH, Muizelaar JP, Vinas FC, et al. Mitochondrial dysfunction after experimental and human brain injury and its possible reversal with a selective N-type calcium channel antagonist (SNX-111). *Neurol Res.*1997;19(3):334–339.
36. Xiong Y, Gu Q, Peterson PL, et al. Mitochondrial dysfunction and calcium perturbation induced by traumatic brain injury. *J Neurotrauma* .1997;14(1):23–34.
37. Lifshitz J, Sullivan PG, Hovda DA, et al. Mitochondrial damage and dysfunction in traumatic brain injury. *Mitochondrion.* 2004;4(5–6):705–13.
38. Robertson CL, Saraswati M, Fiskum G. Mitochondrial dysfunction early after traumatic brain injury in immature rats. *J Neurochem.* 2007;101(5):1248–57.
39. Yoshino A, Hovda DA, Kawamata T, Katayama Y, Becker DP. Dynamic changes in local cerebral glucose utilization following cerebral conclusion in rats: evidence of a hyper- and subsequent hypometabolic state. *Brain Res.*1991;561(1):106-119. doi:10.1016/0006-8993(91)90755-k

40. Laurer HL, Bareyre FM, Lee VM, et al. Mild head injury increasing the brain's vulnerability to a second concussive impact. *J Neurosurg.* 2001;95(5):859-870. doi:10.3171/jns.2001.95.5.0859
41. Longhi L, Saatman KE, Fujimoto S, et al. Temporal window of vulnerability to repetitive experimental concussive brain injury. *Neurosurgery.* 2005;56(2):364-374. doi: 10.1227/01.NEU.0000149008.73513.44
42. Vagnozzi R, Tavazzi B, Signoretti S, et al. Temporal window of metabolic brain vulnerability to concussions: Mitochondrial-related impairment—part I. *Neurosurgery.* 2007; 61:379-389. doi:10.1227/01.NEU.0000280002.41696.D8
43. Tavazzi B, Vagnozzi R, Signoretti S, et al. Temporal window of metabolic brain vulnerability to concussions: oxidative and nitrosative stresses--part II. *Neurosurgery.* 2007;61(2):390-396. doi:10.1227/01.neu.0000255525.34956.3f
44. Vagnozzi R, Signoretti S, Tavazzi B, et al. Temporal window of metabolic brain vulnerability to concussion: a pilot 1H-magnetic resonance spectroscopic study in concussed athletes-part III. *Neurosurgery.* 2008;62(6):1286-1296. doi:10.1227/01.NEU.0000316421.58568.AD
45. Dewan MC, Rattani A, Gupta S, et al. Estimating the global incidence of traumatic brain injury. *J Neurosurg*. 2018;130(4):1080-1097. doi:10.3171/2017.10.JNS17352
46. Tran TM, Fuller AT, Kiryabwire J, et al. Distribution and characteristics of severe traumatic brain injury at Mulago National Referral Hospital in Uganda. *World Neurosurg*. 2015;83(3):269-277. doi:10.1016/j.wneu.2014.12.028
47. Viano DC, Parenteau CS, Xu L, Faul M. Head injuries (TBI) to adults and children in motor vehicle crashes. *Traffic Inj Prev*. 2017;18(6):616-622. doi:10.1080/15389588.2017.1285023
48. Adeleye AO, Ogun MI. Clinical epidemiology of head injury from road-traffic trauma in a developing country in the current era. *Front Neurol*. 2017;8:695. doi:10.3389/fneur.2017.00695
49. Duan A, Zhou M, Qiu J, Feng C, Yin Z, Li K. A 6-year survey of road traffic accidents in Southwest China: emphasis on traumatic brain injury. *J Safety Res*. 2020;73:161-169. doi:10.1016/j.jsr.2020.02.010
50. Cameron KL, Marshall SW, Sturdivant RX, Lincoln AE. Trends in the incidence of physician-diagnosed mild traumatic brain injury among active duty U.S. military personnel between 1997 and 2007. *J Neurotrauma*. 2012;29(7):1313-1321. doi:10.1089/neu.2011.2168
51. Rona RJ, Jones M, Fear NT, et al. Mild traumatic brain injury in UK military personnel returning from Afghanistan and Iraq: cohort and cross-sectional analyses. *J Head Trauma Rehabil*. 2012;27(1):33-44. doi:10.1097/HTR.0b013e318212f814
52. Schwab K, Terrio HP, Brenner LA, et al. Epidemiology and prognosis of mild traumatic brain injury in returning soldiers: a cohort study. *Neurology*. 2017;88(16):1571-1579. doi:10.1212/WNL.0000000000003839
53. Al-Hajj S, Hammoud Z, Colnaric J, et al. Characterization of traumatic brain injury research in the Middle East and North Africa Region: a systematic review. *NED*. 2021;55(1):20-31. doi:10.1159/000511554
54. Dengler BA, Agimi Y, Stout K, et al. Epidemiology, patterns of care and outcomes of traumatic brain injury in deployed military settings: implications for future military operations. *J Trauma Acute Care Surg*. 2022;93(2):220-228.

doi:10.1097/TA.0000000000003497
55. Garber BG, Rusu C, Zamorski MA. Deployment-related mild traumatic brain injury, mental health problems, and post-concussive symptoms in Canadian armed forces personnel. *BMC Psychiatry*. 2014;14(1):325. doi:10.1186/s12888-014-0325-5
56. Iverson KM, Pogoda TK. Traumatic brain injury among women veterans: an invisible wound of intimate partner violence. *Med Care*. 2015;53(4):S112-S119. doi:10.1097/MLR.0000000000000263
57. Iverson KM, Dardis CM, Pogoda TK. Traumatic brain injury and PTSD symptoms as a consequence of intimate partner violence. *Compr Psychiatry*. 2017;74:80-87. doi:10.1016/j.comppsych.2017.01.007
58. Haag H (Lin), Sokoloff S, MacGregor N, Broekstra S, Cullen N, Colantonio A. Battered and brain injured: assessing knowledge of traumatic brain injury among intimate partner violence service providers. *J Womens Health (Larchmt)*. 2019;28(7):990-996. doi:10.1089/jwh.2018.7299
59. Rowe RK, Murphy SM, Handmaker H, Lifshitz J. Population-level epidemiology of concussion concurrent with domestic violence in Arizona, USA. *J Neurotrauma*. 2021;38(16):2301-2310. doi:10.1089/neu.2021.0022
60. Langlois JA, Rutland-Brown W, Wald MM. The epidemiology and impact of traumatic brain injury: a brief overview. *J Head Trauma Rehabil.* 2006;21(5):375-378. doi:10.1097/00001199-200609000-00001
61. Thurman DJ, Branche CM, Sniezek JE. The epidemiology of sports-related traumatic brain injuries in the United States: recent developments. *J Head Trauma Rehabil*. 1998;13(2):1-8. doi:10.1097/00001199-199804000-00003
62. Schulz MR, Marshall SW, Mueller FO, et al. Incidence and risk factors for concussion in high school athletes, North Carolina, 1996-1999. *Am J Epidemiol*. 2004;160(10):937-944. doi:10.1093/aje/kwh304
63. Collins MW, Iverson GL, Lovell MR, McKeag DB, Norwig J, Maroon J. On-field predictors of neuropsychological and symptom deficit following sports-related concussion. *Clin J Sport Med*. 2003;13(4):222-229. doi:10.1097/00042752-200307000-00005
64. Sarmiento K, Thomas KE, Daugherty J, et al. Emergency department visits for sports- and recreation-related traumatic brain injuries among children — United States, 2010–2016. *MMWR Morb Mortal Wkly Rep*. 2019;68(10):237. doi:10.15585/mmwr.mm6810a2
65. Gordon KE, Kuhle S. Canadians reporting sport-related concussions: increasing and now stabilizing. *Clin J Sport Med*. 2022;32(3):313-317. doi:10.1097/JSM.0000000000000888
66. Public Health Agency of Canada. Results: Mortality, hospitalization and emergency department visits. *Injury in Review 2020 Edition: Spotlight on Traumatic Brain Injuries Across the Life Course.* 2020; 32-49.
67. Zuckerman SL, Kerr ZY, Yengo-Kahn A, Wasserman E, Covassin T, Solomon GS. Epidemiology of sports-related concussion in NCAA athletes from 2009-2010 to 2013-2014: incidence, recurrence, and mechanisms. *Am J Sports Med*. 2015;43(11):2654-2662. doi:10.1177/0363546515599634
68. Covassin T, Moran R, Elbin RJ. Sex differences in reported concussion injury rates and time loss from participation: an update of the National Collegiate Athletic Association Injury Surveillance Program from 2004-2005 through 2008-2009. *J Athl Train*. 2016;51(3):189-194. doi:10.4085/1062-6050-51.3.05

69. Chandran A, Boltz AJ, Morris SN, et al. Epidemiology of concussions in National Collegiate Athletic Association (NCAA) Sports: 2014/15-2018/19. *Am J Sports Med*. 2021:3635465211060340. doi:10.1177/03635465211060340
70. Kerr ZY, Dompier TP, Snook EM, et al. National collegiate athletic association injury surveillance system: review of methods for 2004-2005 through 2013-2014 data collection. *J Athl Train*. 2014;49(4):552-560. doi:10.4085/1062-6050-49.3.58
71. Meeuwisse WH, Love EJ. Development, implementation, and validation of the Canadian Intercollegiate Sport Injury Registry. *Clin J Sport Med*. 1998;8(3):164-177. doi:10.1097/00042752-199807000-00003
72. Meeuwisse WH, Hagel BE, Mohtadi NGH, Butterwick DJ, Fick GH. The distribution of injuries in Men's Canada West University Football: a 5-year Analysis. *Am J Sports Med*. 2000;28(4):516-523. doi:10.1177/03635465000280041201
73. Hagel BE, Fick GH, Meeuwisse WH. Injury risk in men's Canada West university football. *Am J Epidemiol*. 2003;157(9):825-833. doi:10.1093/aje/kwg050
74. Meeuwisse WH, Sellmer R, Hagel BE. Rates and risks of injury during intercollegiate basketball. *Am J Sports Med*. 2003;31(3):379-385. doi:10.1177/03635465030310030901
75. Schick DM, Meeuwisse WH. Injury rates and profiles in female ice hockey players. *Am J Sports Med*. 2003;31(1):47-52. doi:10.1177/03635465030310011901
76. Rishiraj N, Lloyd-Smith R, Lorenz T, Niven B, Michel M. University men's ice hockey: rates and risk of injuries over 6-years. *J Sports Med Phys Fitness*. 2009;49(2):159-166.
77. Echlin PS, Skopelja EN, Worsley R, et al. A prospective study of physician-observed concussion during a varsity university ice hockey season: incidence and neuropsychological changes. Part 2 of 4. *Neurosurg Focus*. 2012;33(6):E2:1-11. doi:10.3171/2012.10.FOCUS12286
78. Black AM, Sergio LE, Macpherson AK. The epidemiology of concussions: number and nature of concussions and time to recovery among female and male Canadian varsity athletes 2008 to 2011. *Clin J Sport Med*. 2017;27(1):52-56. doi:10.1097/JSM.0000000000000308
79. Hurtubise JM, Hughes CE, Sergio LE, Macpherson AK. Comparison of baseline and postconcussion SCAT3 scores and symptoms in varsity athletes: an investigation into differences by sex and history of concussion. *BMJ Open Sport Exerc Med*. 2018;4(1):e000312. doi:10.1136/bmjsem-2017-000312
80. Harmon KG, Clugston JR, Dec K, et al. American Medical Society for Sports Medicine position statement on concussion in sport. *Br J Sports Med*. 2019;53(4):213-225. doi:10.1136/bjsports-2018-100338
81. Henry LC, Elbin RJ, Collins MW, Marchetti G, Kontos AP. Examining recovery trajectories after sport-related concussion with a multimodal clinical assessment approach. *Neurosurgery*. 2016;78(2):232-241. doi:10.1227/NEU.0000000000001041
82. Feddermann-Demont N, Echemendia RJ, Schneider KJ, et al. What domains of clinical function should be assessed after sport-related concussion? A systematic review. *Br J Sports Med*. 2017;51(11):903-918. doi:10.1136/bjsports-2016-097403
83. Schneider KJ. Concussion - Part I: the need for a multifaceted assessment. *Musculoskelet Sci Pract*. 2019;42:140-150. doi:10.1016/j.msksp.2019.05.007
84. Herring S, Kibler WB, Putukian M, et al. Selected issues in sport-related concussion (SRC|mild traumatic brain injury) for the team physician: a consensus statement. *Br J Sports Med.* 2021;55(22):1251-1261. doi:10.1136/bjsports-2021-104235

85. Kontos AP, Sufrinko A, Sandel N, Emami K, Collins MW. Sport-related concussion clinical profiles: clinical characteristics, targeted treatments, and preliminary evidence. *Curr Sports Med Rep*. 2019;18(3):82-92. doi:10.1249/JSR.0000000000000573
86. Hynes LM, Dickey JP. Is there a relationship between whiplash-associated disorders and concussion in hockey? A preliminary study. *Brain Inj*. 2006;20(2):179-188. doi:10.1080/02699050500443707
87. Marshall CM, Vernon H, Leddy JJ, Baldwin BA. The role of the cervical spine in post-concussion syndrome. *Phys Sportsmed*. 2015;43(3):274-284. doi:10.1080/00913847.2015.1064301
88. Ellis MJ, Leddy J, Willer B. Multi-disciplinary management of athletes with post-concussion syndrome: an evolving pathophysiological approach. *Front Neurol*. 2016;7:136. doi:10.3389/fneur.2016.00136
89. Cook NE, Sapigao RG, Silverberg ND, et al. Attention-deficit/hyperactivity disorder mimics the post-concussion syndrome in adolescents. *Front Pediatr*. 2020;8:2. doi:10.3389/fped.2020.00002
90. Nelson LD, Guskiewicz KM, Marshall SW, et al. Multiple self-reported concussions are more prevalent in athletes with ADHD and learning disability. *Clin J Sport Med*. 2016;26(2):120-127. doi:10.1097/JSM.0000000000000207
91. Cottle JE, Hall EE, Patel K, Barnes KP, Ketcham CJ. Concussion baseline testing: preexisting factors, symptoms, and neurocognitive performance. *J Athl Train*. 2017;52(2):77-81. doi:10.4085/1062-6050-51.12.21
92. Iverson GL, Silverberg ND, Mannix R, et al. Factors associated with concussion-like symptom reporting in high school athletes. *JAMA Pediatr*. 2015;169(12):1132-1140. doi:10.1001/jamapediatrics.2015.2374
93. Covassin T, Elbin RJI, Larson E, Kontos AP. Sex and age differences in depression and baseline sport-related concussion neurocognitive performance and symptoms. *Clin J Sport Med*. 2012;22(2):98-104. doi:10.1097/JSM.0b013e31823403d2.
94. Champigny CM, Rawana J, Iverson GL, Maxwell B, Berkner PD, Wojtowicz M. Influence of anxiety on baseline cognitive testing and symptom reporting in adolescent student athletes. *J Neurotrauma*. 2020;37(24):2632-2638. doi:10.1089/neu.2020.7079
95. Iverson GL, Lange RT. Examination of "postconcussion-like" symptoms in a healthy sample. *Appl Neuropsychol*. 2003;10(3):137-144. doi:10.1207/S15324826AN1003_02
96. Black AM, Miutz LN, KV VW, Schneider KJ, Yeates KO, Emery CA. Baseline performance of high school rugby players on the Sport Concussion Assessment Tool 5. *J Athl Train*. 2020;55(2):116-123. doi:10.4085/1062-6050-123-19
97. Covassin T, Elbin RJ, Harris W, Parker T, Kontos A. The role of age and sex in symptoms, neurocognitive performance, and postural stability in athletes after concussion. *Am J Sports Med*. 2012;40 (6):1303-1312. doi:10.1177/0363546512444554
98. Ono KE, Burns TG, Bearden DJ, McManus SM, King H, Reisner A. Sex-based differences as a predictor of recovery trajectories in young athletes after a sports-related concussion. *Am J Sports Med*. 2016;44(3):748-752. doi:10.1177/0363546515617746
99. Hannah TC, Li AY, Spiera Z, et al. Sex-related differences in the incidence, severity and recovery of concussion in adolescent student-athletes between 2009 and 2019. *Am J Sports Med*. 2021;49 (7):1929-1937. doi:10.1177/03635465211008596
100. Brooks BL, Silverberg N, Maxwell B, et al. Investigating effects of sex differences and prior concussions on symptom reporting and cognition among adolescent soccer players.

Am J Sports Med. 2018;46 (4):961-968. doi:10.1177/0363546517749588
101. Covassin T, Swanik CB, Sachs M, et al. Sex differences in baseline neuropsychological function and concussion symptoms of collegiate athletes. *Br J Sports Med.* 2006; 40 (11):923-927. doi:10.1136/bjsm.2006.029496.
102. Shehata N, Wiley JP, Richea S, Benson BW, Duits L, Meeuwisse WH. Sport concussion assessment tool: baseline values for varsity collision sport athletes. *Br J Sports Med.* 2009;43(10):730-734. doi:10.1136/bjsm.2009.059832.
103. Chin EY, Nelson LD, Barr WB, McCrory P, McCrea MA. Reliability and validity of the sport concussion assessment tool–3 (SCAT3) in high school and collegiate athletes. *Am J Sports Med*. 2016; 44 (9):2276-2285. doi:10.1177/0363546516648141
104. Register-Mihalik JK, Mihalik JP, Guskiewicz KM. Association between previous concussion history and symptom endorsement during preseason baseline testing in high school and collegiate athletes. *Sports Health*. 2009;1(1):61-65. doi:10.1177/1941738108325920.
105. Petit KM, Savage JL, Bretzin AC, Anderson M, Covassin T. The sport concussion assessment tool-5 (SCAT5): baseline assessments in NCAA Division I collegiate student-athletes. *Int J Exerc Sci*. 2020;13(3):1143-1155.
106. McCrea M, Guskiewicz K, Randolph C, et al. Incidence, clinical course, and predictors of prolonged recovery time following sport-related concussion in high school and college athletes. *J Int Neuropsychol Soc*. 2013;19(1):22-33. doi:10.1017/S1355617712000872
107. Williams RM, Puetz TW, Giza CC, Broglio SP. Concussion recovery time among high school and collegiate athletes: a systematic review and meta-analysis. *Sports Med*. 2015;45(6):893-903. doi:10.1007/s40279-015-0325-8
108. Wasserman EB, Kerr ZY, Zuckerman SL, Covassin T. Epidemiology of sports-related concussions in National Collegiate Athletic Association Athletes from 2009-2010 to 2013-2014: symptom prevalence, symptom resolution time and return-to-play time. *Am J Sports Med*. 2016;44(1):226-233. doi:10.1177/0363546515610537
109. Zemek R, Barrowman N, Freedman SB, et al. Clinical risk score for persistent postconcussion symptoms among children with acute concussion in the ED. *JAMA*. 2016;315(10):1014-1025. doi:10.1001/jama.2016.1203
110. Schneider KJ, Nettel-Aguirre A, Palacios-Derflingher L, et al. Concussion burden, recovery and risk factors in elite youth ice hockey players. *Clin J Sport Med*. 2021;31(1):70-77. doi:10.1097/JSM.0000000000000673
111. Zuckerman SL, Apple RP, Odom MJ, Lee YM, Solomon GS, Sills AK. Effect of sex on symptoms and return to baseline in sport-related concussion. *J Neurosurg Pediatr*. 2014;13(1):72-81. doi:10.3171/2013.9.PEDS13257
112. Morgan CD, Zuckerman SL, Lee YM, et al. Predictors of postconcussion syndrome after sports-related concussion in young athletes: a matched case-control study. *J Neurosurg Pediatr*. 2015;15(6):589-598. doi:10.3171/2014.10.PEDS14356
113. Asken BM, McCrea MA, Clugston JR, Snyder AR, Houck ZM, Bauer RM. "Playing Through It": delayed reporting and removal from athletic activity after concussion predicts prolonged recovery. *J Athl Train*. 2016;51(4):329-335. doi:10.4085/1062-6050-51.5.02
114. Meehan WP, Mannix R, Monuteaux MC, Stein CJ, Bachur RG. Early symptom burden predicts recovery after sport-related concussion. *Neurology*. 2014;83(24):2204-2210. doi:10.1212/WNL.0000000000001073.
115. Zuckerman SL, Yengo-Kahn AM, Buckley TA, Solomon GS, Sills AK, Kerr ZY.

Predictors of postconcussion syndrome in collegiate student-athletes. *Neurosurg Focus*. 2016;40(4):E13. doi:10.3171/2016.1.FOCUS15593.
116. Guskiewicz KM, McCrea M, Marshall SW, et al. Cumulative effects associated with recurrent concussion in collegiate football players: the NCAA Concussion Study. *JAMA*. 2003;290(19):2549-2555. doi:10.1001/jama.290.19.2549
117. Schilling S, Mansour A, Sullivan L, Ding K, Pommering T, Yang J. Symptom burden and profiles in concussed children with and without prolonged recovery. *Int J Environ Res Public Health.* 2020;17(1). doi:10.3390/ijerph17010351
118. Meehan WP, Mannix RC, Stracciolini A, Elbin RJ, Collins MW. Symptom severity predicts prolonged recovery after sport-related concussion, but age and amnesia do not. *J Pediatr*. 2013;163(3):721-725. doi:10.1016/j.jpeds.2013.03.012
119. Miller JH, Gill C, Kuhn EN, et al. Predictors of delayed recovery following pediatric sports-related concussion: a case-control study. *J Neurosurg Pediatr*. 2016;17(4):491-496. doi:10.3171/2015.8.PEDS14332.
120. Dierijck JK, Wright AD, Smirl JD, Bryk K, van Donkelaar P. Sub-concussive trauma, acute concussion, and history of multiple concussions: effects on quiet stance postural control stability. *Int J Psychophysiol*. 2018;132(Pt A):74-80. doi:10.1016/j.ijpsycho.2018.03.005
121. Maki BE, McIlroy WE. Postural control in the older adult. *Clin Geriatr Med*. 1996;12(4):635-658.
122. Sosnoff JJ, Broglio SP, Shin S, Ferrara MS. Previous mild traumatic brain injury and postural-control dynamics. *J Athl Train*. 2011;46(1):85-91. doi:10.4085/1062-6050-46.1.85
123. Guskiewicz KM. Balance assessment in the management of sport-related concussion. *Clin Sports Med*. 2011;30(1):89-102, ix. doi:10.1016/j.csm.2010.09.004.
124. Sosnoff JJ, Broglio SP, Shin S, Ferrara MS. Previous mild traumatic brain injury and postural-control dynamics. *J Athl Train*. 2011;46(1):85-91. doi:10.4085/1062-6050-46.1.85
125. Valovich McLeod TC, Hale TD. Vestibular and balance issues following sport-related concussion. *Brain Inj*. 2015;29(2):175-184. doi:10.3109/02699052.2014.965206.
126. Starling AJ, Leong DF, Bogle JM, Vargas BB. Variability of the modified Balance Error Scoring System at baseline using objective and subjective balance measures. *Concussion.* 2015;1(1):CNC5. Published 2015 Aug 6. doi:10.2217/cnc.15.5
127. Powers KC, Kalmar JM, Cinelli ME. Recovery of static stability following a concussion. *Gait Posture*. 2014;39(1):611-614. doi:10.1016/j.gaitpost.2013.05.026
128. Rochefort C, Walters-Stewart C, Aglipay M, Barrowman N, Zemek R, Sveistrup H. Balance markers in adolescents at 1-month postconcussion. *Orthop J Sports Med*. 2017;5(3):2325967117695507. doi:10.1177/2325967117695507
129. Rochefort C, Walters-Stewart C, Aglipay M, Barrowman N, Zemek R, Sveistrup H. Self-reported balance status is not a reliable indicator of balance performance in adolescents at one-month post-concussion. *J Sci Med Sport*. 2017;20(11):970-975. doi:10.1016/j.jsams.2017.04.008
130. Sweeny M, Perez OH, Inness EL, et al. The Toronto concussion study: a cross-sectional analysis of balance deficits following acute concussion in community-dwelling adults. *Brain Injury*. 2021;35(5):587-595. doi:10.1080/02699052.2021.1891288
131. Pryhoda MK, Shelburne KB, Gorgens K, Ledreux A, Granholm AC, Davidson BS. Centre of pressure velocity shows impairments in NCAA Division I athletes six months post-concussion during standing balance. *J Sports Sci*. 2020;38(23):2677-2687. doi:10.1080/02640414.2020.1795561

132. Inness EL, Sweeny M, Habib Perez O, et al. Self-reported balance disturbance and performance-based balance impairment after concussion in the general population. *J Head Trauma Rehabil*. 2019;34(3):E37-E46. doi:10.1097/HTR.0000000000000431
133. Perez OH, Green RE, Mochizuki G. Characterization of balance control after moderate to severe traumatic brain injury: a longitudinal recovery study. *Phys Ther*. 2018;98(9):786-795. doi:10.1093/ptj/pzy065
134. Weismiller SA, Monaco R, Womack J, et al. Individual baseline balance assessments in a large sample of incoming NCAA Division I athletes using a force plate system. *Int J Sports Phys Ther*. 2021;16(1):126. doi:10.26603/001c.18713
135. Murray NG, Szekely B, Moran R, et al. Concussion history associated with increased postural control deficits after subsequent injury. *Physiol Meas*. 2019;40(2):024001. doi:10.1088/1361-6579/aafcd8
136. Winter D. Human balance and posture control during standing and walking. *Gait & Posture*. 1995;3(4):193-214. doi:10.1016/0966-6362(96)82849-9
137. Winter DA, Prince F, Frank JS, Powell C, Zabjek KF. Unified theory regarding A/P and M/L balance in quiet stance. *J Neurophysiol*. 1996;75(6):2334-2343. doi:10.1152/jn.1996.75.6.2334
138. Prieto TE, Myklebust JB, Hoffmann RG, Lovett EG, Myklebust BM. Measures of postural steadiness: differences between healthy young and elderly adults. *IEEE Trans Biomed Eng*. 1996;43(9):956-966. doi:10.1109/10.532130
139. Quijoux F, Nicolaï A, Chairi I, et al. A review of center of pressure (COP) variables to quantify standing balance in elderly people: algorithms and open-access code. *Physiol Rep*. 2021;9(22):e15067. doi:10.14814/phy2.15067
140. McCrea M, Kelly JP, Randolph C, et al. Standardized assessment of concussion (SAC): on-site mental status evaluation of the athlete. *J Head Trauma Rehabil*. 1998;13(2):27-35. doi:10.1097/00001199-199804000-00005
141. Guskiewicz KM, Register-Mihalik J, McCrory P, et al. Evidence-based approach to revising the SCAT2: introducing the SCAT3. *Br J Sports Med*. 2013;47(5):289-293. doi:10.1136/bjsports-2013-092225
142. Echemendia RJ, Broglio SP, Davis GA, et al. What tests and measures should be added to the SCAT3 and related tests to improve their reliability, sensitivity and/or specificity in sideline concussion diagnosis? A systematic review. *Br J Sports Med*. 2017;51(11):895-901. doi:10.1136/bjsports-2016-097466
143. Echemendia RJ, Meeuwisse W, McCrory P, et al. The sport concussion assessment tool 5th edition (SCAT5): background and rationale. *Br J Sports Med*. 2017;51(11):848-850. doi:10.1136/bjsports-2017-097506
144. Sport concussion assessment tool - 5th edition. *Br J Sports Med*. 2017;51(11):851-858. doi:10.1136/bjsports-2017-097506SCAT5
145. Broshek DK, Kaushik T, Freeman JR, Erlanger D, Webbe F, Barth JT. Sex differences in outcome following sports-related concussion. *J Neurosurg*. 2005;102(5):856-863. doi:10.3171/jns.2005.102.5.0856
146. Baker JG, Leddy JJ, Darling SR, Shucard J, Makdissi M, Willer BS. Gender differences in recovery from sports-related concussion in adolescents. *Clin Pediatr (Phila)*. 2016;55(8):771-775. doi:10.1177/0009922815606417
147. Master CL, Katz BP, Arbogast KB, et al. Differences in sport-related concussion for female and male athletes in comparable collegiate sports: a study from the NCAA-DoD

Concussion Assessment, Research and Education (CARE) Consortium. *Br J Sports Med*. 2021;55(24):1387-1394. doi:10.1136/bjsports-2020-103316
148. McCrea M, Guskiewicz KM, Marshall SW, et al. Acute effects and recovery time following concussion in collegiate football players: the NCAA Concussion Study. *JAMA*. 2003;290(19):2556-2563. doi:10.1001/jama.290.19.2556
149. Downey RI, Hutchison MG, Comper P. Determining sensitivity and specificity of the Sport Concussion Assessment Tool 3 (SCAT3) components in university athletes. *Brain Inj*. 2018;32(11):1345-1352. doi:10.1080/02699052.2018.1484166.
150. McCrea M. Standardized mental status testing on the sideline after sport-related concussion. *J Athl Train*. 2001;36(3):274.
151. Barr WB, McCrea M. Sensitivity and specificity of standardized neurocognitive testing immediately following sports concussion. *J Int Neuropsychol Soc*. 2001;7(6):693-702. doi:10.1017/S1355617701766052
152. McCrea M, Kelly JP, Randolph C, Cisler R, Berger L. Immediate neurocognitive effects of concussion. *Neurosurgery*. 2002;50(5):1032-1042. doi:10.1097/00006123-200205000-00017
153. McCrea M, Barr WB, Guskiewicz K, et al. Standard regression-based methods for measuring recovery after sport-related concussion. *J Int Neuropsychol Soc*. 2005;11(1):58-69. doi:10.1017/S1355617705050083
154. Wang Y, Nelson LD, LaRoche AA, et al. Cerebral blood flow alterations in acute sport-related concussion. *J Neurotrauma*. 2016;33(13):1227. doi:10.1089/neu.2015.4072
155. Tucker R, Falvey E, Fuller G, Brown J, Raftery M. Baseline SCAT performance in men and women: comparison of baseline concussion screens between 6288 elite men's and 764 women's rugby players. *Clin J Sport Med*. 2021;31(6):e398-e405. doi:10.1097/JSM.0000000000000847
156. Jinguji TM, Bompadre V, Harmon KG, et al. Sport Concussion Assessment Tool – 2: baseline values for high school athletes. *Br J Sports Med*. 2012;46(5):365-370. doi:10.1136/bjsports-2011-090526
157. Tucker R, Falvey EC, Fuller GW, Hislop MD, Patricios J, Raftery M. Sport Concussion Assessment Tool: baseline and clinical reference limits for concussion diagnosis and management in elite Rugby Union. *J Sci Med Sport*. 2021;24(2):122-128. doi:10.1016/j.jsams.2020.07.006
158. Norheim N, Kissinger-Knox A, Cheatham M, Webbe F. Performance of college athletes on the 10-item word list of SCAT5. *BMJ Open Sport Exerc Med.* 2018;4(1):e000412. doi:10.1136/bmjsem-2018-000412
159. Bruce JM, Thelen J, Meeuwisse W, et al. Use of the Sport Concussion Assessment Tool 5 (SCAT5) in professional hockey, part 2: which components differentiate concussed and non-concussed players? *Br J Sports Med*. 2021;55(10):557-565. doi:10.1136/bjsports-2020-102072
160. Guskiewicz KM. Balance assessment in the management of sport-related concussion. *Clin Sports Med*. 2011;30(1):89-102, ix. doi:10.1016/j.csm.2010.09.004
161. Buckley TA, Munkasy BA, Clouse BP. Sensitivity and specificity of the modified balance error scoring system in concussed collegiate student athletes. *Clin J Sport Med*. 2017;28(2):174-176. doi:10.1097/JSM.0000000000000426
162. Murray N, Salvatore A, Powell D, Reed-Jones R. Reliability and validity evidence of multiple balance assessments in athletes with a concussion. *J Athl Train.* 2014;49(4):540-

549. doi:10.4085/1062-6050-49.3.32
163. Harmon KG, Whelan BM, Aukerman DF, et al. Diagnostic accuracy and reliability of sideline concussion evaluation: a prospective, case-controlled study in college athletes comparing newer tools and established tests. *Br J Sports Med*. 2022;56(3):144-150. doi:10.1136/bjsports-2020-103840
164. Wilkins JC, Valovich McLeod TC, Perrin DH, Gansneder BM. Performance on the Balance Error Scoring System decreases after fatigue. *J Athl Train*. 2004;39(2):156-161.
165. Oldham JR, Difabio MS, Kaminski TW, Dewolf RM, Howell DR, Buckley TA. Efficacy of tandem gait to identify impaired postural control after concussion. *Medicine & Science in Sports & Exercise*. 2018;50(6):1162-1168. doi:10.1249/MSS.0000000000001540
166. Fuller GW, Miles J, Tucker R, et al. Diagnostic Utility of New SCAT5 Neurological Screen Sub-tests. *Sports Med Open*. 2021;7(1):14. doi:10.1186/s40798-021-00303-z
167. Gunabushanam G, Kummant L, Scoutt LM. Vertebral artery ultrasound. *Radiol Clin North Am*. 2019;57(3):519-533. doi:10.1016/j.rcl.2019.01.011
168. Netter FH. Arteries to brain and meninges. [Image]. In: Hansen JT, Benninger B, Brueckner-Collins J, Hoagland TM, Tubbs RS, eds. *Atlas of Human Anatomy*. 7th ed. Elsevier; 2019:147.
169. Michael-Titus A, Shortland P, Revest P. Chapter 11: Stroke and head injury. In: Horne T, Stader L, eds. *The Nervous System: Basic Science and Clinical Conditions*. 2nd ed. Churchill Livingstone/Elsevier; 2010:199-226.
170. Bautista C. Chapter 20: Disorders of brain function. In: Grossman SC, Porth CM, eds. *Porth Pathophysiology: Concepts of Altered Health States*. 9th ed. Wolters Kluwer Health/Lippincott Williams & Wilkins; 2014:489-524.
171. Snell RS. Chapter 17: The blood supply of the brain and spinal cord. In: Horvath K, Malakoff-Klein E, Taylor C, eds. *Clinical Neuroanatomy*. 7th ed. Wolters Kluwer Health/Lippincott Williams & Wilkins; 2010:474-500.
172. Willie CK, Tzeng YC, Fisher JA, Ainslie PN. Integrative regulation of human brain blood flow. *J Physiol*. 2014;592(5):841-859. doi:10.1113/jphysiol.2013.268953
173. Netter FH. Cerebral arterial circle (of Willis). [Image]. In: Hansen JT, Benninger B, Brueckner-Collins J, Hoagland TM, Tubbs RS, eds. *Atlas of Human Anatomy*. 7th ed. Elsevier; 2019:151.
174. Fantini S, Sassaroli A, Tgavalekos KT, Kornbluth J. Cerebral blood flow and autoregulation: current measurement techniques and prospects for noninvasive optical methods. *Neurophotonics*. 2016;3(3):031411. doi:10.1117/1.NPh.3.3.031411
175. Bishop CC, Powell S, Rutt D, Browse NL. Transcranial Doppler measurement of middle cerebral artery blood flow velocity: a validation study. *Stroke*. 1986;17(5):913-915. doi:10.1161/01.str.17.5.913
176. Valdueza JM, Balzer JO, Villringer A, Vogl TJ, Kutter R, Einhäupl KM. Changes in blood flow velocity and diameter of the middle cerebral artery during hyperventilation: assessment with MR and transcranial Doppler sonography. *AJNR Am J Neuroradiol*. 1997;18(10):1929-1934.
177. Eames PJ, Blake MJ, Dawson SL, Panerai RB, Potter JF. Dynamic cerebral autoregulation and beat to beat blood pressure control are impaired in acute ischaemic stroke. *J Neurol Neurosurg Psychiatry*. 2002;72(4):467-472. doi:10.1136/jnnp.72.4.467
178. Peebles K, Celi L, McGrattan K, Murrell C, Thomas K, Ainslie PN. Human cerebrovascular and ventilatory CO2 reactivity to end-tidal, arterial and internal jugular

vein PCO2. *J Physiol*. 2007;584(Pt 1):347-357. doi:10.1113/jphysiol.2007.137075
179. Wright AD, Smirl JD, Bryk K, Fraser S, Jakovac M, van Donkelaar P. Sport-related concussion alters indices of dynamic cerebral autoregulation. *Front Neurol*. 2018;9:196. doi:10.3389/fneur.2018.00196
180. Wright AD, Smirl JD, Bryk K, Jakovac M, van Donkelaar P. A prospective transcranial doppler ultrasound-based evaluation of the effects of repetitive subconcussive head trauma on neurovascular coupling dynamics. *Clin J Sport Med*. 2020;30 Suppl 1:S53-S60. doi:10.1097/JSM.0000000000000578
181. Petcharunpaisan S, Ramalho J, Castillo M. Arterial spin labeling in neuroimaging. *World J Radiol*. 2010;2(10):384-398. doi:10.4329/wjr.v2.i10.384
182. Grade M, Hernandez Tamames JA, Pizzini FB, Achten E, Golay X, Smits M. A neuroradiologist's guide to arterial spin labeling MRI in clinical practice. *Neuroradiology*. 2015;57(12):1181-1202. doi:10.1007/s00234-015-1571-z
183. Wang Y, Nencka AS, Meier TB, et al. Cerebral blood flow in acute concussion: preliminary ASL findings from the NCAA-DoD CARE Consortium. *Brain Imaging Behav*. 2019;13(5):1375-1385. doi:10.1007/s11682-018-9946-5
184. Meier TB, Bellgowan PSF, Singh R, Kuplicki R, Polanski DW, Mayer AR. Recovery of cerebral blood flow following sports-related concussion. *JAMA Neurol*. 2015;72(5):530-538. doi:10.1001/jamaneurol.2014.4778
185. Barlow KM, Marcil LD, Dewey D, et al. Cerebral perfusion changes in post-concussion syndrome: a prospective controlled cohort study. *J Neurotrauma*. 2017;34(5):996-1004. doi:10.1089/neu.2016.4634
186. Churchill NW, Hutchison MG, Graham SJ, Schweizer TA. Symptom correlates of cerebral blood flow following acute concussion. *Neuroimage Clin*. 2017;16:234-239. doi:10.1016/j.nicl.2017.07.019
187. Schöning M, Walter J, Scheel P. Estimation of cerebral blood flow through color duplex sonography of the carotid and vertebral arteries in healthy adults. *Stroke*. 1994;25(1):17-22. doi:10.1161/01.STR.25.1.17
188. Scheel P, Ruge C, Petruch UR, Schöning M. Color duplex measurement of cerebral blood flow volume in healthy adults. *Stroke*. 2000;31(1):147-150. doi:10.1161/01.str.31.1.147
189. Scheel P, Ruge C, Schöning M. Flow velocity and flow volume measurements in the extracranial carotid and vertebral arteries in healthy adults: reference data and the effects of age. *Ultrasound Med Biol*. 2000;26(8):1261-1266. doi:10.1016/s0301-5629(00)00293-3
190. Albayrak R, Degirmenci B, Acar M, Haktanir A, Colbay M, Yaman M. Doppler sonography evaluation of flow velocity and volume of the extracranial internal carotid and vertebral arteries in healthy adults. *J Clin Ultrasound*. 2007;35(1):27-33. doi:10.1002/jcu.20301
191. Yazici B, Erdoğmuş B, Tugay A. Cerebral blood flow measurements of the extracranial carotid and vertebral arteries with Doppler ultrasonography in healthy adults. *Diagn Interv Radiol*. 2005;11(4):195-198.
192. Dörfler P, Puls I, Schliesser M, Mäurer M, Becker G. Measurement of cerebral blood flow volume by extracranial sonography. *J Cereb Blood Flow Metab*. 2000;20(2):269-271. doi:10.1097/00004647-200002000-00007
193. Kalkat R. Sex-specific differences in the association between history of concussion and cerebral blood flow volume. [Master's thesis]. York University; 2021. Accessed December 1st, 2020. http://130.63.180.190/xmlui/handle/10315/38763

194. Claassen JAHR, Thijssen DHJ, Panerai RB, Faraci FM. Regulation of cerebral blood flow in humans: physiology and clinical implications of autoregulation. *Physiol Rev*. 2021;101(4):1487-1559. doi:10.1152/physrev.00022.2020
195. Brassard P, Labrecque L, Smirl JD, et al. Losing the dogmatic view of cerebral autoregulation. *Physiol Rep*. 2021;9(15):e14982. doi:10.14814/phy2.14982
196. Lassen NA. Cerebral blood flow and oxygen consumption in man. *Physiol Rev*. 1959;39(2):183-238. doi:10.1152/physrev.1959.39.2.183
197. Armstead WM. Cerebral blood flow autoregulation and dysautoregulation. *Anesthesiol Clin*. 2016;34(3):465-477. doi:10.1016/j.anclin.2016.04.002
198. ter Laan M, van Dijk JMC, Elting JWJ, Staal MJ, Absalom AR. Sympathetic regulation of cerebral blood flow in humans: a review. *Br J Anaesth*. 2013;111(3):361-367. doi:10.1093/bja/aet122
199. Hamner JW, Tan CO. Relative contributions of sympathetic, cholinergic, and myogenic mechanisms to cerebral autoregulation. *Stroke*. 2014;45(6):1771-1777. doi:10.1161/STROKEAHA.114.005293
200. Ainslie PN, Duffin J. Integration of cerebrovascular CO2 reactivity and chemoreflex control of breathing: mechanisms of regulation, measurement, and interpretation. *Am J Physiol Regul Integr Comp Physiol*. 2009;296(5):R1473-R1495. doi:10.1152/ajpregu.91008.2008
201. Len TK, Neary JP. Cerebrovascular pathophysiology following mild traumatic brain injury. *Clin Physiol Funct Imaging*. 2011;31(2):85-93. doi:10.1111/j.1475-097X.2010.00990.x
202. Haider MN, Leddy JJ, Hinds AL, et al. Intracranial pressure changes after mild traumatic brain injury: a systematic review. *Brain Inj*. 2018;32(7):809-815. doi:10.1080/02699052.2018.1469045
203. Jünger EC, Newell DW, Grant GA, et al. Cerebral autoregulation following minor head injury. *J Neurosurg*. 1997;86(3):425-432. doi:10.3171/jns.1997.86.3.0425
204. Strebel S, Lam AM, Matta BF, Newell DW. Impaired cerebral autoregulation after mild brain injury. *Surg Neurol*. 1997;47(2):128-131. doi:10.1016/s0090-3019(96)00459-4
205. Pomschar A, Koerte I, Lee S, et al. MRI evidence for altered venous drainage and intracranial compliance in mild traumatic brain injury. *PLoS One*. 2013;8(2):e55447. doi:10.1371/journal.pone.0055447
206. Toth A, Kovacs N, Perlaki G, et al. Multi-modal magnetic resonance imaging in the acute and sub-acute phase of mild traumatic brain injury: can we see the difference?. *J Neurotrauma*. 2013;30(1):2-10. doi:10.1089/neu.2012.2486
207. Lumba-Brown A, Harley J, Lucio S, Vaida F, Hilfiker M. Hypertonic saline as a therapy for pediatric concussive pain: a randomized controlled trial of symptom treatment in the emergency department. *Pediatr Emerg Care*. 2014;30(3):139-145. doi:10.1097/PEC.0000000000000084
208. Jarrett M, Tam R, Hernández-Torres E, et al. A prospective pilot investigation of brain volume, white matter hyperintensities, and hemorrhagic lesions after mild traumatic brain injury. *Front Neurol*. 2016;7:11. doi:10.3389/fneur.2016.00011
209. Bolouri H, Säljö A, Viano DC, Hamberger A. Animal model for sport-related concussion; ICP and cognitive function. *Acta Neurol Scand*. 2012;125(4):241-247. doi:10.1111/j.1600-0404.2011.01614.x
210. Säljö A, Bolouri H, Mayorga M, Svensson B, Hamberger A. Low-level blast raises

intracranial pressure and impairs cognitive function in rats: prophylaxis with processed cereal feed. *J Neurotrauma*. 2010;27(2):383-389. doi:10.1089/neu.2009.1053
211. Donovan V, Bianchi A, Hartman R, Bhanu B, Carson MJ, Obenaus A. Computational analysis reveals increased blood deposition following repeated mild traumatic brain injury. *NeuroImage Clin*. 2012;1(1):18-28. doi:10.1016/j.nicl.2012.08.001
212. Wei EP, Kontos HA, Patterson JL. Dependence of pial arteriolar response to hypercapnia on vessel size. *Am J Physiol*. 1980;238(5):697-703. doi:10.1152/ajpheart.1980.238.5.H697
213. Faraci FM, Heistad DD, Mayhan WG. Role of large arteries in regulation of blood flow to brain stem in cats. *J Physiol*. 1987;387:115-123. doi:10.1113/jphysiol.1987.sp016566
214. Faraci FM, Brian JE. Nitric oxide and the cerebral circulation. *Stroke*. 1994;25(3):692-703. doi:10.1161/01.str.25.3.692
215. Oizumi XS, Akisaki T, Kouta Y, et al. Impaired response of perforating arteries to hypercapnia in chronic hyperglycemia. *Kobe J Med Sci*. 2006;52(1-2):27-35
216. Willie CK, Macleod DB, Shaw AD, et al. Regional brain blood flow in man during acute changes in arterial blood gases. *J Physiol*. 2012;590(14):3261-3275. doi:10.1113/jphysiol.2012.228551
217. Hotta H, Masamoto K, Uchida S, et al. Layer-specific dilation of penetrating arteries induced by stimulation of the nucleus basalis of Meynert in the mouse frontal cortex. *J Cereb Blood Flow Metab*. 2013;33(9):1440-1447. doi:10.1038/jcbfm.2013.92
218. Verbree J, Bronzwaer ASGT, Ghariq E, et al. Assessment of middle cerebral artery diameter during hypocapnia and hypercapnia in humans using ultra-high-field MRI. *J Appl Physiol (1985)*. 2014;117(10):1084-1089. doi:10.1152/japplphysiol.00651.2014
219. Coverdale NS, Badrov MB, Shoemaker JK. Impact of age on cerebrovascular dilation versus reactivity to hypercapnia. *J Cereb Blood Flow Metab*. 2017;37(1):344-355. doi:10.1177/0271678X15626156
220. Kontos HA, Raper AJ, Patterson JL. Analysis of vasoactivity of local pH, PCO2 and bicarbonate on pial vessels. *Stroke*. 1977;8(3):358-360. doi:10.1161/01.str.8.3.358
221. Golding EM, Steenberg ML, Contant CF, Krishnappa I, Robertson CS, Bryan RM. Cerebrovascular reactivity to CO_2 and hypotension after mild cortical impact injury. *Am J Physiol*. 1999;277(4):H1457-1466. doi:10.1152/ajpheart.1999.277.4.H1457
222. Sergio LE, Gorbet DJ, Adams MS, Dobney DM. The effects of mild traumatic brain injury on cognitive-motor Integration for skilled performance. *Front Neurol*. 2020;11. doi:10.3389/fneur.2020.541630
223. Herd SA, Banich MT, O'Reilly RC. Neural mechanisms of cognitive control: an integrative model of stroop task performance and FMRI data. *J Cogn Neurosci*. 2006;18(1):22-32. doi:10.1162/089892906775250012
224. Goghari VM, MacDonald AW. The neural basis of cognitive control: response selection and inhibition. *Brain Cogn*. 2009;71(2):72-83. doi:10.1016/j.bandc.2009.04.004
225. Slobounov SM, Zhang K, Pennell D, Ray W, Johnson B, Sebastianelli W. Functional abnormalities in normally appearing athletes following mild traumatic brain injury: a functional MRI study. *Exp Brain Res*. 2010;202(2):341-354. doi:10.1007/s00221-009-2141-6
226. Grandjean J, D'Ostilio K, Phillips C, et al. Modulation of brain activity during a Stroop inhibitory task by the kind of cognitive control required. *PLOS ONE*. 2012;7(7):e41513. doi:10.1371/journal.pone.0041513
227. Tremblay S, Henry LC, Bedetti C, et al. Diffuse white matter tract abnormalities in

clinically normal ageing retired athletes with a history of sports-related concussions. *Brain*. 2014;137(Pt 11):2997-3011. doi:10.1093/brain/awu236
228. Brown JA, Dalecki M, Hughes C, Macpherson AK, Sergio LE. Cognitive-motor integration deficits in young adult athletes following concussion. *BMC Sports Sci Med Rehabil*. 2015;7(1):25. doi:10.1186/s13102-015-0019-4
229. Hurtubise J, Gorbet D, Hamandi Y, Macpherson A, Sergio L. The effect of concussion history on cognitive-motor integration in elite hockey players. *Concussion*. 2016;1(3):CNC17. doi:10.2217/cnc-2016-0006
230. Dalecki M, Gorbet DJ, Macpherson A, Sergio LE. Sport experience is correlated with complex motor skill recovery in youth following concussion. *Eur J Sport Sci*. 2019;19(9):1257-1266. doi:10.1080/17461391.2019.1584249
231. Dalecki M, Albines D, Macpherson A, Sergio LE. Prolonged cognitive-motor impairments in children and adolescents with a history of concussion. *Concussion*. 2016;1(3):CNC14. doi:10.2217/cnc-2016-0001
232. Amaral CA. The effect of concussion history on an on-field assessment of cognitive-motor integration in male and female varsity athletes: reliability of the HurtSHynes™ Test. [Master's thesis]. York University; 2022.
233. Ventura RE, Balcer LJ, Galetta SL. The neuro-ophthalmology of head trauma. *Lancet Neurol*. 2014;13(10):1006-1016. doi:10.1016/S1474-4422(14)70111-5
234. Ventura RE, Balcer LJ, Galetta SL, Rucker JC. Ocular motor assessment in concussion: current status and future directions. *J Neurol Sci*. 2016;361:79-86. doi:10.1016/j.jns.2015.12.010
235. Master CL, Scheiman M, Gallaway M, et al. Vision diagnoses are common after concussion in adolescents. *Clin Pediatr (Phila)*. 2016;55(3):260-267. doi:10.1177/0009922815594367
236. Johnson B, Zhang K, Hallett M, Slobounov S. Functional neuroimaging of acute oculomotor deficits in concussed athletes. *Brain Imaging Behav*. 2015;9(3):564-573. doi:10.1007/s11682-014-9316-x
237. Johnson B, Hallett M, Slobounov S. Follow-up evaluation of oculomotor performance with fMRI in the subacute phase of concussion. *Neurology*. 2015;85(13):1163. doi:10.1212/WNL.0000000000001968
238. Webb B, Humphreys D, Heath M. Oculomotor executive dysfunction during the early and later stages of sport-related concussion recovery. *J Neurotrauma*. 2018;35(16):1874-1881. doi:10.1089/neu.2018.5673
239. Cochrane GD, Christy JB, Almutairi A, Busettini C, Swanson MW, Weise KK. Visuo-oculomotor function and reaction times in athletes with and without concussion. *Optom Vis Sci*. 2019;96(4):256-265. doi:10.1097/OPX.0000000000001364
240. Heitger MH, Anderson TJ, Jones RD, Dalrymple-Alford JC, Frampton CM, Ardagh MW. Eye movement and visuomotor arm movement deficits following mild closed head injury. *Brain*. 2004;127(3):575-590. doi:10.1093/brain/awh066
241. Heitger MH, Jones RD, Dalrymple-Alford JC, Frampton CM, Ardagh MW, Anderson TJ. Motor deficits and recovery during the first year following mild closed head injury. *Brain Inj*. 2006;20(8):807-824. doi:10.1080/02699050600676354
242. Heitger MH, Jones RD, Macleod AD, Snell DL, Frampton CM, Anderson TJ. Impaired eye movements in post-concussion syndrome indicate suboptimal brain function beyond the influence of depression, malingering or intellectual ability. *Brain*. 2009;132(10):2850-2870.

doi:10.1093/brain/awp181
243. Jensen AR, Rohwer WD Jr. The Stroop color-word test: a review. *Acta Psychol (Amst)*. 1966;25(1):36-93. doi:10.1016/0001-6918(66)90004-7
244. Bohnen N, Twijnstra A, Jolles J. Performance in the Stroop color word test in relationship to the persistence of symptoms following mild head injury. *Acta Neurol Scand*. 1992;85(2):116-121. doi:10.1111/j.1600-0404.1992.tb04009.x
245. Stroop JR. Studies of interference in serial verbal reactions. *J. Exp. Psychol.*1935;18(6):643-662. doi:10.1037/h0054651
246. Golden CJ. Identification of brain disorders by the Stroop Color and Word Test. *J Clin Psychol*. 1976;32(3):654-658. doi:10.1002/1097-4679(197607)32:3<654::aid-jclp2270320336>3.0.co;2-z
247. MacLeod CM, Dunbar K. Training and Stroop-like interference: evidence for a continuum of automaticity. *J Exp Psychol Learn Mem Cogn*. 1988;14(1):126-135. doi:10.1037//0278-7393.14.1.126
248. Laird AR, McMillan KM, Lancaster JL, et al. A comparison of label-based review and ALE meta-analysis in the Stroop task. *Hum Brain Mapp*. 2005;25(1):6-21. doi:10.1002/hbm.20129
249. Nee DE, Wager TD, Jonides J. Interference resolution: insights from a meta-analysis of neuroimaging tasks. *Cogn Affect Behav Neurosci*. 2007;7(1):1-17. doi:10.3758/cabn.7.1.1
250. Roberts KL, Hall DA. Examining a supramodal network for conflict processing: a systematic review and novel functional magnetic resonance imaging data for related visual and auditory stroop tasks. *J Cogn Neurosci*. 2008;20(6):1063-1078. doi:10.1162/jocn.2008.20074
251. Caffey AL, Dalecki M. Evidence of residual cognitive deficits in young adults with a concussion history from adolescence. *Brain Res*. 2021;1768:147570. doi:10.1016/j.brainres.2021.147570
252. Subotic A, Ting WKC, Cusimano MD. Characteristics of the King-Devick test in the assessment of concussed patients in the subacute and later stages after injury. *PLOS ONE*. 2017;12(8):e0183092. doi:10.1371/journal.pone.0183092
253. Moore RD, Lepine J, Ellemberg D. The independent influence of concussive and sub-concussive impacts on soccer players' neurophysiological and neuropsychological function. *Int J Psychophysiol*. 2017;112:22-30. doi:10.1016/j.ijpsycho.2016.11.011
254. Clough M, Mutimer S, Wright DK, et al. Oculomotor cognitive control abnormalities in Australian rules football players with a history of concussion. *J Neurotrauma*. 2018;35(5):730-738. doi:10.1089/neu.2017.5204
255. McIlroy WE, Maki BE. Preferred placement of the feet during quiet stance: development of a standardized foot placement for balance testing. *Clin Biomech (Bristol, Avon)*. 1997;12(1):66-70. doi:10.1016/s0268-0033(96)00040-x
256. Smeha N, Kalkat R, Sergio LE, Hynes LM. Sex-related differences in visuomotor skill recovery following concussion in working-aged adults. *BMC Sports Sci Med Rehabil*. 2022;14(1):72. doi:10.1186/s13102-022-00466-6
257. Modica MJ. Sex-related differences in oculomotor and cognitive Control in asymptomatic varsity athletes with and without a history of concussion. [Master's thesis]. York University; 2021.Accessed December 1st,2020. https://yorkspace.library.yorku.ca/xmlui/handle/10315/38718
258. Rice SG; American Academy of Pediatrics Council on Sports Medicine and Fitness.

Medical conditions affecting sports participation. *Pediatrics*. 2008;121(4):841-848. doi:10.1542/peds.2008-0080
259. Kerr ZY, Register-Mihalik JK, Kroshus E, Baugh CM, Marshall SW. Motivations associated with nondisclosure of self-reported concussions in former collegiate athletes. *Am J Sports Med*. 2016;44(1):220-225. doi:10.1177/0363546515612082
260. Katz BP, Kudela M, Harezlak J, et al. Baseline performance of NCAA athletes on a concussion assessment battery: a report from the CARE Consortium. *Sports Med*. 2018;48(8):1971-1985. doi:10.1007/s40279-018-0875-7
261. Eckner JT, Wang J, Nelson LD, et al. Effect of routine sport participation on short-term clinical neurological outcomes: a comparison of non-contact, contact, and collision sport athletes. *Sports Med*. 2020;50(5):1027-1038. doi:10.1007/s40279-019-01200-y
262. Rea LM and Parker RA. Chapter 10: Analyzing cross-tabulated data. *Designing and Conducting Survey Research: A Comprehensive Guide*. 4th ed. John Wiley & Sons, Inc; 2014: 203-204.
263. Zimmer A, Marcinak J, Hibyan S, Webbe F. Normative values of major SCAT2 and SCAT3 components for a college athlete population. *Appl Neuropsychol Adult*. 2015;22(2):132-140. doi:10.1080/23279095.2013.867265
264. Asken BM, Snyder AR, Clugston JR, Gaynor LS, Sullan MJ, Bauer RM. Concussion-like symptom reporting in non-concussed collegiate athletes. *Arch Clin Neuropsychol*. 2017;32(8):963-971. doi:10.1093/arclin/acx018
265. Asken BM, Snyder AR, Smith MS, Zaremski JL, Bauer RM. Concussion-like symptom reporting in non-concussed adolescent athletes. *Clin Neuropsychol*. 2017;31(1):138-153. doi:10.1080/13854046.2016.1246672
266. Mihalik JP, Lengas E, Register-Mihalik JK, Oyama S, Begalle RL, Guskiewicz KM. The effects of sleep quality and sleep quantity on concussion baseline assessment. *Clin J Sport Med*. 2013;23(5):343-348. doi:10.1097/JSM.0b013e318295a834
267. Asken BM, Houck ZM, Bauer RM, Clugston JR. SCAT5 vs. SCAT3 symptom reporting differences and convergent validity in collegiate athletes. *Arch Clin Neuropsychol*. 2020;35(3):291-301. doi:10.1093/arclin/acz007
268. Silverberg ND, Berkner PD, Atkins JE, Zafonte R, Iverson GL. Relationship between short Sleep duration and preseason concussion testing. *Clin J Sport Med*. 2016;26(3):226-231. doi:10.1097/JSM.0000000000000241
269. Combs PR, Ford CB, Campbell KR, Carneiro KA, Mihalik JP. Influence of self-reported fatigue and sex on baseline concussion assessment scores. *Orthop J Sports Med*. 2019;7(1):2325967118817515. doi:10.1177/2325967118817515
270. Mah CD, Kezirian EJ, Marcello BM, Dement WC. Poor sleep quality and insufficient sleep of a collegiate student-athlete population. *Sleep Health*. 2018;4(3):251-257. doi:10.1016/j.sleh.2018.02.005
271. Caccese JB, Iverson GL, Hunzinger KJ, et al. Factors associated with symptom reporting in U.S. Service Academy Cadets and NCAA student athletes without concussion: findings from the CARE Consortium. *Sports Med*. 2021;51(5):1087-1105. doi:10.1007/s40279-020-01415-4
272. Iverson GL, Gaetz M, Lovell MR, Collins MW. Cumulative effects of concussion in amateur athletes. *Brain Inj*. 2004;18(5):433-443. doi:10.1080/02699050310001617352
273. Bruce JM, Echemendia RJ. Concussion history predicts self-reported symptoms before and following a concussive event. *Neurology*. 2004;63(8):1516-1518.

doi:10.1212/01.WNL.0000142088.32204.82
274. Brown DA, Elsass JA, Miller AJ, Reed LE, Reneker JC. Differences in symptom reporting between males and females at baseline and after a sports-related concussion: a systematic review and meta-analysis. *Sports Med*. 2015;45(7):1027-1040. doi:10.1007/s40279-015-0335-6
275. Freeman EW, Halberstadt SM, Rickels K, Legler JM, Lin H, Sammel MD. Core symptoms that discriminate premenstrual syndrome. *J Womens Health (Larchmt)*. 2011;20(1):29-35. doi:10.1089/jwh.2010.2161
276. Schmelzer K, Ditzen B, Weise C, Andersson G, Hiller W, Kleinstäuber M. Clinical profiles of premenstrual experiences among women having premenstrual syndrome (PMS): affective changes predominate and relate to social and occupational functioning. *Health Care Women Int*. 2015;36(10):1104-1123. doi:10.1080/07399332.2014.954701
277. Schneider KJ, Emery CA, Kang J, Schneider GM, Meeuwisse WH. Examining Sport Concussion Assessment Tool ratings for male and female youth hockey players with and without a history of concussion. *Br J Sports Med*. 2010;44(15):1112-1117. doi:10.1136/bjsm.2009.071266
278. Howell DR, Hanson E, Sugimoto D, Stracciolini A, Meehan WP 3rd. Assessment of the postural stability of female and male athletes. *Clin J Sport Med*. 2017;27(5):444-449. doi:10.1097/JSM.0000000000000374
279. Goble DJ, Rauh MJ, Baweja HS. Normative data for the BTrackS Balance Test concussion-management tool: results from 10045 athletes aged 8 to 21 years. *J Athl Train*. 2019;54(4):439-444. doi:10.4085/1062-6050-178-18
280. Murray NG, Grimes KE, Shiflett ED, et al. Repetitive head impacts do not affect postural control following a competitive athletic season. *Int J Psychophysiol*. 2018;132(Pt A):81-86. doi:10.1016/j.ijpsycho.2017.09.018
281. Hamer J, Churchill NW, Hutchison MG, Graham SJ, Schweizer TA. Sex differences in cerebral blood flow associated with a history of concussion. *J Neurotrauma*. 2020;37(10):1197-1203. doi:10.1089/neu.2019.6800
282. McCrea M, Hammeke T, Olsen G, Leo P, Guskiewicz K. Unreported concussion in high school football players: implications for prevention. *Clin J Sport Med*. 2004;14(1):13-17. doi:10.1097/00042752-200401000-00003
283. Kroshus E, Garnett B, Hawrilenko M, Baugh CM, Calzo JP. Concussion under-reporting and pressure from coaches, teammates, fans, and parents. *Soc Sci Med*. 2015;134:66-75. doi:10.1016/j.socscimed.2015.04.011
284. Cusimano MD, Topolovec-Vranic J, Zhang S, Mullen SJ, Wong M, Ilie G. Factors influencing the underreporting of concussion in sports: a qualitative study of minor hockey participants. *Clin J Sport Med*. 2017;27(4):375-380. doi:10.1097/JSM.0000000000000372
285. Conway FN, Domingues M, Monaco R, et al. Concussion symptom underreporting among incoming National Collegiate Athletic Association Division I college athletes. *Clin J Sport Med*. 2020;30(3):203-209. doi:10.1097/JSM.0000000000000557
286. Delaney JS, Caron JG, Correa JA, Bloom GA. Why professional football players chose not to reveal their concussion symptoms during a Practice or Game. *Clin J Sport Med*. 2018;28(1):1-12. doi:10.1097/JSM.0000000000000495

APPENDICIES

Appendix A: License details and terms and conditions provided by Wolters Kluwer Health, Inc. and Copyright Clearance Center for Figure 1

This Agreement between York University -- Ben Migotto ("You") and Wolters Kluwer Health, Inc. ("Wolters Kluwer Health, Inc.") consists of your license details and the terms and conditions provided by Wolters Kluwer Health, Inc. and Copyright Clearance Center.

License Number: 5434850367379

License date: Nov 23, 2022

Licensed Content Publisher: Wolters Kluwer Health, Inc.

Licensed Content Publication: Neurosurgery

Licensed Content Title: The New Neurometabolic Cascade of Concussion

Licensed Content Author: Christopher Giza and David Hovda

Licensed Content Date: Oct 1, 2014

Licensed Content Volume: 75

Type of Use: Dissertation/Thesis

Requestor type: University/College

Sponsorship: No Sponsorship

Format: Print and electronic

Will this be posted online?: Yes, on an unrestricted website

Portion: Figures/tables/illustrations

Number of figures/tables/illustrations: 1

Author of this Wolters Kluwer article: No

Will you be translating?: No

Intend to modify/change the content: No

Title: Descriptive Analysis of Preseason Baseline Data Collected From University Varsity Student-athletes Using a Comprehensive Concussion Assessment Battery

Institution name: York University

Expected presentation date: Dec 2022

Portions: Figure 2. Diagram of the acute cellular biological processes occurring after concussion/mild TBI. Image located on page 19 of author manuscript.

Requestor Location: York University
4700 Keele Street
Campus Phone #: (416) 736- 2100
Toronto, ON M3J1P3
Canada

Attn: Ben Migotto, York University, 4700 Keele Street Toronto, ON, M3J1P3

Publisher Tax ID: 895524239 RT0001

Total: 0.00 CAD

Wolters Kluwer Health Inc. Terms and Conditions

Duration of License: Permission is granted for a one time use only. Rights herein do not apply to future reproductions, editions, revisions, or other derivative works. This permission shall be effective as of the date of execution by the parties for the maximum period of 12 months and should be renewed after the term expires.

When content is to be republished in a book or journal the validity of this agreement should be the life of the book edition or journal issue.

When content is licensed for use on a website, internet, intranet, or any publicly accessible site (not including a journal or book), you agree to remove the material from such site after 12 months, or request to renew your permission license

Credit Line: A credit line must be prominently placed and include: For book content: the author(s), title of book, edition, copyright holder, year of publication; For journal content: the author(s), titles of article, title of journal, volume number, issue number, inclusive pages and website URL to the journal page; If a journal is published by a learned society the credit line must include the details of that society.

Warranties: The requestor warrants that the material shall not be used in any manner which may be considered derogatory to the title, content, authors of the material, or to Wolters Kluwer Health, Inc.

Indemnity: You hereby indemnify and hold harmless Wolters Kluwer Health, Inc. and its respective officers, directors, employees and agents, from and against any and all claims, costs, proceeding or demands arising out of your unauthorized use of the Licensed Material

Geographical Scope: Permission granted is non-exclusive and is valid throughout the world in the English language and the languages specified in the license.

Copy of Content: Wolters Kluwer Health, Inc. cannot supply the requestor with the original artwork, high-resolution images, electronic files or a clean copy of content.

Validity: Permission is valid if the borrowed material is original to a Wolters Kluwer Health, Inc. imprint (J.B Lippincott, Lippincott-Raven Publishers, Williams & Wilkins, Lea & Febiger, Harwal, Rapid Science, Little Brown & Company, Harper & Row Medical, American Journal of

Nursing Co, and Urban & Schwarzenberg - English Language, Raven Press, Paul Hoeber, Springhouse, Ovid), and the Anatomical Chart Company

Third Party Material: This permission does not apply to content that is credited to publications other than Wolters Kluwer Health, Inc. or its Societies. For images credited to non-Wolters Kluwer Health, Inc. books or journals, you must obtain permission from the source referenced in the figure or table legend or credit line before making any use of the image(s), table(s) or other content.

Adaptations: Adaptations are protected by copyright. For images that have been adapted, permission must be sought from the rightsholder of the original material and the rightsholder of the adapted material.

Modifications: Wolters Kluwer Health, Inc. material is not permitted to be modified or adapted without written approval from Wolters Kluwer Health, Inc. with the exception of text size or color. The adaptation should be credited as follows: Adapted with permission from Wolters Kluwer Health, Inc.: [the author(s), title of book, edition, copyright holder, year of publication] or [the author(s), titles of article, title of journal, volume number, issue number, inclusive pages and website URL to the journal page].

Full Text Articles: Republication of full articles in English is prohibited.

Branding and Marketing: No drug name, trade name, drug logo, or trade logo can be included on the same page as material borrowed from Diseases of the Colon & Rectum, Plastic Reconstructive Surgery, Obstetrics & Gynecology (The Green Journal), Critical Care Medicine, Pediatric Critical Care Medicine, the American Heart Association publications and the American Academy of Neurology publications.

Open Access: Unless you are publishing content under the same Creative Commons license, the following statement must be added when reprinting material in Open Access journals: "The Creative Commons license does not apply to this content. Use of the material in any format is prohibited without written permission from the publisher, Wolters Kluwer Health, Inc. Please contact permissions@lww.com for further information."

Translations: The following disclaimer must appear on all translated copies: Wolters Kluwer Health, Inc. and its Societies take no responsibility for the accuracy of the translation from the published English original and are not liable for any errors which may occur.

Published Ahead of Print (PAP): Articles in the PAP stage of publication can be cited using the online publication date and the unique DOI number.

Disclaimer: Articles appearing in the PAP section have been peer-reviewed and accepted for publication in the relevant journal and posted online before print publication. Articles appearing as PAP may contain statements, opinions, and information that have errors in facts, figures, or interpretation. Any final changes in manuscripts will be made at the time of print publication and will be reflected in the final electronic version of the issue. Accordingly, Wolters Kluwer Health, Inc., the editors, authors and their respective employees are not responsible or liable for the use of any such inaccurate or misleading data, opinion or information contained in the articles in this section.

Termination of Contract: Wolters Kluwer Health, Inc. must be notified within 90 days of the original license date if you opt not to use the requested material.

Waived Permission Fee: Permission fees that have been waived are not subject to future waivers, including similar requests or renewing a license.

Contingent on payment: You may exercise these rights licensed immediately upon issuance of the license, however until full payment is received either by the publisher or our authorized vendor, this license is not valid. If full payment is not received on a timely basis, then any license preliminarily granted shall be deemed automatically revoked and shall be void as if never granted. Further, in the event that you breach any of these terms and conditions or any of Wolters Kluwer Health, Inc.'s other billing and payment terms and conditions, the license is automatically revoked and shall be void as if never granted. Use of materials as described in a revoked license, as well as any use of the materials beyond the scope of an unrevoked license, may constitute copyright infringement and publisher reserves the right to take any and all action to protect its copyright in the materials.

STM Signatories Only: Any permission granted for a particular edition will apply to subsequent editions and for editions in other languages, provided such editions are for the work as a whole in situ and do not involve the separate exploitation of the permitted illustrations or excerpts. Please view: STM Permissions Guidelines

Warranties and Obligations: LICENSOR further represents and warrants that, to the best of its knowledge and belief, LICENSEE's contemplated use of the Content as represented to LICENSOR does not infringe any valid rights to any third party.

Breach: If LICENSEE fails to comply with any provisions of this agreement, LICENSOR may serve written notice of breach of LICENSEE and, unless such breach is fully cured within fifteen (15) days from the receipt of notice by LICENSEE, LICENSOR may thereupon, at its option, serve notice of cancellation on LICENSEE, whereupon this Agreement shall immediately terminate.

Assignment: License conveyed hereunder by the LICENSOR shall not be assigned or granted in any manner conveyed to any third party by the LICENSEE without the consent in writing to the LICENSOR.

Governing Law: The laws of The State of New York shall govern interpretation of this Agreement and all rights and liabilities arising hereunder.

Unlawful: If any provision of this Agreement shall be found unlawful or otherwise legally unenforceable, all other conditions and provisions of this Agreement shall remain in full force and effect.

For Copyright Clearance Center / RightsLink Only:

Service Description for Content Services: Subject to these terms of use, any terms set forth on the particular order, and payment of the applicable fee, you may make the following uses of the ordered materials:

Content Rental: You may access and view a single electronic copy of the materials ordered for the time period designated at the time the order is placed. Access to the materials will be provided through a dedicated content viewer or other portal, and access will be discontinued upon expiration of the designated time period. An order for Content Rental does not include any rights to print, download, save, create additional copies, to distribute or to reuse in any way the full text or parts of the materials.

Content Purchase: You may access and download a single electronic copy of the materials ordered. Copies will be provided by email or by such other means as publisher may make available from time to time. An order for Content Purchase does not include any rights to create additional copies or to distribute copies of the materials.

Appendix B: License details and terms and conditions provided by Elsevier and Copyright Clearance Center for Figure 2

This Agreement between York University -- Ben Migotto ("You") and Elsevier ("Elsevier") consists of your license details and the terms and conditions provided by Elsevier and Copyright Clearance Center.

License Number: 5434861488851

License date: Nov 23, 2022

Licensed Content Publisher: Elsevier

Licensed Content Publication: Radiologic Clinics of North America

Licensed Content Title: Vertebral Artery Ultrasound

Licensed Content Author: Gowthaman Gunabushanam, Lauren Kummant, Leslie M. Scoutt

Licensed Content Date: May 1, 2019

Licensed Content Volume: 57

Licensed Content Issue: 3

Licensed Content Pages: 15

Start Page: 519

End Page: 533

Type of Use: reuse in a thesis/dissertation

Portion: figures/tables/illustrations

Number of figures/tables/illustrations: 1

Format: electronic

Are you the author of this Elsevier article?: No

Will you be translating?: No

Title: Descriptive Analysis of Preseason Baseline Data Collected From University Varsity Student-athletes Using a Comprehensive Concussion Assessment Battery

Institution name: York University

Expected presentation date: Dec 2022

Portions: Fig. 1. Schematic image showing vertebral artery anatomy. CCA, common carotid artery. Image on page 2.

Requestor Location: York University
4700 Keele Street
Campus Phone #: (416) 736- 2100
Toronto, ON M3J1P3
Canada

Attn: Ben Migotto York University, 4700 Keele Street, Toronto, ON M3J1P3

Publisher Tax ID: GB 494 6272 12

Total: 0.00 CAD

Terms and Conditions

INTRODUCTION

1. The publisher for this copyrighted material is Elsevier. By clicking "accept" in connection with completing this licensing transaction, you agree that the following terms and conditions apply to this transaction (along with the Billing and Payment terms and conditions established by Copyright Clearance Center, Inc. ("CCC"), at the time that you opened your Rightslink account and that are available at any time at http://myaccount.copyright.com).

GENERAL TERMS

2. Elsevier hereby grants you permission to reproduce the aforementioned material subject to the terms and conditions indicated.

3. Acknowledgement: If any part of the material to be used (for example, figures) has appeared in our publication with credit or acknowledgement to another source, permission must also be sought from that source. If such permission is not obtained then that material may not be included in your publication/copies. Suitable acknowledgement to the source must be made, either as a footnote or in a reference list at the end of your publication, as follows:
"Reprinted from Publication title, Vol /edition number, Author(s), Title of article / title of chapter, Pages No., Copyright (Year), with permission from Elsevier [OR APPLICABLE SOCIETY COPYRIGHT OWNER]." Also Lancet special credit - "Reprinted from The Lancet, Vol. number, Author(s), Title of article, Pages No., Copyright (Year), with permission from Elsevier."

4. Reproduction of this material is confined to the purpose and/or media for which permission is hereby given.

5. Altering/Modifying Material: Not Permitted. However figures and illustrations may be altered/adapted minimally to serve your work. Any other abbreviations, additions, deletions and/or any other alterations shall be made only with prior written authorization of Elsevier Ltd. (Please contact Elsevier's permissions helpdesk here). No modifications can be made to any Lancet figures/tables and they must be reproduced in full.

6. If the permission fee for the requested use of our material is waived in this instance, please be advised that your future requests for Elsevier materials may attract a fee.

7. Reservation of Rights: Publisher reserves all rights not specifically granted in the combination of (i) the license details provided by you and accepted in the course of this licensing transaction, (ii) these terms and conditions and (iii) CCC's Billing and Payment terms and conditions.

8. License Contingent Upon Payment: While you may exercise the rights licensed immediately upon issuance of the license at the end of the licensing process for the transaction, provided that you have disclosed complete and accurate details of your proposed use, no license is finally effective unless and until full payment is received from you (either by publisher or by CCC) as provided in CCC's Billing and Payment terms and conditions. If full payment is not received on a timely basis, then any license preliminarily granted shall be deemed automatically revoked and shall be void as if never granted. Further, in the event that you breach any of these terms and conditions or any of CCC's Billing and Payment terms and conditions, the license is automatically revoked and shall be void as if never granted. Use of materials as described in a revoked license, as well as any use of the materials beyond the scope of an unrevoked license, may constitute copyright infringement and publisher reserves the right to take any and all action to protect its copyright in the materials.

9. Warranties: Publisher makes no representations or warranties with respect to the licensed material.

10. Indemnity: You hereby indemnify and agree to hold harmless publisher and CCC, and their respective officers, directors, employees and agents, from and against any and all claims arising out of your use of the licensed material other than as specifically authorized pursuant to this license.

11. No Transfer of License: This license is personal to you and may not be sublicensed, assigned, or transferred by you to any other person without publisher's written permission.

12. No Amendment Except in Writing: This license may not be amended except in a writing signed by both parties (or, in the case of publisher, by CCC on publisher's behalf).

13. Objection to Contrary Terms: Publisher hereby objects to any terms contained in any purchase order, acknowledgment, check endorsement or other writing prepared by you, which terms are inconsistent with these terms and conditions or CCC's Billing and Payment terms and conditions. These terms and conditions, together with CCC's Billing and Payment terms and conditions (which are incorporated herein), comprise the entire agreement between you and publisher (and CCC) concerning this licensing transaction. In the event of any conflict between your obligations established by these terms and conditions and those established by CCC's Billing and Payment terms and conditions, these terms and conditions shall control.

14. Revocation: Elsevier or Copyright Clearance Center may deny the permissions described in this License at their sole discretion, for any reason or no reason, with a full refund payable to you. Notice of such denial will be made using the contact information provided by you. Failure to receive such notice will not alter or invalidate the denial. In no event will Elsevier or Copyright Clearance Center be responsible or liable for any costs, expenses or damage incurred by you as a result of a denial of your permission request, other than a refund of the amount(s) paid by you to Elsevier and/or Copyright Clearance Center for denied permissions.

LIMITED LICENSE

The following terms and conditions apply only to specific license types:

15. Translation: This permission is granted for non-exclusive world **English** rights only unless your license was granted for translation rights. If you licensed translation rights you may only translate this content into the languages you requested. A professional translator must perform all translations and reproduce the content word for word preserving the integrity of the article.

16. Posting licensed content on any Website: The following terms and conditions apply as follows: Licensing material from an Elsevier journal: All content posted to the web site must maintain the copyright information line on the bottom of each image; A hyper-text must be included to the Homepage of the journal from which you are licensing at http://www.sciencedirect.com/science/journal/xxxxx or the Elsevier homepage for books at http://www.elsevier.com; Central Storage: This license does not include permission for a scanned version of the material to be stored in a central repository such as that provided by Heron/XanEdu.

Licensing material from an Elsevier book: A hyper-text link must be included to the Elsevier homepage at http://www.elsevier.com . All content posted to the web site must maintain the copyright information line on the bottom of each image.

Posting licensed content on Electronic reserve: In addition to the above the following clauses are applicable: The web site must be password-protected and made available only to bona fide students registered on a relevant course. This permission is granted for 1 year only. You may obtain a new license for future website posting.

17. For journal authors: the following clauses are applicable in addition to the above:
Preprints: A preprint is an author's own write-up of research results and analysis, it has not been peer-reviewed, nor has it had any other value added to it by a publisher (such as formatting, copyright, technical enhancement etc.).Authors can share their preprints anywhere at any time. Preprints should not be added to or enhanced in any way in order to appear more like, or to substitute for, the final versions of articles however authors can update their preprints on arXiv or RePEc with their Accepted Author Manuscript (see below).

If accepted for publication, we encourage authors to link from the preprint to their formal publication via its DOI. Millions of researchers have access to the formal publications on ScienceDirect, and so links will help users to find, access, cite and use the best available version. Please note that Cell Press, The Lancet and some society-owned have different preprint policies. Information on these policies is available on the journal homepage.

Accepted Author Manuscripts: An accepted author manuscript is the manuscript of an article that has been accepted for publication and which typically includes author-incorporated changes suggested during submission, peer review and editor-author communications.
Authors can share their accepted author manuscript:

- immediately
  - via their non-commercial person homepage or blog
  - by updating a preprint in arXiv or RePEc with the accepted manuscript
  - via their research institute or institutional repository for internal institutional uses or as part of an invitation-only research collaboration work-group
  - directly by providing copies to their students or to research collaborators for their personal use
  - for private scholarly sharing as part of an invitation-only work group on commercial sites with which Elsevier has an agreement
- After the embargo period
  - via non-commercial hosting platforms such as their institutional repository
  - via commercial sites with which Elsevier has an agreement

In all cases accepted manuscripts should:

- link to the formal publication via its DOI
- bear a CC-BY-NC-ND license - this is easy to do
- if aggregated with other manuscripts, for example in a repository or other site, be shared in alignment with our hosting policy not be added to or enhanced in any way to appear more like, or to substitute for, the published journal article.

Published journal article (JPA): A published journal article (PJA) is the definitive final record of published research that appears or will appear in the journal and embodies all value-adding publishing activities including peer review co-ordination, copy-editing, formatting, (if relevant) pagination and online enrichment.
Policies for sharing publishing journal articles differ for subscription and gold open access articles:

Subscription Articles: If you are an author, please share a link to your article rather than the full-text. Millions of researchers have access to the formal publications on ScienceDirect, and so links will help your users to find, access, cite, and use the best available version.
Theses and dissertations which contain embedded PJAs as part of the formal submission can be posted publicly by the awarding institution with DOI links back to the formal publications on ScienceDirect.

If you are affiliated with a library that subscribes to ScienceDirect you have additional private sharing rights for others' research accessed under that agreement. This includes use for classroom teaching and internal training at the institution (including use in course packs and courseware programs), and inclusion of the article for grant funding purposes.

Gold Open Access Articles: May be shared according to the author-selected end-user license and should contain a CrossMark logo, the end user license, and a DOI link to the formal publication on ScienceDirect.

Please refer to Elsevier's posting policy for further information.
18. For book authors the following clauses are applicable in addition to the above: Authors are permitted to place a brief summary of their work online only. You are not allowed to download and post the published electronic version of your chapter, nor may you scan the printed edition to create an electronic version.

Posting to a repository: Authors are permitted to post a summary of their chapter only in their institution's repository.

19. Thesis/Dissertation: If your license is for use in a thesis/dissertation your thesis may be submitted to your institution in either print or electronic form. Should your thesis be published commercially, please reapply for permission. These requirements include permission for the Library and Archives of Canada to supply single copies, on demand, of the complete thesis and include permission for Proquest/UMI to supply single copies, on demand, of the complete thesis. Should your thesis be published commercially, please reapply for permission. Theses and dissertations which contain embedded PJAs as part of the formal submission can be posted publicly by the awarding institution with DOI links back to the formal publications on ScienceDirect.

Elsevier Open Access Terms and Conditions
You can publish open access with Elsevier in hundreds of open access journals or in nearly 2000 established subscription journals that support open access publishing. Permitted third party re-use of these open access articles is defined by the author's choice of Creative Commons user license. See our open access license policy for more information.

Terms & Conditions applicable to all Open Access articles published with Elsevier:
Any reuse of the article must not represent the author as endorsing the adaptation of the article nor should the article be modified in such a way as to damage the author's honour or reputation. If any changes have been made, such changes must be clearly indicated. The author(s) must be appropriately credited and we ask that you include the end user license and a DOI link to the formal publication on ScienceDirect. If any part of the material to be used (for example, figures) has appeared in our publication with credit or acknowledgement to another source it is the responsibility of the user to ensure their reuse complies with the terms and conditions determined by the rights holder.

Additional Terms & Conditions applicable to each Creative Commons user license:
CC BY: The CC-BY license allows users to copy, to create extracts, abstracts and new works from the Article, to alter and revise the Article and to make commercial use of the Article (including reuse and/or resale of the Article by commercial entities), provided the user gives appropriate credit (with a link to the formal publication through the relevant DOI), provides a link to the license, indicates if changes were made and the licensor is not represented as endorsing the use made of the work. The full details of the license are available at http://creativecommons.org/licenses/by/4.0.

CC BY NC SA: The CC BY-NC-SA license allows users to copy, to create extracts, abstracts and new works from the Article, to alter and revise the Article, provided this is not done for commercial purposes, and that the user gives appropriate credit (with a link to the formal publication through the relevant DOI), provides a link to the license, indicates if changes were made and the licensor is not represented as endorsing the use made of the work. Further, any new works must be made available on the same conditions. The full details of the license are available at http://creativecommons.org/licenses/by-nc-sa/4.0.

CC BY NC ND: The CC BY-NC-ND license allows users to copy and distribute the Article, provided this is not done for commercial purposes and further does not permit distribution of the Article if it is changed or edited in any way, and provided the user gives appropriate credit (with a link to the formal publication through the relevant DOI), provides a link to the license, and that the licensor is not represented as endorsing the use made of the work. The full details of the license are available at http://creativecommons.org/licenses/by-nc-nd/4.0. Any commercial reuse of Open Access articles published with a CC BY NC SA or CC BY NC ND license requires permission from Elsevier and will be subject to a fee.
Commercial reuse includes:

- Associating advertising with the full text of the Article
- Charging fees for document delivery or access
- Article aggregation
- Systematic distribution via e-mail lists or share buttons

Posting or linking by commercial companies for use by customers of those companies.

Appendix C: Licence details and terms and conditions provided by Elsevier and Copyright Clearance Center for Figure 3.

This Agreement between York University -- Ben Migotto ("You") and Elsevier ("Elsevier") consists of your license details and the terms and conditions provided by Elsevier and Copyright Clearance Center.

License Number: 5434890907285

License date: Nov 23, 2022

Licensed Content Publisher: Elsevier

Licensed Content Publication: The Lancet Neurology

Licensed Content Title: The neuro-ophthalmology of head trauma

Licensed Content Author: Rachel E Ventura, Laura J Balcer, Steven L Galetta

Licensed Content Date: Oct 1, 2014

Licensed Content Volume: 13

Licensed Content Issue: 10

Licensed Content Pages: 11

Start Page: 1006

End Page: 1016

Type of Use: reuse in a thesis/dissertation

Portion: figures/tables/illustrations

Number of figures/tables/illustrations: 1

Format: electronic

Are you the author of this Elsevier article?: No

Will you be translating?: No

Title: Descriptive Analysis of Preseason Baseline Data Collected From University Varsity Student-athletes Using a Comprehensive Concussion Assessment Battery

Institution name: York University

Expected presentation date: Dec 2022

Portions: Figure 1: Major cortical areas in control of eye movements and visual processing, with projections illustrating saccade generation. Image on page 1008.

Requestor Location: York University
4700 Keele Street
Campus Phone #: (416) 736- 2100
Toronto, ON M3J1P3
Canada

Attn: Ben Migotto, York University, 4700 Keele Street, Toronto, ON M3J1P3

Publisher Tax ID: GB 494 6272 12

Total: 0.00 CAD

Terms and Conditions

INTRODUCTION

1. The publisher for this copyrighted material is Elsevier. By clicking "accept" in connection with completing this licensing transaction, you agree that the following terms and conditions apply to this transaction (along with the Billing and Payment terms and conditions established by Copyright Clearance Center, Inc. ("CCC"), at the time that you opened your Rightslink account and that are available at any time at http://myaccount.copyright.com).

GENERAL TERMS

2. Elsevier hereby grants you permission to reproduce the aforementioned material subject to the terms and conditions indicated.

3. Acknowledgement: If any part of the material to be used (for example, figures) has appeared in our publication with credit or acknowledgement to another source, permission must also be sought from that source. If such permission is not obtained then that material may not be included in your publication/copies. Suitable acknowledgement to the source must be made, either as a footnote or in a reference list at the end of your publication, as follows:
"Reprinted from Publication title, Vol /edition number, Author(s), Title of article / title of chapter, Pages No., Copyright (Year), with permission from Elsevier [OR APPLICABLE SOCIETY COPYRIGHT OWNER]." Also Lancet special credit - "Reprinted from The Lancet, Vol. number, Author(s), Title of article, Pages No., Copyright (Year), with permission from Elsevier."

4. Reproduction of this material is confined to the purpose and/or media for which permission is hereby given.

5. Altering/Modifying Material: Not Permitted. However figures and illustrations may be altered/adapted minimally to serve your work. Any other abbreviations, additions, deletions and/or any other alterations shall be made only with prior written authorization of Elsevier Ltd. (Please contact Elsevier's permissions helpdesk here). No modifications can be made to any Lancet figures/tables and they must be reproduced in full.

6. If the permission fee for the requested use of our material is waived in this instance, please be advised that your future requests for Elsevier materials may attract a fee.

7. Reservation of Rights: Publisher reserves all rights not specifically granted in the combination of (i) the license details provided by you and accepted in the course of this licensing transaction, (ii) these terms and conditions and (iii) CCC's Billing and Payment terms and conditions.

8. License Contingent Upon Payment: While you may exercise the rights licensed immediately upon issuance of the license at the end of the licensing process for the transaction, provided that you have disclosed complete and accurate details of your proposed use, no license is finally effective unless and until full payment is received from you (either by publisher or by CCC) as provided in CCC's Billing and Payment terms and conditions. If full payment is not received on a timely basis, then any license preliminarily granted shall be deemed automatically revoked and shall be void as if never granted. Further, in the event that you breach any of these terms and conditions or any of CCC's Billing and Payment terms and conditions, the license is automatically revoked and shall be void as if never granted. Use of materials as described in a revoked license, as well as any use of the materials beyond the scope of an unrevoked license, may constitute copyright infringement and publisher reserves the right to take any and all action to protect its copyright in the materials.

9. Warranties: Publisher makes no representations or warranties with respect to the licensed material.

10. Indemnity: You hereby indemnify and agree to hold harmless publisher and CCC, and their respective officers, directors, employees and agents, from and against any and all claims arising out of your use of the licensed material other than as specifically authorized pursuant to this license.

11. No Transfer of License: This license is personal to you and may not be sublicensed, assigned, or transferred by you to any other person without publisher's written permission.

12. No Amendment Except in Writing: This license may not be amended except in a writing signed by both parties (or, in the case of publisher, by CCC on publisher's behalf).

13. Objection to Contrary Terms: Publisher hereby objects to any terms contained in any purchase order, acknowledgment, check endorsement or other writing prepared by you, which terms are inconsistent with these terms and conditions or CCC's Billing and Payment terms and conditions. These terms and conditions, together with CCC's Billing and Payment terms and conditions (which are incorporated herein), comprise the entire agreement between you and publisher (and CCC) concerning this licensing transaction. In the event of any conflict between your obligations established by these terms and conditions and those established by CCC's Billing and Payment terms and conditions, these terms and conditions shall control.

14. Revocation: Elsevier or Copyright Clearance Center may deny the permissions described in this License at their sole discretion, for any reason or no reason, with a full refund payable to you. Notice of such denial will be made using the contact information provided by you. Failure to receive such notice will not alter or invalidate the denial. In no event will Elsevier or Copyright Clearance Center be responsible or liable for any costs, expenses or damage incurred by you as a result of a denial of your permission request, other than a refund of the amount(s) paid by you to Elsevier and/or Copyright Clearance Center for denied permissions.

LIMITED LICENSE

The following terms and conditions apply only to specific license types:

15. Translation: This permission is granted for non-exclusive world **English** rights only unless your license was granted for translation rights. If you licensed translation rights you may only translate this content into the languages you requested. A professional translator must perform all translations and reproduce the content word for word preserving the integrity of the article.

16. Posting licensed content on any Website: The following terms and conditions apply as follows: Licensing material from an Elsevier journal: All content posted to the web site must maintain the copyright information line on the bottom of each image; A hyper-text must be included to the Homepage of the journal from which you are licensing at http://www.sciencedirect.com/science/journal/xxxxx or the Elsevier homepage for books at http://www.elsevier.com; Central Storage: This license does not include permission for a scanned version of the material to be stored in a central repository such as that provided by Heron/XanEdu.

Licensing material from an Elsevier book: A hyper-text link must be included to the Elsevier homepage at http://www.elsevier.com . All content posted to the web site must maintain the copyright information line on the bottom of each image.

Posting licensed content on Electronic reserve: In addition to the above the following clauses are applicable: The web site must be password-protected and made available only to bona fide students registered on a relevant course. This permission is granted for 1 year only. You may obtain a new license for future website posting.

17. For journal authors: the following clauses are applicable in addition to the above:
Preprints: A preprint is an author's own write-up of research results and analysis, it has not been peer-reviewed, nor has it had any other value added to it by a publisher (such as formatting, copyright, technical enhancement etc.).
Authors can share their preprints anywhere at any time. Preprints should not be added to or enhanced in any way in order to appear more like, or to substitute for, the final versions of

articles however authors can update their preprints on arXiv or RePEc with their Accepted Author Manuscript (see below).
If accepted for publication, we encourage authors to link from the preprint to their formal publication via its DOI. Millions of researchers have access to the formal publications on ScienceDirect, and so links will help users to find, access, cite and use the best available version. Please note that Cell Press, The Lancet and some society-owned have different preprint policies. Information on these policies is available on the journal homepage.

Accepted Author Manuscripts: An accepted author manuscript is the manuscript of an article that has been accepted for publication and which typically includes author-incorporated changes suggested during submission, peer review and editor-author communications.
Authors can share their accepted author manuscript:

- immediately
    - via their non-commercial person homepage or blog
    - by updating a preprint in arXiv or RePEc with the accepted manuscript
    - via their research institute or institutional repository for internal institutional uses or as part of an invitation-only research collaboration work-group
    - directly by providing copies to their students or to research collaborators for their personal use
    - for private scholarly sharing as part of an invitation-only work group on commercial sites with which Elsevier has an agreement
- After the embargo period
    - via non-commercial hosting platforms such as their institutional repository
    - via commercial sites with which Elsevier has an agreement

In all cases accepted manuscripts should:

- link to the formal publication via its DOI
- bear a CC-BY-NC-ND license - this is easy to do
- if aggregated with other manuscripts, for example in a repository or other site, be shared in alignment with our hosting policy not be added to or enhanced in any way to appear more like, or to substitute for, the published journal article.

Published journal article (JPA): A published journal article (PJA) is the definitive final record of published research that appears or will appear in the journal and embodies all value-adding publishing activities including peer review co-ordination, copy-editing, formatting, (if relevant) pagination and online enrichment.
Policies for sharing publishing journal articles differ for subscription and gold open access articles:

Subscription Articles: If you are an author, please share a link to your article rather than the full-text. Millions of researchers have access to the formal publications on ScienceDirect, and so links will help your users to find, access, cite, and use the best available version.

Theses and dissertations which contain embedded PJAs as part of the formal submission can be posted publicly by the awarding institution with DOI links back to the formal publications on ScienceDirect.
If you are affiliated with a library that subscribes to ScienceDirect you have additional private sharing rights for others' research accessed under that agreement. This includes use for classroom teaching and internal training at the institution (including use in course packs and courseware programs), and inclusion of the article for grant funding purposes.

Gold Open Access Articles: May be shared according to the author-selected end-user license and should contain a CrossMark logo, the end user license, and a DOI link to the formal publication on ScienceDirect.

Please refer to Elsevier's posting policy for further information.
18. For book authors the following clauses are applicable in addition to the above: Authors are permitted to place a brief summary of their work online only. You are not allowed to download and post the published electronic version of your chapter, nor may you scan the printed edition to create an electronic version.

Posting to a repository: Authors are permitted to post a summary of their chapter only in their institution's repository.

19. Thesis/Dissertation: If your license is for use in a thesis/dissertation your thesis may be submitted to your institution in either print or electronic form. Should your thesis be published commercially, please reapply for permission. These requirements include permission for the Library and Archives of Canada to supply single copies, on demand, of the complete thesis and include permission for Proquest/UMI to supply single copies, on demand, of the complete thesis. Should your thesis be published commercially, please reapply for permission. Theses and dissertations which contain embedded PJAs as part of the formal submission can be posted publicly by the awarding institution with DOI links back to the formal publications on ScienceDirect.

Elsevier Open Access Terms and Conditions
You can publish open access with Elsevier in hundreds of open access journals or in nearly 2000 established subscription journals that support open access publishing. Permitted third party re-use of these open access articles is defined by the author's choice of Creative Commons user license. See our open access license policy for more information.

Terms & Conditions applicable to all Open Access articles published with Elsevier:
Any reuse of the article must not represent the author as endorsing the adaptation of the article nor should the article be modified in such a way as to damage the author's honour or reputation. If any changes have been made, such changes must be clearly indicated. The author(s) must be appropriately credited and we ask that you include the end user license and a DOI link to the formal publication on ScienceDirect. If any part of the material to be used (for example, figures) has appeared in our publication with credit or acknowledgement to another source it is the responsibility of the user to ensure their reuse complies with the terms and conditions determined by the rights holder.

Additional Terms & Conditions applicable to each Creative Commons user license:
CC BY: The CC-BY license allows users to copy, to create extracts, abstracts and new works from the Article, to alter and revise the Article and to make commercial use of the Article (including reuse and/or resale of the Article by commercial entities), provided the user gives appropriate credit (with a link to the formal publication through the relevant DOI), provides a link to the license, indicates if changes were made and the licensor is not represented as endorsing the use made of the work. The full details of the license are available at http://creativecommons.org/licenses/by/4.0.

CC BY NC SA: The CC BY-NC-SA license allows users to copy, to create extracts, abstracts and new works from the Article, to alter and revise the Article, provided this is not done for commercial purposes, and that the user gives appropriate credit (with a link to the formal publication through the relevant DOI), provides a link to the license, indicates if changes were made and the licensor is not represented as endorsing the use made of the work. Further, any new works must be made available on the same conditions. The full details of the license are available at http://creativecommons.org/licenses/by-nc-sa/4.0.

CC BY NC ND: The CC BY-NC-ND license allows users to copy and distribute the Article, provided this is not done for commercial purposes and further does not permit distribution of the Article if it is changed or edited in any way, and provided the user gives appropriate credit (with a link to the formal publication through the relevant DOI), provides a link to the license, and that the licensor is not represented as endorsing the use made of the work. The full details of the license are available at http://creativecommons.org/licenses/by-nc-nd/4.0. Any commercial reuse of Open Access articles published with a CC BY NC SA or CC BY NC ND license requires permission from Elsevier and will be subject to a fee.
Commercial reuse includes:

- Associating advertising with the full text of the Article
- Charging fees for document delivery or access
- Article aggregation
- Systematic distribution via e-mail lists or share buttons

Posting or linking by commercial companies for use by customers of those companies.