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

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Abstract

Current metrics for assessing athlete performance following concussion measures cognition followed by movement. Success in sport performance requires the simultaneous integration of cognition and action, cognitive-motor integration (CMI). Athletes with a history of concussion (HOC) exhibit performance deficits on CMI tasks. Here, we observed the effects of concussion history on a new CMI sideline assessment task, the HurtSHynes™ Test, in varsity student-athletes. Females with HOC were the least likely to incur an error and were on average faster than females with no HOC. Males with HOC were on average slower than males with no HOC. Performance of females with HOC suggests that females may have better visuomotor skill recovery than males post-injury. The HurtSHynes™ Test demonstrated excellent inter-rater reliability (ICC > 0.90) and good-to-excellent intra-rater reliability (ICC > 0.75). We suggest this measure may be useful as a quick and objective measure to assist in guiding return-to-play decisions.

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Glossary of Terms

AD – Alzheimer's disease
AE – Athlete exposure
AFL – Australian Football League
ANOVA – Analysis of Variance
ASL – Arterial spin labelling
ATCP – Athletic Therapy Certificate Program
ATP – Adenosine triphosphate
AUS – Atlantic University Sport
BCBT – Buffalo Concussion Bike Test
BCTT – Buffalo Concussion Treadmill Test
BESS – Balance Error Scoring System
BOLD – Blood oxygen level-dependent
BrDI™ – Brain Dysfunction Indicator
CBF – Cerebral blood flow
CCHS – Canadian Community Health Survey
CI – Confidence interval
CISG – Concussion in Sport Group
CMA – Cingulate motor area
    CCZ – Caudal cingulate zones
    RCZ – Rostral cingulate zones
CMI – Cognitive-motor integration
CR – Cognitive reserve
CT – Computed tomography
CW – Canada West
dFC – Dorsal frontal cortex
DLPC – Dorsolateral prefrontal cortex
DMN – Default mode network
DSM-IV – Diagnostic and Statistical Manual of Mental Disorders, 4th Edition
DTI – Diffusion tensor imaging
EAA – Excitatory amino acid
ED – Emergency department
EEG – Electroencephalogram
ERP – Event-related potentials
fMRI – Functional magnetic resonance imaging
    rs-fMRI – Resting state functional magnetic resonance imaging
FPN – Frontoparietal network
GCS – Glasgow Coma Scale
HOC – History of concussion
ICC – Intraclass Correlation Coefficient
ICD – International Classification of Diseases
ICD-10 – International Statistical Classification of Diseases and Related Health Problems, 10th Revision
ICD-10-CA – International Statistical Classification of Diseases and Related Health Problems, 10th Revision, Canada

ICD-11 – International Statistical Classification of Diseases and Related Health Problems, 11th Revision
ID – Identification
IFC – Inferior frontal cortex
ImPACT – Immediate Post- Concussion Assessment and Cognitive Testing
IPL – Inferior parietal lobule
IPS – Intraparietal sulcus
IQ – Intelligence quotient
ISP – Injury Surveillance Program
K^+ – Potassium
M1 – Primary motor cortex
mCC – Middle cingulate cortex
MCI- Mild cognitive impairment
MLB – Major League Baseball
MLS – Major League Soccer
MRI – Magnetic resonance imaging
MRS – Magnetic resonance spectroscopy
MS – Multiple sclerosis
mTBI – Mild traumatic brain injury
NA^+ – Sodium
NART – National Adult Reading Test
NBA – National Basketball Association
NCAA – National Collegiate Athletic Association
NFL – National Football League
NHL – National Hockey League
OHIP – Ontario Health Insurance Plan
OUA – Ontario University Athletics
PCS – Post-concussion syndrome
PCSS – Post-Concussion Symptom Scale
PHIPA – Personal Health Information Protection Act
PMC – Premotor cortex
    PMd – Dorsal premotor cortex
    PMv – Ventral premotor cortex
PPC – Posterior parietal cortex
RSEQ – Réseau du sport étudiant du Québec
RTP – Return-to-play
S1 – Somatosensory cortex
SCAT5 – Sport Concussion Assessment Tool- Version 5
SD – Standard deviation
SMC – Supplementary motor cortex
    pre-SMA – Pre-supplementary motor area
    SMA – Supplementary motor area
SMI – Sensorimotor integration
SPL – Superior parietal lobule
SPSS – Statistical Package for the Social Science

S-R – Stimulus-response
SRC – Sports-related concussion
TBI –Traumatic brain injury
TCA – Tricarboxylic acid cycle
TMS – Transcranial magnetic stimulation
WHO – World Health Organization
WTAR – Wechsler Test of Adult Reading

Chapter 1: Introduction and Literature Review

Concussion

A concussion is a subset of mild traumatic brain injury (mTBI), characterized by a transient disturbance of neurological function.[1] Traumatic brain injuries (TBIs) are classified as mild, moderate, or severe in accordance with the Glasgow Coma Scale (GCS)[2]. The GCS was originally developed in 1974 by Teasdale and Jennett,[2] as a means for doctors and nurses to determine one's severity of coma, level of consciousness, and any underlying brain dysfunction 6 hours after head trauma.[2–4] A score is given based on a patient's behavioural response in three domains: eye opening, best verbal response, and best motor response where each domain has a defined set of responses scored in rank order to indicate the degree of dysfunction.[5] The score from each section is added together to give a final GCS score that can range from 3 to 15 where the lower the score is on the scale the more severe the head injury is. A GCS score less than 8 is classified as a severe TBI, a score between 9-12 is a moderate TBI, and a score between 13-15 is classified as a mTBI.[6]

It is important to note that the GCS was not intended to be used as a means to classify brain injury like it is today, with some suggesting that the simplistic classification of head injury using the GSC is not sufficient or inherently useful.[7] For instance the word "mild" in mTBI is indicative of the absence of structural brain damage[8] but it does not reflect the severity of the underlying metabolic and physiological properties of concussion injuries nor does it provide any specific information pertaining to the pathophysiological mechanisms that cause neurological deficits.[8,9] Given that the two terms refer to different pathophysiological constructs[8] it becomes problematic in the literature when the terms concussion and mTBI are often used interchangeably. Concussions are a subset of mTBI and are at the mild end of the mTBI spectrum, so while all concussions can be classified as mTBIs not all mTBIs are concussions.[10]

The World Health Organization Collaborating Centre for Neurotrauma, Prevention, Management and Rehabilitation Task Force (WHO Task Force) on mTBI clinically identifies a mTBI as having; (i) 1 or more of the following: confusion or disorientation, loss of consciousness for 30 minutes or less, post-traumatic amnesia for less than 24 hours, and/or other transient neurological abnormalities; (ii) Glasgow Coma Scale score of 13-15 after 30 minutes post-injury or later upon presentation for healthcare.[11]

The most consistently used definition of concussion is the one put forth by the Concussion in Sport Group (CISG) who define a concussion as a TBI induced by biomechanical forces that may be caused "either by a direct blow to the head, face, neck or elsewhere on the body with an impulsive force transmitted to the head."[1] The CISG also uses this definition when referring to a sports-related concussion (SRC)[1] which is a concussion that is sustained while actively participating in sport. This definition put forth by the CISG helps to highlight the fact that concussions are not solely caused by a direct head impact and there are many mechanisms of concussion injury such as slips/falls, struck by/against, assault, motor vehicle collisions, sports, etc.

As previously mentioned, the terms mTBI and concussions are often used interchangeably in the literature which sometimes results in concussions being grouped together with all mild, moderate, and severe TBIs. This results in a lack of a consistent definition and reporting of concussions across the literature making comparisons across studies difficult. As such, for the purpose of this thesis the words concussion or SRC will be used as a means to differentiate it from all other TBIs where possible in reference to the literature.

Concussions can result in balance and/or cognitive impairment, behavioural and emotional changes, sleep/wake disturbances, amnesia, loss of consciousness[1] in addition to other possible symptoms listed on the Post-Concussion Symptom Scale (PCSS)[12] that includes headaches, nausea, dizziness, and light and/or noise sensitivity to name a few. For the majority of individuals symptom resolution and clinical recovery occurs within 10 to 14 days where impairments of neurological function tend to resolve spontaneously and are short-lived.[1] However, 10 to 30% of individuals will continue to have prolonged symptoms[13–15] and do not recover for months or even years after injury.[16–20] Those who continue to have symptoms beyond the typical timeframe of clinical recovery (greater than 10 to 14 days in adults) are diagnosed as having persistent post-concussion symptoms in accordance with the CISG[1] or post-concussion syndrome (PCS) in accordance with the Diagnostic and Statistical Manual of Mental Disorders, 4th Edition (DSM-IV)[21] or the World Health Organization's International Statistical Classification of Diseases and Related Health Problems, 10th Revision (ICD-10).[22]

To be diagnosed as having PCS the ICD-10 requires 3 or more symptoms from a list in comparison to the DSM-IV that requires the presence of 3 or more symptoms from a similar but different list that have lasted 3 months following injury, in addition to the presence of cognitive deficits in attention and/or memory and a significant decline in social and/or occupation functioning.[18,23]

Findings from a systematic review by Kamins et al.[24] reported that much of the data in the literature suggests that physiological recovery after a SRC appears to exceed clinical recovery, with some studies noting physiological disturbances and metabolic abnormalities lasting roughly 15 to 30 days post-injury. This is of concern as a repeated injury while the brain is still metabolically vulnerable can result in irreversible brain damage, apoptotic cell death, impaired neurotransmission, and in the case of second impact syndrome (occurring when an athlete sustains a second concussion while still symptomatic and recovering from an initial concussion);[25] cerebral edema that could result in coma, severe neurologic deficits, and even death.[26–29]

Pathophysiology

The pathophysiology of a concussion, first described by Giza and Hovda[26] as the neurometabolic cascade of concussion (Figure 1), begins immediately after injury where there is disruption/damage of neuronal cell membranes and axonal stretching/shearing. This results in an indiscriminate flux of ions through previously regulated ion channels causing widespread release of neurotransmitters, particularly excitatory amino acids (EAAs) such as glutamate, that bind to ionic channels.[26,28,30] Binding of these EAAs causes further neuronal depolarization that leads to an efflux of potassium and influx of calcium ions into the cells, resulting in increased activity of the sodium/potassium (NA^+/K^+) Adenosine triphosphate (ATP) dependent pump to restore ionic and cellular homeostasis.[26–28]

With the increase in pump activity and thus a need for more ATP there is an increase in glucose metabolism causing a depletion of intracellular energy reserves that triggers a cellular energy crisis due to diminished cerebral blood flow (CBF).[26–28] Normally, CBF is tightly coupled to neuronal activity and cerebral glucose metabolism[26] to ensure the consistent delivery of oxygenated blood to brain tissues to meet regional metabolic demands[31] whereby an increase in metabolism would result in an increase in CBF. However, immediately following a concussion CBF becomes dysregulated and there is a reduction in CBF known as hypoperfusion.[28,32,33] With the increase of metabolism occurring in a setting of diminished CBF, there is now a mismatch between supply and demand consequently resulting in a cerebral energy crisis.[26,27]

Under normal conditions the production of ATP from glucose needed to activate the NA^+/K^+ pumps is conducted aerobically however as previously mentioned, the increase in pump activation quickly reduces intracellular energy stores which in turn causes a shift from aerobic to anerobic metabolism/glycolysis to try and meet metabolic demands.[26] Concurrently oxidative metabolism is impaired due to mitochondrial dysfunction as a result of excess intracellular calcium and oxidative stress which can lead to reduced ATP production, further providing a secondary need for hyperglycolysis.[26,28] In turn lactate, which is a by-product of glycolysis, continues to accumulate because there is a disruption of the tricarboxylic acid (TCA) cycle leading to a decrease in lactate metabolism.[26,34–36]

This is of concern as increases in concentrations of lactate can lead to acidosis, cell membrane damage, altered blood-brain barrier permeability, altered or inhibited cellular function, cerebral edema, and/or ischemia.[26,36–39] Immediately following a concussion injury the brain therefore is in a vulnerable state but injured cells are capable of recovering over time and full metabolic recovery is possible.[26,29] However, a second head injury occurring within the window of metabolic brain vulnerability before the initial injury has resolved causes further mitochondrial dysfunction and leaves the brain more susceptible to severe and irreversible cellular injury and can even lead to cell death.[8,26,29] It has been reported that 2 concussions that occur too close in temporal proximity to one another can simulate a severe TBI injury, indicating that the metabolic effects of 2 concussions can be additive depending on when they occur in proximity to each other.[8,40] Due to this complex physiological nature of concussion injury, it is imperative that athletes are not returned to sport prematurely in order to prevent a second injury from occurring when the brain is still metabolically vulnerable.

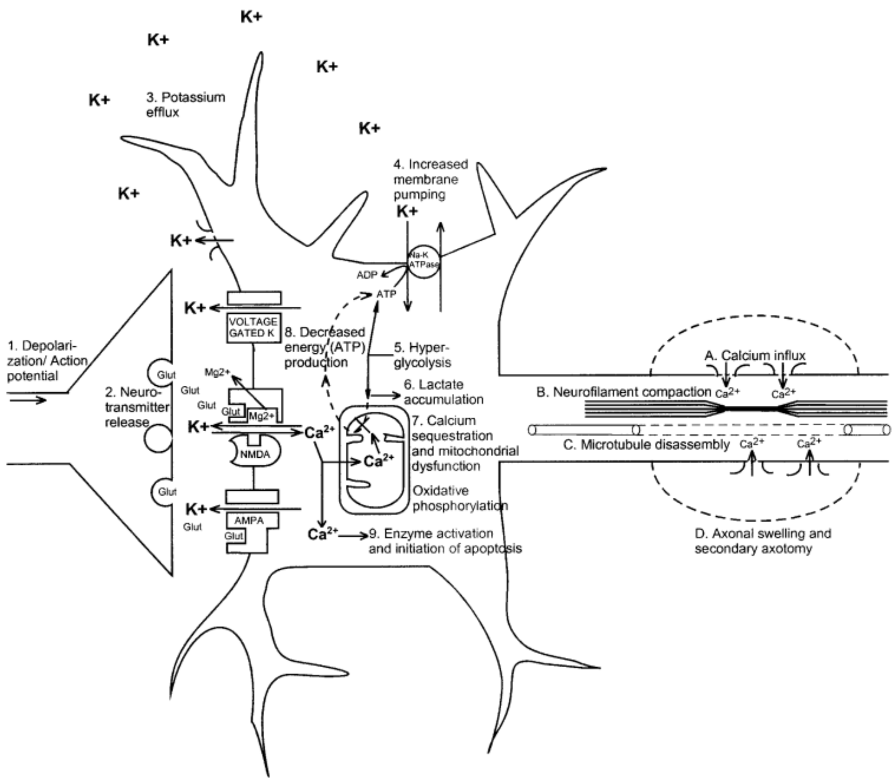

Figure 1. The neurometabolic cascade of concussion.[26]

Neuroimaging

In the majority of concussion injuries conventional neuroimaging techniques using Computed tomography (CT) or Magnetic resonance imaging (MRI) rarely reveal gross structural brain abnormalities after a concussion,[1,41–45] providing little value in the detection of injury and monitoring of recovery.[46] This is due to the fact that concussion symptoms “largely reflect a functional disturbance rather than a structural injury.”[1] A functional injury can include, but is not limited to; metabolic changes, impaired neurotransmission, or ionic shifts.[26] Microstructural injuries are not easily detectable on these conventional scans and as a result neuroimaging is rarely needed in the evaluation of concussions for most cases. Despite this, studies have suggested that physicians may be ordering unnecessary imaging[47] as they are still using it as part of their concussion diagnoses more frequently than what’s recommended by evidence-based guidelines.[48] The problem with this is twofold; (1) it exposes patients to excessive radiation (in the case of CT scans) and (2) it increases healthcare costs[47] which is of concern given the costs concussions already place on healthcare systems and the increase in reported concussions to the emergency department (ED) and physicians' offices.[49–52]

There are cases however when a CT scan is warranted such as when there is a loss of consciousness, deteriorating level of consciousness, seizure, severe headache, suspicion for macrostructural injuries, bone fractures and/or intracranial bleeding.[44,53] Computed tomography is the standard imaging method for many reasons such as its "availability, speed, depiction of bony fractures, and high sensitivity for acute intracranial hemorrhage."[53] Although conventional brain MRI has superior sensitivity to CT for the identification of hemorrhagic axonal injury and small contusions,[45,53] it is not currently recommended in most guidelines for routine management and in the evaluation of acute concussion.[44,53] Rather, MRI is often used in the clinical management of subacute or chronic concussions where there is persistent or worsening symptoms that result in prolonged recovery.[24,44,53]

Systematic reviews have described novel, advanced multimodal MRI technologies that are being used to understand the neurobiological effects and recovery after a concussion such as diffusion tensor imaging (DTI), functional magnetic resonance imaging (fMRI) which consists of two main types: task-based fMRI and resting state fMRI (rs-fMRI), magnetic resonance spectroscopy (MRS), and arterial spin labelling (ASL).[24,45,54,55] Work is also being done using transcranial magnetic stimulation (TMS), electrophysiology, cerebral blood flow, fluid biomarkers, etc.[24,45,54,55] However, currently there are no reliable biomarkers to monitor recovery after a concussion has been sustained[24] along with a lack of quick and easy accessibility to these MRI technologies for the general community. This in turn places both a need and a heavy reliance on multiple subjective and objective clinical assessments that don't rely on imaging to diagnose a concussion and monitor recovery to help guide return-to-play (RTP) decisions.

Epidemiology

Traumatic brain injuries have been referred to in the literature as a silent epidemic[56–60] as many cases are unrecognized by healthcare professionals or go unreported by the patient, resulting in an underrepresentation of TBI rates.[58] In relation to the World Health Organization (WHO) regions, the incidence rate of all TBIs was found to be highest in the Region of the Americas and the European Region.[61] Recent model projections by Dewan et al.[61] estimate that 69 million people worldwide (95% CI 64-74 million) or 939 cases per 100,000 will suffer a TBI each year with the majority of them being a mTBI (55.9 million people per year or 740 cases per 100,000). After a systematic review of world literature the WHO Task Force on mTBI estimated the incident rate of mTBI's is at least 600 cases per 100,000 people but is most likely higher given that a large number of cases of mTBI's are not treated at hospitals.[62]

In Canada, where healthcare is publicly funded, data from the most recent 2017/18 Canadian Community Health Survey (CCHS) revealed that the overall incidence rate of reported SRCs or other brain injuries was 221 per 100,000 Canadians and that in the preceding year at least 1 in 450 Canadians reported SRCs or other brain injuries as their most severe disabling injury.[63] However, the incidence rate of SRCs in Canada is likely to be higher than this given that the response rate for the CCHS survey was only 58.8%[63] and therefor isn't reflective of the entire Canadian population.

Emergency departments across the provinces in Canada have the ability to provide more accurate epidemiological data on concussion rates using the WHO's International Classification of Diseases (ICD) diagnostic codes. Countries are able to develop national extensions of the ICD to suit their requirements[64] as is the case in Canada where the ICD-10 is referred to as the International Statistical Classification of Diseases and Related Health Problems, 10th Revision, Canada (ICD-10-CA). As of January 2022 the new version of the ICD, International Statistical Classification of Diseases and Related Health Problems, 11th Revision (ICD-11), came into effect where with every new version of the ICD the syntax of the diagnostic codes change.[64] However, all concussion rates in EDs across Canada described below are in accordance with the ICD-10 where diagnostic code ICD-10 S06.0 was specifically used universally in countries and regions across the globe to identify those diagnosed with a concussion.

In the province of Ontario, Canada's most populous province, the Ontario Health Insurance Plan (OHIP) Physician Billing Database can also be used to identify concussions diagnosed by primary care physicians outside of an ED setting using OHIP billing code 850.[20,65] In Ontario, OHIP is a taxpayer-funded health insurance plan for all eligible residents within the province.[20] Therefore, in addition to the ICD-10 concussion diagnostic code used in EDs, Ontario also allows for epidemiological concussion data to be reported from primary care physicians. This is important as a considerable number of patients with mTBIs in Ontario present to a family physician's office first as opposed to an ED.[66]

Between 2008 and 2016 there were 1,330,336 individuals in Ontario who were diagnosed with a concussion either in the ED or by a general practitioner, with a mean incidence rate of 1153 per 100,000 people or greater than 1% of the population per year.[67] Between fiscal years 2003 to 2013 in the province there were 176, 685 pediatric visits amongst those aged 5 to 18 for concussion in EDs and physicians offices in the province with sports being the most common mechanism for concussion.[65] There was a 4.4 fold increase in visits over this 11 year period, particularly from 2010 onward.[65]

However it is important to note that the number of concussions in the province may be a conservative number due to misdiagnoses or underreporting, especially if a study only reports on ED visits given that a number of those who sustain a mTBI tend to present to a family physician's office first,[66] as previously mentioned. Rates may also differ based on geographical location as Ryu et al.[66] found that patients in Ontario were more likely to receive a mTBI diagnosis if they presented to EDs at a teaching hospital in an urban setting.

Increases in incident rates of concussion and health care utilization is of concern as it places a higher demand on our healthcare systems.[65,68] Based on the number of TBI cases presenting to Ontario ED's between April 2009 to March 2010, annual lifetime costs for 2009 were conservatively estimated to be approximately CAD 945 million; $292 million in medical treatment and $653 million in productivity costs.[69] During that year the incident rate for TBI's specifically treated in the ED for sports as the mechanism of injury was 97.2 per 100,000 people, amounting to a total of $81,928 in annual lifetime costs; $25, 647 in medical costs and $56,281 in productivity loss.[69]

Varsity Athlete Population

In the United States it is estimated that there are 1.6 to 3.8 million sports-related TBIs each year but may be higher given that many of these injuries go unrecognized or are underreported.[70] In terms of epidemiological data available for a varsity athlete population within the United States, the National Collegiate Athletic Association (NCAA) Injury Surveillance Program (ISP) was established in 1982 by the NCAA Sport Science Institute and is the largest ongoing collegiate sports injury database in the world.[71] It is funded by the NCAA and is maintained by an independent non-profit research organization, Datalys Center for Sports Injury Research and Prevention.[71] As of the 2018-2019 academic year approximately 30% of NCAA membership institutions were participating in the ISP.[71] Injury data is recorded by certified athletic trainers from participating institutions who receive training materials regarding ISP participation before contributing any data.[71] Since its inception the ISP has collected sport-related injury data on nearly all NCAA-sponsored sports and collects a multitude of exposure and injury variables such as playing surface, mechanism of injury, sport division, concussion symptoms, etc.[71] A full list of all exposure and injury variables have been reported by Chandran et al.[71]

Using data from the NCAA ISP Zuckerman et al.[72] reported on the epidemiology of SRCs across 25 sports from 2009-2010 to 2013-2014. A total of 1670 SRCs were reported (n= 1129 males, n= 541 females) with an injury rate of 4.47 per 10,000 athlete exposures (AEs) where they defined an AE as “1 student athlete participating in 1 NCAA-sanctioned practice or competition in which he or she was exposed to the possibility of athletic injury, regardless of the time associated with that participation.”[72] The greatest number of concussions occurred in football (n= 603) followed by men’s ice hockey (n= 224), and women’s soccer (n= 136) with player contact accounting for the most common mechanism of SRC injury (68%).[72] Although football had the highest number of SRCs, men’s wrestling had the highest overall concussion rate of all sports at 10.92 per 10,000 AEs.[72]

U SPORTS is the national governing body of university sport in Canada and is comprised of 56 member institutions and over 14,000 student athletes.[73] Universities are organized into 4 regional associations: Atlantic University Sport (AUS), Réseau du sport étudiant du Québec (RSEQ), Ontario University Athletics (OUA), and Canada West (CW).[73] However, unlike in the United States there is currently no national surveillance program in Canada to record concussion incidence rates across all institutions and thus available injury data is often limited to reported findings by individual universities making gross comparisons difficult.

Sex Differences

Sex-related differences in the literature is mixed where comparisons can be difficult given the multitude of different outcome measures and assessments analyzed across studies, sample size, age, length of time since most recent concussion from assessment, TBI population, number of previous concussions, etc. The previous consensus statement on concussion in sport stated that there is no unanimous agreement that there is enough conclusive evidence to suggest that sex is a modifying factor in concussion management although it may be a risk factor for injury or influence injury severity.[74] There is also currently no hallmark of a female concussion compared to male concussion that a team physician or clinician can rely on.[75]

Based on previously published systematic and literature reviews pertaining to sex-related differences in SRC[76–84] there appears to be some consistent findings; (1) incidence of concussions is greater in females than males in sex-comparable sports, attributed to intrinsic factors such as increased head to ball ratio and a decreased head-neck strength compared to males; (2) there are different symptom responses to baseline and post-concussion neuropsychological testing between males and females; (3) females tend to endorse greater post-concussion symptoms compared to males; (4) possible cultural factors could attribute to sex differences in concussion rates such that females are more likely to report a concussion injury compared to males.

Cognitive Reserve Models

The concept of reserve was put forward as a means to attempt to account for differences between individuals in the face of a brain injury and/or in their susceptibility to age-related brain changes such as dementia or Alzheimer's disease (AD).[85] Reserve models are classified into either passive models, where reserve is defined in terms of the amount of brain damage that can be sustained before reaching a threshold for clinical expression of symptoms or active models, where the brain actively attempts to compensate for brain damage by using pre-existing cognitive processes.[86]

Passive Models

Based on the literature review of the threshold theory by Paul Satz[87] the concepts of threshold and brain reserve in the field of dementia were first introduced in the post-mortem studies by Roth, Blessed, and Tomlinson[88,89] in 1967/68 who found correlations between plaque counts and measures of dementia whereby functional incapacity increased as the mean plaque count increased.

1) Brain Reserve

According to the brain reserve model, which is a hypothetical construct, the brain's ability to cope with damage is based on individual differences in brain volume and the number of neurons and synapses.[90,91] If two people were to acquire the same injury the brain reserve model postulates that an individual with less brain reserve is more likely to show neurocognitive impairment whereas the onset of symptoms may be delayed in an individual with greater reserve.[87]

2) Threshold Model

Brain reserve is tightly tied to the threshold model which states that once injury reduces one's brain reserve beyond a certain threshold, functional decline occurs and impairment is inevitable.[91] This model is based on the assumption that the amount of brain tissue or neuronal loss is the same across all individuals and that there is a certain threshold of brain damage where deficits are produced for all individuals.[86,87] The brain damage is either sufficient or insufficient to deplete one's reserve to some critical level,[86] therefore you can think of it as someone with more reserve has a buffer in the face of injury or cognitive decline. Stern[86] provides an example in the case of dementia whereby the threshold model would assume that when synapses are depleted beyond a critical point, dementia will appear. In patients with more reserve, synaptic loss would need to be greater before clinical symptoms appear and these symptoms would also appear at a later point in time in comparison to someone with less reserve who would present with earlier onset of symptoms.[86]

Active Models

1) Cognitive Reserve

The concept of cognitive reserve (CR) postulates that some individuals are able to cope better than others with similar brain injury/damage due to their ability to process tasks in a more efficient manner as a result of differences in cognitive processes.[86] Although there is no current readily used definition of CR, one was proposed by Yaakov Stern who defined CR as "the ability to optimize or maximize performance through differential recruitment of brain networks."[86] Individuals who use brain networks more efficiently or are able to use alternate brain networks in response to increased task demands may have more cognitive reserve.[86,92]

2) Neural Compensation

Compensation differs from CR in that in order to compensate for brain damage, individuals may use brain structures or networks they wouldn't have normally used prior to injury as an attempt to maintain or improve task performance even while injured.[86,92] Hyperconnectivity in brain regions has been proposed as a compensatory response to neurological injury whereby there is a nonspecific increase in neural resource use that aims to act as a buffer against network disruption.[93] Although increased connectivity may permit continued communication during these disruptions, it may result in slowed information processing speed, reduced efficiency, and cognitive fatigue, and there may also be a ceiling effect in terms of the maximum number of connections a neural system can take advantage of.[93] It is important to note that hyperconnectivity unlikely occurs in isolation, suggesting that there is some combination of connectivity loss and gain throughout neural networks.[93]

Cognitive-Motor Integration (CMI)

Success in sport performance, as well as aspects of daily life and work, requires the simultaneous integration of cognition and action known as cognitive-motor integration (CMI). An action consists of movements that are necessary for goal-directed activity and implicitly involves "various integrated cognitive functions that allow successful motor performance."[94] Cognitive and motor function are controlled by brain areas such as the cerebellum, basal ganglia, and the frontal lobes which are all part of a neuronal system that interact with each other to govern and control executive function and the intentionality of movements.[94,95]

Motor Areas

The frontal lobe is the largest brain region and is responsible for the motor control of voluntary movements, motivation and emotional regulation, reasoning, and executive functions such as working memory and inhibition.[96] Motor-related cortical regions that are involved in the processing of motor information and motor control within the frontal lobe include the primary motor cortex (M1), premotor cortex (PMC) which is divided into the dorsal and ventral premotor areas (PMd and PMv), supplementary motor cortex (SMC) which can be divided into the supplementary motor area (SMA) and the pre-supplementary motor area (pre-SMA), and the cingulate motor areas (CMAs); rostral cingulate zone (RCZ) and caudal cingulate zones (CCZ)[94,97,98] (Figure 2).

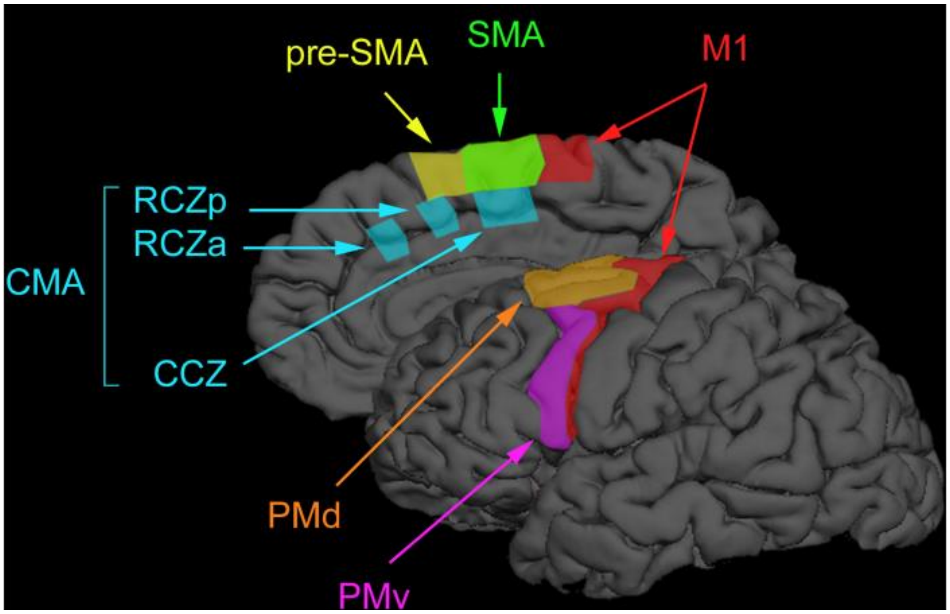

Figure 2. Motor areas in the frontal lobe;[98] the premotor cortex is divided into the PMd and the PMv, the supplementary motor cortex is divided into the SMA and pre-SMA, and the cingulate motor areas into the RCZ and CCZ.

M1 is interconnected with the parietal lobe, PMC, SMA, basal ganglia, and the cerebellum.[99] It has a critical role in the execution of voluntary movements[100] and is important for motor learning and the consolidation of motor skills. The PMC is involved in the selection of visually guided movements and limb positioning in space.[94,98] The PMd is concerned with the selection of movements according to learned associations but it is not clear as to what extent it has a role in the adjustment and redirection of an ongoing movement.[101] The SMA specifically is involved in the organization of motor sequences[94,98] and the pre-SMA plays a role in task-set switching.[102] Together the SMA, M1 and premotor areas are all active when movement anticipation is required.[94]

The cerebellum, the second largest part of the brain, is involved with the co-ordination, precision, and timing of smooth muscular movements, gaze fixation, balance and posture, and body positions.[96,99,103] It is also important for adapting movements to changes in feedback from the environment.[99] The basal ganglia are large masses of gray matter located within each cerebral hemisphere and help to co-ordinate skeletal muscle movement by relaying information via the thalamus to motor areas of the cerebral cortex.[96] In particular the striatum, which is the largest structure in the basal ganglia, play a role in the learning, planning, and execution of new motor skills.[104]

Other important motor areas includes the parietal cortex that is involved with the preparation of movements, where the left parietal cortex specifically is involved in disengaging and switching focus of motor attention from one movement to the next which is important for movement sequencing.[105] The posterior parietal cortex (PPC), comprised of Brodmann Area 5,7,39, and 40, is connected to M1 and the PMC via the superior longitudinal fasciculus.[100] The PPC combines inputs from a multitude of brain areas such as visual, motor, somatosensory, and auditory where different areas of the PPC are involved in several cognitive processes such as early motor planning, spatial attention, decision making, working memory, and sensorimotor integration (SMI).[106]

Sensorimotor integration is the ability to incorporate sensory inputs that provide us with information about our body and the external environment to help inform co-ordinated motor outputs.[100] Through successful integration of information we can generate the most efficient motor plan to optimize current and future performance when executing a given task.[100] The process of integrating sensory and motor information involves three main cortical regions: M1, PPC, and primary somatosensory cortex (S1) along with other cortical and subcortical brain areas.[100] It has been suggested that the superior parietal lobule (SPL) also has a key role in sensorimotor integration.[107]

Frontoparietal Network (FPN)

The integration of cognitive information and motor functions into a motor plan involves large neural networks along with greater activation within the frontoparietal network (FPN) to perform CMI tasks.[108–111] The FPN is associated with skilled movements and consists of the dorsolateral prefrontal cortex (DLPFC), inferior parietal lobule (IPL), dorsal frontal cortex (dFC), intraparietal sulcus (IPS), precuneus, and middle cingulate cortex (mCC).[112] This network of prefrontal, frontal, and parietal regions of the brain connects the DLPFC and rostral prefrontal cortex with visuomotor planning areas such as the SMA, PMd, and the SPL via white matter tracks.[113] Damage to these white matter tracks after a concussion injury may affect performance on visuomotor transformations.[114]

The PMd receives input from the parietal cortex and is involved in the planning of non-standard visually guided movements[115,116] while the medial PMC is involved in incorporating explicit rules into motor plans to satisfy the context of a given CMI task.[117] In addition, sensory signals from the PPC and S1 relays important information about somatosensation, proprioception, and visuomotor transformations to M1.[100]

Visuomotor Transformations

By manipulating the mapping of visual information to a required motor response (visuomotor transformations) we are able to examine CMI in a laboratory setting.[108] Visuomotor transformations rely on our ability to integrate visual information and relay that information to motor regions that control muscle and joint movement.[118] In a sport context visuomotor tasks require an athlete to look at a target or object and respond with a physical movement.

Visuomotor transformations are classified as either standard mapping, when the visual stimulus guiding an action is the target of the action or non-standard, when we attend to stimuli in locations that differ from the target of the action.[116] In hockey, an example of standard mapping would be making a pass when looking at one's teammate, in comparison to non-standard mapping that would involve passing to one's teammate on the left, while looking to avoid a body check from an opponent on one's right.[108]

Cognitive-motor integration is what allows us to perform non-standard visuomotor mapping tasks which "use specific spatial algorithms to relate the position of the visual cue to the direction of action."[117] Non-standard mappings require learning new context dependent rules and novel spatial mappings and then incorporating them into movement for successful performance, requiring an increase in cognitive load as more cognitive resources (i.e. neural networks, active cortical regions, information processing) are needed to perform them.[109–111,119] They also require the decoupling of vision and action because our eyes must move in a different direction and/or in another plane than the performed motor action.[113] Therefore, motor responses to a visual cue "can vary depending on the context and requirements of the task."[115]

It has been proposed that widespread brain injury after sustaining a concussion can reduce rule-based skill performance, attributed to an inability of cognitive brain networks to communicate between each other.[108,117] The frontoparietal networks that are required for the integration of cognitive information into a motor plan could also be compromised.[119]

Brain Dysfunction Indicator (BrDI™) Test

A laboratory task designed to assess CMI is an eye-hand coordination task developed by Dr. Lauren Sergio at York University, Toronto, Ontario, Canada called the Brain Dysfunction Indicator (BrDI™) Test. The BrDI™ Test "was developed based on years of research on the neural underpinnings of cognitive-motor integration as well as on deficits in neurological populations in such behavior."[120] This test requires participants to slide a finger of their dominant hand along touch screens to displace a cursor from a home target to one of four different peripheral targets (up, down, right, left) in two conditions (standard and non-standard mapping)[121] (Figure 3).

In the standard visuomotor mapping condition the spatial location of the viewed target and the required movement of cursor displacement are in alignment (participants slide their finger directly to targets on a vertical screen).[121] In the non-standard mapping condition, which requires CMI, targets are viewed again on a vertical screen but participants now have to slide their finger along a horizontal touch screen and in the opposite direction to displace the cursor.[121] The number of errors incurred are collected during the test along with 8 kinematic measures to assess task performance which include mean reaction time, total movement time, path length, peak velocity, and movement and accuracy precision.[121]

A multitude of studies have reported on participant performance on the BrDI™ Test in different populations: those with mild cognitive impairment (MCI),[111] early AD or those at risk for the development of AD,[118,122–126] history of SRCs,[108,121,127,128] females with and without PCS,[114] healthy children and adolescents,[113] working-aged adults,[129] and Canadian Armed Forces' breaching instructors and range staff.[130] The BrDI™ Test has also been shown to be able to discriminate athletes with a history of a concussion from those without with an accuracy of 70%[121] and 94%[128] as well as between individuals at low and high AD risk with a classification accuracy of 86.4% (sensitivity: 81.8%, specificity: 90.9%).[125]

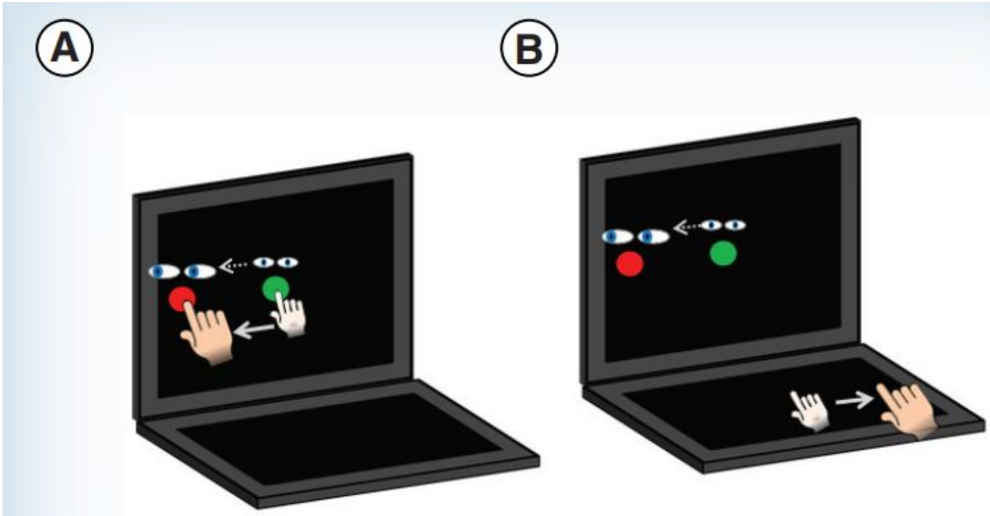

Figure 3. Illustration of the BrDI™ Test.[108] The green circle denotes the central home target from where all movements begin. A red target appears in one of 4 peripheral directions (top, bottom, left, or right of central home target) after 4000 ms which serves as the "Go" cue. (A) Standard visuomotor mapping condition. Eye and arm movements both move to the same peripheral target. (B) Non-Standard cognitive-motor integration (CMI) condition. Vision and movement are decoupled due to a plane dissociation (eyes look at vertical screen while hand moves along horizontal screen) and visual feedback reversal (movement of cursor is 180° rotated from hand motion).

Dual-Tasks

Dual-task performance is the ability to perform a primary task while executing a concurrent secondary task or put more simply, it is the ability to perform two tasks simultaneously.[131] Dual-tasks enables one to assess the change in performance on a particular task when it is performed alone in comparison to when it is performed in combination with another task.[131] In the concussion literature dual-tasks typically involve the completion of a cognitive task while walking to assess the interaction between cognition and movement.[132] A systemic review by Kleiner et al.[132] concluded that individuals with a concussion experience decreased gait velocity and more cognitive errors when completing dual-tasks and that performance differences on dual-tasks may help to distinguish those with and without concussion. Both dual-tasks and integration tasks are considered to be more difficult for those who have sustained a concussion.[117]

However, there is a clear distinction between the two whereby dual-tasks involve performing two tasks within the same domain and requires task switching in comparison to integration tasks, such as CMI or sensorimotor, that combine behaviours from two different domains.[117] Briefly, the word domain is used to describe a network of brain regions involved in a specific type of information processing where regions within the network process different types of information (e.g. sensory, motor, etc.) about the same domain or multiple domains.[133,134] For instance, CMI tasks requires the integration of cognitive information and motor functions via large neural networks that require greater activation within the frontoparietal network (FPN).[108–111]

Although dual-tasks have shown that there are performance deficits in those following a concussion injury, they may still be inadequate in determining if an individual has truly fully recovered from concussion and is able to RTP given that dual-tasks are testing the same domain at one time (e.g., motor, motor or cognitive, cognitive). Task paradigms that concurrently use both task switching and integration tasks,[117] such as the BrDI™ Test, may be a better means at assessing recovery post-injury.

Intraclass Correlation Coefficient (ICC)

There are currently a variety of measures and assessments to help support clinical examinations of concussions that test motor control, reaction time, quality of life, neurocognitive function, athlete-reported symptoms, vestibular-ocular function, etc.[135] In the literature intra class correlation coefficients (ICCs) are the most readily used method to calculate the reliability of tests used to evaluate concussion injuries.[135–142] However according to the American Medical Society for Sports Medicine's position statement on concussion in sport[44] "the test-retest reliability of commonly used sideline concussion evaluation tests is below the generally accepted threshold for clinical utility (0.75-0.90)."

The ICCs are scored on a scale from 0 to 1.0 and used to determine the strength of agreement, where ICC values closer to 1 represent stronger reliability.[143] Intraclass correlation coefficients less than 0.5 are indicative of poor reliability, 0.5 to 0.75 is considered moderate, 0.75 to 0.90, good and values greater than 0.90, excellent.[143] Intraclass correlation coefficients can be used to determine both intra- and inter-rater reliability. Intra-rater reliability reflects the variation of data measured by a single rater across two or more testing sessions compared to inter-rater reliability that reflects the variation between 2 or more raters testing the same group of subjects.[143] A stronger intra- and inter-rater reliability (ie. higher ICC value) tells us that a measurement or test is reproducible over time by different raters as well as across different settings.[144]

Purpose and Rationale

A large portion of research on sports-related concussions have focused on studying the effects of concussion on cognition[145–147] with less focus on studying its effects on visually guided motor actions[148] and cognition integrated with movement in a sport context.[149] In addition, the current assessment tools used for diagnosing a concussion and/or monitoring recovery post injury such as the Sport Concussion Assessment Tool- Version 5 (SCAT5),[150] Balance Error Scoring System (BESS),[136,151] Immediate Post- Concussion Assessment and Cognitive Testing (ImPACT),[152] Buffalo Concussion Treadmill Test (BCTT),[137,153] and Buffalo Concussion Bike Test (BCBT)[154] tests an athlete's cognition and motor performance in isolation rather than concurrently. However, in 2018 Johanna Hurtubise initially formulated a "field specific" version of testing cognitive-motor integration. The newly developed HurtSHynes™ Test is unique in that it is reflective of movements executed by athletes during sport performance while simultaneously enabling the assessment of their ability to think and move at the same time (i.e CMI) as the participant is actively running while responding to visual directional cues by an examiner.

Objectives

1. *Explore sex-related differences and the effect of concussion history on a newly developed cognitive-motor integration (CMI) task (the HurtSHynes™ Test)*

Sex-related differences in SRC have been reported in the literature[76–84] where consistent findings have noted that the incidence of concussions is greater in females than males in sex-comparable sports, there are different symptom responses to baseline and post-concussion neuropsychological testing between males and females, and females tend to endorse greater post-concussion symptoms compared to males. Previous studies of the BrDI™ Test in an athlete population found that sex as a main effect yielded no significant differences for all dependent variables[121,127,128] but there where effects of concussion history whereby those with a previous concussion history were significantly slower than those without on CMI tasks for some of the dependent variables.[108,121,127,128]

2. *Evaluate the inter- and intra-rater reliability of the HurtSHynes™ Test*

There is a need for more objective and reliable measures for concussion diagnosis and RTP management[155,156] in addition to tests that assess cognition and movement simultaneously.

Although cognitive skills such as perception, working memory, attention, and decision-making are key components to successful sport performance, tasks that require CMI may be more beneficial to understand the effects of concussions when combined with current concussion testing metrics.[148] Evaluating inter- and intra-rater reliability of the HurtSHynes™ Test is the first process to determine if our novel CMI test can be used as a sideline assessment for RTP management by examining if performance on our test can consistently be assessed by multiple raters.

Hypotheses

1. We expect to see no significant differences in the standard mapping condition between participants with a HOC and those without but expect participants with no prior HOC to perform better (complete the condition faster) in the non-standard mapping condition compared to those with a HOC. We also expect all participants, regardless of concussion history, to incur more errors and take longer to complete the non-standard mapping task in comparison to standard mapping performance.

Previous studies on the BrDI™ Test have reported that performance outcomes related to both timing and accuracy on the non-standard visuomotor mapping tasks were significantly different when comparing athletes with a previous history of concussion to healthy controls but there were no differences on the standard mapping tasks.[108,121,127,128] Similar findings were also observed in patients with dementia, mild cognitive impairment, and early-stage Alzheimer's disease who had difficulty with CMI tasks on the BrDI™ Test but performed no differently than healthy controls on the standard mapping tasks.[111,118,122–124,126]

Regardless of previous concussion history, studies on the BrDI™ Test have reported that performance timing measures such as reaction time, movement time, total movement time, etc. were longer for all participants in the non-standard tasks compared to the standard tasks, but were even longer for those with a previous history of concussion compared to controls in the non-standard.[108,121,128] These studies also reported that variable errors (i.e precision) and constant errors (i.e movement accuracy) were larger in the non-standard conditions compared to the standard, denoting decreased accuracy and precision in the non-standard compared to standard tasks.[108,128] In addition, those with a previous history of concussion showed larger constant errors compared to those without a history.[108] In terms of direction reversal errors, which can only be incurred on CMI tasks, these studies found no statistically significant differences in the number of errors between history and no history groups.[108,128]

2. Both the standard and non-standard mapping conditions will demonstrate good-to-excellent (ICC > .75) inter- and intra-rater reliability.

The HurtSHynes™ Test is an easy and quick to administer test where examiners are using a stopwatch to measure time and record any errors a participant incurs while completing the test. There are only 4 visual cues a participant needs to respond to by the examiner in each of the conditions, allowing for examiners and raters to easily detect any errors that might be incurred.

Chapter 2: Manuscript

THE EFFECT OF CONCUSSION HISTORY ON A SIDELINE ASSESSMENT OF COGNITIVE-MOTOR INTEGRATION (HurtSHynes™ TEST) IN MALE AND FEMALE VARSITY ATHLETES

Chapter 2: Manuscript

Introduction

Concussion is a form of mild traumatic brain injury (mTBI) where biomechanical forces caused by either a direct blow to the head, face, neck, or elsewhere on the body are transmitted to the brain, resulting in a temporary disturbance of neurological function.[1] In the United States it is estimated that there are 1.6 to 3.8 million sports-related traumatic brain injuries (TBIs) each year but may be higher given that many of these injuries go unrecognized or are underreported.[70] In Canada, where healthcare is publicly funded, data from the most recent 2017/18 Canadian Community Health Survey (CCHS) revealed that the overall incidence rate of reported sport-related concussions (SRCs) or other brain injuries was 221 per 100,000 Canadians and that in the preceding year at least 1 in 450 Canadians reported SRCs or other brain injuries as their most severe disabling injury.[63]

A large portion of research on SRCs have focused on studying the effects of concussion on cognition[145–147] with less focus on studying its effects on visually guided motor actions[148] and cognition integrated with movement in a sport context.[149] In addition, the current assessment tools used for diagnosing a concussion and/or monitoring of recovery post injury such as the Sport Concussion Assessment Tool- Version 5 (SCAT5),[150] Balance Error Scoring System (BESS),[136,151] Immediate Post- Concussion Assessment and Cognitive Testing (ImPACT),[152] Buffalo Concussion Treadmill Test (BCTT),[137,153] and Buffalo Concussion Bike Test (BCBT)[154] often tests one's cognition and motor performance in isolation rather then concurrently. However, success in sport performance, as well as aspects of daily life and work, requires the simultaneous integration of cognition and action known as cognitive-motor integration (CMI).

Cognitive-motor integration is what allows us to perform non-standard visuomotor mapping tasks. Visuomotor transformations are classified as either standard mapping, when the visual stimulus guiding an action is the target of the action or non-standard, when we attend to stimuli in locations that differ form the target of the action.[116] In hockey, an example of standard mapping would be making a pass when looking at one's teammate, in comparison to nonstandard mapping that would involve passing to one's teammate on the left, while looking to avoid a body check from an opponent on one's right.[108,113]

It has been proposed that widespread brain injury after sustaining a concussion can reduce rule-based skill performance, attributed to an inability of cognitive brain networks to communicate between each other.[108,117] Parietal-frontal networks that are required for the integration of cognitive information into a motor plan could also be compromised.[119] Studies have repeatedly observed that athletes with a history of concussion have performance deficits in CMI tasks in comparison to healthy controls, even though the athletes were considered asymptomatic and cleared to return-to-play (RTP).[108,121,127,128] Studies by Dalecki et al.[121,127] have shown that these deficits can last approximately 18 to 24 months post-concussion in athletes aged 9 to 17.

Although cognitive skills such as perception, working memory, attention, and decision-making are key components to successful sport performance, visuomotor tasks that require CMI may be more beneficial to understand the effects of concussions, in addition to the current standard tests of cognition.[148] Modelled from the Brain Dysfunction Indicator (BrDI™) Test,[121] our group at York University is developing the HurtSHynes™ Test as a means to better assist in guiding an athlete’s RTP following a concussion injury.

Developed by Hurtubise, Sergio, and Hynes,[114] the HurtSHynes™ Test is unique in that it is reflective of movements executed by athletes during sport performance while simultaneously enabling the assessment of their ability to think and move together (i.e. CMI). Based on previous findings from the BrDI™ Test in athlete populations,[108,121,127,128] we hypothesized that athletes with a previous history of concussion will perform similarly to healthy controls in the standard mapping visuomotor condition of our test but will incur more errors and take longer to complete the CMI, non-standard visuomotor condition. The aim of this pilot study was to explore sex-related differences and the effect of concussion history on our newly developed CMI task, the HurtSHynes™ Test.

Methods

The HurtSHynes™ Test

The HurtSHynes™ Test required participants, positioned at a start cone, to respond to 4 visual directional cues (up, down, right, left) presented by an examiner while running 26 meters to an end cone in two conditions. The visual directional cues were denoted by an outstretched hand of the examiner who was holding a football to ensure the participant could view the cues as they progressed through the test. Participants were instructed to keep their eye on the football the entire time as they were completing both conditions.

Condition 1 was a standard visuomotor mapping task where the spatial location of the directional cue by the examiner and the required movement by the participant was in alignment. The participant's response matched the visual cue of the examiner (Figure 4) whereby an outstretched rightward or leftward arm by the examiner holding the football required the participant to cut two steps laterally in the direction of the outstretched arm. When the examiner raised the football above their head the participant was to jump vertically with both hands in the air and if the football was placed below the examiner's waist, the participant was to drop down in a push up stance, get back up, and continue running towards the end cone.

A. B.

Figure 4. Schematic description of 2 of the 4 visual directional cues in Condition 1. (A) In this visual directional cue the examiner raised the football above their head. In response, the participant jumped up with both hands in the air. (B) In this visual directional cue an outstretched leftward arm by the examiner required the participant to cut two steps laterally in the direction of the outstretched arm.

Condition 2 was a non-standard mapping task, requiring CMI and the disassociation of vision and action. In this condition the eyes of the participant were moving in a different direction and/or in another plane than the performed motor action as the participant's response was opposite to the visual cue of the examiner (Figure 5). When the examiner raised the football above their head the participant was to drop down in the push up stance and when it was placed below the examiner's waist the participant was to jump vertically with both hands in the air. An outstretched rightward or leftward arm by the examiner required the participant to cut two steps laterally in the opposite direction of the examiner's arm.

A. B.

Figure 5. Schematic description of 2 of the 4 visual directional cues in Condition 2.
(A) In this visual directional cue the examiner raised the football above their head. In response, the participant dropped down into a push-up stance. (B) In this visual directional cue an outstretched leftward arm by the examiner required the participant to cut two steps laterally in the opposite direction of the outstretched arm.

Participants were positioned at the start denoted by a yellow cone on the floor (Matrix 20x20x5cm) and were asked to wait for the examiner to yell "3, 2, 1, go" with the word "Go" serving as the go-signal for the participant to begin the test. They were instructed to run as fast as they could towards the examiner while responding to a visual directional cue administered roughly every 5 metres. The examiner was located directly in front of them 26 metres away standing beside a second yellow cone (Matrix 20x20x5cm) that served as the end point of the test. Prior to test commencement the participant was instructed to always continue running towards the end cone after their response to a visual cue had been made. With the use of a manual stopwatch (ULTRAK 340) the total duration time for task completion was recorded by the examiner. Time began the moment the go-signal was given and concluded once the participant passed the end cone.

In total, participants responded to 8 visual directional cues (4 responses per condition). The order at which the examiner administered the 4 visual directional cues was randomized for each participant for both conditions and each participant was randomly assigned to complete either Condition 1 or 2 first to control for potential learning effects. Number of errors for an incorrect response to the visual stimulus were recorded by the examiner with 8 being the maximum errors a participant could incur (4 per condition). An error occurred any time a participant; (1) responded incorrectly to a visual cue; (2) made an initial incorrect response to a visual cue, realized their mistake, and proceeded to respond correctly after initial movement error; (3) did not put their hands above their head when they were required to jump. For this current study a single examiner tested all participants to maintain consistency of test administration across all athletes.

Participants

Participants were student-athletes recruited from York Lions varsity sports teams at York University, Keele Campus, Toronto, ON, Canada. Men's and women's teams included in this study were soccer, hockey, volleyball, and basketball, along with coed wrestling, track and field, and cross country. Men's football, women's rugby, and women's field hockey were also included. Participation in the study was part of the varsity athletes' pre-season baseline medical testing conducted from August 1, 2019 to September 25, 2019 at York University and was approved by York University's Ethics Review Board. Self-reported history of concussion by the athletes were recorded at the time of baseline testing but remained unknown to the examiner until data analyses. All athletes with a concussion history at the time of testing were defined as asymptomatic in accordance with current return-to-sport protocol guidelines[1] by members of the Sports Medicine Team at the Gorman/Shore Sport Injury Clinic at York University. Athletes who were not medically cleared to participate in sport were excluded from study participation. Athletes were not given any remuneration for their participation.

Statistical Analysis

The two dependent variables in this study were; (1) the time taken in seconds (s) to complete Condition 1 and Condition 2; (2) number of errors incurred in Conditions 1 and 2. There were 8 independent variables; (1) age of athlete at time of testing; (2) sex; (3) concussion history (yes, no); (4) total number of previous concussions; (5) length of time since most recent concussion (<12 months, 12-24 months, >24 months); (6) years of education; (7) varsity team (soccer, hockey, volleyball, basketball, football, rugby, field hockey, wrestling, cross country, track and field); (8) playing surface (field, court, ice, other).

Two hundred eighteen athletes completed the HurtSHynes™ Test during the baseline testing period. Previous history of concussion was measured as none, one, or two or more concussions sustained prior to the baseline study period. Athletes who self-reported as having no previous history of concussions served as healthy controls in our study. Those whose self-reported history of previous concussions were missing at the time of baseline data collection (n = 13) were excluded from all statistical analyses. This variable is important to our study given that the most recent consensus statement on concussion in sport[1] reported that having a previous SRC is a risk factor for having a future one and that multiple previous concussions have been associated with more physical, cognitive, and emotional symptoms prior to participation in a sporting season.

To prevent any learning effects through multiple administrations of the test, athletes were given no practice trials and were to complete each of the two conditions only once. As such, any athlete who required multiple attempts to complete the test (n = 25) were also excluded, leaving a total of 180 athletes that were included in the final statistical analyses.

Years of education was recorded based on the number of completed academic years of schooling from grade one to the study period. For example, an athlete who had just graduated high school and was to begin their first year of university was recorded as having completed 12 years of education. Similarly, if an athlete had completed two years of undergraduate studies and was to begin their third year, they were recorded as having completed 14 years of education.

Given that athletes self-reported the length of time since their most recent concussion there was some variability in reporting whereby some could only remember the month of a particular year when the injury occurred or simply just the year of injury, in comparison to others who were able to recall the exact date. As a result, length of time since most recent concussion was analyzed as a categorical variable comprised of three levels: <12 months, 12 months to 24 months, and >24 months.

The total sample size for each of the 10 sports was less than 30 athletes except for soccer that had a total of 36 athletes. To account for any statistically significant differences that may have attributed to the sampling size for this independent variable, all varsity teams were also analyzed as a categorical variable comprised of four levels based on the type of playing surface where the sport was played: field, court, ice, other. Field included men and women's soccer along with football, women's rugby, and women's field hockey. Court included men and women's volleyball and basketball. Ice was comprised solely of men and women's hockey and other included coed wrestling, track and field, and cross country. Categorizing teams by playing surface was more appropriate for our study as opposed to creating a dichotomous variable in terms of contact and non-contact sports given that the majority of the varsity teams in the current study were contact sports. Therefore, this level of categorization would not help to address sampling size concerns for this independent variable.

Lastly, to adjust for history of concussion (HOC) and sex four cohort groups were formed: male athletes without a history of concussion (Male No HOC), female athletes without a history of concussion (Female No HOC), male athletes with a history of concussion (Male HOC), and female athletes with a history of concussion (Female HOC). The creation of these four cohort groups was similar to the work by Hamer et al.[31] who reported on history of concussion differences in CBF for males and females. However, our statistical analyses differ in that we chose to do direct comparisons across all four groups as opposed to conducting separate analyses by sex and only comparing males with a HOC to males without a HOC, and females with a HOC to females without a HOC. A direct four group comparison would allow us to determine if there were any differences in performance between females with a HOC and males with a HOC that could allude to a better recovery in either males or females following a concussion injury on our novel test.

Statistical significance levels were set at an a priori level of significance of $\alpha = 0.05$ and all analyses were performed using Statistical Package for the Social Science (SPSS) Version 28 (IBM Corp., Armonk, NY). Parametric and non-parametric tests conducted included independent sample t-tests, One-Way Analysis of Variance (ANOVA), and Pearson Chi-Square tests which were performed to examine the associations and relationships between the dependent and independent variables.

Stratified Analysis

To account for order and condition effects of the HurtSHynes™ Test two models were designed for stratified analyses. Participants were stratified based on the condition of the HurtSHynes™ Test they were randomly assigned to complete first. Model A (n = 90) was comprised of those who were randomly assigned to complete Condition 1 first (standard mapping), followed by Condition 2 (non-standard mapping) and Model B (n = 90) included those who were randomly assigned to complete Condition 2 first followed by Condition 1. Frequency histograms displaying the normal curve were conducted in both models for the independent variable time and normality was assessed using the Shapiro-Wilk test along with skewness and kurtosis. Based on the work by West et al.[157] a substantial departure from normality is an absolute skew value greater than 2 and a kurtosis value greater than 7. Therefore, in terms of skewness and kurtosis, data for our study was considered to be normally distributed if skewness was less than 2 and kurtosis was less than 7.

Stratified Analysis: Linear and Logistic Regressions

All linear and logistic regression models only included the four cohort groups for analyses. The independent variable, number of previous concussions, was not included in linear and logistic regression models to prevent collinearity with the four cohort groups. In both models Males with no HOC completed the HurtSHynes™ Test the fastest and females with no HOC completed the test the slowest regardless of the condition assigned. As such both were used as the reference group in two separate analyses for both linear and logistic regressions in both models to determine best model fit. For logistic regressions the total number of errors on the HurtSHynes™ Test for each participant was analyzed as a dichotomous variable, No errors and Errors, to allow for modelling the probability of incurring one or more errors on the test.

Performance as a Level of Dissociation

Modelled after previous studies in the literature that reported on findings from the BrDI™ Test in a concussed sample[108,128] we compared the athletes performance on the HurtSHynes™

Test as a function of their change from their own Condition 1 (standard mapping) time. This was done to test the hypothesis that performance declines would be significant in the Condition 2 (non-standard mapping) time compared to Condition 1 time. To do this we subtracted the athlete's Condition 1 time from their Condition 2 time in both of our statistical models and conducted independent sample t-tests with concussion history (yes, no) as the independent variable.

Results

Descriptive Statistics

Of the 180 athletes n = 99 were female (55%) and n = 81were male (45%). The mean age for females and males were 19.82 ± 1.83 yrs and 20.05 ± 1.90 yrs respectfully (Table 1). The current reported mean and standard deviation for males is for an n of 80 as age was missing for one male athlete (1.2%). The mean years of education for females was 14.21 ± 1.56 where the majority (n = 25) were entering into their third year of undergraduate studies. The current reported mean and standard deviation for years of education in females is for an n of 97 as data for this variable was missing for two female athletes (2%). In comparison, the mean years of education for males was 13.49 ± 1.30 where the majority (n = 20) were entering into their second year of undergraduate studies. Years of education was missing for 20 male athletes (24.7%) and thus the current reported mean and standard deviation for this variable is for an n of 61 males.

Table 1. Demographic characteristics of varsity athletes by sex

	Male	Female
n	81	99
Age (mean ± SD) *	20.05 ± 1.90	19.82 ± 1.83
Years of Education (mean ± SD) *	13.49 ± 1.30	14.21 ± 1.56

* For this variable there were missing data

In total n = 103 (57.2%) athletes had no prior HOC (51 females, 52 males) and n = 77 (42.8%) had a prior HOC (48 females, 29 males). Of the 77 athletes who reported having a previous history of concussion, n = 42 (54.5%) had one previous concussion, and n = 35 (45.5%) had 2 or more (Table 2). The length of time since an athlete's last concussion was obtained during baseline medicals for only 45 of the 77 athletes. Of those 45 athletes, 51.1% (n = 23) sustained their last concussion greater than 24 months, 46.7% (n = 21) sustained their last concussion less than 12 months ago, and 2.2% (n = 1) sustained their last concussion between 12 to 24 months.

Table 2. Concussion history information

	n (%)	n	n
		Male	Female
No Prior Concussion History	103 (57.2)	52	51
Prior History of Concussion	77 (42.8)	29	48
Previous Number of Concussions			
1	42 (54.5)	15	27
2+	35 (45.5)	14	21
Total	77	29	48
Length of Time Since Last Concussion			
<12 months	21 (27.3)	5	16
12-24 months	1 (1.3)	0	1
> 24 months	23 (29.9)	11	12
Missing	32 (41.6)	13	19
Total	77	29	48

The majority of athletes were part of a varsity team that played on a field surface, n = 88 (48.9%), compared to n = 49 (27.2%) who played on a court, ice n = 29 (16.1%), or other n = 14 (7.8%) (Figure 6).

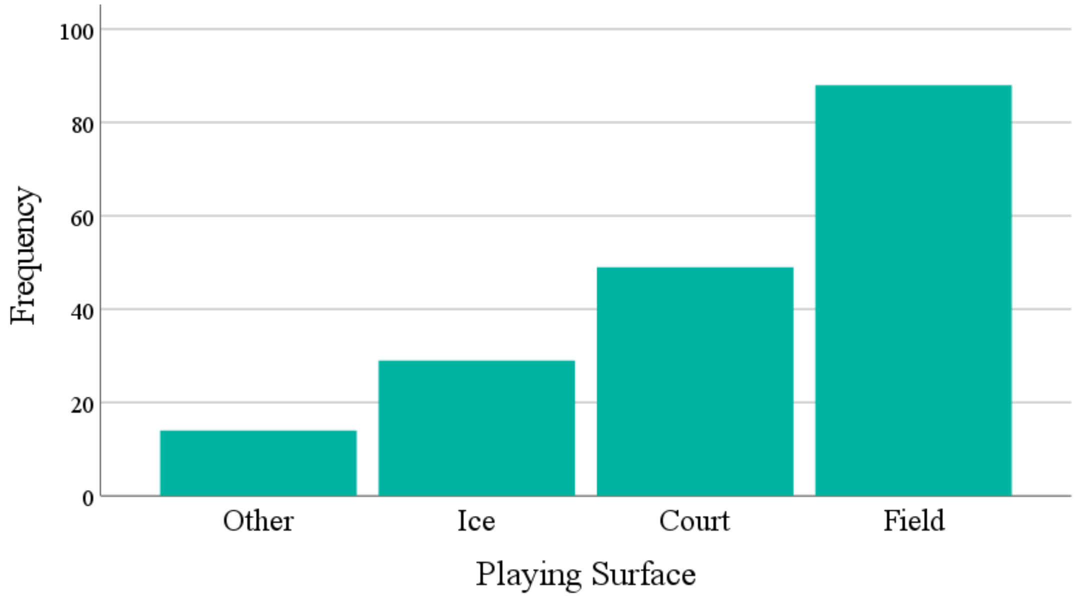

Figure 6. Frequency histogram of the number of athletes who were part of a varsity team that played on a field, court, ice, or other (n = 180).

Across all teams, women's rugby (n = 9) and women's field hockey (n = 9) had the highest number of athletes with a self-reported history of concussion (Table 3). Similar to procedures done by Black et al.,[158] due to the low incidence of athletes with a previous history of concussions in wrestling, cross country, track and field, and men's basketball and volleyball, the total number of athletes could not be reported in accordance with the Personal Health Information Protection Act (PHIPA). However, there were a total of 13 athletes with a self-reported history of concussion in these sports.

Table 3. Total number of athletes who had a previous history of concussion by sport and playing surface.

	Male (n)	Female (n)
Sport		
Football	7	N/A
Rugby	N/A	9
Field Hockey	N/A	9
Basketball	-	8
Volleyball	-	5
Hockey	6	7
Soccer	6	7
Cross Country/Track & Field	-	-
Wrestling	-	-
Playing Surface		
Field	13	25
Court	8	13
Ice	6	7
Other	-	-

N/A, not applicable

For the four cohort groups created there were 52 male participants (28.9%) and 51 female participants (28.3%) without a HOC compared to 29 male participants (16.1%) and 48 female participants (26.7%) with a HOC.

Statistical Analysis: Total Study Sample (n = 180)

For the variable sex: Independent sample t-tests revealed no statistically significant differences between sex and age (t = 0.83, df = 177, p = 0.410) and sex and number of previous concussions (t = 0.77, df = 178, p = 0.442). Pearson Chi-Square tests revealed no statistically significant differences between sex and time since last concussion (x^2 = 3.33, df = 2, p = 0.189) or sex and concussion history (yes, no) (x^2 = 2.93, df = 1, p = 0.087). Pearson Chi-Square tests revealed no statistically significant differences between number of previous concussions (0, 1, 2+) and playing surface (x^2 = 5.97, df = 6, p = 0.426) or sport (x^2 = 25.48, df = 26, p = 0.492). There were also no statistically significant differences between concussion history (yes, no) and playing surface (x^2 = 0.34, df = 3, p = 0.952) or sport (x^2 = 12.82, df = 13, p = 0.462).

Independent sample t-tests did reveal a statistically significant difference between sex and years of education whereby women on average had more years of education (t = 2.98, df = 156, p = 0.003). A One-Way ANOVA was performed between the 4 cohort groups and years of education and found to be statistically significant (F = 3.60, df = 3,157, p = 0.015). A Bonferroni post-hoc test was performed and revealed a statistically significant difference only between the Male No HOC group and Female HOC group (p = 0.012). Females with a HOC on average had more years of education compared to Males with no HOC.

Stratified Analysis: Shapiro-Wilk Test, Skewness, and Kurtosis

Prior to any statistical analyses on the dependent variable time, frequency histograms displaying the normal curve were conducted (Figures 7 and 8) and normality was assessed using the Shapiro-Wilk test along with skewness and kurtosis. Those whose condition times were 2 standard deviations (SDs) away from the means were deemed to be outliers and removed to better meet statistical assumptions of linearity.

Model A (Condition 1 First- Standard, Condition 2 Second- Non-Standard)

Based on the Shapiro-Wilk test normality assumptions were violated for Condition 1 (p = 0.003) but were met for Condition 2 (p = 0.941). However, in addition to the Shapiro-Wilk test data is considered to be normally distributed if skewness is less than 2 and kurtosis is less than 7.[157] For Condition 1 skewness was 0.847 and kurtosis was 1.487. Despite normality assumptions being violated based on the Shapiro-Wilk test for this condition, the researcher felt confident proceeding with further statistical analyses on this variable given normality was met based on skewness and kurtosis and the frequency histogram displayed a fairly good normal distribution (Figure 7). For Condition 2 skewness was 0.182 and kurtosis was 0.345, further confirming results from the Shapiro-Wilk test that normality assumptions were met for this condition in Model A. In this model there were 3 athletes whose Condition 1 time were identified as outliers and 1 athlete for Condition 2 time. The overall mean time and SD for Condition 1 time was 10.33 ± 1.595 (s) and 10.27 ± 1.414 (s) for Condition 2.

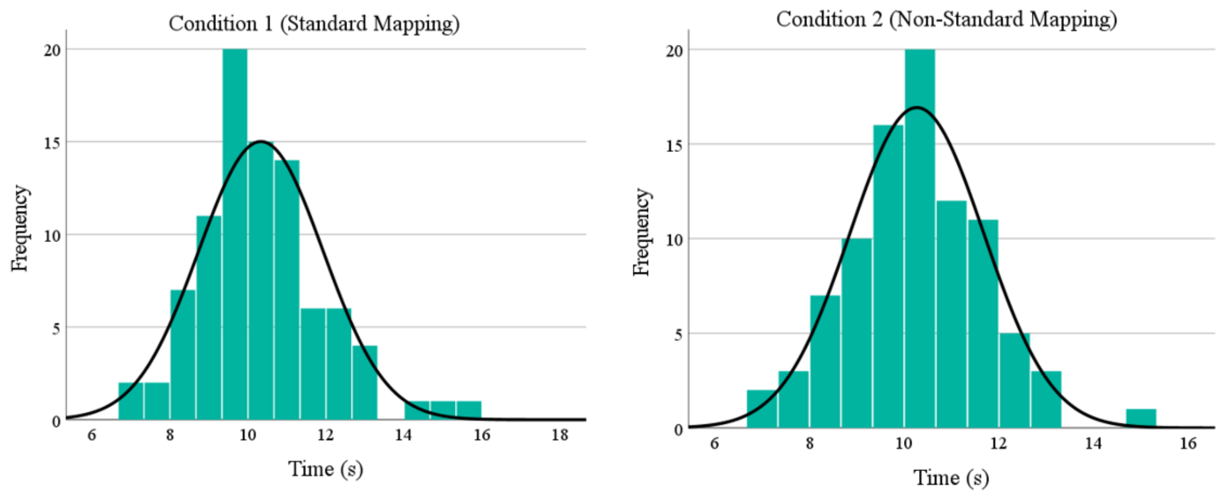

Figure 7. Frequency histograms with normal distribution curves of Condition 1 and Condition 2 test completion time in seconds (s) for all study participants (n = 90) in Model A. This model was comprised of those who were randomly assigned to complete Condition 1 first, followed by Condition 2.

Model B (Condition 2 First- Non-Standard, Condition 1 Second- Standard)

Based on the Shapiro-Wilk test normality assumptions were met for Condition 2 ($p = 0.583$) and Condition 1 ($p = 0.210$). Skewness and kurtosis was 0.298 and 0.414 respectively for Condition 2 and for Condition 1 skewness and kurtosis was 0.357 and 0.228 respectively. Frequency histograms for both conditions displayed a fairly good normal distribution (Figure 8). In this model there were 4 athletes whose Condition 2 time were identified as outliers and 3 athletes for Condition 1 time. The overall mean time and SD for Condition 2 time was 11.20 ± 1.645 (s) and 10.13 ± 1.319 (s) for Condition 1.

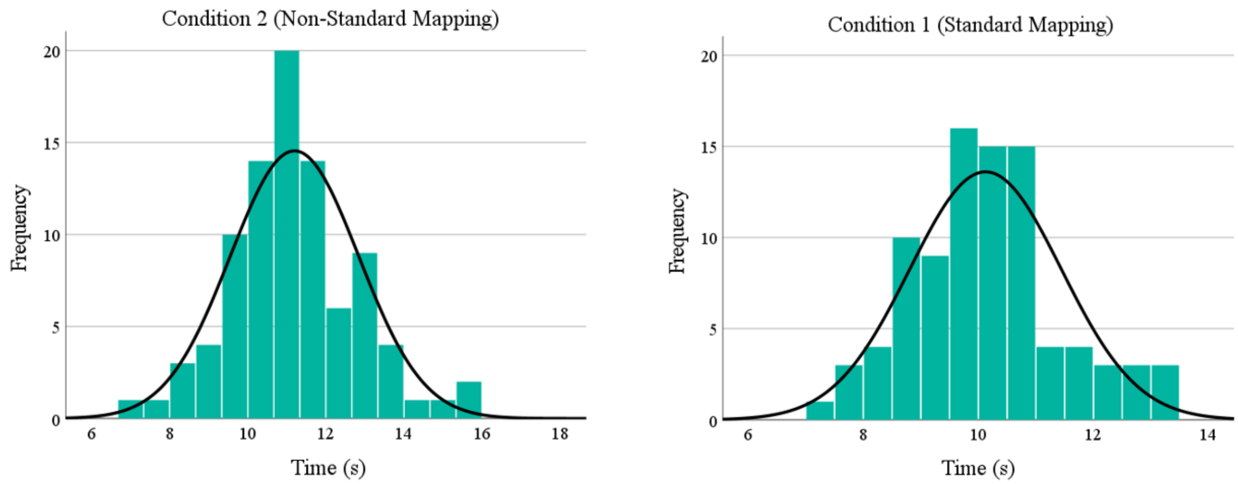

Figure 8. Frequency histograms with normal distribution curves of Condition 2 and Condition 1 test completion time in seconds (s) for all study participants (n = 90) in Model B. This model was comprised of those who were randomly assigned to complete Condition 2 first, followed by Condition 1.

Stratified Analysis: Independent Sample T-Test, One-Way ANOVA, Pearson Chi-Square Test

In SPSS Bonferroni post-hoc tests cannot be performed when there are fewer than two cases for any variable. As such, prior to conducting One-Way ANOVAs in the two models, any independent variable that had less than 2 athletes on any of the categorical levels were excluded from all stratified analyses for that category.

Model A (Condition 1 First- Standard, Condition 2 Second- Non-Standard)

For the independent variable age, any athlete who was 24 years of age or older was excluded from the One-Way ANOVA (n = 1). After running this parametric test results revealed no statistically significant differences between age and Condition 1 time (F = 0.84, df = 6,79, p = 0.542) nor Condition 2 time (F = 1.92, df = 6,81 p = 0.088). For the independent variable years of education, athletes who had 18 or more years of education (n = 1) were excluded for this analysis. After conducting a One-Way ANOVA there were no statistically significant differences between years of education and Condition 1 time (F = 0.38, df = 5,69, p = 0.864) or Condition 2 time (F = 0.97, df = 5,70, p = 0.442).

For the independent variable time since last concussion, there was only one athlete whose last concussion was between 12 to 24 months. After excluding this athlete, leaving only two categorical levels for this independent variable (<12 months and >24 months), an independent samples t-test was performed. There were no statistically significant differences between time since last concussion and Condition 1 time (t = -0.54, df = 19, p = 0.598) and Condition 2 time (t= -0.59, df = 21, p = 0.561).

For the 4 cohort groups created, average time for completion of Condition 1 was 9.72(s) for Males with no HOC, 10.61 (s) for Females with no HOC, 10.36 (s) for Females with a HOC, and 9.88 (s) for Males with a HOC. A One-Way ANOVA was performed between the 4 cohort groups and Condition 1 time and found to be not statistically significant (F = 2.38, df = 3,83, p = 0.075) (Figure 9). Average time for completion for Condition 2 was 9.70 (s) for Males with no HOC, 10.70 (s) for Females with no HOC, 10.47 (s) for Females with a HOC, and 9.94 (s) for Males with a HOC.

A One-Way ANOVA was performed between the 4 cohort groups and Condition 2 time and found to be statistically significant (F = 3.09, df = 3,85, p = 0.031). A Bonferroni post-hoc test was performed and revealed a statistically significant difference only between the Male No HOC group and Female No HOC group (p = 0.040) (Figure 9). Males with no HOC on average were faster in Condition 2 compared to females with no HOC.

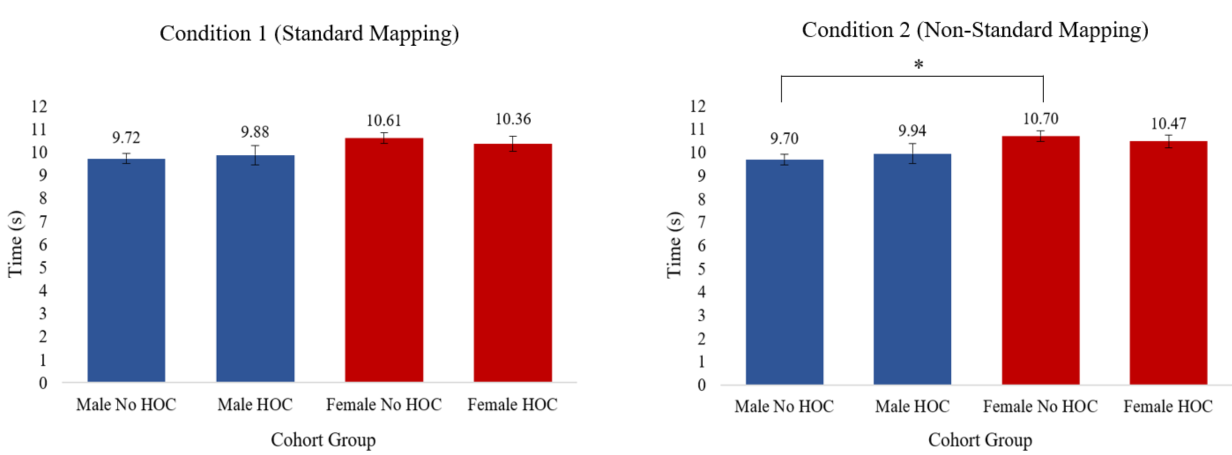

Figure 9. Average time to condition completion, in seconds (s), for all 4 cohort groups in Model A. This model comprised all those who were randomly assigned to complete Condition 1 first, followed by 2 (n = 90). * = p < 0.05, ** = p < 0.01. Error bars represent standard error of the mean.

A One-Way ANOVA was performed between playing surface and condition times and found to be not statistically significant for Condition 1 Time (F = 2.10, df = 3,83, p = 0.107) or Condition 2 Time (F = 0.24, df = 3,85, p = 0.869). There were also no statistically significant differences between number of concussions (0, 1, 2+) and Condition 1 time ($F = 0.05$, $df = 2,84$, $p = 0.951$) or Condition 2 time ($F = 0.90$, $df = 2,86$, $p = 0.410$).

A One-Way ANOVA was performed between varsity team and condition times and found to be statistically significant in both conditions; Condition 1 ($F = 3.70$, $df = 12,74$, $p < 0.001$) and Condition 2 ($F = 4.31$, $df = 12, 76$, $p < 0.001$). A Bonferroni post-hoc test was performed and revealed statistically significant differences in Condition 1 between men's soccer and football ($p = 0.011$), women's basketball ($p = 0.012$), women's field hockey ($p < 0.001$), women's soccer ($p = 0.024$), men's hockey ($p = 0.027$), men's basketball ($p = 0.018$), women's hockey ($p = 0.001$), women's volleyball ($p = 0.012$), and coed cross country ($p = 0.027$) and wrestling ($p = 0.024$) whereby men's soccer on average was faster than these 10 varsity teams. For Condition 2 a Bonferroni post-hoc test was performed and revealed statistically significant differences between men's soccer and football ($p < 0.001$), women's basketball ($p = 0.002$), women's rugby ($p = 0.001$), women's field hockey ($p < 0.001$), women's soccer ($p = 0.002$), men's hockey ($p = 0.011$), women's hockey ($p = 0.004$), women's volleyball ($p = 0.017$), and men's basketball ($p = 0.033$) where men's soccer was on average faster than these 9 varsity teams.

For the dependent variable number of errors, information pertaining to the number of athletes who incurred either 0, 1, 2, 3, or 4 in Conditions 1 and 2 can be found in Table 4. There were 82 athletes who had 0 errors and 8 who had one error in Condition 1. Given the low frequency of those who committed one error in Condition 1, Pearson Chi-Square tests were not conducted for this condition. In Condition 2 there were 56 athletes who had 0 errors, 28 who had 1 error, 5 who had 2 errors and 1 who had 3 errors. Similar to Condition 1, Pearson Chi-Square tests were not conducted for this condition given the low frequency counts.

Table 4. Number of athletes who incurred either 0, 1, 2, 3, or 4 errors on Conditions 1 and 2 of the HurtSHynes™ Test in Model A.

Number of Errors	Condition 1 n (%)	Condition 2 n (%)
0	82 (91.1)	56 (62.2)
1	8 (8.9)	28 (31.1)
2	0	5 (5.6)
3	0	1 (1.1)
4	0	0

Model B (Condition 2 First- Non-Standard, Condition 1 Second- Standard)

A One-Way ANOVA was performed between playing surface and condition times and found to be not statistically significant for Condition 2 Time (F = 1.76, df = 3,82, p = 0.161) or Condition 1 Time (F = 1.92, df = 3,83, p = 0.132). There were also no statistically significant differences between number of concussions (0, 1, 2+) and Condition 2 time (F = 1.40, df = 2,83, p = 0.253) or Condition 1 time (F = 1.07, df = 2,84, p = 0.347). For the independent variable years of education, athletes who had 17 or more years of education (n=1) were excluded for this analysis. After conducting a One-Way ANOVA, there were no statistically significant differences between years of education and Condition 2 time (F = 0.61, df = 4,71, p = 0.660) or Condition 1 time (F = 0.63, df = 4,71, p = 0.640). For the independent variable time since last concussion there were no athletes who sustained their last concussion between 12-24 months. An independent samples t-test revealed no statistically significant differences between time since last concussion and Condition 2 time (t = 0.08, df = 18, p = 0.934) and Condition 1 time (t = -0.82, df = 18, p = 0.422). For the independent variable age, any athlete who was 25 years of age or older (n = 2) was excluded from the One-Way ANOVA. After running this parametric test results revealed no statistically significant differences by age and Condition 2 time (F = 1.12, df = 7,75, p = 0.360) nor Condition 1 time (F = 1.25, df = 7,76, p = 0.284).

For the 4 cohort groups, average time for completion of Condition 2 was 10.30 (s) for Males with no HOC, 11.50 (s) for Females with no HOC, 11.20 (s) for Females with a HOC, and 11.57 (s) for Males with a HOC. A One-Way ANOVA was performed between the 4 cohort groups and Condition 2 time and found to be statistically significant (F = 4.01, df = 3,82, p = 0.010). A Bonferroni post-hoc test was performed and revealed statistically significant differences between the Male No HOC group and Female No HOC group (p = 0.017) and the Male No HOC group and Male HOC group (p = 0.048) whereby males with no HOC on average were faster in Condition 2 compared to Females with no HOC and Males with a HOC (Figure 10).

Average time for completion of Condition 1 was 9.19 (s) for Male No HOC, 10.59 (s) for Female No HOC, 10.34 (s) for Female HOC, and 9.89 (s) for Male HOC. A One-Way ANOVA was performed between the 4 cohort groups and Condition 1 time and found to be statistically significant (F = 8.00, df = 3,83, p <0.001). A Bonferroni post-hoc test was performed and revealed statistically significant differences between the Male No HOC group and Female No HOC group (p <0.001) and the Male No HOC group and Female HOC group (p = 0.001) whereby the Male No HOC group on average were faster in Condition 1 compared to Female No HOC and Female HOC groups (Figure 10).

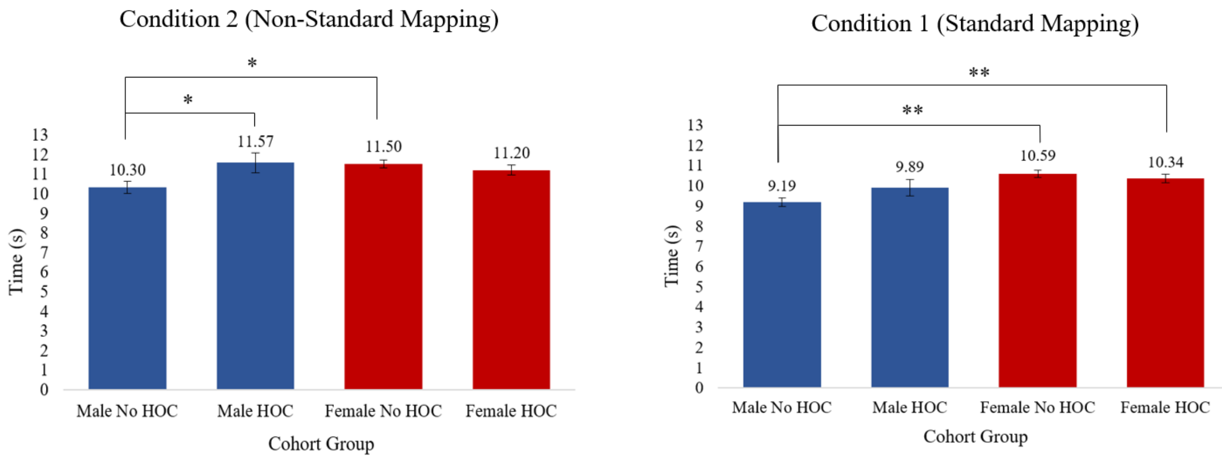

Figure 10. Average time to condition completion, in seconds (s), for all 4 cohort groups in Model B. This model comprised all those who were randomly assigned to complete Condition 2 first, followed by 1 (n = 90). * = p < 0.05, ** = p < 0.01. Error bars represent standard error of the mean.

In order to determine if there were any statistically significant differences between sport and the condition times, any sports that had fewer than two athletes in this model were excluded. The only sport where there were fewer than 2 athletes was track and field (n = 1). After excluding track and field from the analysis in this model, One-Way ANOVAs revealed statistically significant differences between varsity sport and Condition 2 time (F = 2.61, df = 12,72, p = 0.006) and Condition 1 time (F = 4.85, df = 12,73, p < 0.001). A Bonferroni post-hoc test was performed and revealed statistically significant differences in Condition 2 between men's soccer and football (p = 0.018), women's rugby (p = 0.042), and coed cross country (p = 0.025) where men's soccer on average was faster than these 3 varsity teams. In Condition 1 there were statistically significant differences between men's soccer and football (p = 0.007), women's basketball (p < 0.001), women's rugby (p = 0.004), women's field hockey (p < 0.001), women's soccer (p < 0.001), men's hockey (p = 0.041), women's hockey (p = 0.012), and coed cross country (p < 0.001) and wrestling (p = 0.025) where men's soccer was on average faster than these 9 varsity teams.

For the dependent variable number of errors, information pertaining to the number of athletes who incurred either 0, 1, 2, 3, or 4 in Conditions 2 and 1 can be found in Table 5. There were 41 athletes who had 0 errors, 31 who had 1 error, 15 who had 2 errors and 3 who had 3 errors in Condition 2 compared to 81 athletes who had 0 errors and 9 who had one error in Condition 1. Similar to Model A, Pearson Chi-Square tests were not conducted in Model B in either condition given the low frequency counts.

Table 5. Number of athletes who incurred either 0, 1, 2, 3, or 4 errors on Conditions 2 and 1 of the HurtSHynes™ Test in Model B.

Number of Errors	Condition 2 n (%)	Condition 1 n (%)
0	41 (45.6)	81 (90.0)
1	31 (34.4)	9 (10.0)
2	15 (16.7)	0
3	3 (3.3)	0
4	0	0

Stratified Analysis: Linear and Logistic Regressions

Given the small sample sizes of athletes in each of the respective varsity teams, the number of missing data for time since last concussion (n = 32), and the number of males with missing years of education (n = 20), only the 4 cohort groups were entered into all linear and logistical regression analyses. Dummy variables were created for these cohort groups as it would provide absolute beta coefficients when comparing cohort groups to a reference group. Results from One-Way ANOVAs in each of the two models revealed Males no HOC group completed the conditions the fastest while females with no HOC completed the conditions the slowest, regardless of the condition assigned first. As such, two linear and logistical analyses will be conducted in both Model A and B where males with no HOC serve as the reference group in one analysis and females with no HOC serve as the reference group in a secondary analysis to determine best model fit.

Linear Regression

Model A (Condition 1 First- Standard, Condition 2 Second- Non-Standard)

A linear regression for the dependent variable time was conducted with Male No HOC serving as the reference group (Table 6). Results showed that for Condition 1 there were significant differences in the Female No HOC group whereby females with no HOC took 0.89

(s) longer than males with no HOC to complete this condition (β = 0.89; 95% CI 0.17 - 1.61; p = 0.016). Females with a HOC took 0.64 (s) longer (β = 0.64; 95% CI -0.13 - 1.40; p = 0.100) and males with a HOC took 0.17 (s) longer (β = 0.17; 95% CI -0.70 - 1.03; p = 0.703) but these results were not statistically significant.

For Condition 2 statistically significant differences were found between the reference group and the Female No HOC group (β = 1.00; 95% CI 0.28 - 1.71; p = 0.007) and the Female HOC group (β = 0.77; 95% CI 0.02 - 1.53; p = 0.045) whereby females with no HOC took 1 (s) longer and females with a HOC took 0.77 (s) longer. Males with a HOC took 0.24 (s) longer to complete this condition but the results were not statistically significant (β = 0.24; 95% CI -0.57 - 1.06; p = 0.556).

Table 6. Linear regression analysis of the time taken (in seconds) to complete both conditions in Model A. Male No HOC served as the reference group.

	Condition 1			Condition 2		
Group	β	95% CI Lower to Upper Bound	*p*	β	95% CI Lower to Upper Bound	*p*
Female No HOC	0.89	0.17 to 1.61	0.016 *	1.00	0.28 to 1.71	0.007 **
Female HOC	0.64	-0.13 to 1.40	0.100	0.77	0.02 to 1.53	0.045 *
Male HOC	0.17	-0.70 to 1.03	0.703	0.24	-0.57 to 1.06	0.556

HOC, history of concussion; β, beta coefficient; CI, confidence interval
* = p < 0.05; ** = p < 0.01

A secondary linear regression for the dependent variable time was conducted with Female No HOC serving as the reference group (Table 7). Results showed that for Condition 1 there were statistically significant differences in the Male No HOC group whereby males with no HOC completed the condition 0.89 (s) faster than females with no HOC (β = -0.89; 95% CI -1.61 - -0.17; p = 0.016). Males with a HOC completed the condition 0.73 (s) faster (β = -0.73; 95% CI -1.59 - 0.14; p = 0.097) and females with a HOC completed it 0.25 (s) faster (β = -0.25; 95% CI -1.02 - 0.51; p = 0.509) but these results were not statistically significant.

For Condition 2 statistically significant differences were found between the reference group and the Male No HOC group (β = -1.00; 95% CI -1.71 - -0.28; p = 0.007) whereby males with no HOC completed the condition 1 (s) faster. Males with a HOC completed this condition 0.75 (s) faster (β = - 0.75; 95% CI -1.57 - 0.06; p = 0.070) and females with a HOC completed it 0.22 (s) faster (β = -0.22; 95% CI -0.98 - 0.53; p = 0.558) but the results were not statistically significant (β = 0.24; 95% CI -0.57 - 1.06; p = 0.556).

Table 7. Linear regression analysis of the time taken (in seconds) to complete both conditions in Model A. Female No HOC served as the reference group.

Group	Condition 1			Condition 2		
	β	95% CI Lower to Upper Bound	*p*	β	95% CI Lower to Upper Bound	*p*
Male No HOC	-0.89	-1.61 to -0.17	0.016 *	-1.00	-1.71 to -0.28	0.007 **
Male HOC	-0.73	-1.59 to 0.14	0.097	-0.75	-1.57 to 0.06	0.070
Female HOC	-0.25	-1.02 to 0.51	0.509	-0.22	-0.98 to 0.53	0.558

HOC, history of concussion; β, beta coefficient; CI, confidence interval
* = p < 0.05; ** = p < 0.01

Model B (Condition 2 First- Non-Standard, Condition 1 Second- Standard)

A linear regression for the dependent variable time was conducted with Male No HOC serving as the reference group (Table 8). Results showed that for Condition 2 statistically significant differences were found between the reference group and all three groups, Female No HOC group (β = 1.20; 95% CI 0.42 - 1.98; p = 0.003), Female HOC group (β = 0.90; 95% CI 0.13 - 1.66; p = 0.022), and Male HOC group (β = 1.27; 95% CI 0.34 - 2.20; p = 0.008). Females with no HOC took 1.20 (s) longer, females with a HOC took 0.90 (s) longer and males with a HOC took 1.27 (s) longer.

For Condition 1 statistically significant differences were found in the Female no HOC group (β = 1.40; 95% CI 0.78 - 2.01; p < 0.001) and the Female HOC group (β = 1.14; 95% CI 0.55 - 1.74; p < 0.001) whereby females with no HOC took 1.40 (s) longer and females with a HOC took 1.14 (s) longer. Males with a HOC took 0.69 (s) longer but these results were not statistically significant (β = 0.69; 95% CI -0.05 - 1.44; p = 0.069).

Table 8. Linear regression analysis of the time taken (in seconds) to complete both conditions in Model B. Male No HOC served as the reference group.

Group	Condition 2			Condition 1		
	β	95% CI Lower to Upper Bound	*p*	β	95% CI Lower to Upper Bound	*p*
Female No HOC	1.20	0.42 to 1.98	0.003 **	1.40	0.78 to 2.01	<0.001 **
Female HOC	0.90	0.13 to 1.66	0.022 *	1.14	0.55 to 1.74	<0.001 **
Male HOC	1.27	0.34 to 2.20	0.008 **	0.69	-0.05 to 1.44	0.069

HOC, history of concussion; β, beta coefficient; CI, confidence interval
* = p < 0.05; ** = p < 0.01

A secondary linear regression for the dependent variable time was conducted with Female No HOC serving as the reference group (Table 9). Results showed that for Condition 2 there were statistically significant differences in the Male No HOC group whereby males with no HOC completed the condition 1.20 (s) faster than females with no HOC (β = -1.20; 95% CI -1.98 - -0.42; p = 0.003). Males with a HOC took 0.06 (s) longer to complete the condition (β = 0.06; 95% CI -0.86 - 0.99; p = 0.889) and females with a HOC completed it 0.31 (s) faster (β = -0.31; 95% CI -1.06 - 0.45; p = 0.425) but these results were not statistically significant.

For Condition 1 statistically significant differences were found between the reference group and the Male No HOC group (β = -1.40; 95% CI -2.01 - -0.78; p < 0.001) whereby males with no HOC completed the condition 1.40 (s) faster. Males with a HOC completed this condition 0.70 (s) faster (β = -0.70; 95% CI -1.46 - 0.05; p = 0.068) and females with a HOC completed it 0.25 (s) faster (β = -0.25; 95% CI= -0.86 - 0.35; p = 0.406) but the results were not statistically significant.

Table 9. Linear regression analysis of the time taken (in seconds) to complete both conditions in Model B. Female No HOC served as the reference group.

Group	Condition 2			Condition 1		
	β	95% CI Lower to Upper Bound	*p*	β	95% CI Lower to Upper Bound	*p*
Male No HOC	-1.20	-1.98 to -0.42	0.003 **	-1.40	-2.01 to -0.78	<0.001 **
Male HOC	0.06	-0.86 to 0.99	0.889	-0.70	-1.46 to 0.05	0.068
Female HOC	-0.31	-1.06 to 0.45	0.425	-0.25	-0.86 to 0.35	0.406

HOC, history of concussion; β, beta coefficient; CI, confidence interval
* = p < 0.05; ** = p < 0.01

Logistic Regression

Male NO HOC Reference Group

A binary logistic regression for the dependent variable total number of errors was conducted with Male No HOC serving as the reference group (Table 10). As previously mentioned, the total number of errors on the HurtSHynes™ Test for each participant was analyzed as a dichotomous variable, No errors and Errors, which allowed for modelling the probability of the cohort groups incurring one or more errors on the test.

Model A (Condition 1 First- Standard, Condition 2 Second- Non-Standard)

Compared to the Male No HOC reference group females with no HOC were 69% less likely to make an error (OR 0.31; 95% CI 0.10 - 0.96; p = 0.042) and females with a HOC were 83% less likely to make an error (OR 0.17; 95% CI 0.05 - 0.60; p = 0.006). These results were statistically significant. Males with no HOC were also less likely to make an error, 59% less likely, (OR 0.41; 95% CI 0.11 - 1.48; p = 0.173) but this result was not statistically significant.

Model B (Condition 2 First- Non-Standard, Condition 1 Second- Standard)

Compared to the Male no HOC reference group females with no HOC were 38% less likely to make an error (OR 0.62; 95% CI 0.19 - 1.99; p = 0.424), females with a HOC were 64% less likely to make an error (OR 0.36; 95% CI 0.12 - 1.10; p = 0.072), and males with a HOC were 48% less likely to make an error (OR 0.52; 95% CI 0.13 - 2.04; p = 0.348) but these results were not statistically significant.

Table 10. Logistic regression analysis of the likelihood of incurring an error in Models A and B. Male NO HOC served as the reference group.

	Model A			Model B		
Group	OR	95% CI Lower to Upper Bound	*p*	OR	95% CI Lower to Upper Bound	*p*
Female No HOC	0.31	0.10 to 0.96	0.042 *	0.62	0.19 to 1.99	0.424
Female HOC	0.17	0.05 to 0.60	0.006 **	0.36	0.12 to 1.10	0.072
Male HOC	0.41	0.11 to 1.48	0.173	0.52	0.13 to 2.04	0.348

HOC, history of concussion; OR, odds ratio; CI, confidence interval
* = p < 0.05; ** = p < 0.01

Female NO HOC Reference Group

A secondary binary logistic regression for the dependent variable total number of errors was conducted with Female No HOC serving as the reference group (Table 11).

Model A (Condition 1 First- Standard, Condition 2 Second- Non-Standard)

Compared to the Female No HOC reference group females with a HOC were 47% less likely to make an error (OR 0.53; 95% CI 0.15 - 1.90; p = 0.330) but this result was not statistically significant. Males with a HOC were 1.32 times more likely to make an error (OR 1.32; 95% CI 0.38 - 4.66; p = 0.664) but was not statistically significant. In comparison males with no HOC were 3.21 times more likely to make an error and this result was statistically significant (OR 3.21; 95% CI 1.04 - 9.88; p = 0.042).

Model B (Condition 2 First- Non-Standard, Condition 1 Second- Standard)

Compared to the Female No HOC reference group females with a HOC were 43% less likely to make an error (OR 0.57; 95% CI 0.19 - 1.74; p = 0.324) and males with a HOC were 17% less likely to make an error (OR 0.83; 95% CI 0.21 - 3.24; p = 0.793) but these results were not statistically significant. In comparison males with no HOC were 1.61 times more likely to make an error but these results were also not statistically significant (OR 1.61; 95% CI 0.50 - 5.14; p = 0.424).

Table 11. Logistic regression analysis of the likelihood of incurring an error in Models A and B. Female NO HOC served as the reference group.

Group	Model A			Model B		
	OR	95% CI Lower to Upper Bound	*p*	OR	95% CI Lower to Upper Bound	*p*
Female HOC	0.53	0.15 to 1.90	0.330	0.57	0.19 to 1.74	0.324
Male HOC	1.32	0.38 to 4.66	0.664	0.83	0.21 to 3.24	0.793
Male No HOC	3.21	1.04 to 9.88	0.042*	1.61	0.50 to 5.14	0.424

HOC, history of concussion; OR, odds ratio; CI, confidence interval
* = p < 0.05; ** = p < 0.01

Performance as a Level of Dissociation

After conducting an independent t-test in Model A (t = 0.52, df = 85, p = 0.601) and Model B (t = -0.56, df = 82, p = 0.579) for performance as a level of dissociation, there were no statistically significant differences in performance between those with a concussion and those without (Table 12). Despite there being no statistically significant differences, those with a concussion history showed a larger change in performance than those without in Model B.

Table 12. Descriptive statistics of group, by level of dissociation (Non-Standard – Standard) and statistical outcomes of independent t-tests for Models A and B.

	Healthy Control mean (SD)	Concussion History mean (SD)	*p*
Model A			
Δ Time (s)	0.03 ± 0.70	-0.06 ± 0.98	0.601
Model B			
Δ Time (s)	0.99 ± 0.86	1.10 ± 0.98	0.579

SD, standard deviation

Discussion

This pilot study is the first to our knowledge to evaluate sex-related differences and the effects of previous history of concussion on a standard and non-standard visuomotor running task, the HurtSHynes™ Test. Despite minimal differences in overall mean time to complete the conditions between the four cohort groups, notable sex-related differences were seen, regardless of the condition assigned first. In terms of time, we hypothesized that there would be no statistically significant differences in Condition 1, standard mapping condition, between athletes with a history of concussion (HOC) and those without. In Condition 2, non-standard mapping condition, we hypothesized that athletes with no prior HOC would perform better (complete the condition faster and incur less errors) compared to those with a HOC. We also hypothesized that regardless of concussion history, athletes will incur more errors and take longer to complete the non-standard mapping condition in comparison to the standard mapping condition.

In Model A where Condition 1 was administered first, a One-Way ANOVA was performed between the 4 cohort groups and Condition 1 time and found to be not statistically significant ($F = 2.38$, $df = 3,83$, $p = 0.075$). In Model B where Condition 1 was administered second, a One-Way ANOVA was performed between the 4 cohort groups and Condition 1 time and found to be significant ($F = 8.00$, $df = 3,83$, $p < 0.001$). A Bonferroni post-hoc test was performed and revealed statistically significant differences between the Male No HOC group and Female No HOC group ($p < 0.001$) and the Male No HOC group and Female HOC group ($p = 0.001$) whereby the Male No HOC group on average were faster in Condition 1 compared to Female No HOC and Female HOC groups.

In Model B where Condition 2 was administered first, a One-Way ANOVA was performed between the 4 cohort groups and Condition 2 time and found to be statistically significant ($F = 4.01$, $df = 3,82$, $p = 0.010$). A Bonferroni post-hoc test was performed and revealed statistically significant differences between the Male No HOC group and Female No HOC group ($p = 0.017$) as well as between the Male No HOC group and Male HOC group ($p = 0.048$). Males with no HOC on average were faster in Condition 2 compared to Females with no HOC and Males with a HOC.

In Model A when Condition 2 was administered second, a One-Way ANOVA was performed between the 4 cohort groups and Condition 2 time and found to be statistically significant ($F = 3.09$, $df = 3,85$, $p = 0.031$). A Bonferroni post-hoc test was performed and revealed a statistically significant difference only between the Male No HOC group and Female No HOC group ($p = 0.040$). Males with no HOC on average were faster in Condition 2 compared to females with no HOC.

These findings both support and refute some of our hypotheses. We hypothesized that there would be no statistically significant differences in Condition 1, standard mapping condition, between athletes with and without a previous HOC. When Condition 1 was randomly administered first, there were no statistically significant differences in mean time between those with and without a previous HOC suggesting that athletes with a previous HOC perform similarly to those without a HOC. However, when Condition 1 was administered second there were statistically significant differences between the Male No HOC group and Female No HOC group ($p < 0.001$) as well as between the Male No HOC group and Female HOC group ($p = 0.001$) whereby males with no HOC were on average faster than the Female No HOC group as well as the Female HOC group.

In Condition 2, non-standard mapping condition, we hypothesized that athletes with no prior HOC would complete the condition faster compared to those with a prior HOC. Our findings showed that regardless of concussion history and whether Condition 2 was administered first or second, the majority of the groups on average took longer to complete this condition compared to Condition 1. The exception to this was the Male No HOC group who completed Condition 2 on average faster than Condition 1 but only when it was administered second. In addition, the difference in performance was almost negligible, 9.72 (s) for Condition 1 compared to 9.70 (s) in Condition 2.

Of interest is that when Condition 2 was administered first, males with a HOC on average took longer than males without a HOC to complete this condition ($p = 0.048$). However, there were no statistically significant differences between the Female HOC group and the Female No HOC group which suggests that on average females with a HOC were performing similarly to females with no prior HOC.

There have been noted sex-differences in the efficiency of motor planning whereby females demonstrate an advantage at the level of motor planning and the acquisition of novel movement sequences in comparison to males.[159] There have also been sex-related differences in brain activity with the preparation phase of visually guided reaching movements in both standard and non-standard tasks whereby females showed greater amounts of blood oxygen level-dependent

(BOLD) activity relative to males in standard mapping tasks, in comparison to non-standard mapping tasks where males showed greater amounts of activity.[115]

Briefly, BOLD signals provide an indirect measure of brain activity in humans and is dependent on the relationship between cerebral blood flow (CBF) and neural activity.[160] An increase in neural activity leads to adenosine triphosphate (ATP) expenditure, evoking an increase in oxygen consumption to regenerate ATP which is followed by an increase in CBF to the active area.[160] Greater BOLD activity in males during non-standard mapping tasks suggest that they require more attentional resources to perform these types of tasks compared to females. This could be attributing to why males with a HOC on average took longer than males without a HOC to complete Condition 2, the non-standard mapping task, when it was administered first ($p = 0.048$) but there were no statistically significant differences between the Female HOC group and the Female No HOC.

Several studies have also previously reported sex-related differences in the preparation of visually guided reaching movements such that in both CMI and standard mapping tasks, women have a more bilateral pattern of activity in premotor and parietal regions compared to men.[115,117,161,162] Sex-differences in activity in the dorsal premotor area (PMd) during non-standard tasks suggests that both performance of learned mappings and the acquisition of new non-standard mappings may differ in males and females.[115] In right-handed individuals the left and right superior parietal lobules and the left PMd are active in both males and females but the right PMd region is usually active only in females.[115,162] Therefore, premotor cortical activity occurs mainly in the hemisphere contralateral to arm movement in males but occurs bilaterally in females.[162] This suggests a potential redundancy in the premotor cortex in females[117,162] which could attribute to a better visuomotor skill recovery after sustaining a concussion.

A potential better visuomotor skill recovery in females compared to males with a previous HOC is supported in our findings in both conditions. Regardless of the condition assigned first the Female HOC group on average performed the conditions faster in comparison to the Female No HOC group. In comparison, the Male HOC group on average took longer to complete the conditions compared to the Male No HOC group. Specifically in relation to Condition 2, the non-standard visuomotor mapping condition which requires CMI, performance of females with a HOC suggests that females could be more proficient than males in task switching and response inhibition. Task switching requires executive control to be able to change from one task to another and time to load new stimulus-response (S-R) mappings and choose which attributes to attend to.[163] Task switching may also include the inhibition or suppression of competing S-R links when the context changes depending on the specifications of the task since S-R mappings that may have been appropriate for one task is no longer appropriate for the current task.[163,164] Response inhibition is defined as the cognitive process required to cancel an intended movement, involving the suppression of inappropriate responses[163] with key motor response inhibition areas including the right inferior frontal cortex, right dorsolateral prefrontal cortex, bilateral temporo-parietal regions, and the cerebellum.[165]

Response inhibition is important as previous studies with the Brain Dysfunction Indicator (BrDI™) Test, which the HurtSHynes™ Test is modelled from, have shown that there are different patterns of activity in the medial premotor cortex between CMI and standard tasks suggesting that this brain area is involved in incorporating explicit rules into motor plans to satisfy the context of a given CMI task.[117] Increasing involvement of cognitive and attentional factors are needed to perform CMI tasks as one is required to implement task-related rules, such as moving in a direction opposite to a cued target.[109] In Condition 2 of the HurtSHynes™ Test participants have to suppress what could be a default tendency to move in the direction of the cue of the examiner. A previous functional magnetic resonance imaging (fMRI) study has shown sex differences in inhibition brain activation on a Stop task whereby females were faster in inhibiting their motor responses and had enhanced activation in the left ventrolateral and superior prefrontal cortices, insula, and putamen compared to males.[165] This could be attributing to why females with a HOC were on average faster than males with a HOC on Condition 2 of our task, 11.20 (s) and 11.57 (s) respectively when it was administered first, although the results were not statistically significant.

Findings from the binary logistic regressions showed that when compared to the Male No HOC reference group, regardless of the condition assigned first, females with a HOC were the least likely to incur an error. However, only Condition 1 (standard mapping) was statistically significant (OR 0.17; 95% CI 0.05 - 0.60; p = 0.006). Regardless of the condition assigned first, males with a HOC were less likely to make errors when compared to the reference group but results were not statistically significant. In addition to being more proficient than males in task switching and response inhibition, females could also be making better use of a cognitive reserve (CR).

The concept of CR postulates that some individuals are able to cope better than others with similar brain injury/damage due to their ability to process tasks in a more efficient manner as a result of differences in cognitive processes.[86] Although there is no current readily used definition of CR, one was proposed by Yaakov Stern who defined CR as "the ability to optimize or maximize performance through differential recruitment of brain networks."[86] Individuals who use brain networks more efficiently or are able to use alternate brain networks in response to increased task demands may have more CR.[86,92]

There are several studies in the literature pertaining to CR and mild to severe TBI sample populations[166–171] but a limited focus on solely mTBI[172–174] and those specifically with SRCs.[175] Cognitive reserve is measured based on 4 factors: pre-morbid intelligence quotient (IQ), occupational attainment, years of education, and cognitively stimulating activities.[176] However, a multitude of studies of CR in TBI tend to focus on pre-morbid IQ and/or years of education as exemplified in a meta-analysis by Mathias and Wheaton[177] who consolidated data from 90 studies that were published prior to 2015. Recent publications in a TBI population since then seem to be continuing to place a focus on those 2 factors[166,169,170] although some have included occupational attainment and skill level.[167,172] In these studies pre-morbid IQ is often assessed using the Wechsler Test of Adult Reading (WTAR)[178] or the National Adult Reading Test (NART).[179]

In our study sex differences in pre-morbid IQ could not be determined as participants were not administered the WTAR or the NART at time of baseline medicals nor was any data pertaining to occupational attainment or lists of cognitively stimulating activities acquired. However, varsity-level sport involvement is a cognitively stimulating activity that was shared by all participants in this current study. Out of the 4 factors commonly reported in the literature in relation to CR, years of education was obtained as part of demographic data for athletes in our study.

Independent sample t-tests revealed a statistically significant difference between sex and years of education whereby women on average had more years of education ($t = 2.98$, $df = 156$, $p = 0.003$). The mean years of education for females was 14.21 ± 1.56 where the majority ($n = 25$) were entering into their third year of undergraduate studies. In comparison, the mean years of education for males was 13.49 ± 1.30 where the majority ($n = 20$) were entering into their second year of undergraduate studies. This suggests that given the statistically significant differences in terms of years of education between males and females, females in our study could have a larger CR due to more years of education.

With the exception of statistically significant differences found between the Male No HOC group and Male HOC group when Condition 2 was administered first, that absence of any other statistically significant differences in the CMI task between our HOC and no HOC groups of varsity athletes may be attributed to a superior frontoparietal network that allows for greater compensation following concussion, resulting in fewer performance differences. This has already been proposed by Hurtubise et al.[108] who noticed a similar pattern in previously concussed National Hockey League (NHL) draft combine athletes. Similar findings are also seen in CMI tasks with breaching instructors in the Canadian Armed Forces who have experienced long-term exposure to repeated low-level blasts and whose years of military training has possibly attributed to superior fronto-parietal networks.[130]

Compensation differs from CR in that in order to compensate for brain damage, individuals may use brain structures or networks they wouldn't have normally used prior to injury as an attempt to maintain or improve task performance even while injured.[86,92] Hyperconnectivity in brain regions has been proposed as a compensatory response to neurological injury whereby there is a nonspecific increase in neural resource use that aims to act as a buffer against network disruption.[93] Although increased connectivity may permit continued communication during these disruptions, it may result in slowed information processing speed, reduced efficiency, and cognitive fatigue, and there may also be a ceiling effect in terms of the maximum number of connections a neural system can take advantage of.[93] It is important to note that hyperconnectivity unlikely occurs in isolation, suggesting that there is some combination of connectivity loss and gain throughout neural networks.[93]

Although years of previous sport experience was not collected for athletes at time of baseline medicals, it can be assumed that a large portion of the athletes in our study have had multiple years of previous experience and involvement in sport. Recent findings by Dalecki et al.[127] have shown that more years of visuomotor sport-related experience through sport participation and training can also attribute to compensatory mechanisms through development of more efficient neurological processes for CMI tasks. When comparing the performance of youth, varsity athletes, and NHL draft prospects in those with a previous HOC, there is an inverse relationship between CMI deficits and skill level which suggests that visuomotor sports-related experience could be resulting in a compensation for CMI deficits post-concussion by making use of sports-related cognitive motor reserves.[108,127,180]

Motor learning is defined in the literature as an improvement in motor skill from one's baseline performance that leads to a reduction in performance errors along with the ability to move faster and more accurately.[100,181] This improvement can continue for years and be retained over time.[100,181] In addition, patterns of brain activity associated with motor skills can also change over the course of skill acquisition[109] contributing to possible compensatory mechanisms when a concussion injury occurs. More expertise in a motor skill is associated with a reduction in brain activity needed to execute the particular skill and is indicative of greater neural efficiency.[182]

Lastly, it is also likely that although we tried to account for potential learning effects by randomizing the condition order administered first and only allowing athletes to complete each condition only once, learning effects still occurred in terms of mean group times. When Condition 2 was administered first, all cohort groups on average completed Condition 1 faster than their Condition 2 time. However, when Condition 1 was administered first, the majority of the cohort groups on average took longer to complete Condition 2. The exception was the Male No HOC group who completed Condition 2, 0.02 (s) seconds faster. Overall, in terms of the non-standard visuomotor mapping condition, athletes who are administered it second appear to receive time saving benefits from having completed the standard mapping condition first.

These preliminary results highlight the importance of continuing to explore concussion history and sex-related differences in CMI performance. There is a need for more objective and reliable measures for concussion diagnosis and RTP management[155,156] in addition to tests that assess cognition and movement simultaneously. Similar to the BrDI™ Test, which the HurtSHynes™ Test is modelled from, our test allows for the assessment of CMI performance on a non-standard visuomotor task following a previous concussion injury. The BrDI™ Test incorporates two forms of non-standard mapping: Explicit rule integration and implicit spatial vision-to-hand-motion realignment (sensorimotor recalibration) as the visual information guiding the action and required motor goals/responses are in different spatial locations.[117]

Participants performing the CMI conditions on the BrDI™ Test were heard talking to themselves ("target is down…slide up slide up!") which has been suggested by the researchers as an indication that they are tapping into explicit rule integration associated with the mental rotation aspect of the test.[117] Similarly, after the examiner had explained what was required to perform Condition 2 (non-standard mapping) of the HurtSHynes™ Test some participants would repeatedly say out loud (up is down, down is up and/or right is left and left is right) prior to condition commencement. This could suggest that like the BrDI™ Test, participants on our test are also tapping into explicit rule integration as they are having to use specific spatial algorithms to relate the position of where the examiner is holding the football to denote a visual cue to the direction of action.[117]

Although there are similarities between these two tests, what makes the HurtSHynes™ Test unique is that the BrDI™ Test requires participants to be stationary and interact with a tablet or computer screen while seated to complete the tasks. In comparison, the HurtSHynes™ Test requires participants to actively run while responding to visual cues presented by an examiner which are reflective of movements executed by athletes during sport performance, enabling us to simultaneously assess their ability to think and move together (i.e CMI). Our test allows for the evaluation of visuomotor performances beyond the gross motor skills typically tested during a clinical assessment, suggesting it may be a useful and quick objective measure to assist in guiding return-to-play decisions.

Chapter 3: Manuscript

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

Chapter 3: Manuscript

Introduction

Concussion is a form of mild traumatic brain injury (mTBI) where biomechanical forces caused by either a direct blow to the head, face, neck, or elsewhere on the body are transmitted to the brain, resulting in a temporary disturbance of neurological function.[1] In Canada the overall incidence rate of reported sport-related concussions (SRCs) or other brain injuries is 221 per 100,000 Canadians.[63] In comparison, it is estimated that there are 1.6 to 3.8 million sports-related traumatic brain injuries (TBIs) each year in the United States[70] but these numbers are most likely higher in both countries as many of these injuries go unrecognized or are underreported.

There are currently a variety of measures and assessments to help support clinical examinations of concussions that test motor control, reaction time, quality of life, neurocognitive function, athlete-reported symptoms, vestibular-ocular function, etc.[135] However, a large portion of research on SRCs have focused on studying the effects of concussion on cognition[145–147] with less focus on studying its effects on visually guided motor actions[148] and cognition integrated with movement in a sport context.[149] In addition, the current assessment tools used for diagnosing a concussion and/or monitoring of recovery post injury often tests one's cognition and motor performance in isolation rather then concurrently. However, success in sport performance requires the simultaneous integration of cognition and action known as cognitive-motor integration (CMI). Thus, although cognitive skills such as perception, working memory, attention, and decision-making are key components to successful sport performance, tasks that require CMI may be more beneficial to understand the effects of concussions when combined with current concussion testing metrics.[148]

In the literature intra class correlation coefficients (ICCs) are the most readily used method to calculate the reliability of tests used to evaluate concussion injuries.[135–142] The ICCs are scored on a scale from 0 to 1.0 and used to determine the strength of agreement, where ICC values closer to 1 are indicative of stronger reliability.[143] A stronger reliability (ie. higher ICC value) tells us that a measurement or test is reproducible over time by different raters as well as across different settings.[144] Intraclass correlation coefficients can be used to determine both intra- and inter-rater reliability where intra-rater reliability reflects the variation of data measured by a single rater across two or more testing sessions and inter-rater reliability reflects the variation between 2 or more raters testing the same group of subjects.[143]

According to the American Medical Society for Sports Medicine's position statement on concussion in sport[44] "the test-retest reliability of commonly used sideline concussion evaluation tests is below the generally accepted threshold for clinical utility (0.75 - 0.90)." Thus, there is a need for more objective and reliable measures for concussion diagnosis and monitoring of recovery post injury to assist with return-to-play management,[155,156] in addition to tests that assess CMI. To address this need in the literature, the HurtSHynes™ Test was developed by Hurtubise, Sergio, and Hynes[114] to evaluate an athlete's ability to think and move together after sustaining a concussion.

A previously described pilot study (Chapter 2) evaluated the effects of concussion history in a varsity student-athlete population on the HurtSHynes™ Test and found that females with a history of concussion (HOC) were the least likely to incur an error and were on average faster than females with no HOC to complete test conditions. In comparison males with a HOC were on average slower than males with no HOC (see Chapter 2). Performance of females with a HOC suggests that females may have better visuomotor skill recovery than males after sustaining a concussion.

The HurtSHynes™ Test is an easy and quick to administer test, requiring very minimal equipment (a stopwatch, 2 cones, and a measuring tape). Examiners are using a stopwatch to measure time and record any errors a participant incurs while completing two conditions of the test. There are only 4 visual cues that a participant needs to respond to by the examiner in each of the two conditions, allowing for examiners and raters to easily detect any errors that might be incurred and limiting language requirements.

Given that our test is easy and quick to adminsiter, we hypothesized that both conditions would demonstrate good-to-excellent (ICC > 0.75) inter- and intra-rater reliability. Evaluating inter- and intra-rater reliability of the HurtSHynes™ Test was the first process to determine if our novel CMI test could be a beneficial sideline assessment for return-to-play management. This study was designed to assess the reliabilty of the HurtSHynes™ Test to acurately identify when athletes made errors on the task and time taken for task completion. Athletic therapy students in the York Unvieristy Athletic Therapy Certificate Program (ATCP) were asked to review pre-recorded videos of first year students in the ATCP executing both conditions of the test and record the time it took each student to complete the conditions and any errors incurred.

Methods

Participants

Participants were undergraduate students between the ages of 18 to 30 years old who were currently enroled in the ATCP at York University, Keele Campus, Toronto, Ontario, Canada. The study was conducted at York University and approved by York University's Ethics Review Board. All members of the research team and study participants were in compliance with York University's COVID-19 health and safety plans at the time of data collection. Demograhic information related to sex and age were collected for all participants. A total of 20 students participated in the study and were placed in two distinct groups; Runners and Raters, and were pre-assigned an identificaiton number for confidentiality. The runners (n = 11) consisted of students in their first year of the ATCP who completed the HurtSHynes™ Test while being filmed and the raters (n = 9) consisted of students in their second or third/final year of the ATCP who watched the 11 runner videos at two different time points.

While watching the pre-recorded videos, raters were instructed to record the time it took the runners to complete the test and any errors that were incurred. This was done to evaluate intra- and inter-rater reliability. Students from the ATCP were chosen as the raters for the reliability evaluation of the HurtSHynes™ Test as these students are learning the skills of professionals involved with post-concussion care (ie. certified athletic therapists, physical therapists, etc.). A detailed description of the HurtSHynes™ Test has been previously provided in Chapter 2.

All participants were given a Starbucks gift card for their time; all runners received a $10.00 gift card while raters received $10.00 for attending video viewing session 1 and another $10.00 for attending video viewing session 2. Methods for determining reliability of the HurtSHynes™ Test were modelled from two previously published reliability studies in the literature for the Balance Error Scoring System (BESS)[183] and the Child-Focused Injury Risk Screening Tool (ChildFIRST).[184]

Runners

There were a total of 11 runners (n = 9 female, n = 2 male) with a mean age of 20.45 ± 0.52 yrs. To be included as a participant in the runner group students had to meet four criteria; (1) currently registered as a first year student of the ATCP; (2) were between 18 to 30 years old; (3)

were healthy, active, and free of any lower body musculoskeletal injuries for the past 6 months; (4) have not sustained a concussion in the past two years. Based on findings of a potential learning effect from the study previously described in Chapter 2, all runners completed Condition 2 first (non-standard mapping) followed by Condition 1 (standard mapping).

The filming of the HurtSHynes™ Test took place in the Upper Gym (68 x 99 ft) at the Tait MacKenzie Centre, York University, Keele Campus. Four different filming sessions were held over the course of two days during which time students were scheduled in either groups of 2, 3, or 4 to complete the filming portion of the study. Filming took 15 minutes per participant. Prior to arrival at the gym all participants were instructed to wear any black athletic clothing they felt comfortable running in along with appropriate foot attire for running. Black attire was chosen as this colour of clothing was the most distinct on camera against the white walls of the gym.

Prior to the start of filming each participant was given a detailed description of the test and randomly assigned to purposely commit a pre-determined number of errors by the research team in each of the two conditions (no errors, 1 error, 2 errors, or 3 errors). The rationale for this is ICC values cannot be calculated when a lack of variance occurs (all athletes commit 0 errors on both conditions of the test) as has been previously reported in the literature for reliability studies of the BESS for the firm surface double-leg stance.[136,183,185,186] A similar process of pre-assigning participants to perform in a pre-determined manner was done by Leddy et al.[137] who assigned 14 athletes, whom they referred to as athletic actors, to accurately portray the experience of symptom exacerbation of a patient with a diagnosed concussion and post-concussion syndrome (PCS) on a treadmill exercise test to determine retest reliability by the raters.

Data analysis from York University varsity athletes having completed Condition 2 followed by 1 of the HurtSHynes™ Test (n = 90), as previously described in Chapter 2, revealed 45.6% of athletes incurred 0 errors, 34.4% incurred 1 error, and 20% incurred 2 or 3 in Condition 2. In comparison, 90% of athletes incurred 0 errors and 10% only incurred 1 error in Condition 1. This data was used to pre-determine how many errors the runners were going to be asked to incur in each condition while they were being filmed (Table 13).

Table 13. Number of runners who were pre-assigned to incur either 0, 1, 2, 3, or 4 errors on Conditions 2 and 1 of the HurtSHynes™ Test during filming (n = 11 runners).

Number of Errors	Number of Runners Condition 2	Number of Runners Condition 1
0	2	9
1	3	2
2	4	0
3	2	0
4	0	0

The 11 runners were filmed using a Canon EOS Rebel T5i with an EFS 18-55mm lens secured to a tripod (Neewar®, 56 inch). Filming was stored and collected on a 128GB standard definition (SD) memory card (SanDisk Extreme Pro 170MB/S). The tripod was placed 2 metres behind the runners who were positioned at the start cone so that only the backs of the participants could be seen during the test to maintain participant privacy. The start position was denoted by an orange cone (Matrix 12 x 12 x 23cm) placed on the gym floor. A fibreglass tape measure (Mastercraft™, 200-ft) was used to measure 2 metres behind the start cone to place the tripod and was also used to measure 26 metres, the length of the HurtSHynes™ Test. A second orange cone (Matrix 12 x 12 x 23cm) was placed at the end of the 26 metres to denote the end point of the test. Given the size of the gym (68 x 99 ft) and the need for runners to have enough space to slow down and come to a stop after passing the end cone, the HurtSHynes™ Test was conducted on a diagonal angle along the gym floor as opposed to vertically in line with the court floor markings.

Two to three members of the research team were present at all filming sessions; the lead investigator of the team, administered the test to all 11 runners to ensure consistency. This investigator administered the test to over 200 varsity athletes in the previously described study in Chapter 2, providing extensive experience in administering the test. In addition to administering the visual directional cues they also recorded the time it took each runner to complete the two conditions using a hand-held stopwatch (Ultrak 340). The other two members of the research team were responsible for filming the runners and ensuring both the examiner and the runners could be seen on video at all times throughout the test.

Any runner who didn’t commit their pre-determined number of errors were instructed to return back to the start cone and attempt the test again. Due to runners being filmed from behind, a dry erase whiteboard (Quartet®, 8.5 x 11 inch) was used to write the identification (ID) number of each runner and the condition number that the runner was completing in the video as a means to enable raters to properly evaluate these runners at a later date. All members of the research team who filmed the runners followed the same filming procedure: they began the video and extended their arm that was holding the whiteboard in front of the lens to show ID and condition information as previously described. The whiteboard was held for 4 to 6 seconds and then removed. Prior to the examiner yelling "3, 2, 1, go" for the runner to begin the test a 3-5 second delay was taken after the removal of the whiteboard to allow for the lens to autofocus on the runner at the start cone. Once the runner was in focus, the lead investigator was given a signal (denoted by a rasied hand behind the camera) to begin administering the test.

Raters

There were a total of 9 raters (n = 4 female, n = 5 male), with a mean age 22.44 ± 0.88 yrs. To be included as a participant in the rater group students had to be either in their second or third/final year of the ATCP at York University and be between 18 to 30 years of age. All participants were pre-assigned an identification number to maintain confidentiality. According to Walter et al.[187] and Shoukri et al.,[188] a sample size of at least 9 raters is needed to get an expected ICC of 0.80 with $\alpha = 0.05$ and $\beta = 0.20$ with two viewing sessions. All viewing sessions took place in the same room with a large screen to enable an opportunity for multiple raters to view the videos of the 11 runners projected at the same time and to allow for adequate spacing between raters in accordance with York University's COVID-19 policy at the time of study participation. The first video viewing session for the raters took place 5 days after filming of the 11 runners had been completed.

Video Viewing Session 1

The first video viewing session took approximately one hour for all raters to complete and began with a 30-to-40-minute training session. A training session was needed as all 9 raters had limited or no previous knowledge of the HurtSHynes™ Test as well as no previous experience with evaluating participant performance on the test. The lead investigator who administered the HurtSHynes™ Test to the 11 runners led all training and video viewing sessions. The content of the training session was created on Microsoft PowerPoint and was projected on a screen at the front of the room (Projector: Epson® PowerLite L510U, Projector Screen: Draper®). Raters were seated at tables 5.5 to 6.5 metres away from the screen.

The training session began with background on concussions but was brief given the knowledge base of the ATCP students regarding concussion awareness and evaluation training. They were then provided with information on visuomotor transformations, standard and non-standard, the involvement of cognitive-motor integration (CMI) in non-standard mappings, along with a brief overview of the literature pertaining to performance of athletes with a previous history of concussions on CMI tasks.

The majority of the rater training time was spent receiving a thorough background of the HurtSHynes™ Test, how it is administered, and explanations of how to identify movement errors in both conditions of the test. Raters were also provided with a brief overview of the definitions of intra- and inter-rater reliability. At this portion of the training session raters were then instructed on how to record the time and number of errors on the HurtSHynes™ Test Rater Evaluation Form. This one-page form was designed exclusively for the purpose of this reliability study and was printed double-sided on letter size paper and attached to a clipboard (Officemate, letter size, wood). Each rater received their own copy of the form and had their identification number on the top right-hand corner.

To record the amount of time it took participants to complete the test on the form, hand-held stopwatches were used (Adanac® 4000, Ultrak 340, GoZone Black/Lime, or GoodLife Fitness Tough Timer). The use of hand-held stopwatches provided both raters and administrators the ability to accurately record time while maintaining constant eye-contact with the participant to enable the proper detection of any errors. In the videos, the raters could hear the lead investigator yell “3,2,1 go” and were instructed to start the stopwatch when they heard the word “go” and were instructed to stop the time the moment they saw the participant cross the end cone in the video.

To ensure all raters had a thorough understanding of how to evaluate the runners completing the test, four training videos were shown to the raters. These training videos were taken of members of the research team, referred to during the session as “testers,” completing both conditions of the test where errors were purposely committed. The raters were instructed to practice recording the time it took each tester to complete each condition while simultaneously looking for any errors that were incurred on the rater evaluation form. They were given the opportunity to be shown any of these training videos as many times as needed until the raters were confident in their ability to properly assess individuals completing the test. After each training video the lead investigator discussed the correct time and errors for both conditions for each tester as a group so that the raters could compare their evaluations. The correct time was deemed to be the time recorded by the lead investigator at the time of test administration on the day of filming of the 11 runners. The lead investigator also provided screenshots from the videos where the tester responded incorrectly to the visual cue with discussion regarding how the response constituted an error.

Once all raters in the room were in agreement that they were confident in the ability to evaluate videos of individuals performing the test, the lead investigator proceeded with showing the raters the 11 runner videos. This portion of the viewing session took 15 to 20 minutes. Prior to beginning to show these videos, the raters were instructed that they would be shown each video only once; they would not be given an opportunity to rewatch the videos. The 11 runner videos were shown in a pre-determined randomized order where order was determined using an online number generator (numbergenerator.org).

The identification number of the runner along with the condition number they were completing was displayed at the start of the video because in order to determine if errors were incurred the rater needed to be aware of whether the video they were watching was of the runner completing Condition 2 or 1 of the test. As such, raters were not blinded to the conditions. Each rater was instructed to record the number of errors and time it took all participants to complete the conditions on their evaluation form as they watched the videos.

Video viewing session 1 was held twice (two days apart from each other) and raters were given the opportunity to select which of the two session times best suited their availability. As such, there was one group of four raters and a second group of five raters for video viewing session 1. Raters were seated either two per table (one at either end of the table) or one per table to prevent raters from looking at each other’s evaluation form.

Video Viewing Session 2

Two to three weeks later the raters (n = 8) returned to the same room to watch the same 11 runner videos again. For this viewing session there was one drop-out and thus only 8 raters returned. The same videos were shown in a new radomized order from the first video session and were pre-determined using the same online number generator as the video viewing session 1 (numbergenerator.org). The new randomized order along with the 14 to 21 day delay between the two viewing sessions was chosen to reduce the chances that raters would remember how a participant performed on the test. There was no training session for this second video viewing, however to ensure consistency across all second video viewing sessions, the raters were given a brief review of the two conditions of the HurtSHynes™ Test, how it is administered, and how to identify movement errors in both conditions of the test. As in video viewing session 1 this was all done through Microsoft PowerPoint and the contents were projected on a screen at the front of the room (details of materials previously described above).

The raters were shown one of the tester videos, Tester B, who had incurred 1 error in Condition 2, and 1 error in Condition 1. Unlike in video viewing session 1 raters were not required to record the time from the stopwatch and errors on their evaluation form while watching this tester video. The examiner again provided screenshots from the video of where Tester B responded incorrectly to the visual cue and how the response constituted an error. Before the 11 runner videos were played the raters had an opportunity to ask any questions or watch the tester video as many times as needed. All the raters were given a new evaluation form that contained their participant ID number on the top right-hand corner. Once all raters in the room were in agreement that they were confident in the ability to evaluate videos of individuals performing the test, the lead investigator proceeded with showing the 11 runner videos. The identification number of the runner along with the condition number the particular runner was completing was displayed at the start of the video and each rater was instructed to record the number of errors and time it took all participants to complete the conditions on their evaluation form as they watched the videos.

This second video viewing session took 15 to 20 minutes to complete. If multiple raters attended the same session for video viewing 2 the raters were again seated either two per table (one at either end of the table) or one per table to prevent raters from looking at each other's evaluation form. Video viewing session 2 was held on four different occasions and raters were given the opportunity to select which of the four session times best suited their availability, as long as at least 14 days but no more than 21 days had passed since they attended video viewing session 1. The mean number of days between video viewing session 1 and 2 for the 8 raters was

17.25 ± 2.82. A total of n = 2 raters returned 14 days later, n = 1 15 days, n = 1 16 days, n = 2 19 days, n = 1 20 days, and n = 1 21 days.

Statistical Analysis

To determine inter- and intra-rater reliability of the HurtSHynes™ Test ICCs were calculated (ICC average measures) and reported with 95% confidence intervals (CIs). Intraclass correlation coefficients are scored on a scale from 0 to 1.0 and used to determine the strength of agreement, where ICC values closer to 1 are indicative of stronger reliability.[143] There are 10 different forms of ICCs as first defined by McGraw and Wong[189] that can be selected for reliability analyses. For the HurtSHynes™ Test we were interested to what extent all the raters were able to assign the same number of errors for Conditions 2 and 1 of the 11 runners, providing us with an indication of how well raters were able to properly detect errors from a video.

Therefore, for this research study we selected the two-way mixed effects, absolute agreement, multiple raters model, ICC (3, *k*), where 3 denotes two-way mixed model and *k* is the number of raters. According to Koo and Li,[143] this model is chosen if the selected raters are the only raters of interest. "With this model, the results only represent the reliability of the specific raters involved in the reliability experiment."[143] Absolute agreement was chosen for our analysis, as opposed to consistency, as absolute agreement is concerned with different raters assigning the same score to the same subject, i.e the extent to which *y* equals *x*.[143] Given that we wanted to know the extent to which the raters were able assign the same number of errors this level of agreement was more appropriate.

The time for condition completion, condition errors, and total errors incurred by the 11 runners in the videos that were recorded by the raters were used to determine inter-rater reliability both at video viewing session 1 and at video viewing session 2. As one rater did not return for video viewing session 2, inter-rater reliability was calculated for an n = 9 at video viewing session 1 and an n = 8 at video viewing session 2. To determine intra-rater reliability, the same variables recorded from video viewing session 1 was compared to their recorded measurements from video session 2 that took place 14 to 21 days later. Given that one rater did not return for video viewing session 2, intra-rater reliability could only be calculated for an n = 8.

Although the lead investigator recorded the time it took the runners to complete both conditions, they were not included as one of the raters for inter-rater reliability. The strength of agreement using the ICC for our study was determined by the criteria proposed by Koo and Li.[143] Intraclass correlation coefficients less than 0.5 are indicative of poor reliability, 0.5 to 0.75 is considered moderate, 0.75 to 0.90, good, and values greater than 0.90, excellent.[143] All analyses were performed using Statistical Package for the Social Science (SPSS) Version 28 (IBM Corp., Armonk, NY) where average measures ICC values were reported as average measures is used to measure agreement between several raters.[139,189]

Results

All 5 HurtSHynes™ Test variables: Condition 2 time, Condition 2 errors, Condition 1 time, Condition 1 errors, and total errors demonstrated excellent inter-rater reliability (ICC > 0.90) for both video viewing session 1 and 2 where ICC values ranged from 0.94 to 1.00. In terms of the 95% CIs, inter-rater reliability was regarded as excellent (95% CI 0.95 - 1.00) for video viewing session 1 and good-to-excellent (95% CI 0.88 - 1.00) for video viewing session 2. The ICC values and the 95% CIs for the individual variables at both video viewing sessions can be found in Table 14.

Table 14. Results of ICC calculations using Absolute-Agreement, 2-Way Mixed Effects Model for inter-rater reliability.

Video Viewing Session 1 (n = 9 Raters)					
	Condition 2 Time	**Condition 2 Errors**	**Condition 1 Time**	**Condition 1 Errors**	**Total Errors**
ICC	0.99	0.98	0.99	0.99	0.98
95% CI	0.99 to 1.00	0.95 to 0.99	0.98 to 1.00	0.97 to 1.00	0.95 to 0.99
Video Viewing Session 2 (n = 8 Raters)					
	Condition 2 Time	**Condition 2 Errors**	**Condition 1 Time**	**Condition 1 Errors**	**Total Errors**
ICC	1.00	0.97	0.99	0.94	0.96
95% CI	0.99 to 1.00	0.92 to 0.99	0.98 to 1.00	0.88 to 0.98	0.90 to 0.99

ICC, interclass correlation coefficient; CI, confidence interval

Based on ICC values, the HurtSHynes™ Test demonstrated excellent intra-rater reliability (ICC > 0.90) for Condition 2 time, Condition 2 errors, Condition 1 time and total errors, and good intra-rater reliability (ICC = 0.88) for Condition 1 errors. In terms of the 95% CIs, inter-rater reliability was regarded as moderate-to-excellent (95% CI 0.60 - 1.00). The ICC values and the 95% CIs for the individual variables can be found in Table 15. All reported ICC values and 95% CIs are calculated as the average of all raters. As one rater did not return for video viewing session 2, these ICC and 95% CI values were for an n of 8 raters, as raters are needed to be present for both video viewsing sessions inorder for intra-rater reliability to be calculated.

Table 15. Results of ICC calculations using Absolute-Agreement, 2-Way Mixed Effects Model for intra-rater reliability. Reported ICC and 95% CI values based on averages of 8 raters.

	Condition 2 Time	**Condition 2 Errors**	**Condition 1 Time**	**Condition 1 Errors**	**Total Errors**
ICC	0.99	0.92	0.98	0.88	0.91
95% CI	0.93 to 1.00	0.70 to 0.98	0.90 to 1.00	0.60 to 0.97	0.67 to 0.98

ICC, interclass correlation coefficient; CI, confidence interval

Discussion

The primary purpose of this study was to determine the reliability of administration of our novel CMI test, the HurtSHynes™ Test. Based on ICC values, raters demonstrated excellent inter-rater reliability (ICC = 0.94 to 1.00) and good-to-excellent intra-rater reliability (ICC = 0.88 to 0.99) across the 5 testing variables suggesting that our test is relatively easy to evaluate and master. With a mean of 17.25 ± 2.82 days between both viewing sessions, second and third/final students in the ATCP at York University were able to record relatively consistent times and errors for the runners across the two viewing sessions. Not only did the ICCs demonstrate excellent inter-rater reliability and good-to-excellent intra-rater reliability, but with ICCs of 0.98, 0.99, and even 1.00, some of the test variables showed perfect or close to perfect absolute agreement. The HurtSHynes™ Test also requires minimial equipment and the test length of 26m has been designed to allow for administration in both outdoor and indoor settings such as a field, track, gym, etc.

In the majority of concussion injuries conventional neuroimaging techniques using Computed tomography (CT) or Magnetic resonance imaging (MRI) rarely reveal gross structural brain abnormalities after a concussion,[1,41–45] providing little value in the detection of injury and monitoring of recovery.[46] Currently there are also no reliable biomarkers to monitor recovery after a concussion has been sustained.[24] This in turn places both a need and a heavy reliance on multiple subjective and objective clinical assessments to diagnose concussion injuries and monitor recovery post injury to help guide return-to-play (RTP) decisions. Therefore, determining ICCs for concussion assessments is important as it helps to inform clinicians and medical personnel if certain performance metrics on tests are more reliable than others when trying to determine if a concussion injury has occurred or if an athlete who has had an injury is now recovered and can RTP.

Assessments that show poor reliability, which is categorized as ICCs < 0.50,[143] are of concern as it has been argued that poor reliability can lead to an increased risk of Type II errors.[190] A Type II error, also known as a "false negative," occurs when one's level of performance on an assessment would classify an athlete as having recovered from a concussion injury, when in fact they are still experiencing impairments.[190] In comparison a Type I error, known as a "false positive," would occur when one's level of performance on an assessment would classify an athlete as having a decline in performance following a concussion injury when no true decline in performance exists.[139]

A Type II error is concerning given a repeated concussion injury while the brain is still metabolically vulnerable can result in irreversible brain damage, apoptotic cell death, impaired neurotransmission, and in the case of second impact syndrome (occurring when an athlete sustains a second concussion while still symptomatic and recovering from an initial concussion);[25] cerebral edema that could result in coma, severe neurologic deficits, and even death.[26–29] A Type I error is also problematic given that an athlete not being cleared to RTP when they have in fact recovered can result in financial loss if playing at a professional level, effect management perception of future player value, have a negative effect on playing time,[191,192] potential mental heath ramifications from time spent away from training and/or competition, etc. This all stresses the need for, and importance of having reliable and objective concussion assessments. However, according to the American Medical Society for Sports Medicine's position statement on concussion in sport[44] "the test-retest reliability of commonly used sideline concussion evaluation tests is below the generally accepted threshold for clinical utility (0.75 - 0.90)."

In the literature ICCs are the most readily used method to calculate the reliability of tests used to evaluate concussion injuries.[135–142] It is customary to report 95% confidence intervals (CIs) alongside the ICC for reliability measures where the CI defines a range in which the true ICC lies within a given probability.[144] At a CI level of 95%, the lower bound of the two-sided 95% CI has to be above 0 to indicate that reliability is better than chance.[144] In our study 95% CIs demonstrated excellent inter-rater reliability across all 5 variables in video viewing session 1 and good-to-excellent in video viewing session 2 suggesting that ICCs for inter-rater reliability were not due to chance. Both Condition 1 and 2 times consistently demonstrated excellent inter- and intra-rater reliability when looking at both the ICCs (ICC = 0.98 - 1.00) and their 95% CIs (0.90 - 1.00). These findings suggest that condition times 1 and 2 may be a valid measurement of CMI performance when the same raters are used for repeat testing.

However, the 95% CIs demonstrated moderate-to-excellent intra-rater reliability for two of the eight individual raters, 95% CI lower bounds were -0.18 and -0.24 for the Condition 1 error variable. This suggests that the ICC for these two raters for Condition 1 errors could have been due to chance and could be attributing to why Condition 1 errors showed moderate intra-rater reliability (95% CI 0.60 - 0.97). This in turn can also be affecting the total errors ICCs for intra-rater reliability (95% CI 0.67 - 0.98) as this variable is calculated by adding the number of errors a runner incurred in Condition 2 with that of Condition 1. Given that there is only a maximum of 4 errors that can be incurred in each condition and the majority of runners were pre-assigned to commit 0 errors on Condition 1, it is possible that there was close to zero variance for this variable.

Broglio et al.,[135] who evaluated test-retest reliability of common concussion assessment tools, found the majority of the instruments they evaluated demonstrated lower than acceptable reliability standards set for clinical utility but are still being broadly implemented and utilized. This is due to the fact that while the majority of these assessments don’t individually meet the reliability standards, “there is evidence that combining them in a multifaced assessment model provides a high level of sensitivity.”[135] This is to say that there is no standalone tool for the diagnosis and management of SRC. As such the most recent consensus statement on concussion in sport has stated that “the recognition of suspected SRC is therefore best approached using multidimensional testing guided via expert consensus.”

According to Davis et al.[193] “researchers should continue to strive to identify tests that are reliable in the early diagnosis of concussion, that predict concussion severity and duration, that monitor progress and recovery, and provide results that enhance return-to-play decision-making.” It is also imperative that these tests are not only reliable but are affordable and widely available in the general community.[193] While we ackowledge that the HurtSHynes™ Test cannot be used as a standalone tool, the findings from this study demonstrated good-to-excellent interand intra-rater reliability, suggesting that it is a quick, accessible, and easy to master test that can be combined with other concussion assessments. The HurtSHynes™ Test also requires minimial equipment and the test length of 26m has been designed to allow for administration in both outdoor and indoor settings such as a field, track, gym, etc. making its utility applicable to a multitude of sports. The reported ICCs from our study also suggest that our test is likely to have a reduced risk of Type II errors.

However, our reliability study was conducted on a non-varsity athletic population who have not sustained a concussion within the past two years from the time of HurtSHynes™ Test filming. As such, future studies should investigate the reliability of our novel test in a varsity athlete population. According to Walter et al.[187] and Shoukri et al.,[188] a sample size of at least 9 raters is needed to get an expected ICC of 0.80 with $\alpha = 0.05$ and $\beta = 0.20$ with two viewing sessions. While we had exactly 9 raters at video viewing session 1, we had one drop-out leaving only 8 raters for video viewing session 2 and therefore only 8 raters for intra-rater reliability analysis. Therefore, the sample size of the number of raters in our study could also have attributed to the findings we observed due to a lack of statistical power. Future studies should investigate reliability of our test with a larger sample size of raters as a means to reduce the possiblity of reported ICCs values being due to chance.

Chapter 4: Discussion and Conclusions

Discussion

Our studies investigated both the effects of concussion history on an on-field assessment of cognitive-motor integration (CMI), the HurtSHynes™ Test, in male and female varsity athletes, along with reliability of the test in a student athletic therapy population. Our overall findings showed that regardless of the condition assigned first, females with a history of concussion (HOC) were on average faster than females with no HOC but males with no HOC were on average faster than males with a HOC. However, these findings were statistically significant only between the Male HOC and Male no HOC groups in Condition 2 when it was administered first ($p = 0.048$).

Regardless of the condition assigned first, males with no HOC were on average faster than females with no HOC. These findings were statistically significant for Condition 1 only when it was administered second ($p < 0.001$) and Condition 2 when it was administered first ($p = 0.017$) as well as when it was administered second ($p = 0.040$). When compared to the Male No HOC reference group, regardless of the condition assigned first, females with a HOC were the least likely to incur an error amongst the cohort groups. However, only Condition 1 was statistically significant (OR 0.17; 95% CI 0.05 - 0.60; $p = 0.006$). Finally, second and third/final year Athletic Therapy Certificate Program (ATCP) students demonstrated excellent inter-rater reliability (ICC = 0.94 - 1.00) and good-to-excellent intra-rater reliability (ICC = 0.88 - 0.99) of the HurtSHynes™ Test.

Black et al.[158] noted that there “has been a gap in the published surveillance data in the Canadian university population” when it comes to concussion injuries in a sport setting. Our current study reported on findings from a larger initiative focussed on collecting multiple variables during baseline medicals for a varsity student- athlete population, with and without a self-reported HOC at York University. In total 103 athletes in our study had no prior HOC (51 females, 52 males) and 77 had a prior HOC. The majority of athletes with a self-reported HOC were females (n = 48, 62.34%) compared to males (n = 29, 37.66%). Of the 77 athletes who reported having a previous HOC, n = 42 (54.5%) had one previous concussion, and n = 35 (45.5%) had 2 or more. Similar findings in terms of number of concussions sustained by females compared to males were found by Black et al.[158] and Hurtubise et al.[194] who reported on the epidemiology of concussions from the same sample population; varsity student- athletes at York University, Keele Campus, Toronto, Ontario, Canada.

Over the course of 3 seasons from 2008-2009 to 2010-2011 Black et al.[158] found that out of 759 athletes who were part of a varsity team in at least 1 of the 3 seasons, 75 (9.88%) sustained a concussion at least once. They found that significantly more female athletes were concussed than male athletes and that athletes with a previous history of concussion were more likely to sustain a concussion within the study period. Hurtubise et al.[194] found that out of 1657 sports injuries included in their study from August 1, 2008 to July 31, 2012, 127 (7.7%) were concussions. Female athletes had a significantly higher proportion of concussions compared to males and were at higher odds of sustaining a concussion in varsity sport participation.

Hurtubise et al.[194] also found that women's ice hockey, rugby, and basketball had the highest proportion of concussions when compared with all other teams in their study. Black et al.[158] found that the number of concussions was highest in contact sports and the highest incidence of concussions was found in women's rugby. In our study, women's rugby and field hockey had the highest number of athletes with a self-reported previous history of concussion, followed by women's basketball.

In the United States it can be argued that the Ivy League-Big Ten Epidemiology of Concussion Study provides the most accurate data pertaining to sports-related concussions (SRCs) sustained by athletes who compete in Ivy League and Big Ten sports. It is the premier study being undertaken by the Big Ten-Ivy League Traumatic Brain Injury Research Collaboration which was formed in 2012.[195] The study has a standard data collection protocol across all participating sites and recruits student-athletes who sustain either an SRC or a non-SRC in NCAA sports, non-NCAA sports, and club sports.[195]

Across 5 athletic seasons from 2013-2014 to 2017-2018, 15 universities participated in the study where there was a total of 2241 reported concussions with 1922 of them specifically sports-related concussions (n = 1653 occurring in season and n = 269 out of season). Of the 1653 SRCs that occurred in season there were more males (n = 1004) than females (n = 649) who sustained a concussion. Out of all 1922 SRCs the five sports with the highest number of cases were football (n = 495, 25.8%), women's rugby (n = 119, 6.2%), men's ice hockey (n = 106, 5.5%), men's lacrosse (n = 105, 5.5%), and women's soccer (n = 103, 5.4%). Injury data from the Ivy League-Big Ten Epidemiology of Concussion Study supports our findings along with that of Black et al.[158] and Hurtubise et al.[194] that women's rugby is a sport that consistently has one of the highest incidence rates of concussion.

According to Clarke et al.[196] there has been a growing number of studies exploring pre- and post-concussion game metrics to determine if athlete performance is compromised after a concussion in various professional sports leagues such as the National Hockey League,[191,197–199] National Football League,[192,200–202] Major League Baseball,[203–206] National Basketball Association[207,208] Major League Soccer,[209] and Australian Football League (AFL).[210] Consistent findings across the majority of these studies[197–202,207,208,210] reported that returning to sport following a concussion does not have an impact on athlete performance when compared to their pre-injury metrics or that of controls.

The exception to this are studies reporting on athlete performance in the MLB.[203–206] Studies have reported that in the 14 to 15 days after players have returned from a concussion injury, they have a significant decrease in batting average (BA) and on-base percentage (OBP) when compared to their own baseline[205] as well as significantly worse BA, OBP, slugging percentage (SLG), and on-base percentage plus slugging percentage (OPS) when compared to controls.[205] However between 15 to 42 days after injury there were no significant differences between any of the performance metrics, showing a return back to baseline levels.[204,205] Sabesan et al.[206] also reported that BA and OBP decreased following a return from a SRC but their results were not significant. This could be attributed to the fact that unlike Wasserman et al.[204] and Chow et al.[205] they did not report the specific amount of days after return when these metrics were determined and thus the lack of significant findings could have been influenced by confounding factors.

It has been suggested in the literature that the reason why MLB studies have shown performance deficits following a return from a concussion injury in comparison to other sports is that in hockey, football, soccer, basketball, and Australian rules football for instance, a player's performance is assessed in accordance with one's interaction with teammates which may be masking performance deficits following concussion injury, unlike MLB studies where a batter's performance is analyzed individually.[197,198] Multiple studies have attributed the differences reported in MLB that the skills required to hit a baseball may be more vulnerable to neurocognitive deficits after concussion as batting requires complex neurological function such as reaction time, attentional focus, and visual acuity which in turn requires ocular and attentional networks, vestibular and cerebellar networks, inhibitory control, etc.[197–199,207] Even though the performance of athletes in other team sports requires multiple cognitive demands, they may not be relying on these networks as much to the extent that batters do due to the fact that other teammates they are interacting with may be helping to compensate for any deficiencies. Therefore, batting performance in the MLB may be more sensitive to any lingering effects of SRC as it is a highly individualized task.[198,199]

The study by Wasserman et al.[204] reported that despite results on ImPACT showing resolution of symptoms and a return to baseline cognition, MLB players still experienced impaired functioning and performance deficits in BA, OBP, slugging percentage, and OPS 14 days after injury. Although batters' performance metrics may be more sensitive to the detection of any lingering deficits post-concussion in comparison to other team sports, Wasserman et al.[204] suggested that using these performance metrics to determine recovery and RTP may still not be sensitive enough to detect any lingering deficits in some neurocognitive domains in MLB players after a concussion injury.

Studies assessing individual kinematic differences rather than game performance metrics may be a better solution in the detection of any lingering differences. The BrDI™ Test includes 8 kinematic measures to assess task performance which includes mean reaction time, total movement time, path length, peak velocity, and movement and accuracy precision.[121] Studies that have used the BrDI™ Test have repeatedly observed that athletes with a HOC have performance deficits in CMI tasks in comparison to healthy controls, even though the athletes were considered asymptomatic and cleared to RTP.[108,121,127,128] Brown et al.[128] suggests that when athletes with a HOC perform these CMI tasks that "pushes the system," behavioural deficits across a range of brain functions become apparent. They propose that these findings "reflect a problem in the communication between brain regions responsible for planning and executing skilled movements when there is an element of cognition involved."[128]

In a two-part study by Hutchison et al.[211,212] who looked at medically diagnosed concussions in the National Hockey League (NHL) during 3.5 seasons from 2006/2007 to the end of December 2009 reported that there were 260 concussions that occurred over 4299 NHL regular season games, or 6.05 injuries per 100 games. Of the 197 that were included in their statistical analyses they reported that the majority of concussions were; (1) sustained by forwards (65%); (2) occurred in the first period of play (47%) and (3) were sustained by contact with an opponent (88%), with the player's head being the most common body part initially contacted by the hitter's shoulder. Of interest is that in 42% of the cases where a concussion was sustained due to contact with an opponent, the player who suffered a concussion had just released the puck.[211] Of importance is that in the majority of these cases, the time from puck release to contact was less than 0.5 seconds (s) or 500 milliseconds (ms).[211]

As described in Chapter 1, the ability to pass to one's teammate in hockey while looking to avoid a body check from an opponent on one's right is an example of non-standard mapping that requires CMI.[108] In the previous study, 42% of NHL players who suffered a concussion due to contact with an opponent had just released the puck where time from puck release to contact was less than 500 (ms).[211] In the CMI study by Hurtubise et al.[108] NHL draft combine athletes with a history of concussion were approximately 10% slower to react compared to those without a previous history when simultaneous thinking and skilled action was required (i.e CMI). In terms of reaction time those with a previous history of concussion took on average 44.63 (ms) longer than those without a prior history on non-standard mapping tasks,[108] suggesting that even minor deficits in reaction time to a given stimulus could pose a risk to player safety and negatively effect player performance given that the NHL study demonstrated it took less than 500 (ms) for a player to release a puck and be checked by an opponent which resulted in a concussion injury. Players who have lingering deficits in CMI performance, which are not distinguishable on the current assessment tools being used today, may be more vulnerable to sustaining a second concussion. It is also important to note that all these studies mentioned only provide findings in professional male athletes. Future work should put a greater emphasis on exploring performance metrics in a female professional athlete population.

In addition, findings from a systematic review by Kamins et al.[24] reported that much of the data in the literature suggests that physiological recovery after a sports related concussion appears to exceed clinical recovery, with some studies noting physiological disturbances and metabolic abnormalities lasting roughly 15 to 30 days post-injury. With a majority of studies imploring a cross-sectional design with single time points or cohort studies that don't follow subjects until full recovery, there is a scarcity of longitudinal cohort studies that are needed.[24] Specifically, Kamins et al.[24] stated future longitudinal cohort studies should follow participants from time of injury until resolution of physiological dysfunction, correlating it to clinical recovery measures.

It is also imperative that studies "examine within-subject changes in the months to years following symptom resolution, to determine if and when functional and structural markers of concussion have dissipated."[213] While some studies reporting on MLB athletes found that there were no significant differences in performance metrics 15 to 42 days after injury,[204,205] Peterson et al.[203] reported that batters demonstrated a statistically significant post-concussion decline in BA, OBP, and SLG 1 year after concussion as well as throughout the remainder of their career.

Finally, there also is a need for more objective and reliable concussion assessments, as according to the American Medical Society for Sports Medicine's position statement on concussion in sport[44] "the test-retest reliability of commonly used sideline concussion evaluation tests is below the generally accepted threshold for clinical utility (0.75 - 0.90)." Broglio et al.,[135] who evaluated test-retest reliability of common concussion assessment tools, found the majority of the instruments they evaluated demonstrated lower than acceptable reliability standards set for clinical utility but are still being broadly implemented and utilized. This is due to the fact that while the majority of these assessments don't individually meet the reliability standards "there is evidence that combining them in a multifaced assessment model provides a high level of sensitivity."[135]

While we ackowledge that our novel test, the HurtSHynes™ Test, cannot be used as a standalone concussion assessment tool to determine RTP readiness, findings from our reliability study showed that raters demonstrated excellent inter-rater reliability (ICC = 0.94 - 1.00) and good-to-excellent intra-rater reliability (ICC = 0.88 - 0.99) across the 5 testing variables. Not only did the ICCs demonstrate excellent inter-rater reliability and good-to-excellent intra-rater reliability, but with ICCs of 0.98, 0.99, and even 1.00, some of the test variables showed perfect or close to perfect absolute agreement, suggesting that our test is relatively easy to evaluate and master. The HurtSHynes™ Test also requires minimial equipment and the test length of 26m has been designed to allow for administration in both outdoor and indoor settings. These findings suggest that the HurtSHynes™ Test could help to fill a gap in the literature for the need of reliable concussion assessment tools that meet the accepted threshold for clinical utility. However, future studies are needed to investigate the reliability of our novel test in a varsity athlete population.

Strengths and Limitations

Currently there are some gaps in the literature that the HurtSHynes™ Test would help to fill; (1) as previously mentioned, a large portion of research on SRCs have focused on studying the effects of concussion on cognition[145–147] with less focus on studying its effects on visually guided motor actions[148] and cognition integrated with movement in a sport context;[149] (2) the current assessment tools used for diagnosing a concussion and/or monitoring of recovery post injury such as the Sport Concussion Assessment Tool- Version 5 (SCAT5),[150] Balance Error Scoring System (BESS),[136,151] Immediate Post- Concussion Assessment and Cognitive Testing (ImPACT),[152] Buffalo Concussion Treadmill Test (BCTT),[137,153] and Buffalo Concussion Bike Test (BCBT)[154] often tests one's cognition and motor performance in isolation rather then concurrently. However, success in sport performance, as well as aspects of daily life and work, requires the simultaneous integration of cognition and action known as CMI; (3) there is a need for more objective and reliable measures for concussion diagnosis and RTP management;[155,156] (4) according to the American Medical Society for Sports Medicine's position statement on concussion in sport[44] "the test-retest reliability of commonly used sideline concussion evaluation tests is below the generally accepted threshold for clinical utility (0.75 - 0.90)."

The HurtSHynes™ Test is reflective of movements executed by athletes during sport performance while simultaneously assessing CMI. Our test helps to address the need for more assessments that integrate cognition with movement while allowing for the evaluation of visuomotor performances beyond the gross motor skills typically tested during a clinical assessment. Intra- and inter-reliability analyses of our reliability study revealed excellent ICC values of greater than 0.90 which is well above reported findings from commonly used sideline concussion evaluations in the literature.[44] Specifically, our raters demonstrated excellent inter-rater reliability (ICC = 0.94 - 1.00) and good-to-excellent intra-rater reliability (ICC = 0.88 - 0.99) across the 5 testing variables.

Given the results of the intra- and inter-reliability analyses and findings from our pilot test, the HurtSHynes™ Test is a useful and quick objective measure to assess CMI performance. The test is also simple to administer, requires minimal training and equipment, making it both affordable and accessible. One of the strengths of our reliability study is that we had a brief secondary training session when the raters returned 14 to 21 days later so that even with a mean of 17.25 ± 2.82 days between both video viewing sessions, second and third/final students in the

ATCP at York University were able to record relatively consistent times and errors for the runners across the two viewing sessions. This also helped to demonstrate that the HurtSHynes™ Test is a quick and easy test to master as these findings suggest that raters were confident and knowledgeable in their ability to consistently determine the number of errors our runners incurred and the length of time it took the runners to complete both testing conditions.

A strength of our pilot study of administration of the HurtSHynes™ Test in a varsity athlete population was that it was conducted on a relatively balanced sample of male and female varsity athletes across a multitude of sports. We also collected data on a number of variables such as concussion history, total number of previous concussions, length of time since most recent concussion, years of education, etc. While these variables are important in trying to determine if any had an effect on performance on the HurtSHynes™ Test, one of our main limitations was that data was missing for a multitude of athletes for several of our independent variables. A lack of a sufficient sample size for some variables, which we defined as an n greater than 30, could be accounting for some of the statistically significant findings we found as well as some of the findings where there were no statistical significant differences.

For example, results in Chapter 2 reported that there were statistically significant differences in terms of mean time on Conditions 1 and 2 of the test whereby men's soccer on average performed faster than a majority of the other sports teams. However, all male, female, and coed sports teams had less than 20 athletes with the exception of women's rugby that had an n of 22. Also, sex differences found in terms of years of education could be attributed to the missing data for male athletes in our study. Years of education for females was reported for an n of 97 where data was missing for only 2 athletes (2%) compared to males where data was reported for an n of 61 males and missing for 20 male athletes (24.7%).

This appears to be supported by findings from a One-Way ANOVA that was performed between the 4 cohort groups and years of education and found to be significant ($F = 3.60$, $df = 3,157$, $p = 0.015$) (see Chapter 2). A Bonferroni post-hoc test was performed and revealed a significant difference only between the Male No HOC group and Female HOC group ($p = 0.012$). Females with a HOC on average had more years of education compared to males with no HOC. However, years of education was missing for a $n = 13$ in the Male No HOC group, $n = 7$ for the Male HOC group, $n = 1$ in the Female No HOC group, and $n = 1$ in the Female HOC group.

Although length of time since an athlete's last concussion was obtained during baseline medicals, only 45 of the 77 athletes who had a previous history of concussion reported the length of time since their last concussion. Thus, data from 32 athletes was missing. Of those 45 athletes, 51.1% (n = 23) sustained their last concussion greater than 24 months ago, 46.7% (n = 21) sustained their last concussion less than 12 months ago, and 2.2% (n = 1) sustained their last concussion between 12 to 24 months ago. Gathering this information in the future would enable us to investigate whether performance deficits on the HurtSHynes™ Test could be related to length of time since last concussion. Following statistical analyses previously reported by Dalecki et al.[121] this would enable us to correlate time since last concussion with time taken to complete Conditions 1 and 2 with a linear regression analysis.

Future Directions

In addition to continuing to explore sex-related differences in a Canadian university aged population, a future aim of our study is to expand our database to include non-university aged athletes, specifically those between the ages of 10 to 16. Studies by Dalecki et al.[121,127] have shown that performance deficits, observed in athletes with a history of concussion on CMI tasks on the BrDI™ Test, can last approximately 18 to 24 months post-concussion in athletes aged 9 to 17.

We intend to gather information about when athletes started playing their respective sport as this would enable us to evaluate metrics such as eye-limb coordination-related sport experience (i.e years of sport experience) as previously done in the study by Dalecki et al.[127] In this study they found that youth with a history of concussion that had more sport experience "demonstrated quicker CMI recovery compared to their peers with less experience" whereby those with 7 to 12 years of sport experience reached CMI performance levels matching their non-concussed peers after around 12 months compared to around 30 months in those with 1 to 6 years of sport experience.[127]

We would also like to gather data pertaining to athlete exposures (AEs) for all varsity athletes at York University as sex-related differences found in our study could be due to exposure times. Athletes who perform better tend to get more playing time in games, resulting in a higher exposure rate which puts them at a higher risk for sustaining a concussion. It is important to note though that according to Black et al.[158] there is a lack of a consistent exposure measurement across the concussion literature in terms of how AEs are defined and calculated, making it difficult to compare AE rates across studies.

Finally, an important future direction is to administer the HurtSHynes™ Test during Stage 4 of the Sport Concussion Assessment Tool- Version 5 (SCAT 5) RTP protocol to help guide RTP decisions for varsity athletes. The aim of Stage 4 is non-contact training drills where the goal is exercise, coordination, and increased thinking.[1] We plan to conduct future studies to explore athlete performance on the HurtSHynes™ Test during Stage 4 of the SCAT-5 following a concussion injury in a varsity student-athlete population, as the COVID-19 pandemic permits.

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