CUMULATIVE EFFECTS OF SPORTS-RELATED SUBCONCUSSIVE HITS ON RESPONSE INHIBITION

by

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Abstract

Whereas it has been demonstrated that sustaining multiple concussions can detrimentally affect neurophysiologic health and cognitive abilities, there is no consensus on the cumulative effect of repetitive subconcussive head impacts in contact sports. Subconcussive hits are head impacts that are typically less forceful than concussive impacts. They occur much more frequently, and do not produce obvious or immediate clinical symptoms. The global objective of this research was to investigate how cumulative exposure to repetitive subconcussive hits, as experienced through participation in one season of competitive American football, affects response inhibition, one of many executive functions of the brain. In addition, accelerometers were used to collect biomechanical data to determine the cumulative number and magnitude of these repetitive head impacts and relate this to changes in response inhibition.

Response inhibition was probed with the use of a complex neurocognitive sensorimotor KINARM hit-and-avoid task. This required the subject to use robotic arms to respond to virtual targets while avoiding multiple distractors presented simultaneously on a 2D virtual screen. The results showed a significant difference between the contact and non-contact sport athletes from pre-season to post-season, and therefore support this hypothesis.

In addition, it was hypothesized that contact-sport athletes who experienced a greater cumulative number of head impacts over a season would show significantly poorer performance on the task of response inhibition compared to the contact-sport athletes who experienced a lesser cumulative number of head impacts.

It was also hypothesized that contact-sport athletes who experienced a greater cumulative magnitude of head impacts over a season would show significantly greater poorer performance on the task of response inhibition compared to those athletes who experienced a lesser cumulative magnitude over the season. Interestingly, the results fail to support this hypothesis, and instead appear to support the opposite hypothesis.

The findings from this thesis indicate that experiencing a season's worth of subconcussive hits does appear to affect the specific executive function of response inhibition in contact-sport athletes, however other factors besides head impact data may play an important role in these adverse effects.

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Preface

The methods used in this study were approved by the Clinical Research Ethics Board (CREB) at the University of British Columbia, as part of a larger study involving a wide variety of methods and hypotheses (H14-02996). Pre- and post-season data was collected at the University of British Columbia, Okanagan (Kelowna, BC) by Kelsey N. Bryk, Krista Fjeld, Alexander D. Wright, and Jonathan D. Smirl. In-season accelerometer data was collected by Kelsey N. Bryk and Alexander D. Wright.

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List of Abbreviations

ANOVA	Analysis of variance
ANT	Attentional Network Test
CTE	Chronic traumatic encephalopathy
DLPFC	Dorsolateral prefrontal cortex
fMRI	Functional magnetic resonance imaging
GNG	Go/ no-go (task)
HIT	Head Impact Telemetry [system]
ImPACT	Immediate Post-concussion Assessment and Cognitive Testing
LOC	Loss of consciousness
LOFC	Lateral orbitofrontal cortex
mTBI	Mild traumatic brain injury
OHA	Object Hit-and-Avoid task
PFC	Prefrontal cortex
RHI	Repetitive head impact
RT	Reaction time
SCAT3	Sports Concussion Assessment Tool – 3rd Edition
SST	Stop-signal task
SSRT	Stop-signal reaction time
SRC	Sports-related concussion
TMT	Trail making task
TST	Task-switching task
WM	White matter

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all throughout my undergrad and now through my master's degree, even when we are three provinces apart.

Dedication

This thesis is dedicated to my grandpa Klassen. You lived everyday following your passion and taught me that if I truly love what I do, I'll never work a day in my life.

Chapter 1: Introduction

Concussions are a broad and widespread mild traumatic brain injury (mTBI). Statistics Canada reported as many as 20,000 sports-related concussions occur each year among 12-19-year-olds. Understanding the pathophysiological and biomechanical properties of this injury requires an interdisciplinary approach. The recent expanse of knowledge in this field (a PubMed search for 'concussion' resulted in <100 studies/ year before 2000, and 670 studies in 2015) can be at least partially attributed to this approach. Defined as "a complex pathophysiological process affecting the brain, induced by biomechanical forces," a concussion can result in a wide variety of symptoms and cognitive difficulties (McCrory et al., 2013). This head injury is thought to occur in two phases, the first being the moment of impact, involving linear and rotational accelerations, caused by a either a direct impact to the head or to the body in which the force is transmitted to the head (McCrory et al., 2013). The second is the pathophysiological sequelae, which includes the immediate and delayed alterations in cellular structure and function and the associated cognitive and behavioural deficits (Bailes, Petraglia, Omalu, Nauman, & Talavage, 2013). The most commonly reported acute symptoms from a concussive event include headache (93.4%), dizziness (75.9%), difficulty concentrating (61.4%) and disorientation/confusion (51.7%) (Kerr et al., 2014); however, such symptoms typically resolve within 7-10 days in 80 – 90% of cases (McCrory et al., 2013). A common misconception is that one must experience loss of consciousness (LOC) to be diagnosed with a concussion, however the Zurich 2012 Consensus Statement on Concussion in Sport states that a concussion may or may not involve LOC. The current and widely

accepted definition of a mild TBI includes a loss of consciousness less than 30 minutes; any LOC between 30 minutes and 6 hours is classified as moderate, and LOC lasting longer than 6 hours is classified as severe ('Management of Concussion/mTBI Working Group, 2009; McCrory et al., 2013). In addition to loss of consciousness, another concussive symptom and measure of severity is post-traumatic amnesia, or how long after the head injury that it takes for a patient to regain the ability to understand and form memories of what is occurring around them. The Glasgow Coma Scale (GCS) is a commonly used severity scale to assess a patient's level of cognitive functioning and consciousness following an injury – a GCS score of 13-15 is classified as mild, whereas a score of 9-12 is moderate, and 3-8 is severe.

There is growing concern that sustaining multiple concussions may lead to a progressive neurodegenerative disease known as chronic traumatic encephalopathy (CTE), characterized by an accumulation of the toxic phosphorylated tau protein in the brain which currently can only be diagnosed post-mortem, and is suspected to be dependent upon sport, position played, years of exposure, age at first exposure to head trauma, as well as genetic predisposition (Gavett, Stern, & McKee, 2011; McKee et al., 2009). McKee and colleagues (2009) reported that 90% of their neuropathologically diagnosed cases of CTE were in the brains of contact sport athletes, however most autopsies were on individuals who were donated by individuals who displayed extreme cognitive impairments at the time of death. A recent retrospective analysis reported a higher incidence of mortality from neuropathologies such as Alzheimer's disease and Amyotrophic Lateral Sclerosis (ALS) compared to the general population, yet these

players showed a lower death rate from causes such as cancer and cardiovascular diseases when compared to the general US population (Lehman, Hein, Baron, & Gersic, 2012).

Clinically, CTE manifests as memory and attentional problems, irritability, increased impulsivity and other behavioural changes similar to Alzheimer's Disease (AD) and other neurodegenerative disorders (McKee et al., 2009). Many individuals suspected to be living with CTE have demonstrated executive dysfunction, (e.g. disinhibition, difficulties in planning) an early and common cognitive symptom of the disease (Baugh et al., 2012). Recently, the term 'traumatic encephalopathy syndrome' (TES) was developed to separate the clinical symptoms associated with CTE from the neuropathologically diagnosed CTE. This term describes the clinical presentation of symptoms typically associated with a history of repetitive brain trauma and is not meant to suggest the presence of CTE (Montenigro et al., 2014). The development of this term helps to distinguish between the symptoms due to repetitive head impacts and other neurodegenerative proteinopathies such as AD and frontotemporal lobar degeneration (FTLD), which are clinically and pathologically similar to CTE. For example, the distinct pathological signs of CTE typically involve a perivascular accumulative of phosphorylated tau protein, as well as in the depths of the sulci and the superficial cortical layers II/ III. In contrast, AD pathology typically does not show perivascular tau deposition or an accumulation in the depths of the sulci (Tartaglia et al., 2014). Clinically, CTE symptoms can include depression, apathy, and anger/irritability, which is not common in AD. In addition, AD is the most common neurodegenerative disease in people over the age of 65, whereas CTE-diagnosed cases have involved people of all ages (Tartaglia et al., 2014). FTLD is the most common neurodegenerative disease in people

under the age of 65 and in clinically and pathologically very similar to CTE, however the pathology of FTLD is more focal compared to the dispersed pathological features of CTE.

Executive dysfunction reflects an impairment of cognitive processes, known as executive functions, which are processed mainly by the prefrontal cortex (McCloskey, Perkins & Van Divner, 2009). Executive functions allow us to have organized, purposeful, self-regulated and goal-directed thoughts to guide our emotions and actions when making decisions. The high incidence of this symptom may be attributed to the prevalence of neuropathology found in the frontal lobes of CTE patients (Baugh et al., 2012; McKee et al., 2009). In fact, almost all CTE cases described by McKee and colleagues (2009) found neuropathological changes and atrophy in the frontal lobe of contact-sport athletes. While most of these pathologically diagnosed athletes had a history of a diagnosed concussion, 16% did not have a history suggesting a potential cumulative effect of subconcussive hits (Stein, Alvarez, & McKee, 2015).

Most sports-related head impacts do not result in a concussion and are referred to as subconcussive hits (reviewed in: Bailes, Petraglia, Omalu, Nauman & Talavage, 2013; Crisco et al., 2010, 2011). Subconcussive hits are head impacts that do not result in observable symptoms consistent with a concussion diagnosis. The frequency of subconcussive hits in various contact sports has led researchers to investigate potential cumulative and long-term cognitive effects. Recently, a large focus has been placed on the biomechanical properties of subconcussive head impacts. This approach has helped to better understand the relationship between any negative effects on cognition following exposure to subconcussive hits and the location, number, and cumulative magnitude of

those hits (Breedlove et al., 2012; Breedlove et al., 2014; Guskiewicz et al., 2007; McAllister et al., 2012; Talavage et al., 2014). The objective of the current research is to evaluate the relationship between executive function and the biomechanics of subconcussive head impacts experienced by football players across a competitive season.

1.1 Sports-Related Concussion

1.1.1 Effects on Executive Functions

The prefrontal cortex (PFC) is primarily responsible for processing information relating to executive function and relaying this information to other regions of the brain. Executive function is comprised of three inherent factors: updating, shifting and inhibition. Each key component has a corresponding primary region of the PFC responsible for proper functioning (Miyake et al., 2000). The current thesis focuses on response inhibition, which is associated with the lateral orbitofrontal cortex (Horn, Dolan, Elliott, Deakin, & Woodruff, 2003), the medial PFC and dorsolateral PFC (DLPFC) (Casey et al., 1997; Erika-Florence, Leech, & Hampshire, 2014; Garavan, Ross, & Stein, 1999; Lüthi et al., 2014; Simmonds, Pekar, & Mostofsky, 2008), depicted in Figure 1.1.

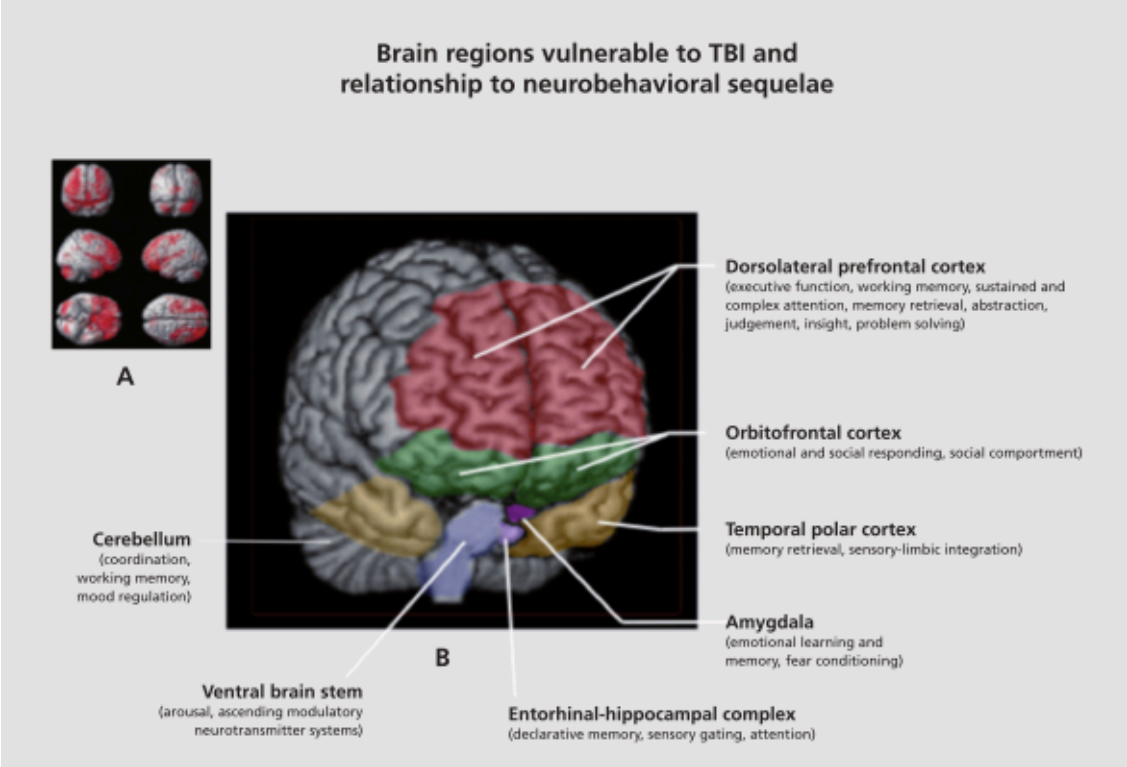

Figure 1.1: Key regions of the prefrontal cortex that are vulnerable in a traumatic brain injury, and their corresponding primary functions. From ref: McAllister et al., (2011), adapted from Arciniegas DB, Beresford TP. Neuropsychiatry: an Introductory Approach. Cambridge, UK: Cambridge University Press; 2001:58. Copyright © Cambridge University Press, 2001.

A sports-related concussion (SRC) commonly results in transient cognitive impairments in executive function, which can manifest as difficulties with problem solving, shifting between tasks, and response inhibition (Collins et al., 1999; Karr, Garcia-Barrera, & Areshenkoff, 2014; Levin & Kraus, 1994; Mattson & Levin, 1990; Stuss et al., 1989). Of particular interest for the current thesis is how impairments in response inhibition (i.e., disinhibition) can present as a deficit in impulse control. This can manifest as poor judgment, seemingly snap decisions and abrupt motor responses to stimuli or situations (McAllister, 2011). A body of evidence has demonstrated executive dysfunction is associated with concussions in the form of attentional and

switching/shifting deficits (Howell, Osternig, Van Donkelaar, Mayr, & Chou, 2013; Mayr et al., 2014), however researchers have suggested response inhibition remains intact (DeHaan et al., 2007; Fischer et al., 2015; Karr et al., 2014; Rieger & Gauggel, 2002).

Karr and colleagues (2014) used three tasks to measure changes in executive function based on the history of concussion: i) the n-back test to probe the ability to update working memory (this task requires subjects to respond to a letter that appeared '*n*' number of letters previously in a sequence of letters; i.e. 2-back task – N – B – N); ii) a global-local task to probe shifting (a large visual stimulus such as a letter (global) is formed by smaller letters (local); i.e. a "T" comprised of smaller "T" 's) and; iii) the go/no-go task to probe inhibition (subjects make a motor response to a visual stimulus and are required to inhibit this response when an auditory tone is presented). Their results showed that only the shifting task discriminated between participants with and without a self-reported history of concussion, based on an increase in reaction times (RT). To investigate the effects of a traumatic brain injury on response inhibition, Rieger and Gauggel (2002) used a stop-signal task (SST) to measure the time it takes to inhibit a motor response in severe TBI patients. Patients were presented with two different tasks, the primary 'go' task where a motor response is made (e.g. making an eye movement) when presented with a visual stimulus, and a 'stop' task where the motor response is to be inhibited at the presentation of an auditory tone (Logan & Cowan, 1984). Here they employed a staircase-tracking algorithm, which adapted to the response rate of the subject in the 'stop' trials to vary the stop-signal delays on subsequent 'stop' trials. A correct response inhibition resulted in an increase in delay, whereas when a response was incorrectly executed, a decrease in stop-signal delay was applied to the next stop trial.

The stop signal reaction time (SSRT) for each subject was estimated as the difference between the average reaction time on the 'go' trials and the average stop-signal delay. The TBI group had an average SSRT which did not differ from the orthopedic control (OC) group; nor did the groups' error rates differ. These results suggest TBI patients may not have difficulties with inhibition of ongoing responses. However, the TBI patient group in this study had a wide range of times since injury (3 weeks to 10 years) and severity based on loss of consciousness (LOC) (13 patients had been unconscious for more than a day), which may have impacted the generalizability of their findings. In contrast to severe TBI patients, DeHaan and colleagues (2007) used a similar SST on mTBI patients who performed the task within 2 days post-injury to investigate the acute effects on response inhibition. DeHaan and colleagues (2007) used a countermanding saccade task in which participants were instructed to inhibit an eye movement in the event of a stop-signal. This signal was presented 0, 25, 50, 75, 100, or 125ms after the visual stimulus. Whereas the group of mTBI patients showed no differences compared to matched controls at cancelling a saccade in response to an auditory stop signal across all delay times, they failed to generate a saccade on 15% of the "go" trials where no auditory stop signal was presented. These results suggest that although response inhibition appears to remain intact following a concussion, the mTBI patients may be employing a compensatory mechanism during the "go" trials in order to increase their inhibition accuracy during the "stop" trials.

van Donkelaar and colleagues (2005) employed a different method (Attentional Network Task (ANT)), to probe the acute effects of a concussion. This study focused on the alerting, orienting and executive aspects of attention in college-aged contact sport

athletes within 2 days post-injury (range: 12-50 hours; mean: 37 hours). The aspect of this task that probes executive function involved the ability to switch between different task demands without difficulty and to resolve contextual conflict in the form of irrelevant stimuli (van Donkelaar et al., 2005). The executive component of the ANT requires participants to respond to a central target (an arrow) surrounded by two flanker arrows on either side. Congruent trials featured the flanker arrows pointing in the same direction as the target arrow, whereas incongruent trials featured all flanker arrows pointing in the opposite direction of the central target arrow. While the alerting aspect was unaffected by a concussion, the concussed participants demonstrated disproportionately longer RTs when making an accurate response during incongruent trials when compared to their matched controls. This implies there are attentional deficits at 48 hours post-injury, specifically in the context of the ability to ignore irrelevant stimuli. In a follow-up study by the same group, both controls and concussed participants improved their RTs over a 1-month period, however the difference between the groups was maintained at 7, 14, and 28 days post-injury (Halterman et al., 2006). Similarly, Howell and colleagues (2013) used the ANT in conjunction with a task-switching paradigm to further investigate the acute and chronic effects of concussion on executive function and attention. In further support of their previous results (van Donkelaar et al., 2005), concussed individuals were observed to have a significantly greater RT difference score (between congruent and incongruent trials) when compared to control subjects reflecting a greater difficulty with ignoring irrelevant stimuli in a context of conflict.

The task-switch task (TST) requires participants to switch between a congruent or incongruent response upon the presentation of a visual stimulus. In the spatial version

(vs. numerical version) of this paradigm, a congruent response required the participant to press the "7" or "4" key if the stimulus appeared at the top or bottom of the screen, respectively, whereas an incongruent response required pressing the "+" if the stimulus appeared at the top, or "–" if it appeared at the bottom of the screen. After two "simple" blocks (either all congruent or all incongruent responses), a "switching" block occurred where participants switched between congruent and incongruent responses every 2nd trial. A "switch cost" was then calculated as the difference between the average response time from the "switching" trials and the trials where the response type stayed consistent (no-switch). This switch cost was 38 ms greater in the concussed group. Although an improvement on both tasks was observed over the 2-month follow-up period for both groups, the differences between the concussed and control groups were maintained throughout the study (Howell et al., 2013). Mayr and colleagues (2014) used a TST over a 1-month post-injury period and similarly observed greater switch costs among concussed individuals compared to controls out to 1-month period, with comparable improvements over the 1-month period.

More recently, Fischer and colleagues (2015) employed a novel tablet-based approach to assess alterations in cognitive status after sustaining a concussion. In the paradigm, participants make a finger-pointing movement in response to a target appearing in 1 of 4 locations around a central 'home' location. To investigate possible sensorimotor deficits following a concussion, one task required a finger-pointing movement towards the target ('Pro-Point' task). In a second task, the pointing response was made in the opposite direction ('Anti-Point' task) and required additional cognitive effort due to the inhibition of the pre-potent motor response of pointing towards the

target. When compared to orthopedic-injury controls and healthy controls, the concussed group had significantly slower initiation times (time it takes for the finger to lift off the home position after the target stimulus appears) compared to both the orthopedic control group and the uninjured healthy control group. The concussed group also had slower response times (time it takes for finger to touch the correct target after it appears) compared to both orthopedic and uninjured healthy controls.

Taken together, it appears these behavioural symptoms can last for 2-months or longer following a concussion. The deficits in executive function appear to be with shifting between tasks and ignoring irrelevant stimuli and appear to last longer than the typical 7-10 day duration of physical symptoms.

1.1.2 Neurophysiology of Concussion

Recently, neuroimaging techniques have been used to further investigate response inhibition deficits following TBI (Krivitzky et al., 2011; Lipszyc et al., 2014). The frontal cortex is responsible for processing information regarding executive function with neuroimaging studies suggesting specific neural regions of this area correspond with specific executive function outcomes. The lateral orbitofrontal cortex, and the medial and dorsolateral PFC have been associated with successful inhibition and information processing response (See Figure 1.1) (Aron, Robbins, & Poldrack, 2014; Casey et al., 1997; Erika-Florence et al., 2014; Horn et al., 2003; Lüthi et al., 2014; Matthews, Simmons, Arce, & Paulus, 2005; Miyake et al., 2000). It has been demonstrated that microstructural and functional changes may occur in the brain following a concussion and have been associated with cognitive and behavioural impairments. For example, Lipszyc and colleagues (2014) used the SST in children with moderate to severe TBI to

probe what they term ‘cancellation inhibition’, a type of response inhibition where participants must cancel an ongoing motor response. In addition to this cognitive test, these researchers employed magnetic resonance imaging (MRI) to classify structural changes in TBI patients into two groups (with and without frontal white matter (WM) damage) and compared these findings to orthopedic (O) and uninjured control groups (U). They observed a longer SSRT in children with frontal WM damage compared to all other groups supporting other research that found frontal lobe lesions are associated with impairments in cancellation inhibition (Aron, Fletcher, Bullmore, Sahakian, & Robbins, 2003).

Although the information to properly execute response inhibition is primarily processed by the frontal lobe, this is not the sole region of the brain responsible for processing these tasks. Other cortical and subcortical connections have been identified using advanced neuroimaging techniques such as functional MRI (fMRI) and diffusion tensor imaging (DTI). This imaging technique is used for examination of the white matter tracts in the brain, which relay information between different brain regions. Post-concussion alterations in frontal WM connections have been observed up to 2 months after the injury and have been associated with executive dysfunction as measured by the paper-and-pen Trail Making Task A & B (TMT) (Caeyenberghs et al., 2014; Kinnunen et al., 2011). Patients with TBI had slower RTs and higher switch costs in the TMT as compared with control subjects. Switch costs were calculated as the difference between total time to complete Part A (draw lines to connect letters from A to Y) and the total time to complete Part B (draw lines to connect letters and numbers in an alternating pattern, i.e.: A-1-2-B-3-C-, etc.).

Similarly, a greater number of errors and a faster RTs on a go/no-go (GNG) paradigm were observed in retired football professional players with a history of multiple concussion as compared to healthy controls, and were correlated with reduced frontal lobe gray matter volume (Goswami et al., 2015). The relationship between these neuroimaging and behavioural findings show that incurring one or more concussions may result in deficits in response inhibition.

1.1.3 Biomechanics of Concussive Head Impacts

The biomechanics of concussive head impacts have been the focus of many studies over the last two decades. Some research has focused on the laboratory-setting reconstruction of head impacts based on video footage to measure the linear and rotational acceleration (Guskiewicz & Mihalik, 2011; Pellman et al., 2003), whereas other research has been able to capture in-game and/or in-practice impact data from sensors worn by contact-sport athletes (Brolinson et al., 2006; Crisco et al., 2010; Duma et al., 2005).

A force imparted to the head has a combination of both a linear acceleration and a rotational acceleration. Linear acceleration is the force that passes through the centre of gravity of the head causing movement of the centre, and is measured in gravitational force (*g*). Rotational acceleration causes the head to rotate about its centre and is measured in radians per second-squared (rad/s^2). All head impacts have a linear and rotational acceleration, and these components have been used to examine the biomechanical nature of concussive and subconcussive head impacts (Slobounov & Sebastianelli, 2014).

Initially, research on the biomechanics of head impacts employed either animal models or cadavers, however technological advances have made it possible to collect this data from human participants in vivo (Gurdjian, Lissner, Hodgson, & Patrick, 1964; Ommaya & Gennarelli 1974; Ono & Kanno, 1996). One of the most popular methods to collect biomechanical head impact data is the Head Impact Telemetry (HIT) system. This system consists of six single-axis linear accelerometers mounted into a specially designed base within a helmet (Crisco, Chu, & Greenwald, 2004; Duma et al., 2005). Resultant linear and rotational acceleration magnitudes are estimated for the centre-of-gravity of the head from the accelerometer data for each impact above collection threshold (Crisco et al., 2004; Duma et al., 2005). Several studies have employed the HIT system to elucidate a biomechanical injury threshold for concussion using linear and rotational acceleration data, however developing a robust threshold has proven difficult given the inconsistencies across these studies (Guskiewicz & Mihalik, 2011).

The National Football League (NFL) commissioned a research project over a decade ago to investigate an injury threshold using helmeted head form dummies (Pellman et al., 2003). They suggested a linear injury threshold of 70-75g would likely result in an mTBI during helmeted impacts. These speculations were somewhat consistent with the reported average peak linear acceleration of 98g ± 28g (range: 48 – 138g) with a duration of 15 milliseconds for the concussive head impacts in their findings. Whereas Pellman and colleagues (2003) focused on the linear acceleration of concussive impacts, Rowson and colleagues (2012) examined the rotational kinematics of thirty-three concussive head impacts in collegiate football players and observed an

average rotational acceleration of 5022 ± 1791 rad/s^2 for concussive impacts using the HIT system.

Broglio and colleagues (2010) examined both linear and rotational forces associated with concussive injuries in high school football players. They reported a concussion was most likely to occur if the player experienced a head impact with a linear acceleration in excess of 96.1g and a rotational acceleration of at least 5582 rad/s^2. Of the 13 concussive injuries recorded, the mean resultant linear acceleration was 105.0 ± 18.0 g (range: 74.0 – 146.0 g) and resultant rotational acceleration was 7229.5 ± 1157.6 rad/s^2 (range: 5582 – 9515.6 rad/s^2). In a later study by the same group, concussions were associated with linear accelerations of 93.6g and rotational accelerations >6402.6 rad/s^2 (Broglio, Eckner, Surma, & Kutcher, 2011). In contrast to their hypothesis, they did not find any correlation between these biomechanical data and post-concussive cognitive scores using the computerized Immediate Post-concussion Assessment and Cognitive Testing (ImPACT) tool.

An earlier study on concussive injuries in collegiate football players recorded 13 concussions with an average peak linear acceleration of 102.8 g (range: 60.51 – 168.71 g), and an average peak rotational acceleration of 5311.58 rad/s^2 (range: 163.35 – 15397.07 rad/s^2) (Guskiewicz et al., 2007). These greater averages and wider ranges may due to the observed difference in frequency of high-level impacts (> 98 g) experienced by collegiate compared to high school football players (Schnebel, Gwin, Anderson, & Gatlin, 2007). The top 1, 2, and 5% of mean linear acceleration for all impacts was also significantly higher for college players compared to their high school counterparts.

Peak linear and rotational accelerations are thought to be two important factors when examining the injury mechanism of a concussive head impact (Guskiewicz & Mihalik, 2011). The relative variability in biomechanical data reflects the heterogeneity of concussive injury mechanisms, which may also reflect the high variability in the type and severity of symptoms and the outcomes observed. Other biomechanical variables, such as severity indices like Gadd Severity Index (GSI) and the Head Injury Criterion (HIC), must be taken into account to establish consistency among these concussive head impacts and to help with the assessment, diagnosis, prognosis and treatment of concussion (Greenwald, Gwin, Chu, & Crisco, 2008).

1.2 Subconcussive Head Impacts

A "subconcussive" head impact is one that does not induce clinical symptoms associated with a concussion, yet recent research suggests these impacts may have a cumulative and long-term effect on brain structure and function (Bailes et al., 2013; Lipton et al., 2013). The acute and chronic effects on response inhibition of a concussion have been well documented over the last decade, however the role and contribution of repetitive subconcussive head impacts is still unclear.

Contact athletes, and football players in particular, are frequently subjected to subconcussive head impacts in both practice and game settings. Such an environment has caused this population to become a focal point of recent research investigating the effects of subconcussive impacts on cognitive and behavioural outcomes (Bailes et al., 2013; Broglio, Eckner, Paulson, & Kutcher, 2012; Kaminski, Wikstrom, Gutierrez, & Glutting, 2007; Lipton et al., 2013; Miller, Adamson, Pink, & Sweet, 2007). Studies on the

cognitive and behavioural effects of repetitive subconcussive head impacts in football have yielded conflicting results to this point in time. Several studies have suggested exposure to just one season of subconcussive blows does not lead to cognitive impairments as assessed using ImPACT, and have demonstrated no association between cognitive performance and biomechanical data acquired via the HIT System (Gysland et al., 2012; McAllister et al., 2012; Miller et al., 2007). Overall, this study reported few differences in the post-season ImPACT scores of the collegiate contact-sport athletes compared to the non-contact sport athlete control group. The control groups' preseason scores were used to establish a predicted ImPACT score and, upon post-season testing, a higher percentage of the contact-sport athletes than control subjects performed more than 1.5 standard deviations (SD) below their predicted ImPACT score for both verbal learning and memory (22% vs. 3.6%, $p<0.006$) (McAllister et al., 2012). Interestingly, the findings from this study showed that HIT data in the last week of the season significantly predicted worse performance on the TMT version B (peak linear acceleration: $r= –0.25$; peak rotational acceleration,: $r= –0.27$; maximum HITsp: $r= –0.27$; and sum HITsp: $r= –0.22$, $p=0.034$). The results also show that season peak linear acceleration significantly predicted worse performance the RT task ($r= –0.19$, $p= 0.017$).

Subsequent research from the same group employed DTI to investigate white matter changes and a possible association with cognitive changes and head impact exposure (McAllister et al., 2014). The findings from this group of contact-sport athletes revealed lower than expected cognitive performance linked with both greater changes in WM diffusivity measures and head impact exposure levels. The authors noted these

changes in WM diffusion do not necessarily explain all of the changes in verbal learning and memory observed in their earlier research (McAllister et al., 2012).

Other studies into the cognitive effects of subconcussive hits have failed to find any significant differences from pre- to post-season assessments in collegiate (Gysland et al., 2012; Miller et al., 2007) and high school contact-sport athletes (Broglio et al., 2011) with performance on the ImPACT as well as other neurocognitive measures such as the Standard Assessment of Concussion (SAC) or the Automated Neuropsychological Assessment Metrics (ANAM). The SAC is widely used as a quick, inexpensive, on-field assessment of immediate memory (repeat 5 words), orientation (e.g. 'what month is it?'), concentration (e.g. list months in the reverse order), and delayed recall of the immediate memory word list as a screening tool to warrant further examination of a possible concussion. The ANAM battery is a computerized neurocognitive test consisting of seven subsets to test simple and procedural reaction time, mental processing speed, and visual, working and delayed memory. Miller and colleagues (2007) found no significant differences in football players' mid- and post-season performance on the SAC and the ImPACT tests compared to their pre-season performance after experiencing a season of subconcussive head impacts. Similarly, Gysland and colleagues (2012) reported no pre- to post-season changes in neurocognitive performance based on the ANAM battery and SAC. In addition, they also noted HIT system data did not predict differences in neurocognitive performance. Although there has been extensive research aimed at detecting subtle cognitive changes after repetitive subconcussive hits, no study to date has focused on explicitly probing response inhibition after a season of exposure to subconcussive hits.

While some studies have suggested there are little to no cognitive deficits following repetitive subconcussive head impact exposure, several neuroimaging studies have found evidence of neurophysiological alterations (Bazarian, Zhu, Blyth, Borrino, & Zhong, 2012; Breedlove et al., 2012; Breedlove et al., 2014; McAllister et al., 2014; Talavage et al., 2014). Diffuse axonal injury as detected by DTI has been found following repetitive subconcussive impacts when compared to control subjects (Bazarian et al., 2012).

Talavage and colleagues (2014) employed the HIT system in conjunction with fMRI and ImPACT to investigate post-season neuropsychological and neurophysiological deficits in relation to head impact exposures. They hypothesized players would fall into two groups based on their impact exposure levels: a group of contact-sport athletes with no clinical symptoms or neurophysiological changes (Control: COI–/FOI–), and a group of contact-sport athletes who were expected to show clinical symptoms and neurophysiological changes (Concussed: COI+/FOI+). Contrary to their hypothesis, the results from this study revealed a group of uninjured high school football players who did not display any clinical concussion symptomology yet still displayed worse performances on certain ImPACT sections after one season (COI–/FOI+) (Talavage et al., 2014). Additionally, this group of players also demonstrated altered activation patterns in the DLPFC when performing an n-back test. Players in this category experienced a higher number of head impacts throughout one season than their concussed counterparts. However, the median peak linear acceleration of this group did not differ from the other two groups (Breedlove et al., 2012). Given the discovery of this third group, the researchers furthered their investigation by hypothesizing that the number

of head impacts would predict neurological impairment as indicated by the ImPACT and/or fMRI. Based on the cumulative number of hits a player experienced at the time of in-season fMRI testing sessions, players were divided into one of two groups using 500 as an approximate and convenient median. Eleven of 12 in-season examinations that fell below the 500 mark were flagged by either fMRI, ImPACT or the results of both combined; of the 10 that were above the 500 mark, all were flagged by one or both tests. That 95.5% of the in-season examinations were flagged by fMRI results, ImPACT performance or results on both tests in otherwise asymptomatic athletes was interpreted as indicative of a cumulative effect of subconcussive head impacts (Breedlove et al., 2014). These results suggest significant neurocognitive differences do not occur after one season of subconcussive impacts, however the lack of sensitivity of these neurocognitive tests like the ImPACT is a limitation of these studies that must be considered (Alsalaheen, Stockdale, Pechumer, & Broglio, 2016).

Whereas all the aforementioned studies have investigated the cognitive, behavioural and physiological effects of subconcussive hits, no study has explicitly examined the cumulative effect on response inhibition and correlated this with accelerometry data. The disparate and limited findings regarding the post-concussion effects of response inhibition might be attributed to the vast network of cortical areas that are involved when inhibiting a motor response. Another reason may be that we simply do not have tasks that are sensitive enough to detect subtle changes in this function over time. Our research addresses the second possible limitation by employing a complex sensorimotor task of response inhibition that has the potential to be more sensitive to subtle changes compared to the classical inhibitory paradigms such as the SST, or the

GNG. The investigation compromising this thesis will utilize two novel methods: the KINARM Object-Hit-and-Avoid Task to assess response inhibition, and the xPatch (X2 Biosystems, Seattle, WA) to collect biomechanical head impact data on the subconcussive hits experienced by elite collegiate-aged football players.

1.3 KINARM Object Hit-and-Avoid Task

The Kinesiological Instrument for Normal and Altered Reaching Movement (KINARM) End-Point Lab (BKIN Technologies, Kingston, Ontario, Canada) bimanual robot arm system was used to implement the 'Object Hit-and-Avoid' (OHA) task, which is analogous to the GNG task with an additional sensorimotor component. In this task, 2 target shapes are presented to the participant on a virtual screen; these targets are to be hit as they descent from the top of the screen while avoiding all other presented shapes (distractors). Participants accomplish these hits by moving the bimanual robotic arms with each of their hands (See Figure 1.2 for KINARM End-Point set-up). The goal of this task is to successfully hit as many target shapes while avoiding all the distractor shapes. It is assumed that the addition of this sensorimotor component increases the complexity compared to the GNG. The additional complexity of the OHA should increase the sensitivity of the task to detect subtle functional changes that may be present following a season of subconcussive head impacts. To accurately assess the ability of a player to inhibit a motor response, we developed a novel measure that quantifies the number of distractor shapes that are pursued by one or both hands but which is cancelled, and/or aborted, before the distractor is contacted – this is referred to as an aborted

distractor hit (ADH). This new variable is analogous to a successful no-go trial in the GNG task.

There is evidence supporting the reliability and sensitivity of this novel robotic technology to detect cognitive deficits in a population of stroke patients (Tyryshkin et al., 2014), mild TBI adult patients (Subbian et al., 2014), and adults with moderate/severe TBI (Debert, Herter, Scott, & Dukelow, 2012). In particular, Subbian and colleagues (2014) were able to show poorer performance on a proprioception test within 24 hours of sustaining an mTBI is a good predictor of post-concussive syndrome (PCS) symptoms present at 3-weeks post-injury. Based on this limited yet promising KINARM End-Point Lab data, it is believed that the use of the OHA task will provide additional insight into the potential cumulative effects of subconcussive head impacts on response inhibition.

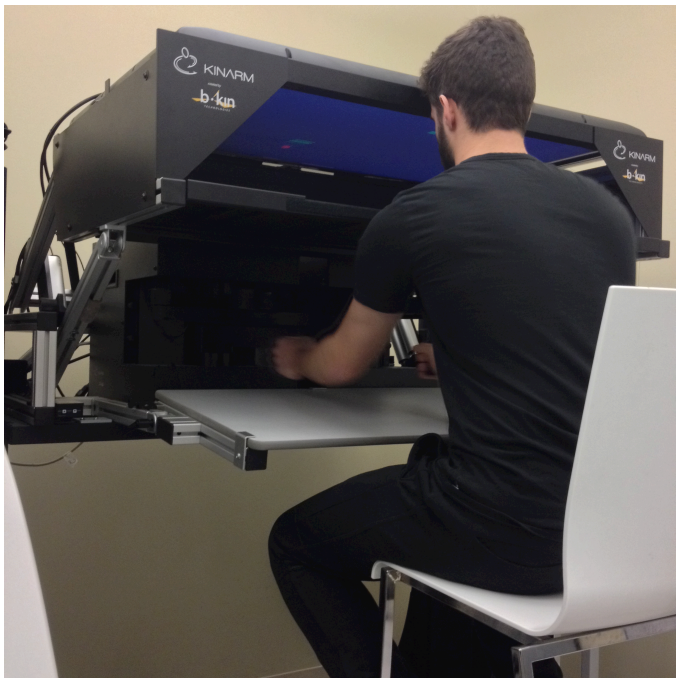

Figure 1.2: KINARM End-Point Lab set up in the Sports Concussion Laboratory.

1.4 Hypotheses

It is hypothesized that repetitive subconcussive head impacts over one season will negatively affect response inhibition of asymptomatic contact-sport athletes. These unfavourable changes between the pre- and post-season assessments are expected to be related to the cumulative number and the cumulative magnitude of these head impacts. Thus the hypotheses for this thesis are three-fold:

1. Asymptomatic contact-sport athletes will have a reduced ability to inhibit motor responses on the OHA task at post-season compared their pre-season task performance, and compared to a control group of non-contact-sport athletes.

2. Players who sustained a greater cumulative number of subconcussive head impacts will display an adverse change in response inhibition performance.

3. Players who experienced subconcussive head impacts with larger cumulative linear and rotational acceleration magnitudes will display an adverse change in response inhibition task performance.

Chapter 2: Methods

2.1 Participants.

Contact-sport athletes were recruited from an elite local junior football team and participated in this study during the 2015 football season. Sixty-six male football players completed the OHA task during pre-season baseline testing. Two of the football players with pre-season data sustained a clinically diagnosed concussion during the season and were excluded from all subsequent analyses for this thesis. Other exclusion criteria included: any neurological disorder(s), history of concussion within 6 months prior to baseline testing, uncorrected visual acuity, or a physical injury that would impair motor control necessary to complete the neurocognitive task.

The control group consisted of students recruited from varsity and intramural sports teams at the University of British Columbia – Okanagan campus. This group of 7 non-contact sport athletes participated in a sport in which they are not routinely exposed to head impacts, but still compete at a high level, including 4 cross-country runners, 2 basketball players, and 1 ultimate disc player. All control athletes were males (20.5 ± 2.1 years old) with 2.9 ± 1.5 years of post-secondary education, and an average IQ of 110.3 ± 6.9.

2.2 Clinical Measures

Clinical measures used included the Sports Concussion Assessment Tool, version 3 (SCAT3: Appendix A), the North American Adult Reading Test (NAART: Appendix B), and a Video Game Questionnaire (VGQ: Appendix C). The SCAT3 was used to collect the following information: age, handedness, concussion history, medical history (i.e.: previous medical imaging for a head injury, current medication use) and presentation of any concussion-like symptoms. The NAART is a quick, valid and reliable assessment used to determine verbal intellectual ability (IQ), and has been widely used among various ages (18-91 years) and years of education (Uttl, 2002). The NAART consists of 61 irregular and/or rare words that are scored for accuracy based on the American and Canadian pronunciation rules. All NAART administers were trained in the proper pronunciation of each word before administering the test to the participants. The VGQ is a questionnaire created by K.N.B and P.v.D and consists of two questions to assess average time per week spent playing video games and which video games were played.

Thirty-eight of the 66 players completed the OHA task during a post-season testing session. The average age of these 38 players was 19.9 ± 1.4 years old, the average number of years of post-secondary education completed is 0.9 ± 0.9 years, and the average IQ (indexed via NAART) is 103.1 ± 6.1.

2.3 Neurocognitive Task.

Participants completed baseline/pre-season testing on the OHA task in a quiet lab setting prior to participation in practices and/or games. Participants were invited to complete a post-season assessment after the last game of the regular season with post-season testing occurring under the same quiet lab conditions. Each testing session consisted of one session using the bimanual KINARM End-Point Lab robot. This set-up is compromised of two graspable End-Point robotic arms (one for each hand) that allow horizontal movement of the arms. The set-up also consists of a 2D virtual reality display for presentation of visual stimuli (Tyryshkin et al., 2014). Sampling frequency is 1000Hz.

Participants completed the task while seated comfortably and the screen height was adjusted to ensure proper visibility of the virtual display while each hand grasped one robotic arm. The seated posture was chosen to eliminate any possible negative effects on balance as these deficits have previously been observed after several subconcussive hits (Slobounov & Sebastianelli, 2013).

Participants completed the KINARM OHA task using both hands while looking at images projected onto a 2D virtual reality screen. Two - 5 cm wide green paddles presented on the screen represented the subject's hands. At the beginning of the task, two virtual shapes were presented as the 'target shapes' that were to be hit throughout the task. During the task, six other 'non-target shapes' were presented as distractors and the subjects were instructed to avoid these shapes. There are six possible combinations of target shapes that were randomly presented to the participant prior to the initiation of the OHA task. When the OHA trial begins, eight different shapes will 'fall' from the top of the screen to the bottom of the screen at different intervals and speeds, two of which will

be the target shapes presented alongside six distractor shapes. Across the session, twenty shapes fell from each of the ten different bins from the top of the screen. As the task progressed, the shapes fell at greater speeds and appeared more frequently. Throughout the entirety of the task, 300 total shapes were presented: 200 target shapes and 100 distractors. The robotic arm produced haptic feedback each time the participant hit a target shape, whereas feedback was not presented when a distractor shape was contacted. The objective of the task was to hit as many target shapes as possible while avoiding all the distractor shapes. Accomplishing this objective required subjects to engage attentional, motor, and response inhibition faculties.

The total testing time for this task was approximately 5 minutes, where 1-2.5 were spent on set-up and explanation of the task and ~2.5 minutes were spent performing the OHA task. Only after the subject verbally confirmed they understood the parameters of the OHA task did the trial begin.

2.4 Head Impact Monitoring

During competitive season games, the football players were equipped with a 6DOF adhesive accelerometer, the xPatch (X2 Biosystems, Seattle, WA, USA). 26 players who wore adhesive accelerometers throughout the season also had post-season OHA scores. It was not feasible to collect data during practices due to time constraints. The xPatch was placed behind the right ear over the mastoid process by a researcher with training and experience in applying these accelerometers. The xPatch records head impacts experienced with a linear acceleration that exceed a threshold of 10 g. Any impacts at or above this threshold triggered 100 ms data collections were stored onboard

the sensor until uploaded at the conclusion of each game. The xPatch sampled linear acceleration at 1kHz and the angular acceleration at 800Hz (Nevins, Smith, & Kensrud, 2015).

The variables of interest from the xPatch for this study were: the total number of hits, the cumulative linear acceleration (measured in g-force: 1 g = 9.8 m/s^2) and the cumulative rotational acceleration (rad/s^2) experienced by each player throughout the competitive season.

Figure 2.1: A participant demonstrating the proper placement of the xPatch over the mastoid process (credit: GreystokePhoto.com).

Non-contact sport athletes did not wear the xPatch while participating in their primary sport.

2.5 Procedure

There were two testing sessions required for each subject in the research presented in this thesis. After obtaining informed consent, participants completed baseline testing prior to the beginning of their season. Because this research is a part of a larger research protocol that involves other tasks and equipment, it should be noted that participants completed the OHA task after they had completed approximately 1-1.5 hours of testing. Once completed, participants were positioned in the KINARM device that was adjusted so as to ensure a clear and unobstructed view of the entire screen. Only after the subject verbally confirmed they understood the subsequent instructions did the task begin.

A subset of football players identified as "starters" (players identified by the coach as those who would likely be involved in the majority of plays in their respective positions during every game over the course of the season), were assigned an xPatch. Each patch was labeled with each player's jersey number. In total, 26 of the 38 players who completed both the pre- and post-season testing met these criteria. Prior to every game, the xPatch was applied to the right mastoid process of starter players. Upon completion of the last regular season game, participants were invited to return to the lab to complete the post-season data collection which followed the same protocols as their pre-season testing session. Again, this procedure is a part of a larger research protocol that involves other tasks administered in the same testing session, however only OHA data was used for this thesis.

2.6 Data Analysis

2.6.1 Object Hit-and-Avoid Data

The variables of interest to this study include:

Overall Task Accuracy:

$$= \frac{Total\ Target\ Hits + (100 - Total\ Distractor\ Hits)}{300}\ x\ 100$$

Equation 1: Task accuracy.

Target hits: percentage of the total 200 target shapes presented that were hit.

Distractor hits: percentage of the total 100 distractor shapes that were hit.

Median Error: percentage of the task that has passed before half of the total errors were made; a higher score represents better performance on the task.

Average target hit speed: average speed across hands when a target hit was made.

Average distractor hit speed: average speed across hands when a distractor hit was made.

Number of aborted distractor hits: This is one of two main measures of response inhibition; it is the total number of aborted hits as indexed by a hand movement towards a distractor that is subsequently cancelled, resulting in no distractor hit, characterizes an aborted trial.

Percentage of pursued distractors that were successfully aborted: This is the second of two main measures of response inhibition. It is calculated by using Equation 1.

$$= \frac{No.of\ ADH}{No.of\ ADH + No.of\ Distractor\ Hits}\ x\ 100$$

Equation 2: The percentage of distractors pursued that were successfully avoided.

Proportion of aborted distractor hits to target hits:

$$= \frac{No.of\ ADH}{No.of\ Target\ Hits}\ x\ 100$$

Proportion of aborted distractor hits to all hits:

$$= \frac{No.of\ ADH}{No.of\ Target\ Hits + No.of\ Distractor\ Hits}\ x\ 100$$

The hand speed of a target hit, a distractor hit, and the number of ADHs was quantified using MATLAB developed with collaborators from the University of South Carolina. This code flagged many false positives, which led to manual filtering of the ADH data provided by MATLAB. The primary researcher of this thesis initially completed this filtering. A second rater who had no involvement in the pre- or post-season testing, and who was also blind to the study ID codes and conditions, also manually filtered the data to determine the inter-rater reliability of this method. The intraclass correlation coefficient was .561 (p = .003). An ADH was removed for several reasons:

1. The hand makes a motion towards a target, however there is a distractor behind the target in the same path of the moving hand.

2. The trajectory of the hand is toward a distractor on the opposite side of the screen. The movement would require one arm to cross over the other to an impossible extent.

3. The hand moves around one shape and in the process, has a resultant trajectory towards a distractor, however speed is maintained. (Note: If hand slows down or stops near the distractor before speeding up to avoid the distractor, this was counted as an aborted hit).

4. Speed of hand while moving towards a distractor does not change or increases. (This was classified as a missed hit, not aborted).

2.6.2 xPatch Biomechanical Data

In addition to the KINARM data, the following variables of interest from the xPatch data were calculated: the total cumulative number of subconcussive hits, the cumulative linear magnitude and the cumulative rotational magnitude experienced throughout the course of one competitive season. These cumulative data were extrapolated based on the raw data using the following formulas:

$$= \left(\frac{Total\ \#\ of\ head\ impacts\ recorded}{Total\ \#\ of\ games\ data\ was\ recorded}\right) * Number\ of\ games\ played$$

Equation 1.1: Cumulative number of hits for the season.

$$= \left(\frac{Cumulative\ acceleration\ recorded}{Total\ \#\ of\ head\ impacts} * \frac{Total\ \#\ of\ head\ impacts\ recorded}{Total\ \#\ of\ games\ data\ was\ recorded}\right)$$

$$* \ Number\ of\ games$$

Equation 1.2: Cumulative linear and rotational acceleration for the season.

There is evidence that these sensors will detect events such as cuts, hard stops and hard kicks at a linear acceleration between 10-20g, therefore the raw data was first filtered to exclude any recorded head impacts with a linear acceleration of less than 20g (McCuen et al., 2015). The time of sensor placement on each athlete was recorded each game to allow for the removal of any artificial impact data that was recorded before the sensor placement.

One player's dataset was removed from subsequent analysis with biomechanical head impact data due to being an outlier for all three variables of interest.

2.7 Statistical Analysis

To answer hypothesis 1, a 2 (team: contact versus non-contact) X 2 (time: pre-season versus post-season) mixed model ANOVA was used to determine if the ability to inhibit a motor response is different between contact sport and non-contact sport athletes over a season. The between-subjects factor is the two groups of athletes (contact or non-contact), and the within-subjects factor is time (pre- and post-season).

To answer hypothesis 2, an independent t-test was used to determine whether or not a group of contact sport athletes exposed to a high cumulative number of head impacts had a worse post-season performance on the OHA task compared to a group of

contact sport athletes exposed to a low cumulative number of subconcussive head impacts, based on a median split.

To answer hypothesis 3, an independent t-test was used to determine whether or not a group of contact sport athletes exposed to a high cumulative magnitude of subconcussive head impacts had a worse post-season performance on the OHA task compared to a group of contact sports athletes exposed to a low cumulative magnitude of head impacts. Linear and rotational acceleration are both considered a measure of "magnitude" but were analyzed individually.

To further address the possible relationship of head impacts and task performance proposed in hypotheses 2 and 3, correlations were used. The relationship between the cumulative number of head impacts, cumulative linear acceleration and cumulative rotational acceleration and the change scores (post-season score minus pre-season score) of all OHA variables (8) were analyzed; 24 correlational tests were run in total.

A Shapiro-Wilk's test of normality was run on all OHA dependent variables. Parametric tests were used to determine significance.

Chapter 3: Results

3.1 Contact Sport Athletes vs. Non-Contact Sport Athletes

The following results reported are from all 38 contact sport male athletes and 7 non-contact sport male athletes who completed preseason and postseason assessments with the OHA task. Contact sport athletes were tested an average of 101.5 (SD = 15.1) days after baseline assessment. Non-contact sport athletes were tested an average of 103.4 days (SD = 31.2) after baseline; this time interval did not differ significantly (MD=-1.9, 95% CI[-17.054,13.196],t(43) = -.257, p = 0.798). Twenty-three contact sport athletes had at least 1 year of post-secondary education, whereas all seven non-contact sport athletes had at least 1 year of post-secondary education. Group characteristics of both groups are provided in Table 3.1.

Twenty-six contact sport athletes had a history of sustaining at least 1 concussion; eleven of these athletes had a history of 3 or more concussions. Only one non-contact sport athlete had a history of 1 concussion. There were no significant differences for all OHA change score variables between the contact and non-contact sport athletes without a history of a diagnosed concussion. When comparing all athletes who have a history of concussion (n=27) to athletes with no history (n=18), the athletes without a history had a significantly greater change score for the total target hits (no Hx: 11.4 ± 13.3, Hx: 2.0 ± 9.9, p = .009). There was no significant difference in the change score for aborted distractor hits (no Hx: 2.8 ± 9.9, Hx: 4.7 ± 7.9, p= .496).

As a part of the SCAT3, five athletes identified that they have received a diagnosis of a learning disability (ADD/ADHD), whereas two athletes identified having been diagnosed with a psychiatric disorder (one – depression; one – anxiety); none of the

non-contact sport athletes had received either of these diagnoses at the time of baseline testing. There were no significant differences in the OHA change score variables between the contact sport athletes with and without a diagnosis of either a learning disability or a psychiatric disorder.

Table 3.1: Group Characteristics of Contact Sport and Non-Contact Sport Athletes

	Contact Athletes (n=38)	Non-Contact Athletes (n=7)	p-value
Age (years)	19.9 ± 1.4	20.9 ± 2.1	.141
NAART IQ	103.1 ± 6.2	113.3 ± 5.6	.002*
Education (years)	0.8 ± 0.8	3.0 ± 1.4	<.001*
Number of Previous Concussions	1.8 ± 2.3	0.1 ± 0.4	.063
Test Interval Time (days)	101.5 ± 15.1	103.4 ± 31.2	.798
No. of Athletes with a Diagnosed Psychiatric Disorder	2	0	--
No. of Athletes with a Diagnosed Learning Disability	5	0	--
BMI	28.8 ± 5.5	23.3 ± 3.6	.015*

OHA variables were subjected to a 2 x 2 mixed repeated measures ANOVA. Overall there was a main effect of time for OHA task accuracy, with a small effect size, $F(1,43) = 6.757$, $p = .013$, partial $\eta^2 = .136$, which shows a significant improvement from preseason to postseason (Figure 3.1). There was no significant main effect of group ($F(1,43) = .687$, $p = .412$, partial $\eta^2 = .016$) or a significant two-way (time x group) interaction $F(1,43) = 2.649$, $p = .111$, partial $\eta^2 = .058$).

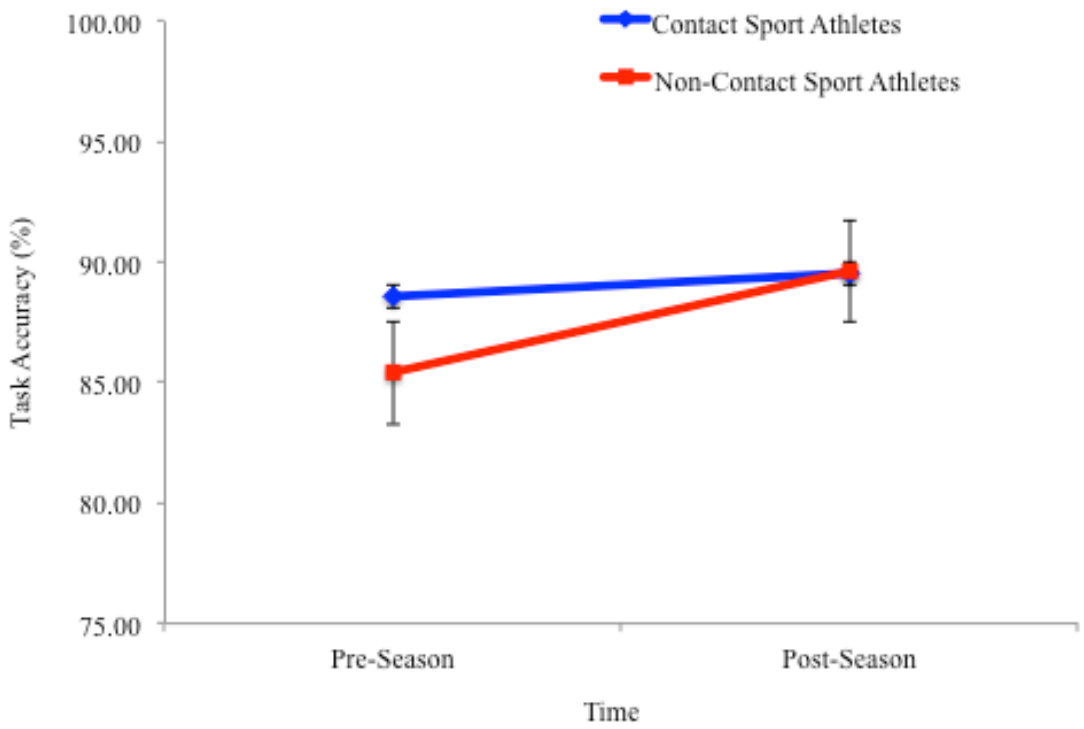

Figure 3.1: The mean overall OHA task accuracy for contact sport athletes and non-contact sport athletes at pre- and post-season assessments.

There was a main effect of time on the total number of targets hit ($F(1, 43) = 15.452$, $p < .001$, $\eta^2 = .264$). There was a statistically significant interaction between the athlete groups and time ($F(1,43) = 4.835$, $p = .033$, $\eta^2 = .101$). Overall, both athlete groups showed improvement, reflected by more target hits, at postseason (Figure 3.2). Non-contact sport athletes (mean difference, MD: 14.72) showed greater improvement than contact sport athletes (MD: 4.16), however there was no main effect of group ($F(1, 43) = 1.082$, $p = .304$, $\eta^2 = .025$).

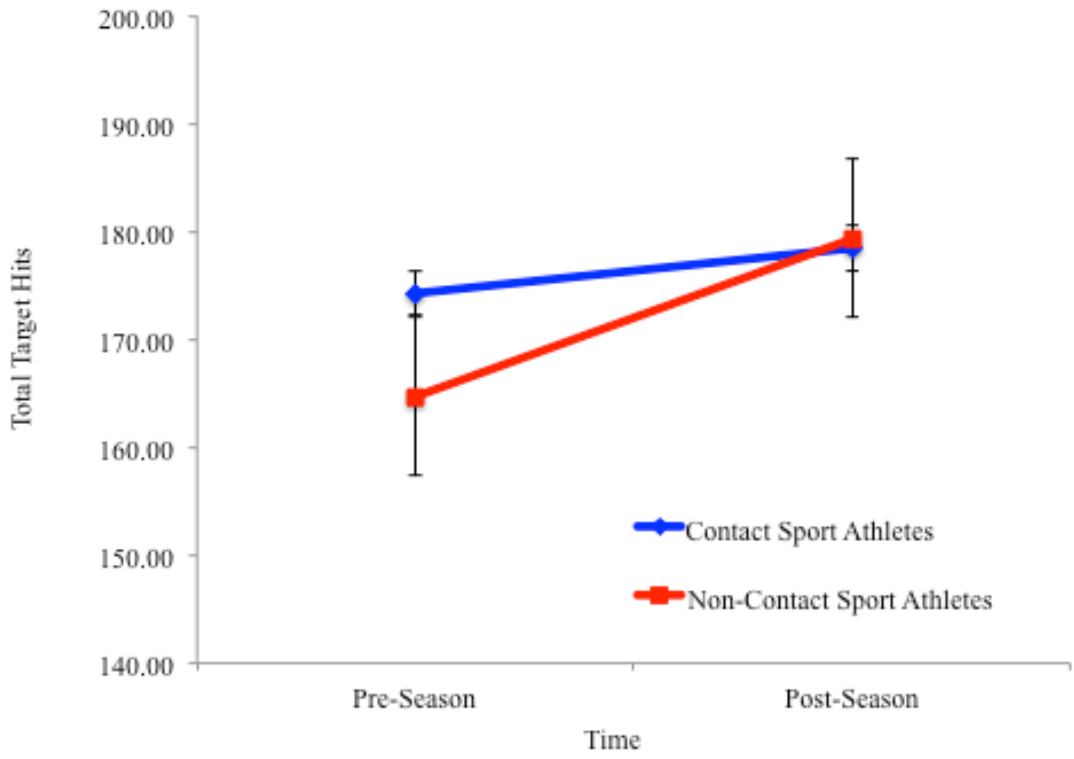

Figure 3.2: The mean total number of target hits of contact sport athletes and non-contact sport athletes at pre- and post-season assessments.

There was a main effect of group on the total number of aborted distractors ($F(1,43) = 6.720$, $p = .013$, $\eta^2 = .135$). There was a significant interaction between group and time ($F(1,43) = 5.800$, $p = .020$, $\eta^2 = .119$), however there was no main effect of time ($F(1,43) = 0.420$, $p = .520$, $\eta^2 = .010$) (Figure 3.3). Similarly, there was a significant main effect of group ($F(1,43) = 9.143$, $p = .004$, $\eta^2 = .175$) and a significant interaction ($F(1,43) = 10.959$, $p = .002$, $\eta^2 = .203$) on the proportion of aborted distractor hits to target hits (not shown), but no main effect of time. There was a significant main effect of group for the proportion of aborted distractor hits to all hits ($F(1,43) = 9.506$, $p = .004$, $\eta^2 = .181$), no main effect of time, and a significant interaction between group and time ($F(1,43) = 9.733$, $p = .003$, $\eta^2 = .185$).

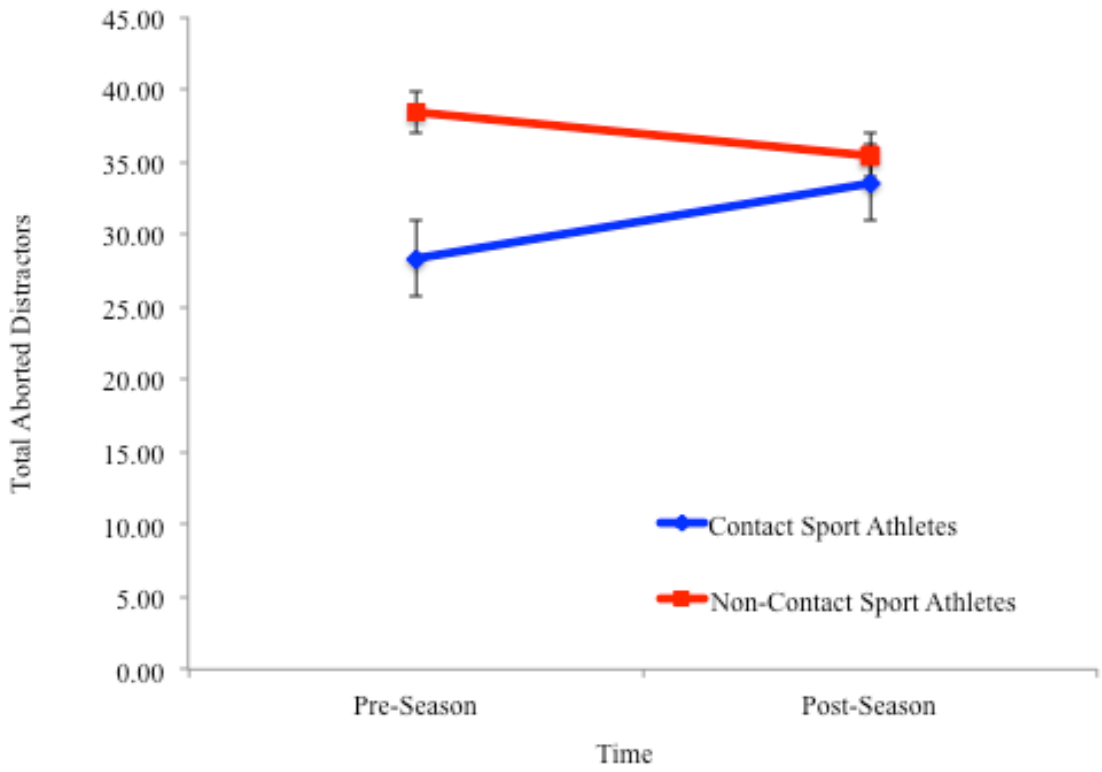

Figure 3.3: The mean total number of aborted distractors for contact sport athletes and non-contact sport athletes at pre- and post-season assessments.

All other OHA variables did not have any significant main effects or interactions. The means for both athlete groups at both time points are displayed in Table 3.2.

Given that the NAART IQ and level of education was significantly different between athlete groups, a correlation between each of this with the change score for all OHA variables was performed. None of the change scores had a significant correlation with either the NAART IQ or level of education. Average weekly time spent playing video games was also recorded and correlated with OHA variable change scores. There was no significant correlation with any of the change scores.