Biomechanics of head impacts in men's university ice hockey

by

Olivia Marie Gareb Aguiar

BSc (Kinesiology), Simon Fraser University, 2018

Thesis Submitted in Partial Fulfillment of the
Requirements for the Degree of
Doctor of Philosophy

in the
Department of Biomedical Physiology and Kinesiology
Faculty of Science

SIMON FRASER UNIVERSITY
Fall 2022

Declaration of Committee

Name:	**Olivia Marie Gareb Aguiar**
Degree:	**Doctor of Philosophy**
Title:	**Biomechanics of head impacts in men's university ice hockey**
Committee:	**Chair: Dawn Mackey** Assistant Professor, Biomedical Physiology & Kinesiology
	Stephen Robinovitch Supervisor Professor, Biomedical Physiology & Kinesiology
	David Cox Committee Member Associate Professor, Psychology
	Rachel Fouladi Committee Member Associate Professor, Psychology
	Lyndia Wu Committee Member Assistant Professor ,Mechanical Engineering University of British Columbia
	Carolyn Sparrey Examiner Associate Professor, Mechatronic Systems Engineering
	Alison Macpherson External Examiner Professor, School of Kinesiology and Health Science York University

Ethics Statement

The author, whose name appears on the title page of this work, has obtained, for the research described in this work, either:

a. human research ethics approval from the Simon Fraser University Office of Research Ethics

or

b. advance approval of the animal care protocol from the University Animal Care Committee of Simon Fraser University

or has conducted the research

c. as a co-investigator, collaborator, or research assistant in a research project approved in advance.

A copy of the approval letter has been filed with the Theses Office of the University Library at the time of submission of this thesis or project.

The original application for approval and letter of approval are filed with the relevant offices. Inquiries may be directed to those authorities.

Simon Fraser University Library
Burnaby, British Columbia, Canada

Update Spring 2016

Abstract

Ice hockey has one of the highest incidences of impacts to the head among team sports. Most head impacts do not result in diagnosed brain injury. Yet growing evidence shows that repetitive head impacts, even at sub-concussive levels, have serious long-term, negative effects on brain health. Efforts are required to reduce the number and severity of head impacts during game play. The goal of this thesis is to generate new evidence on how head impacts occur in ice hockey, and thereby provide an improved basis for preventing and mitigating the severity and number of these events. In partnership with the SFU Men's Ice Hockey team, we collected and analyzed video footage (N=836), paired with head kinematic data from helmet-mounted sensors (N=234) of head impact events. From video analysis, we found that head impacts occurred most often to players checked along the boards in their offensive zone, who did not have puck possession. Glass-to-head impacts represented 28% of cases, four times as common as board-to-head impacts. Hand-to-head impacts accounted for 22% of cases, twice as common as shoulder- or elbow-to-head impacts. By combining video and sensor data, we found that head rotational velocities were greater for impacts where the player was visibly affected by the collision and for impacts which received a major penalty. Building on our evidence that shoulder checks represented the most common and severe body part to impact the head in men's university hockey, we acquired laboratory measures of shoulder displacement and force production as players delivered shoulder checks at varying intensities (impact velocities). Analyzing our results with a mass-spring-damper model, we found that the effective stiffness and damping coefficient of the shoulder averaged 12.8 kN/m and 377 N-s/m, and the effective mass averaged 40.0 kg, or 47% of total body mass. By providing objective evidence on how head impacts occur in hockey, and quantifying the dynamics of a common and severe scenario (shoulder-to-head collision), our results should inform improvements in prevention through changes in rules of play, equipment/rink design, player training, and injury screening.

Keywords: ice hockey; impact biomechanics; sub-concussive; head impact

Acknowledgements

I started my SFU journey in 2012, as an undergraduate student-athlete, before entering the graduate program in 2018. I know what you're thinking… Yes—that was ten years ago! How could I stay at a single institution for ten years?!

In the words of Sheryl Sandberg, "Motivation comes from working on things we care about. It also comes from working with people we care about."

There is an endless amount of people who got me though these wild, ten years at SFU. This includes family, friends, classmates/teammates, faculty, staff, advisors, counsellors, coaches, cafeteria workers, baristas, physiotherapists, Highland Pub (a.k.a. The Study) staff, and many more. Every person and interaction left an impression on me, and from the bottom of my heart I say "thank you" for being part of my journey. That said, I would like to highlight a few people who got me through my graduate studies:

Thank you, to the SFU Men's Ice Hockey team. It was a privilege to work with you over the last five years. Thank you for your partnership, cooperation, and collaboration. Without your contributions, this thesis would (literally) not be possible. A special thank you to Kyle Bergh, for sharing his experience and invaluable insight on the game of hockey. As a former soccer athlete, I hope you find that my interpretations and reflections in this thesis amplify your perspectives and voices.

Thank you, Steve—Without your mentorship, guidance, and patience, I wouldn't have finished this PhD. In 2017, you took a chance on me as an undergraduate Co-op student—giving me wings and trusting I could fly. Back then, I couldn't have imagined or anticipated the growth, experiences, and memories to follow. Thank you for giving me this opportunity of a lifetime.

Thank you, to each member of the Injury Prevention and Mobility Lab: Bianca, Bobbi, Brigitte, Chantel, Colton, Cynthia, Daxton, Emily, Gary, Helen, Jeremiah, Karam, Kim, Natalie, Nina, Olga, Omid, Tim C., Tim L., Rasaval, Rickie, Sukhman, Vicki, Quinn, and many more. Over the last five years, you were the best work family I could have ask for. Thank you for your endless support, platform parties, "nerding" out with me, and enduring my lab presentations. To my favourite desk mate, Karam: Disrupting your workflow was the highlight of my workday. You are truly irreplaceable.

Thank you, to my committee members—David, Lyndia, and Rachel. I admire each of you and your work so much. Thank you for your expertise, guidance, respect, and responsiveness along the way. I can't think of a better group of people (both personally and professionally) to be part of my PhD journey.

Thank you, to my BPK family (students, faculty, and staff). Every day, I am inspired by the work you do, and more importantly by the people you are. Thank you for your empathy, warmth, and kindness. I'm forever grateful for your mentorship, advice, and collegiality (and of course, our good times at the pub).

Thank you, to the friends I've made along the way: Amanda, Benjamin, Brooke, Clara, Erin, Jaylene, Johanna, Karam, Konrad, Konstantin, Matt, Mellie, Natalie, Patrick, Pavreet, Pawel, Ryan, Sabrina, Sayed, Stefanie, Vera, and Vinicius. Life as a graduate student can be very isolating and lonely. Thank you for always being there and making me feel part of this amazing community. To my FunGuys—Karam, Benjamin, and Patrick—to say your friendship is exhausting would be understatement. Thank you for challenging my beliefs, constantly pushing me to grow, showing me how to give and receive love, and always providing a shoulder to lean on.

Finally, thank you to my family. Mom, Dad, Veronica (best "seester" ever), Teta, my cousins/aunts/uncles (there is an endless number of you, and I apologize for not mentioning you all by name), Agata, and Helen—I truly do not know how you put up with me. Your unconditional love and support provide me with sanity, stability, and self-efficacy, especially in the face of uncertainty. Thank you for being my biggest fans, even when you have no idea (and I have no idea) what I'm talking about.

Table of Contents

List of Tables

List of Figures

List of Acronyms

ATD	Anthropometric Test Device
GFT	GForceTracker^{TM}
HITS	Head Impact Telemetry System
HIVE	Head Impact Video Evaluation
NHL	National Hockey League
SFU	Simon Fraser University
TPA	Total Percent Agreement

Glossary

Concussive impact	An impact to the head, neck, face, or body that results in diagnosed concussion.
Damping coefficient	Measure of the resistance of the surrounding environment to the object's motion. Converts kinetic energy of the body's motion into other forms of energy (e.g., heat, sound).
Direct head impact	A force applied directly to the head, which accelerates the head.
Effective mass	The proportion of the body mass participating during the impact phase, or the mass that would have the equivalent motion characteristics at the point of force application.
Elastic collision	A collision which there is no net less in kinetic energy in the system. Both momentum and kinetic energy are conserved.
Head acceleration event	An impact to the head or body, which results in head accelerations above a certain threshold (e.g., more than 10 g of head linear acceleration).
Head impact exposure	A multifactorial term which includes the number (frequency), magnitude (severity) and/or direction/location of impacts sustained over a defined time (e.g., single game, full season).
Impact compliance	Measure of the tolerance of a material to undergoing deformation, or the inverse of stiffness.
Impact frequency	Number of head acceleration events.
Impact mass	Weight of the striking object or person contacting the head.
Impact severity	Magnitude of head acceleration events, as measured by linear and/or rotational accelerations/velocities.
Impact velocity	Measure of the speed of an object when it impacts another surface.
Inclusion threshold	Threshold used based on the peak resultant linear acceleration value to select impacts for analysis.
Indirect head impact	A force applied on the body (not the head), which induces an inertial loading at the head.
Inelastic collision	A collision where there is a loss of kinetic energy. While momentum of the system is conserved, kinetic energy is not.

Stiffness	Measure of the resistance of a material or structure to deformation. Quantified as the ratio of the applied force to the resulting displacement.
Sub-concussive impact	An impact to the head, neck, face, or body that does not result in diagnosed concussion.
Trigger threshold	Threshold used based on raw data to trigger the recording of an impact.

Chapter 1.

Introduction

This chapter provides an overview of the literature related to traumatic brain injury, repetitive head impacts, and biomechanics in ice hockey (hereby referred to as “hockey”). I discuss the role of head impacts with respect to the incidence of sports-related traumatic brain injury and long-term neurological consequences, as well as the definitions and risk factors related to head impact events. Then, I discuss how head impacts are characterized, and how the head and brain respond to a collision. I also provide an overview of the approaches that may be used to examine the circumstances and severity of observed head impacts in hockey. I conclude this section with a summary of the literature (including limitations and gaps of knowledge from previous studies), and outline the objectives of the current thesis.

1.1. The insidious role of impact events in sports-related traumatic brain injury

In spite of important physical, mental, and social health benefits (Bangsbo et al., 2019; True Sport, 2022), participation in sport has considerable risk for injury—including traumatic brain injury. Sports-related traumatic brain injuries were associated with economic burden (Donaldson et al., 2014) and long-term neurological consequences, such as depression and cognitive deficits (Damji & Babul, 2018; Manley et al., 2017). In Canada, 90% of sports and recreation-related head injuries were concussions (Harris et al., 2012; Public Health Agency of Canada, 2020). Concussions are mild traumatic brain injuries induced by biomechanical forces, often from a direct blow to the head, neck or elsewhere on the body (McCrory et al., 2017). Across team sports in Canada and the USA, hockey contributes to the highest rate of concussions (Chandran et al., 2022; Cusimano et al., 2013; Zuckerman et al., 2015). For example, in men’s university hockey, 7.35 concussions occurred in every 10,000 athlete exposures—up to 1.9-fold greater than concussion rates reported in American football, rugby, and wrestling (Chandran et al., 2022). However, many studies have suggested that concussion rates in sports like hockey do not truly convey the extent of the problem, as many concussions are unrecognized and unreported (Damji & Babul, 2018; Kerr et al., 2014). Player contact was the most common mechanism for concussion in elite men’s hockey (Agel et al., 2007; Agel & Harvey, 2010; Chandran et al., 2022; Zuckerman et al., 2015), where up to 92% of concussions were caused by an opposing player delivering a direct blow to the head (Delaney et al., 2014; Hutchison et al., 2015b). Given the link between head impact and brain injury, evidence on the circumstances and risk factors for head impacts in hockey may lead to improvements in the prevention of concussion.

During play, athletes are exposed to impacts to the head which may or may not cause brain injury (Meeuwisse et al., 2007; Schneider et al., 2019). Despite the high incidence of concussion in hockey, most athletes will experience impact to the head without apparent injury or identifiable symptoms and continue to play (Figure 1.1.). These impact events that do not result in diagnosable concussion are often classified as “sub-concussive” (Tierney, 2021). Although a single sub-concussive impact may seem inconsequential, the accumulation of these impacts over one’s hockey career may influence the athletes’ susceptibility for future brain trauma and lead to adverse neurological outcomes (Nauman & Talavage, 2018; Schneider et al., 2019; Tierney, 2021). In the last decade, many research groups assessed how exposure to repetitive head impacts relates to changes in the brain structure and function. Collectively, these neuroimaging studies have shown that, in 70% of examined athletes (primarily from American Football), changes in cognition and brain activation were associated with the number and magnitude of repetitive head impact exposures (Bari et al., 2019; Breedlove et al., 2012; Nauman et al., 2015; Poole et al., 2015; Robinson et al., 2015; Talavage et al., 2014). It is unclear if these short-term brain alterations linked to repetitive head impact observed in a single season will return to baseline, persist, or worsen over time—and how these results translate to other contact sports, such as hockey. That said, there is growing retrospective evidence which suggests that cumulative loading of the athlete’s brain (e.g., career duration, position played, history of repetitive head impact exposure at sub-concussive levels) may lead to long-term neurological consequences—such as chronic traumatic encephalopathy (Guskiewicz et al., 2005, 2007; Mackay et al., 2019; Montenigro et al., 2017; Russell et al., 2021; Schwab et al., 2021; Stemper et al., 2019). Therefore, efforts are required to minimize exposure to impact events which accelerate the head and brain in hockey (Karton & Hoshizaki, 2018; Nauman & Talavage, 2018).

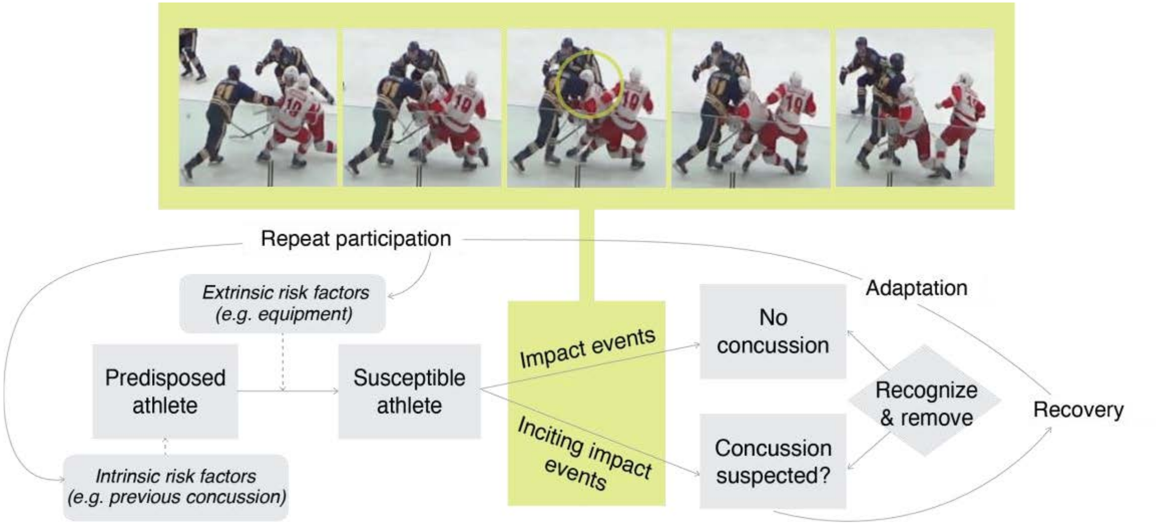


Figure 1.1. Model of factors influencing brain health in sport, adapted from Schneider et al. (2019).

1.2. Biomechanics of head impacts in hockey

In this section, I discuss the biomechanics of head impacts in hockey. I define key terms related to head acceleration events, to establish which head impacts are under investigation in the current thesis. Then, I provide an overview of the literature related to risk factors and characterization of head impact events in hockey, and discuss how the head and brain respond (move) to impact.

1.2.1. Definitions related to head acceleration events

This thesis focuses on the circumstances and severity of direct head impacts in men's university hockey. In recent years, researchers have measured "head impact exposure" in sport, to understand the landscape by which athletes sustain collisions in games and practices and how exposure relates to the risk of brain injury. Head impact exposure is a multifactorial term which includes the number (frequency), magnitude (severity) and/or direction/location of impacts sustained over a defined time (e.g., single game, full season) (Crisco et al., 2011; Le Flao et al., 2022). Estimates of head impact exposure provide insight into the head loading environment in the observed sport, but do not implicitly differentiate between direct head/helmet impacts and inertial head loading events (from impact to the body) (Tierney, 2021). In hockey, head acceleration events may occur from (1) an impact applied directly to the head, (2) an impact applied to the body which induces an inertial loading at the head (referred to as an "indirect" head impact), or (3) rapid (voluntary) movement of the head in the absence of impact (Nguyen et al., 2019; Tierney, 2021). It is important to distinguish between these three types of head loading events to inform prevention strategies (e.g., rule changes, player training, protective gear design). In men's professional and university hockey, a direct blow to the head accounted for 68% and 92% of concussions, respectively (Delaney et al., 2014; Hutchison et al., 2015b). Thus, reducing the frequency and severity of direct head impacts is especially important to the prevention of brain injury (Meeuwisse, 2009; Meeuwisse et al., 2007).

1.2.2. Risk factors of head acceleration events

A hockey player's risk for experiencing head acceleration events is dynamic and changes frequently. It is important to consider which intrinsic (predisposing) factors and extrinsic (environmental) factors interact to make an athlete susceptible to impact.

Each hockey player has their own set of intrinsic risk factors that influence the head acceleration event. Some intrinsic risk factors are modifiable (e.g., neuromuscular or sensorimotor control, body mass index), while others are not (e.g., sex, age, and genetics) (Schneider et al., 2019). Previous history of concussion may reduce an athlete's tolerance for impact and increase their risk for sustaining subsequent concussions (Abrahams et al., 2014; Tierney, 2021), although the exact mechanism is not yet understood (Schneider et al., 2019). Moreover, multiple studies found that male hockey players experienced increased frequency and severity of head acceleration events than their female counterparts (Brainard et al., 2012; Eckner et al., 2018; Mihalik et al., 2020; Wilcox, Beckwith, et al., 2014). Furthermore, female youth hockey players who had a higher body mass index experienced more and higher magnitude head accelerations, but this association was not observed in male youth hockey (Reed et al., 2010). In male youth hockey, cervical muscle strength, anticipation of the collision, safe play knowledge, and aggression also had no effect on the frequency or severity of head accelerations for the player who sustained impacts (Mihalik, Blackburn, et al., 2010; Mihalik et al., 2011; Schmidt et al., 2016). Lastly, it is unclear how playing position associates with the number and magnitude of head acceleration events observed in hockey (Eckner et al., 2018; Mihalik et al., 2008, 2012; Reed et al., 2010, 2017; Wilcox, Beckwith, et al., 2014).

In addition to intrinsic risk factors, the playing environment influences the head acceleration event (Schneider et al., 2019). Extrinsic factors such as equipment, rules of game, and “behavioural” effects of the environment (e.g., spectator environment, level of importance attached to a specific game, officiating decisions) may influence the athlete’s susceptibility to impact and brain injury (Meeuwisse et al., 2007). For example, the incidence (Eckner et al., 2018; Reed et al., 2010; Schmidt et al., 2016; Wilcox, Beckwith, et al., 2014) and magnitude (Mihalik et al., 2008, 2012; Reed et al., 2017; Schmidt et al., 2016).of head acceleration events were greater in hockey games than practices—across age, sex, and skill level. Moreover, Wennburg (2004, 2005) observed that male elite hockey players experienced fewer head impacts in larger (international) rinks than smaller (North American) rinks. Schmitt et al. (2018) showed that flexible board systems may reduce the magnitude of head acceleration upon impact with the glass/boards. As for protective gear, Virani et al. (2017) showed that the addition of 2-cm-thick polyurethane foam over existing shoulder caps decreased peak head linear accelerations and rotational velocities by up to 25% and 12%, respectively. In male youth hockey, regulation of body checking and “zero tolerance for head contact” policy decreased the number of physical/head contacts by up to 30% (Goulet et al., 2016; Malenfant et al., 2012; Williamson et al., 2022), but the effect on head impact magnitude is not known.

More research is required to understand how intrinsic and extrinsic factors modulate risk for head accelerations events in hockey. Of particular interest is how these risk factors affect hockey players from older age groups (university level; >17 years of age). This thesis addresses gaps in knowledge and improve our knowledge of how intrinsic (e.g., mass, anticipation of the collision) and extrinsic risk factors (e.g., penalties, playing zone, location on the rink) influence head impacts in men’s university hockey.

1.2.3. Characterization of head impact events

A detailed biomechanical description of head impact events, although important, is not always sufficient to develop effective prevention methods (Bahr & Krosshaug, 2005; Karton & Hoshizaki, 2018; Le Flao et al., 2022; Tierney, 2021). Research to date in hockey has primarily focused on the biomechanics—such as the analysis of on-ice, sensor-based measures of kinematics during head acceleration events (Brainard et al., 2012; Mihalik et al., 2008, 2012, 2020; Wilcox, Beckwith, et al., 2014). While these studies have improved our understanding of head impact exposure, they provide limited insight on how head impacts occur, and how this depends on situational factors (e.g., puck possession, playing zone) and behavioural factors (e.g., playing style, anticipation of collision)— which is necessary information to guide the design and development of strategies to reduce the frequency and severity of head impact events in hockey. For example, what was the most common object or body part that struck the head? How does the impacting object affect the dynamic response of the head and brain?

A complete description of the mechanism for head impact events in ice hockey needs to include both the biomechanics at the time of impact as well as the events leading to impact (e.g., playing situation; player and opponent behaviour) (Figure 1.2.). The biomechanical, situational, and behavioural factors underlying a head impact event are not completely independent (Krosshaug et al., 2005). Whole-body biomechanics (e.g., impact velocity, head dynamic response) and the loading of the brain tissue (brain dynamic response) were shown to be influenced by the characteristics of the sports situation and player/opponent behaviour (Karton & Hoshizaki, 2018; Le Flao et al., 2022). In this thesis, we expand on biomechanical approaches used by Wilcox, Machan, et al. (2014), and Post et al. (2019), to provide a comprehensive description of the circumstances and severity of head impacts in men's university hockey (discussed in more detail in Section 1.3.).

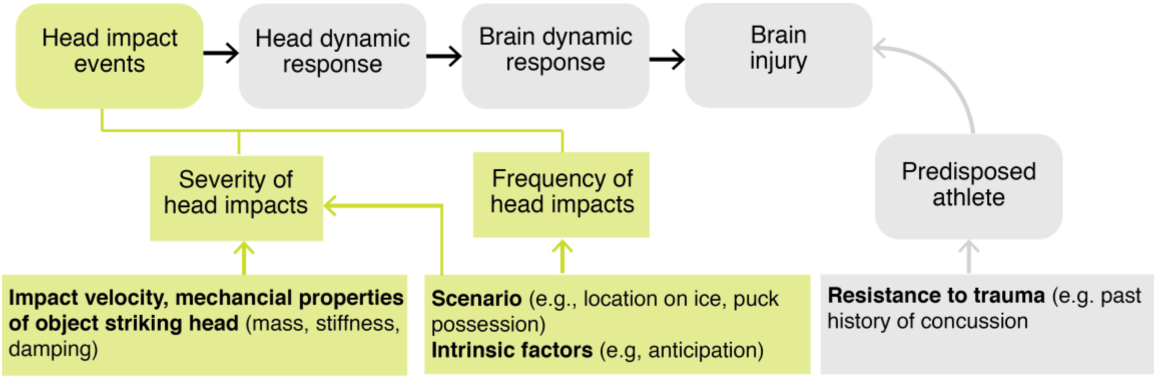


Figure 1.2. Conceptual framework of the current thesis

1.2.4. Head dynamic response

There are two types of head motion in response to impact: linear and rotational (Figure 1.3.). Linear or translational motion involves the head moving in a straight line, and accelerating in the direction of the net force according to Newton's Second Law (net force = mass x acceleration). Rotational motion involves the head rotating about an axis, and accelerating in the direction of the net torque/moment according to Newton's Second Law (net torque = mass moment of inertia x angular acceleration). The net force and torque will depend on the applied force, and on the resistance to motion provided by the muscles and ligaments connecting the head to the neck. Previous studies indicate that, during head impacts, the acceleration impulse applied to the head occurs over a very short time interval, ranging from 5 – 50 ms (Hoshizaki et al., 2017; Karton & Hoshizaki, 2018). This interval is shorter than the time required for reflex or voluntary changes in neck muscle activation (Fice et al., 2018; G. Siegmund, 2001). Accordingly, head acceleration is dominated by the applied force, and the baseline level of muscle excitation, and only moderately affected by changes in neck resistance occurring after the onset of impact (Bland et al., 2018; G. Siegmund, 2001).

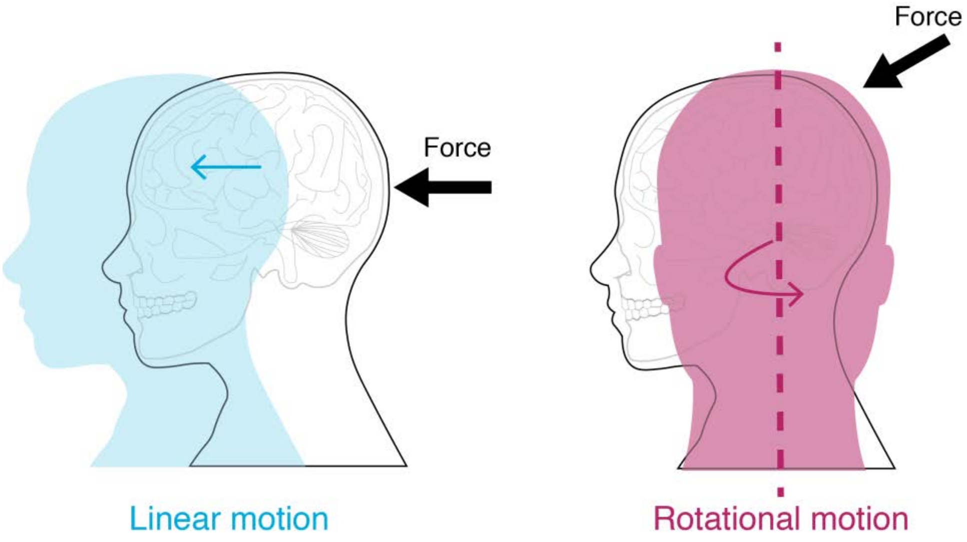


Figure 1.3. Linear and rotational motion of the head upon impact

Decades of biomechanical research focused on understanding the response of the brain to head impact events, and how this relates to injury (Zhan et al., 2021). Guardjian and colleagues found that linear acceleration (and deceleration) were highly associated with skull fractures and changes in pressure gradients throughout the brain tissue (Gurdjian, 1975; Gurdjian et al., 1953, 1964, 1966). Thus, linear acceleration is primarily associated with focal brain injury—localized damage to the brain—such as cerebral contusion and subdural haematoma (Gennarelli, 1993). Given the severity of these injuries, measures of linear acceleration were widely used to develop brain injury criteria, tolerance thresholds, and helmet design (Fernandes & Sousa, 2015; Tierney, 2021; Zhan et al., 2021; Zhang et al., 2004). However, over recent years, more researchers attribute rotational kinematics to the risk for concussion (Kleiven, 2013). Holbourn (1943) was the first to hypothesize that brain deformation would primarily occur from rotational motion, given that brain tissue has a high tolerance to compression (high bulk modulus) but low resistance to shear deformation (low shear modulus). Between the 1960s and 1970s, Ommaya and colleagues tested Holbourn's hypothesis, performing a series of primate experiments (Ommaya et al., 1968, 1970; Ommaya, Hirsch, Flamm, et al., 1966; Ommaya, Hirsch, & Martinez, 1966; Ommaya & Gennarelli, 1974; Ommaya & Hirsch, 1971). While both linear and rotational head motion contributed to focal injuries in the brain, they found that only rotation produced diffuse brain injury—such as concussion. "Real world" impacts in collision sports involve both linear and rotational motion (S. Rowson et al., 2016). Therefore, both types of motion are considered when assessing head impact events (Tierney, 2021).

Each head impact event results in a distinct combination of rotational and linear kinematics. The magnitude, or severity, of the head impact event is influenced by characteristics of the impacting object, including: velocity, mass, stiffness/compliance, damping, and location/angle (Karton & Hoshizaki, 2018). For instance, the amount of energy transferred from the object to the head/brain depends on the velocity and mass of the impacting object. But the level of compliance—or stiffness—between the impacting object and impacted body will influence the duration of energy transmission to the head/brain. Furthermore, the location and direction of the applied force will influence the head's dynamic response, including the degree of head rotation. Clark et al. (2016) and Kendall et al. (2020) reconstructed four different head impact events in collision sports, which resulted in concussion (shoulder collisions, puck impacts, falls to ice, and punches). They used a helmeted, anthropometric (ATD) headform with accelerometers to measure the linear and rotational head acceleration curves (Figure 1.4.). Although each head impact event led to concussion, they observed variation in the shape and duration of the acceleration curves, and peak magnitude of head accelerations for each type of collision. For example, mean peak accelerations for shoulder collisions and punches were lower in magnitude but longer in duration than puck or ice impacts to the head. Differences were attributed to the varying compliance between the impacting object and impacted “dummy” (Clark et al., 2016; Kendall et al., 2020).

In a high-speed, collision sport like ice hockey, the head can be impacted in many ways. As demonstrated by Clark et al. (2016) and Kendall et al. (2020), the characteristics of the sports situation influenced the head dynamic response. The interaction between the characteristics of the impacting object (velocity, mass, compliance/stiffness, damping, duration, location/angle) will determine the motion of the struck head, the magnitude of head acceleration, the stresses and strains experienced by the brain, and ultimately the extent of brain tissue damage (Karton & Hoshizaki, 2018; Post, Dawson, et al., 2019). Therefore, to inform prevention strategies accurately and appropriately (e.g., rule changes, environment changes, training) aimed at reducing the frequency and severity of head impacts, biomechanical research approaches (e.g., field studies, laboratory reconstructions) should also examine the characteristics of the sports situation when measuring and describing head impact events. In the current thesis, we combine biomechanical and situational datasets, to expand our understanding of the dynamic response of the head during direct impacts in men’s hockey and inform head impact prevention strategies.

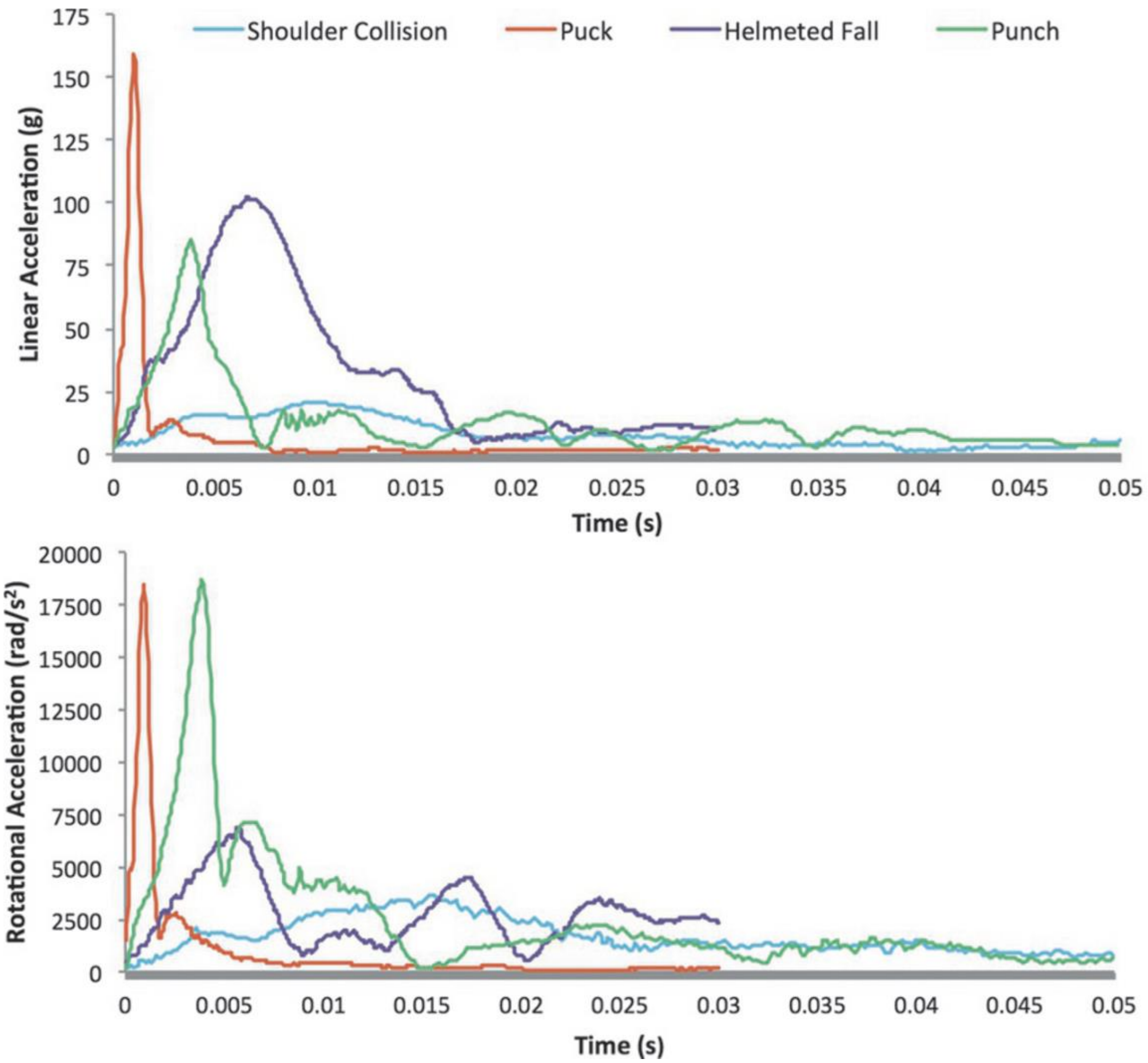


Figure 1.4. **Linear and rotational head acceleration curves of four different impact events from an anthropometric headform with accelerometers. Based on video analysis, in-laboratory physical reconstructions were performed of head impacts resulting in reported concussions occurring in ice hockey (shoulder collision, puck impact, fall to ice) and mixed martial arts (punch).**

Reprinted from Concussive and subconcussive brain trauma: the complexity of impact biomechanics and injury risk in contact sport, Volume 158 (3rd series), Karton and Hoshizaki, Handbook of Clinical Neurology, page 40, Copyright (2018), with permission from Elsevier.

1.2.5. Brain dynamic response

Measuring the brain's response to head acceleration events is a complex task due to its location within the body (suspended in cerebrospinal fluid within the skull) and its unique mechanical properties (e.g., high bulk modulus and low shear modulus). Brain tissue is viscoelastic, meaning that energy is dissipated during its deformation and not completely returned when the tissue regains its initial shape (Budday et al., 2017; Goldsmith & Plunkett, 2004). The amount of energy absorbed prior to brain tissue failure is also influenced by the rate of loading (Galbraith et al., 1993; Laplaca et al., 1997; Singh et al., 2009). Given the relationship between head motion and brain injury (Holbourn, 1943; Ommaya & Gennarelli, 1974), it was hypothesized that brain tissue deformation (stress or strain) induced by acceleration of the head would result in brain changes that lead to clinical injury. Since then, researchers have shown how mechanically induced strains disrupted brain structure and function in physical models (Al-Bsharat et al., 1999; Bayly et al., 2005; Hardy et al., 1997, 2001; Hodgson et al., 1966; Trosseille et al., 1992) and finite element models (Ji et al., 2014; Kleiven, 2007; Kleiven & Hardy, 2002; Takhounts et al., 2013). It is now widely accepted that brain tissue deformation may lead to concussive injury.

Despite these advances, few studies have examined brain tissue deformation in sub-concussive head acceleration events in hockey. Post et al. (2019) reconstructed concussive and sub-concussive impacts in professional hockey from video, using physical and finite element models to measure head kinematics and brain tissue deformation. The magnitudes of strain reported for both concussive and sub-concussive groups were at levels where damage to neural tissue would have been expected (Bain & Meaney, 2000). These results indicated that repetitive head acceleration events sustained in games could lead to cumulative loading and strain of the brain tissue (Karton & Hoshizaki, 2018), supporting studies that observed structural changes to the brain over the course of a single season in contact sport (Nauman & Talavage, 2018). Post and colleagues also found that the relationship between rotational head metrics (acceleration, velocity) and brain tissue strain was stronger when each impact source (shoulder, elbow, ice, puck) was considered independently (Post, Dawson, et al., 2019). In addition to head kinematics, characteristics of the impact should also be considered when evaluating the dynamic response of the brain tissue during head impacts in hockey.

The acute pathophysiology of concussion is thought to be induced by mechanical forces that initiate brain strain. Upon impact, Giza and colleagues reported a transient disruption of the cellular membrane, which led to an abnormal neurotransmitter release and ion flux in the neurons (Giza et al., 2018). A large amount of energy is required for ion pumps to restore to their resting state, placing the neurons in an energy crisis and period of metabolic depression. Consequently, calcium starts to accumulate in the brain cells which disrupts normal neuron function. This neurometabolic disturbance, in combination with cytoskeletal damage, axonal disruption, neurovascular alterations, and/or ongoing inflammation, is thought to result in subsequent symptoms of concussion. However, as stated by Giza and colleagues, one of many important questions remain: “do subsymptomatic impacts (e.g., subconcussive blows) induce brain energy crisis, and if so, how can they be monitored?” (Giza et al., 2018, p. 55).

Given the association between head accelerations and brain trauma, this thesis contributes knowledge on the loading conditions of sub-concussive head impacts, which is an essential piece of the understanding the relationship between collisions in sports and brain tissue damage. Our findings may also be used to inform biomechanical approaches (e.g., finite element models, anthropometric test device reconstructions) in research, test standards and protective gear innovations (e.g., helmets, shoulder padding) aimed at reducing cumulative brain strain from direct head impacts.

1.3. Approaches to examine the circumstances and severity of head impacts in ice hockey

Several approaches have been used to examine the nature of head impacts in hockey. Of relevance to this thesis are systematic video analysis, wearable head sensors, and anthropometric test device reconstructions. In this section, I discuss these research approaches, how they may be used to describe head impacts events, and assess the strengths and limitations of these approaches in contributing to the understanding and prevention of head impacts events.

1.3.1. Wearable head sensors

In the last 20 years, technological advancements have led to the development of wearable sensors to measure the head impact kinematics during real-life impact events in ice hockey (Le Flao et al., 2022). These wearable head sensors include skin patches, mouthguards, helmet-mounted and head-mounted devices (Patton, 2016). Each device is equipped with an accelerometer and/or gyroscope to measure head linear and rotational kinematics during head impacts. Built-in proprietary algorithms estimate the location of head impact, as well as detect and remove false recordings. Across all wearable head sensors, a major concern is the potential for false-positive and false-negative readings (Cortes et al., 2017; Kuo et al., 2018; Patton et al., 2020). In a recent systematic review, Patton et al. (2020) stated that 67% of publications using wearable head sensors in sport did not report video confirmation and/or observer methods to verify sensor-recorded events. Without verification and the removal of false-positive events, measures of direct head impact exposure may be overestimated by up to 35% and 92% for helmet-mounted sensor and mouthguard sensor systems, respectively (Cortes et al., 2017; L. C. Wu et al., 2018). Thus, it is recommended that confirmation methods (video and/or observer) are used in combination with sensor data, to improve the accuracy of estimations for direct head impact exposure (Kuo et al., 2018; Patton et al., 2020).

In hockey, most published studies have utilized the Head Impact Telemetry System (HITS; Simbex, Lebanon, NH, USA) to record head impacts (Table 1.1.). Despite its popularity, recent studies have scrutinized the reliability and validity of HITS, and other helmet-mounted systems, to accurately capture head kinematics during impact events (Cummiskey et al., 2017; Jadischke et al., 2013; L. C. Wu et al., 2016). When compared to “gold-standard” kinematic measures from an anthropometric test dummy head, factors such as impact direction, and helmet make, model, fit, and dislocation, influenced the accuracy and/or classification of impacts measured by HITS (Allison et al., 2014; Jadischke et al., 2013; G. P. Siegmund et al., 2016). An alternative helmet-mounted sensor system is the GForceTracker^{TM} (GFT; Artflex, Markham, ON, Canada). Previously used in lacrosse (Cortes et al., 2017; Kindschi et al., 2017) and football studies (Muise et al., 2016), the GForceTracker^{TM} is a small, cost-effective system which can be easily adhered to the shell of the players’ helmet to measure head impacts. It records linear accelerations and rotational velocities at 3000 Hz and 800 Hz, respectively (Figure 1.5.). Like HITS, helmet dislocation/make/model, and impact direction affected the accuracy of the head acceleration measurement by the GFT (Allison et al., 2015; Campbell et al., 2016; Knowles et al., 2017). However, compared to HITS, a key advantage of the GFT is related to the accuracy of rotational kinematic measurements—which is important given the association between rotational kinematics and risk for brain injury (Weaver et al., 2012). Allison and colleagues compared head kinematics from HITS and GFT mounted in hockey helmets to anthropometric headform measures (Allison et al., 2014, 2015). They found that errors for rotational kinematics were smaller from gyroscope-containing GFT measures (2-18%) than accelerometer-only HITS measures (12-50%). Both rotational velocity and acceleration are good predictors of strain within the brain , however measures of rotational velocity data are inherently less noisy than rotational acceleration data. Thus, Allison and colleagues recommended the use of rotational velocity measures from helmet-based systems (Allison et al., 2015).

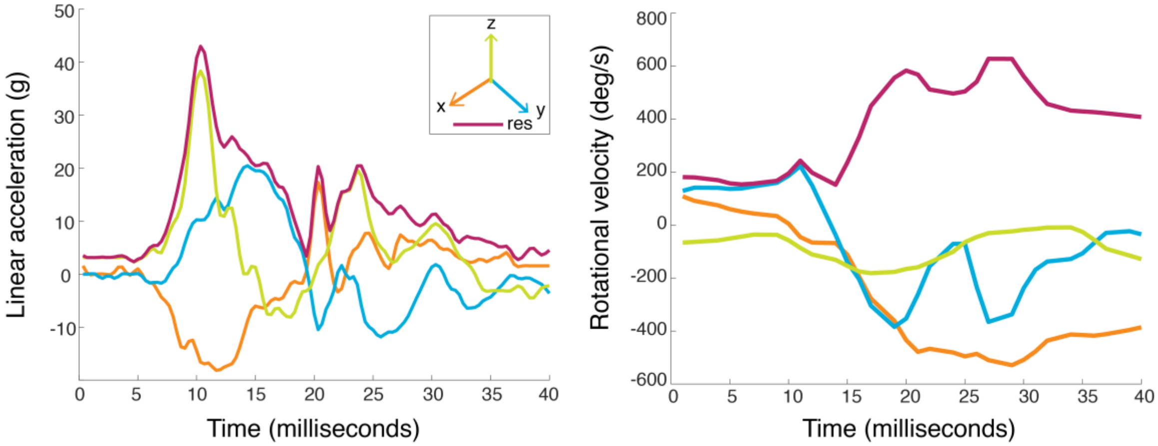


Figure 1.5. **Raw traces of linear acceleration and rotational velocity for GForceTracker^{TM} recordings of a shoulder-to-head impact.**

In hockey, many studies have used sensor-based measures to examine head impact exposure during game play (Brainard et al., 2012; Mihalik et al., 2008, 2012, 2020; Wilcox, Beckwith, et al., 2014). Specifically in men's university hockey, Brainard et al. (2012) and Wilcox, Beckwith, et al. (2014) each recorded over 15,000 head impact events. Wilcox, Beckwith, et al. (2014) reported median peak linear and rotational accelerations of 15.7 g and 1630 rad/s^2 (Table 1.1.), and both studies found that men's university hockey players sustained more impacts to the side (~30%), back (~30%) and front (~30%) of the head than the top (<10%). However, these studies did not combine sensor measures with video capture and analysis of the impact event. Accordingly, they provide little insight on how head impacts occurred, and how this depended on the playing situation (e.g., puck possession, playing zone, visible signs of concussion and anticipation of the collision). Moreover, neither study used video and/or observer confirmation to verify the recorded head impact event (e.g., true-positive). Thus, these estimates of head impact exposure (frequency, severity, and location of impact) from sensor-recorded events in men's hockey were likely inconsistent, overestimated, and consequently may misinform prevention efforts (Cortes et al., 2017; Kuo et al., 2018;

Patton et al., 2020; L. C. Wu et al., 2018). This thesis uses a combination of video and sensor datasets to provide more confidence in our measures of head impact exposure and improve our understanding of scenarios that lead to the most common and severe head impacts.

1.3.2. Systematic video analysis

Systematic video analysis can contribute information on the playing situation and whole-body biomechanics associated with head impact events (Figure 1.6.). Previous studies have focused on using video analysis to understand the mechanism and risk factors for concussive injury in men's professional ice hockey (Bruce et al., 2018; Echemendia et al., 2018; Hutchison et al., 2015b, 2015b), based on a standardized questionnaire for extracting features of the playing situation (Hutchison et al., 2014). Video footage can also be calibrated to allow for one or two-dimensional kinematic estimates of player motion during head impacts. For example, Post et al. (2018) utilized a single camera view to estimate impact speeds and location on the helmet from head impact events in hockey.

A small number of studies have combined head sensor measures with systematic video analysis of head impacts in hockey (Table 1.1.). In men's university hockey, Wilcox, Machan, et al. (2014) examined 270 head impact videos synchronized with helmet-sensor kinematic data. They found that 50% of head impacts were due to contact with another player, but contact with the ice resulted in higher linear accelerations. In male youth hockey, studies found that up to 63% of head impacts occurred along the perimeter of the ice rink (Goulet et al., 2016; Malenfant et al., 2012; Mihalik, Blackburn, et al., 2010), yet open-ice collisions resulted in greater linear and rotational head accelerations (Mihalik, Blackburn, et al., 2010). Moreover, in male youth hockey, anticipated head impacts were nearly six times more common, but were just as severe as unanticipated head impacts (Mihalik, Blackburn, et al., 2010). Lastly, Mihalik, Greenwald, et al. (2010) observed that 17% of head impacts in male youth hockey were penalized and that penalized events were associated with greater head accelerations.

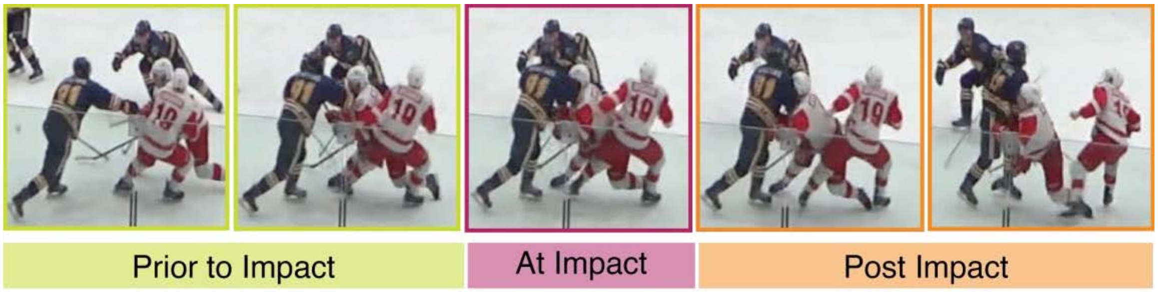


Figure 1.6. **Screenshots of video footage before, during, and after the head impact event.**

There are important limitations to previous studies using video analysis. Most studies used a single camera that followed the puck and reported missing impact events due to occlusion or being outside of the camera's field of view (Goulet et al., 2016; Malenfant et al., 2012; Mihalik, Blackburn, et al., 2010; Mihalik, Greenwald, et al., 2010; Wennberg, 2004; Wilcox, Machan, et al., 2014). A system with two or more cameras may reduce the probability of missed impacts and allow researchers to obtain multiple views of head impact events occurring "behind" or "ahead" of the play (Cortes et al., 2017; Le Flao et al., 2022). Furthermore, previous studies provided few details on the exact body parts and environmental objects that impacted the head (e.g., boards vs glass; shoulder vs elbow or hand), each of which provide specific opportunities for prevention (e.g., modifications to the boards or glass, or padding of the shoulder, elbow or hand) (Bahr & Krosshaug, 2005). This thesis addresses these limitations and provide more detailed evidence on the biomechanical and situational characteristics of head impacts in men's hockey. We collect video footage of direct head impacts from a five-camera system and analyze each video with a structured questionnaire to classify perceived characteristic of the event before, during, and after the head collision.

Table 1.1. Published studies examining head acceleration events from sensor-based measures in ice hockey

Study: Population of hockey players	Device	Trigger threshold*	Inclusion threshold*	Video verification*	Resultant linear acceleration (g)	Resultant rotational acceleration (rad/s^2)
Mihalik et al. (2020):	HITS	NR	10 g	No		
Male youth (n=110, age=13-16)					Median 17.1	Median 1353
Female youth (n=25, age=13-16)					Median 18.1	Median 1502
Kiefer et al. (2018):	GFT	20 g	20 g	No		
Male high school (n=15; mean 17)					Mean 38.4	—
Eckner et al. (2018):	xPatch	10 g	NR	No		
Male high school (n=21; age mean=16)					Mean 17.1	Mean 3058
Female high school (n=19, age mean=16)					Mean 18.8	Mean 2778
Reed et al. (2017):	HITS	10 g	10 g	No		
Female youth (n=27; age=11-14)					Mean 16.6	Mean 1329
Myer et al. (2016):	GFT	10 g	20 g	No		
Male high school (n=15; age mean=16)					Mean 37.4-38.3	—
Schmidt et al. (2016):	HITS	NR	NR	No		
Male youth (n=29; age=13-18)					Mean 20.0-21.1	Mean 1755-1834
Wilcox et al. (2015):	HITS	NR	NR	No		
Female university (n=58, age=NR)					Median 15.3	Median 1249
Wilcox, Beckwith et al. (2014):	HITS	NR	NR	No		
Male university (n=41; age=NR)					Median 15.7	Median 1630
Female university (n=58, age=NR)					Median 15.0	Median 1211
Wilcox, Machan, et al., (2014):	HITS	NR	20 g	Yes		
Male university (n=23; age=19-25)					Mean 31.2	Mean 2881
Female university (n=31; age=19-25)					Mean 28.3	Mean 1767
Brainard et al. (2012):	HITS	9.6 g	10 g	No		
Male university					NR	NR

Study: Population of hockey players	Device	Trigger threshold*	Inclusion threshold*	Video verification*	Resultant linear acceleration (g)	Resultant rotational acceleration (rad/s^2)
(n=37, age=NR) Female university (n=51, age=NR)					NR	NR
Mihalik et al. (2012): Male youth (n=52; age=13-16)	HITS	NR	10 g	No	Mean 18.4	Mean 1465
Mihalik et al. (2011): Male youth (n=37; age=13-16)	HITS	NR	10 g	No	Mean 17.5	Mean 1588
Mihalik, Greenwald, et al. (2010): Male youth (n=16; age=11-14)	HITS	NR	10 g	Yes	Mean 21.5	Mean 1441
Reed et al. (2010): Female youth (n=13, age=13-14)	HITS	NR	10 g	No	Mean 22.1	Mean 1557
Mihalik, Blackburn, et al. (2010): Male youth (n=16; age=11-14)	HITS	10 g	10 g	Yes	Mean 21.0-23.0	Mean 1418-1530
Mihalik et al. (2008): Male youth (n=14, age=11-14)	HITS	10 g	10 g	No	Mean 19.0	—
Naunheim et al. (2000): Male high school (n=1; age=NR)	Custom	10 g	10 g	No	Mean 35.0	—

GFT = GForceTracker™; HITS = Head Impact Telemetry System; NR = Not reported
*Data reported by LeFlao et al., 2021, who defined “trigger threshold” as the threshold used based on raw data to trigger the recording of an impact and “inclusion threshold” as the threshold used based on the peak resultant linear acceleration value to select impacts for analysis.

1.3.3. Anthropometric test device reconstructions

Anthropometric test device (ATD) reconstructions can be performed to examine head impacts in controlled laboratory conditions (Figure 1.7.). Adopted from the automotive industry, an ATD (or crash test dummy) represents the anthropometry and passive articulation of the human body and contains built-in sensors which record the dynamic behaviour of the body segments during impact. In collision sports, researchers have used video-based and/or sensor-based input parameters from real-life impact events to inform the reconstruction of head impacts (Kendall et al., 2020; Post, Hoshizaki, et al., 2019). Typically, a mechanical test system (e.g., linear or pneumatic impactor, drop tower) strikes a helmeted ATD head, which records head kinematics at high frequency and resolution. As mentioned in Section 1.2.3., the accuracy of the reconstruction depends on the "biofidelity" of the system in simulating the velocity, mass, and stiffness of the head and the object striking the head (Payne et al., 2016) .

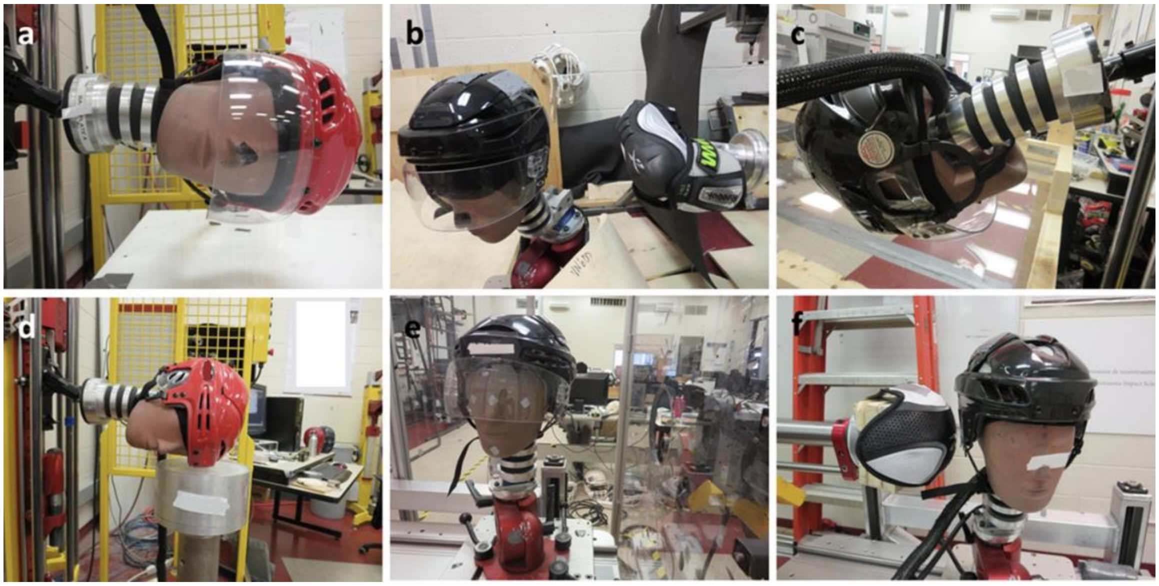


Figure 1.7. Images of the headform physical model reconstructions for: (a) Boards; (b) Elbow; (c) Glass; (d) Ice; (e) Puck; and (f) Shoulder.
Reprinted from The Biomechanics of Concussion for Ice Hockey Head Impact Events, Volume 22, Issue 6, Post et al., Computer Methods in Biomechanics and Biomedical Engineering, page 634, Copyright (2019), with permission from Taylor and Francis Group.

For the current thesis, of particular interest is understanding the impact characteristics (e.g., effective mass, stiffness, and damping) of the body in delivering a shoulder check, which has been observed to be the leading cause of concussions in hockey (Hutchison et al., 2015b). No study has measured shoulder stiffness and damping during checking. Furthermore, the effective mass of the shoulder has been examined only for laboratory simulations of impacts to the head occurring in 'open ice', as opposed to along the boards (Rousseau & Hoshizaki, 2015). In that study, players delivered shoulder checks to a freely moving headform suspended by an overhead cable, while skating through the collision. While open-ice impacts may be the most dangerous, studies have shown that head impacts more commonly occurred along the periphery of the rink to opponents who were contacting or near the boards/glass (Goulet et al., 2016; Malenfant et al., 2012). Moreover, checks were often delivered in a lateral direction, from slow speeds, with the shoulder brought stationary by the collision (Potvin et al., 2019). In the current thesis, we measure the effective stiffness, damping and mass of the body during laboratory experiments where hockey players deliver shoulder checks to a mechanical apparatus, simulating an opponent sandwiched against the boards or glass shielding.

1.4. Summary

There is growing evidence on the association between cumulative head trauma and brain injury, which creates the need to minimize (and ultimately eliminate) head impacts in ice hockey (Karton & Hoshizaki, 2018; Nauman & Talavage, 2018). A more comprehensive understanding of the circumstances of direct head impacts in hockey may inform improvements in brain injury prevention (Bahr & Krosshaug, 2005; Schneider et al., 2019). The combined use of wearable sensors, systematic video analysis, and anthropometric test device reconstruction can improve our understanding of head impacts (Tierney, 2021). There is a lack of understanding on the most common body parts and the most common environmental objects to strike the head in hockey. For example, previous studies have combined upper limb body parts, and boards and glass, but did not report which specific object or body part impacted the head. In hockey, there is also a lack of understanding on the factors that influence impact severity, including the mass, stiffness and damping of the impacting objects. Few studies have compared the head kinematics involved in different impact scenarios, from on-ice sensor-based measures (Wilcox, Machan, et al., 2014) or lab reconstructions (Kendall et al., 2020; Post, Hoshizaki, et al., 2019). Moreover, there is limited research on the impact dynamics governing head collisions in ice hockey (Rousseau & Hoshizaki, 2015).

This thesis addresses these knowledge gaps through a combination of on-ice and off-ice studies conducted in partnership with the Simon Fraser University (SFU) Men's Ice Hockey team. The specific objectives are described in the next section.

1.5. Objectives

In this thesis, we examine the characteristics and risk factors for head impacts in men's university hockey. In partnership with the SFU Men's Ice Hockey team, we conducted an observational study using video and helmet-mounted sensors to identify the circumstances surrounding the most common and severe types of head impacts in men's university hockey. In addition, we also used experiments and mathematical models to characterize the dynamic response of the body during shoulder checking, a leading cause of head impacts and concussions in hockey. By improving our knowledge on the mechanism of head impacts in hockey, we seek to provide an evidence base to inform the design of improved strategies (e.g., injury screening, player training, rink design, equipment, and rules of play) to reduce the frequency and severity of head impacts and brain injuries in hockey. The objectives of this thesis were:

1. To identify the most common scenarios for direct head impacts in men's university ice hockey, through collection and analysis of video footage from game play (**Chapter 2**)
2. To determine how the impact scenario (measured in Objective 1) associates with the severity of direct head impacts in men's university ice hockey, as measured from helmet-mounted sensors (**Chapter 3**); and
3. To measure the effective mass, stiffness, and damping of the body during laboratory simulations of shoulder checks (observed in Objectives 1 and 2) in men's university ice hockey (**Chapter 4**).

1.6. Published studies

Research contained in this thesis has been published in the following peer-reviewed journals:

Chapter 2	Aguiar, OMG., et al., "American Society of Biomechanics Journal of Biomechanics Award 2019: Circumstances of head impacts in men's university ice hockey." Journal of Biomechanics (2020).
Chapter 4	Aguiar, OMG., et al., "Effective stiffness, damping and mass of the body during laboratory simulations of shoulder checks in ice hockey." Sports Biomechanics (2021).

In each chapter, the full articles—including tables, figures, and supplementary data—are provided verbatim (unless otherwise stated) with permission from the publishers.

Chapter 2.

Circumstances of head impacts in men's university ice hockey

This observational study examines the circumstances of head impacts in men's university ice hockey from 836 head impacts across five seasons from 2014-19. A subset of the data (449 head impacts across three seasons from 2014-17) was accepted for publication in the following peer-reviewed journal:

Aguiar, OMG., et al., (2020), "American Society of Biomechanics Journal of Biomechanics Award 2019: Circumstances of head impacts in men's university ice hockey." Journal of Biomechanics, https://doi.org/10.1016/j.jbiomech.2020.109882

In the current thesis, I refer to **Chapter 2** (not the publication) where applicable. This chapter includes text, figures, and tables from Aguiar et al. (2020), which were updated to reflect the larger dataset. Despite differences in sample sizes, the distribution of data across categories, statistical outcomes, and results between this chapter and Aguiar et al. (2020) are nearly identical. **Appendix A and B** of this thesis contains supplementary data (Head Impact Video Evaluation questionnaire) and Table 1. published in Aguiar et al. (2020).

2.1. Abstract

This observational study examined the circumstances of head impacts in men's university ice hockey. Video footage was collected of 836 head impacts experienced by 58 players over 51 games. Videos were analyzed using a reliable, structured questionnaire to classify: playing zone, location on ice, puck possession, direction of gaze, object striking the head, location of head impact, trajectory of colliding players, and penalties. Generalized Linear Models were used to compare response categories for the proportion of players experiencing at least one head impact, and the number of head impacts per player. The majority of events resulting in head impact involved contact with another player (92%). Head impacts occurred most often to players who did not have puck possession, who were checked along the boards in their offensive zone. Players were just as likely to experience head impact with an environmental object, as with an

opposing player’s body part. Glass-to-head impacts represented 28% of cases, four times as common as board-to-head impacts. Hand-to-head impacts accounted for 22% of cases, nearly twice as common as shoulder- or elbow-to-head impacts. In 30% of events, there were two or more successive impacts to the head (e.g., contact with shoulder and then boards). Only 14% of head impacts which involved contact with another player resulted in infractions. Our results support the need for additional research on the benefits of stricter rule enforcement, and modifications to the stiffness of glass and padding of gloves, for reducing the frequency and severity of head impacts in ice hockey.

2.2. Introduction

Ice hockey is a fast-paced sport where players frequently experience impact to the head. The incidence of traumatic brain injury (TBI), including concussion, is higher in ice hockey than other team sports, and accounts for 44% of brain injuries related to team sports in Canada (Cusimano et al., 2013; Zuckerman et al., 2015). Furthermore, cumulative loading of the brain from repeated head impacts, even at sub-concussive levels, may have long-term neurological consequences including depression and cognitive decline (Karton & Hoshizaki, 2018). Accordingly, any opportunity to reduce the frequency and severity of head impacts in hockey should be explored. To inform these efforts, a greater understanding is required on the real-life circumstances of head impacts during game play.

Previous studies have capitalized on the rich potential of video footage to examine the nature of head impacts in ice hockey. For example, Wilcox, Machan, et al. (2014) analyzed videos of 270 head impacts in men’s university-level hockey, and found that 50% of cases involved the head being struck by a body part of an opposing player, and 31% involved the head impacting the glass or boards. Mihalik, Blackburn, et al. (2010) analyzed 666 head impacts in male bantam-level hockey involving collisions with an opposing player. They reported that 63% of events took place along the boards, and 15% of cases seemed to be unanticipated.

These studies were limited by use of a single camera that followed the puck, causing the potential to miss head impacts occurring in regions of the ice away from puck play. Furthermore, they provide few details on the exact body parts and environmental objects that impacted the head, each of which provide specific opportunities for prevention (e.g., modifications to the boards versus glass, or padding of the shoulder versus the elbow or hand). Moreover, they did not examine the number and nature of penalties called by referees in collisions that resulted in head impact by an opposing player.

We conducted this observational study to address these limitations, and to provide more detailed evidence on the biomechanical and situational characteristics of head impacts in men's university hockey. We collected video footage of head impacts in men's university hockey over three seasons of home games and analyzed each video with a structured questionnaire (which we evaluated for inter-rater reliability) to classify perceived characteristics of the event before, during, and after head collision. We hypothesized that differences would exist between response categories in the frequency of head impacts (based on the probability of experiencing at least one head impact, and the number of head impacts per participant). We also hypothesized that, in events involving player-on-player contact, infractions would be more common when the head was the first body part to be struck by an opposing player.

2.3. Materials and methods

2.3.1. Participants

Sixty-eight members (46 forwards and 22 defensemen) of the Simon Fraser University (SFU) Men's Ice Hockey team (British Columbia Intercollegiate Hockey League) participated in the study over five consecutive seasons from 2014-19. The study was approved by the Research Ethics Board of SFU and written informed consent was obtained from all participants.

2.3.2. Video Collection

Video footage of 51 SFU home games were acquired over five seasons. Five video camcorders (2 x Sony HDR-CX330 and 3 x Sony HDR-CX405BKIT, each recording at 60 frames per second and 1920 x 1080 pixel resolution) were stationed around the rink to provide full ice coverage from multiple vantage points, recording from the start to end of the game. Six trained research assistants watched each game from different angles around the rink, and noted the time, location and player numbers for each observed head impact. These game notes, along with corresponding time stamps, were then used to search the video footage and confirm the occurrence of head impacts. Video footage of each head impact was clipped at least 10 seconds before and after the head impact using Adobe Premier Pro (CS4 or above) and stored for further analysis.

2.3.3. Video Analysis

Three raters analyzed each head impact video independently with a structured questionnaire that was assessed for reliability (see section below on Inter-rater reliability). The questionnaire incorporated 12 questions with structured response categories (**Appendix A**). Seven of the 12 questions were adapted or modified from previously published, reliable tools for coding situational factors related to head impact in ice hockey, including the Heads Up Checklist (Hutchison et al., 2014) and the Carolina Hockey Evaluation of Children's Checking List (Mihalik, Blackburn, et al., 2010). Raters were undergraduate students who received training from the authors on how to interpret each question and response category. Using the VLC media player (v2.2.1-3.0.8; VideoLAN, Paris, France) or QuickTime Player (v10.4; Apple, Cupertino, USA), raters were able to review each video as many times as desired, in both regular and slow motion. Final answers for a given video were based on the option chosen by at least 2 of the 3 raters. If there was no consensus between the three raters (on questions that included three or more response categories), a fourth rater selected the best perceived response.

The questionnaire probed observable characteristics before and during impact to the head. Regarding the factors that preceded head impact, we classified: whether the player was looking in the direction of the checking player, the playing zone and location on the ice where the head impact occurred, and whether the player receiving the head impact was in possession of the puck. For location on the ice, the rink was divided into "perimeter" (compromised of the contacting or near the side boards, corners, end boards), "open ice" (interior portion of ice not accounted for by perimeter), and "near the net" (circumference surrounding the net— including the crease area). "No puck possession" included cases where the player just released the puck, was attempting to gain puck possession or had no possession of the puck.

Regarding the factors at the instant of head impact, we examined: the specific object or body part contacting the head, the location on the head receiving the impact, the directions (trajectory) of players involved in collisions, whether the head was the first site of contact, and whether the event caused more than one successive impact to the head (e.g., contact to an opposing player's shoulder followed by contact to the glass). The object striking the head was classified as "hand," "elbow/forearm," "shoulder/upper arm," "glass," "board/caprail," "ice," "puck," "net," "head," "torso," or "lower limb."

Regarding features of the event after head impact, we examined the number of cases involving player-on-player contact that resulted in penalties, including cases involving perceived infractions (where the head was the first body part to be struck, or where the player did not have puck possession). In particular, the video was examined to determine whether the on-ice officials signalled for a penalty related to the impact event. Game notes (jersey number, game clock time, rink location) were matched to box score data from the league's website (*BC Intercollegiate Hockey League*, 2022) to identify the type of infraction.

2.3.4. Inter-rater reliability

We tested the inter-rater reliability of each item in our questionnaire by comparing responses between two independent raters who each reviewed the same 30 videos (Table B.2. in **Appendix B**). We calculated total percent agreement (TPA), Cohen's kappa (k) (Cohen, 1960), and Brennan-Prediger's free marginal kappa (k_n)—which is less influenced by prevalence and bias (Brennan & Prediger, 1981; Sim & Wright, 2005). Based on the recommendations of Landis and Koch (1977) for interpreting kappa values, we observed substantial to near perfect agreement ($k_n \geq 0.61$) for 9 of 12 questions. The exceptions were moderate agreement ($0.60 \geq k_n \geq 0.41$) for whether the head was the initial point of contact, and fair agreement ($0.40 \geq k_n \geq 0.21$) for puck possession and whether the player was looking towards the collision. Specifically for puck possession, by collapsing from four categories (clear possession, attempting to gain possession, just released puck, no possession) into two (clear puck possession or no puck possession), near perfect agreement was achieved (TPA=97%, k_n=0.93).

2.3.5. Statistical analysis

To account for potential correlation among repeated head impacts by a given participant, we used Generalized Linear Models (GLM) to examine associations between the frequency of primary head impacts and situational (explanatory) variables derived from video analysis. For each explanatory variable, we examined whether there were differences between the response categories in two outcome variables: (a) the estimated proportion of participants experiencing at least one head impact, and (b) the estimated number of head impacts per participant. More specifically, we created a dummy variable for head impact (1 when a participant experienced head impact at least once and 0 when they did not experience head impact for each category of the explanatory variable). We then tested for differences across response categories in the estimated proportion of participants with at least one head impact using logistic regression. We also tested for differences in the estimated number of head impacts across response categories using log-linear Poisson regression. Lastly, we examined all possible pairwise comparisons between categories for estimated proportion and number of head impacts. Reported means and confidence intervals were back-transformed for interpretation of the results. All analyses were performed on IBM SPSS Statistics for Macintosh (v25.0; IBM Corp., Armonk, USA).

2.4. Results

2.4.1. Video footage of head impacts

We identified and analyzed a total of 836 events involving head impacts to SFU players over the 51 home games. Head impacts were experienced by 58 unique players, including 15 defensemen (170 events), and 43 forwards (666 events). The average number of head impacts per player per game was 0.28 (range=0.02-1.37). The mean body mass and height of player receiving the head impact were 82.4 kg (SD=7.3, range=68.0-96.1) and 180.1 cm (SD=5.9, range=167.6-198.1). The mean body mass and height of the player delivering the head impact were 86.0 kg (SD=7.5, range=68.2-111.4) and 183.8 cm (SD=6.3, range=154.9-198.1).

In 587 events, there was only a single impact to the head. 249 events (30%) involved two successive impacts to the head, and more than one-fourth of those events (n=54 of 249) involved three impacts to the head (e.g., impact to the head by another player's upper limb, followed by the head impacting the glass, and finally the ice). We refer to these as primary, secondary, and tertiary impacts. Unless stated explicitly, the following analysis focuses on the first (primary) impact to the head.

2.4.2. Situational factors preceding impact to the head

Playing zone. The proportion of participants having at least one head impact was higher for the offensive zone than the defensive or neutral zones (p=0.002). Significant differences were also observed between all zones in the number of head impacts per player (p≤0.001). 53% of events occurred in the offensive zone of the player receiving the head impact, followed by 36% and 11% of events in the defensive and neutral zones, respectively (Table 2.1.).

Location on the ice. The proportion and number of head impacts per participant were significantly higher for the perimeter of the ice than all other categories (p≤0.001). 75% of head impacts occurred while the receiving player was near or in contact with the boards around the perimeter of the rink, and 15% occurred in open ice (Table 2.1.).

Puck possession. The proportion and number of head impacts per participant were significantly lower for those with (versus without) puck possession (p≤0.001). Among the 836 primary head impacts, 89% occurred to players without puck possession, and 11% occurred to players who had puck possession (Table 2.1.). Players did not have puck possession in nearly 89% of events where they received secondary head impacts (n=222 of 249) and 93% of events involving tertiary head impact (n=50 of 54).

Table 2.1. Estimated proportion of players experiencing at least one head impact, and average number of head impacts per player, for situational factors preceding head impact (playing zone, location on ice, puck possession, and direction of gaze).

	Frequency	**Participants experiencing head impact**		**Number of head impact per participant**	
	Number (% of head impacts captured)	Estimated proportion (95% CI)	p value	Estimated count (95% CI)	p value
Playing zone *	n = 836		0.002		≤ 0.001
Offensive zone	440 (52.6%)	0.91 (0.81 – 0.96)		7.6 (6.9 – 8.3)	
Defensive zone	301 (36.0%)	0.78 (0.65 – 0.87)		5.2 (4.6 – 5.8)	
Neutral zone	95 (11.4%)	0.67 (0.54 – 0.78)		1.6 (1.3 – 2.0)	
Location on ice	n = 836		≤ 0.001		≤ 0.001
Perimeter	628 (75.1%)	1.00 (1.00 – 1.00)		10.8 (10.0 – 11.7)	
Open ice	127 (15.2%)	0.55 (0.42 – 0.67)		2.2 (1.8 – 2.6)	
Near the neat (crease)	81 (9.7%)	0.53 (0.41 – 0.66)		1.4 (1.1 – 1.7)	
Puck possession*	n = 836		≤ 0.001		≤ 0.001
No possession	740 (88.5%)	0.64 (0.51 – 0.75)		12.8 (11.9 – 13.7)	
Clear possession	96 (11.5%)	1.00 (1.00 – 1.00)		1.7 (1.4 – 2.0)	
Looking in direction of collision*	n = 836		1.000		0.299
Yes	433 (51.8%)	0.95 (0.85 – 0.98)		7.5 (6.8 – 8.2)	
No	403 (48.2%)	0.95 (0.85 – 0.98)		7.0 (6.3 – 7.7)	

*Relative to the player receiving the head impact.

Direction of gaze. There was no difference in the number of head impacts or proportion of participants experiencing at least one head impact for the player not looking (versus looking) in the direction of the impending collision (p>0.298). In 52% of events, the checked player was perceived to be looking in the direction of the collision (Table 2.1.).

2.4.3. Situational factors observed at the instant of head impact

Objects associated with head impact. In 92% of events (n=779), the scenario leading to head impact involved contact with another player (opponent in 768 cases, teammate in 11; Figure 2.1.). Players were just as likely to experience at least one head impact with an environmental object as a body part (p=0.463; Table 2.2.). However, the number of head impacts was higher for body parts than environmental objects (p≤0.001). The head was struck by another players' body part in 60% of cases and impacted an environmental object in 40% of cases.

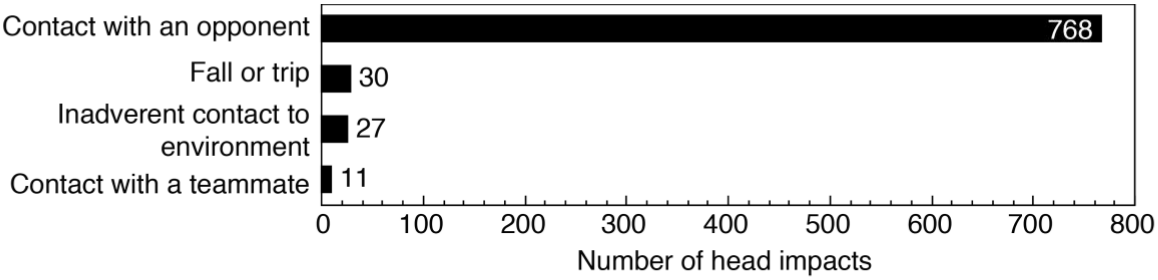


Figure 2.1. Scenarios leading to head impact in men's university hockey (n=836). The numbers represent counts for respective categories.

The most common objects directly striking the head were "board/caprail/glass" and "elbow/ forearm/hand", which accounted for 35% and 33% of 836 cases, respectively (Table 2.2.). The proportion of players receiving at least one head impact, and the number of head impacts per participant, were significantly greater for these two categories than for other categories (p≤0.013). The proportion and number of head impacts associated with "shoulder/ upper arm" and "stick" were significantly greater than "ice" (p≤0.001). The "elbow/forearm/ hand" was the most common object to strike the head in secondary (n=106 of 249) and tertiary (n=37 of 54) impacts, followed by the "board/caprail/glass" (77 secondary and 5 tertiary) and ice (11 secondary and 4 tertiary).

Among upper limb-to-head impacts, the number of head impacts associated with "hand" was significantly greater than for "elbow/forearm" and "shoulder/upper arm" (p≤0.002). "Hand" accounted for 180 of 403 cases (45%), followed by "shoulder/upper arm" (31%) and "elbow/forearm" (24%). For environment-to-head impacts, the proportion and number of head impacts associated with "glass" were significantly greater than for "boards" (p≤ 0.001; Table 2.2.). "Glass" accounted for 80% of 236 cases, and "board/caprail" accounted for 20%. Collectively, this evidence suggests that the three most common objects striking the head were the glass, and the hands and shoulders of opponents.

Impact location on head. The proportion and number of head impacts per participant were significantly greater for impacts to the lateral aspect of the head than for other impact locations (p≤ 0.001). 62% of head impacts were to the lateral aspect of the head (equally divided between the right (31%) and left (31%)), while 18% were to the front of the head, 16% were to the back, and 5% were to the top of the head (Table 2.2.). The number of impacts to the back or front of the head were significantly greater than to the top of the head (p≤0.001).

Table 2.2. Estimated proportion of players experiencing at least one head impact, and average number of head impacts per player, for situational factors at the instant of head impact (objects striking the head, location of impact on the head, initial contact to head, and player trajectories).

	Frequency	Participants experiencing head impact		Number of head impacts per participant	
	Number (% of head impacts captured)	Estimated proportion (95% CI)	p value	Estimated count (95% CI)	p value
Object impacting head	n = 836		≤ 0.001		≤ 0.001
Board/ caprail/ glass	295 (35.3%)	0.91 (0.75 – 0.93)		5.1 (4.5 – 5.7)	
Elbow/ forearm/ hand	277 (33.1%)	0.86 (0.81 – 0.96)		4.8 (4.3 – 5.4)	
Shoulder/ upper arm	126 (15.1%)	0.67 (0.54 – 0.78)		2.2 (1.8 – 2.6)	
Other*	73 (8.7%)	0.57 (0.44 – 0.69)		1.3 (1.0 – 1.6)	
Stick	52 (6.2%)	0.47 (0.34 – 0.59)		0.9 (0.7 – 1.2)	
Ice	13 (1.6%)	0.14 (0.07 – 0.25)		0.2 (0.1 – 0.4)	
Impact to environment object versus another player**	n = 779		0.463		≤ 0.001
Body part	471 (60.5%)	0.95 (0.85 – 0.98)		8.1 (7.4 – 8.9)	
Environmental object	308 (39.5%)	0.91 (0.81 – 0.96)		5.3 (4.8 – 5.9)	
Upper limb contact site***	n = 403		0.087		≤ 0.001
Hand	180 (44.7%)	0.76 (0.63 – 0.85)		3.1 (2.7 – 3.6)	
Shoulder/ upper arm	126 (31.3%)	0.67 (0.54 – 0.78)		2.2 (1.8 – 2.6)	
Elbow/ forearm	97 (24.1%)	0.57 (0.44 – 0.69)		1.7 (1.4 – 2.0)	

	Frequency	Participants experiencing head impact		Number of head impacts per participant	
	Number (% of head impacts captured)	Estimated proportion (95% CI)	p value	Estimated count (95% CI)	p value
Glass versus boards/caprail impacting head	n = 295		≤ 0.001		≤ 0.001
Glass	236 (80.0%)	0.83 (0.71 – 0.90)		4.1 (3.6 – 4.6)	
Board/ caprail	59 (20.0%)	0.53 (0.41 – 0.66)		1.0 (0.8 – 1.3)	
Location of impact on head	n = 836		≤ 0.001		≤ 0.001
Side	514 (61.5%)	1.00 (1.00 – 1.00)		8.9 (8.1 – 9.7)	
Front	152 (18.1%)	0.71 (0.58 – 0.81)		2.6 (2.2 – 3.1)	
Back	131 (15.7%)	0.66 (0.53 – 0.77)		2.3 (1.9 – 2.7)	
Top (crown)	39 (4.7%)	0.40 0.28 – 0.53)		0.7 (0.5 – 0.9)	
Initial contact to head†	n = 779		≤ 0.001		≤ 0.001
No	594 (76.3%)	0.98 (0.89 – 1.00)		10.2 (9.5 – 11.1)	
Yes	185 (23.7%)	0.78 (0.65 – 0.87)		3.2 (2.8 – 3.7)	
Relative trajectory between players*†	n = 779		≤ 0.001		≤ 0.001
Anterolateral	269 (34.5%)	0.90 (0.79 – 0.95)		4.9 (4.4 – 5.5)	
Posterolateral	217 (27.9%)	0.78 (0.65 – 0.87)		3.9 (3.5 – 4.5)	
Anterior	122 (15.7%)	0.69 (0.56 – 0.79)		2.2 (1.8 – 2.6)	
Lateral	96 (12.3%)	0.72 (0.60 – 0.82)		1.8 (1.5 – 2.2)	
Posterior	75 (9.6%)	0.57 (0.44 – 0.69)		1.3 (1.1 – 1.7)	

*Where "other" consists of the puck, net, head, torso, or lower limb; **Where "environment" consists of the boards/caprail, glass, and ice. Excludes n=57 where n=52 for stick, n=2 for puck and n=3 for net; ***Upper limb contact site of player delivering the hit; †Only includes cases involving another player (opponent or teammate)

Head as the initial point of contact. The proportion and number of head impacts per participant was significantly higher for cases where the head was not (versus was) the initial site of contact (p≤0.001). Among events involving contact with another player, the head was the initial point of contact in 185 of 779 (24%) cases (Table 2.2.). These events involved contact to the head by the hands in 29%, "shoulder/upper arm" in 27%, "elbow/forearm" in 20%, and stick in 12% of cases.

Relative trajectory of collision. Among the 779 primary head impacts involving another player, the proportion and number of head impacts associated with anterolateral was significantly greater than trajectories directly to the back, front, or side (p≤0.015). The relative trajectory of the collision (with respect to the checked player) was anterolateral in 34% of cases, and posterolateral in 28% (Table 2.2.).

2.4.4. Situational factors observed after head impact

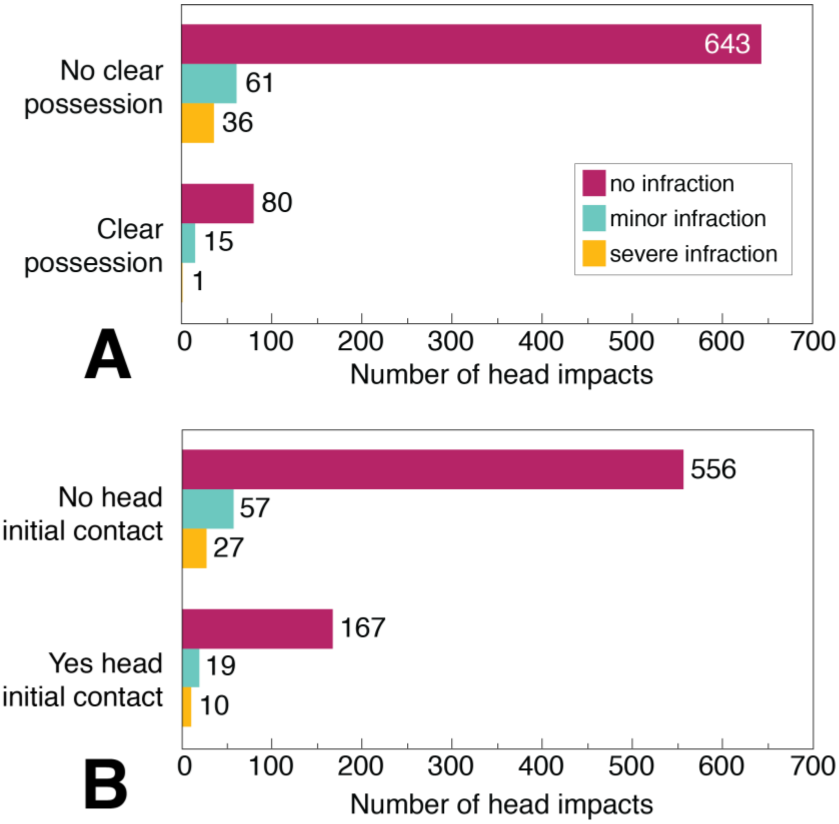


Figure 2.2. Head impact events related to puck possession (N=836) and initial point of contact (N=779; when contact involved another player), based on penalty type. Numbers represent counts for penalty type, and total counts. Penalties were categorized into minor infractions (2 minutes in the penalty box), severe infractions (>2 minutes in the penalty box and/or game suspension/ejection), or no infraction.

Among the 779 head impacts involving a collision with another player, 14% of cases were penalized (Figure 2.2.). 65% of infractions were minor penalties (involving 2 minutes in the penalty box). Infractions were called for 15% of cases where the head was the initial point of contact, and 16% of cases where the head was not the initial site of contact. When players did not have puck possession (no clear possession, attempting to gain or just released the puck), only 14% of head impacts resulted in a penalty (Figure 2.2.).

2.4.5. Discussion

We conducted this observational study to improve our understanding of the circumstances of head impacts in men's university ice hockey games. In particular, we examined situational factors preceding head impact, characteristics of the event at the instant of head impact, and observable consequences of the head impact. From the 449 videos of head impacts collected and analyzed, we found that over 90% of events involved contact with another player. Furthermore, over one in four events involved two or more successive impacts to the head.

For situational factors leading to head impact, we found that head impacts occurred most often to players in their offensive zone, who did not have puck possession, and were checked along the boards by an opposing player moving obliquely from their side. Players were just as likely to look in the direction of the impeding collision as those who did not. Interestingly, our trends are similar to Hutchison et al. (2015b, 2015a) who found that majority of concussive head impacts occurred along the perimeter of the rink (53%), and when players had no possession (34%) or 'just released' the puck (42%). Furthermore, Mihalik, Blackburn, et al. (2010) reported 63% of head impacts to occur along the perimeter of the rink in youth bantam ice hockey. The high number of observed head impacts to players along the perimeter of the rink without clear puck possession, combined with potential for concussive injury in these situations, warrants extra attention by on-ice officials.

Regarding the characteristics of the event at the instant of head impact, players were just as likely to experience at least one event where the head impacted an environmental object (most often the glass) as an opponents' body part (most often the hand). The head impacted the glass in 28% of cases, four times more often than the boards. Other studies have reported a similarly high frequency of head impacts to the glass/boards, but have not separated impacts to the glass versus boards (Hutchison et al., 2015a; Wilcox, Machan, et al., 2014). While the glass serves an essential role for puck containment and travel, it is associated with a high prevalence of head impact in men’s university ice hockey. Reductions to the stiffness of the glass resulted in lower magnitudes of head accelerations in laboratory-based simulations (Schmitt et al., 2018), and a reduced rate of concussions in International and Olympic ice hockey (Tuominen et al., 2017). The high number of head-to-glass impacts observed in our study reinforces the need for further research on design, implementation and evaluation of low-stiffness glass/boards (C. A. Emery et al., 2017).

The hand of the opposing player was the most common body part to strike the head, accounting for 22% of cases, nearly twice as many as the shoulder or elbow. Previous studies have not reported specific body parts (e.g., shoulder versus elbow versus hand) striking the head in non-concussive impacts in ice hockey. For concussive impacts, Hutchison et al. (2015b) reported that the hands were involved in only 5% of cases in professional men’s ice hockey (while the shoulder was involved in 42% of cases, and the elbow in 15%). Moreover, Delaney et al. (2014) did not observe any concussive hand-to-head impacts (out of 25 diagnosed cases) in men’s university ice hockey. When compared to shoulder-to-head impacts, hand-to-head impacts generate higher magnitudes but shorter durations of head acceleration, and smaller peak strains in brain tissue, which may explain these trends (Hoshizaki et al., 2017; Potvin et al., 2019). Regardless, the high number of gloved hand-to-head impacts contributing to cumulative, sub-concussive loading of the brain in men’s university hockey is cause for concern, and highlights the need for further research on modifications to the padding of gloves to reduce the severity of these common impacts. Furthermore, stricter rule enforcement and/or greater consequences for infractions, such as roughing, may reduce the high frequency of gloved hand-to-head impacts.

Impacts to the side of the head were up to four times more common than impacts to the back or front of the head, an observation relevant to the design and evaluation of helmets (B. Rowson et al., 2015). Relatedly, the relative trajectory of the collision was at an angle from the front or back of the checked player in 62% of cases, and the checked player did not appear to be looking in the direction of the checking player in 48% of head impacts. Previous studies have provided contrasting results on the most common site of impact to the head in ice hockey, perhaps due to methodological differences. For example, based on video review, impacts to the side of the head accounted for up to 48% of concussions in professional (Hutchison et al., 2015b) and university hockey (Delaney et al., 2014). However, based on signals from helmet-mounted sensors (but not video review), Wilcox, Machan, et al. (2014) and Brainard et al. (2012) reported equal distributions of impacts to the front, side, and back of the head for non-concussive impacts in men's university hockey.

While nearly half of the events causing head impact appeared to be rule infractions, only 14% of cases resulted in penalties. Many collisions resulting in head impact occurred to players who were nowhere near the puck, and therefore could be deemed as interference or roughing violations. Furthermore, of the 24% of cases where the head was the first point of contact, 76% (or 17% overall) involved the upper limb or stick of an opposing player contacting the head, which is a violation of the head contact rule. Our trends agree with those reported by Hutchison et al. (2015b) and Pauelsen et al. (2017), who found that fewer than 25% of concussive impacts were called as infractions by on-ice officials in professional hockey. In addition, Mihalik, Greenwald, et al. (2010) found that 17% of head impacts in youth hockey were perceived to be infractions (although this study did not confirm whether penalties were actually called). The complex and subjective nature of the head contact rule, which depending on the league, requires referees to judge (a) the severity of the impact, (b) whether it was avoidable, and (c) whether it resulted in apparent injury, may in part explain why implementation of the rule has not contributed to a decline in concussions in university and professional level hockey (Donaldson et al., 2014; Ruhe et al., 2014), and why 81% of direct impacts to the head in our study, by an opposing player's upper limb or stick, were not called as penalties.

Our study has important limitations. Our results are specific to games in men's university ice hockey and may not apply to other contexts (e.g., practice, other levels of play, women's university hockey) involving different rules, skill levels, and levels of aggression (Abbott, 2014). Future research should focus on the most common scenarios leading to head impact in women's and men's hockey at various levels of play. In addition, the accuracy of our outcomes may have been limited by occlusions and sub-optimal camera angles, which created challenges to video analysis. We estimated that ~70% of all head impact events experienced during game play were captured in this analysis (**Appendix C**). However, we used five cameras to capture head impacts occurring in all regions of the ice, reducing the probability of missed impacts (Cortes et al., 2017), when compared to previous video-based studies of head impact in hockey, which used a single camera that followed the puck (Mihalik, Blackburn, et al., 2010;

Mihalik, Greenwald, et al., 2010; Wilcox, Machan, et al., 2014). Furthermore, we observed substantial to perfect inter-rater reliability ($k_n > 0.60$) for most items in our questionnaire, except for “looking in the direction of the collision” which had fair agreement (TPA=67%, $k_n=0.31$). Caution should be used when interpreting the results for this variable. Lastly, we focused on describing the circumstances of head impacts in ice hockey and not the clinical consequences of the observed impacts.

In summary, our results indicate that head impacts in men’s university ice hockey occur most often to players in their offensive zone, who did not have puck possession, and were checked along the boards by an opposing player moving obliquely from their side. The impact event most often caused the lateral aspect of the head to strike the glass or be struck by the opponent’s hand. In 24% of collisions involving another player, the head was the first site of contact. In 30% of events, the head experienced two or more successive impacts. Less than 15% of events led to infractions. Further investigation is required on the potential of modifications to the stiffness of the glass and gloves, as well as improved detection and enforcement of infractions by referees, to reduce the frequency and severity of head impacts in men’s university ice hockey.

Chapter 3.

Associations between the scenario and severity of head impacts in men's university ice hockey

The following chapter is to be submitted for publication in the following peer-reviewed journal:

Aguiar, OMG., et al., "Checking the head: scenario and severity of head impacts in men's university ice hockey." Scientific Reports.

3.1. Abstract

In this observational cohort study, we characterized the circumstances of head impacts in men's university ice hockey and compared the scenarios in terms of impact severity (as measured by peak head linear accelerations and rotational velocities). Video footage of 234 head impacts were analyzed with a validated questionnaire to classify factors before, during, and after the collision. Impact severity data from helmet-sensor measures (GForceTracker^{TM}) were paired with corresponding video footage. Shoulder-to-head impacts were more common than hand- or elbow-, but there were no differences in head kinematics between upper limb contact sites. Glass-to-head impacts were nearly four times more common, but just as severe as board-to-head impacts. Head impacts resulting in major penalties or leading to visible signs of concussion involved greater head rotational velocities. Head impacts occurred most often to the side of the head, along the boards to players in their offensive zone without puck possession. Impacting object, playing zone, direction of gaze, head initial contact, puck possession, location on ice, and head impact location did not influence impact severity. Our results provide further evidence on the most severe and common types of head impact to guide improvements in protective gear, rink modification, player training, and rules to preserve brain health in ice hockey.

3.2. Introduction

Ice hockey has the highest rates of concussion among team sports in Canada (Cusimano et al., 2013; Zuckerman et al., 2015). Furthermore, there is growing evidence that repeated sub-concussive impacts are associated with structural changes to the brain, and acute and chronic symptoms including depression, executive dysfunction, and cognitive impairment (Fickling et al., 2021; Karton & Hoshizaki, 2018; Montenigro et al., 2017). Preserving brain health requires efforts to reduce the severity and frequency of head impacts during game play (Bailes et al., 2013; Schwab et al., 2021). There is a lack of understanding on the most common and most severe types of head impacts in ice hockey. This is a barrier to the design of interventions for preserving brain health through rule changes, skills training, and improvements in protective equipment and environmental design.

Previous studies have analyzed video footage to determine the frequency and circumstances of head impacts in ice hockey (Table 1.1.). Wilcox, Machan, et al. (2014) found that in men’s university ice hockey, 50% of head impacts were due to contact with another player, and 37% were due to contact with the glass/boards. Mihalik, Blackburn, et al. (2010) found that in male youth hockey, 63% of head impacts occur along the perimeter of the ice rink. These studies were limited by the use of a single camera that followed the puck, and the high likelihood of missing impact events occurring outside of the camera’s field of view. In the current thesis, **Chapter 2** addressed this issue by using five cameras capturing the entire ice surface. We observed that the head was impacted nearly twice as often by the (gloved) hand than the “shoulder/upper arm” or “elbow/forearm,” and the head impacted the glass four times more often than the “boards/caprail.” Furthermore, we found that impacts to the side of the head were four times more common than impacts to the back or front.

Other studies have analyzed helmet sensor data to gain insight on the severity of head impacts, based on measures of peak linear acceleration and/or rotational acceleration (Table 1.1.). In men’s university ice hockey, Wilcox, Beckwith, et al. (2014) reported 50th percentile peak head linear accelerations ranging from 15-17 g, and rotational accelerations ranging from 1454-1733 rad/s^2. For the “most severe head impacts” (e.g., 95th percentile), peak head linear accelerations ranged from 37-50 g, and rotational accelerations ranged from 4076-5182 rad/s^2 (Wilcox, Beckwith, et al., 2014).

Based on impact location estimates from the sensor, players sustained more impacts to the side (~30%), back (~30%) and front (~30%) of the head than the top (~10%) (Brainard et al., 2012; Wilcox, Beckwith, et al., 2014). With respect to severity, Wilcox, Beckwith, et al. (2014) found that impacts to the back of the head resulted in greater 95th percentile linear head accelerations than impacts to the front or side, and impacts to the side of the head resulted in greater 95th percentile rotational head accelerations than impacts to the front. A major limitation of these studies is that neither verified the occurrence of head impacts through video and/or direct observation, which can lead to imprecise estimates of impact exposure, severity, and impact location on the head (Cortes et al., 2017; Kuo et al., 2018; Patton et al., 2020). For example, Wilcox, Machan, et al. (2014) used helmet-mounted sensors (HIT system) and recorded 1965 impact events across 12 home games, yet only 270 head impacts were captured on video.

A barrier to the development of targeted prevention strategies is incomplete understanding on the most common and severe types of head impacts in ice hockey. Our current understanding is based on a small number of studies that combined video with helmet sensor data to examine both the circumstances and severity of head impacts (Table 1.1.). For men's university ice hockey, Wilcox, Machan, et al. (2014) found that contact with the ice resulted in higher linear accelerations than contact with another player. In male youth hockey, open-ice collisions resulted in greater head linear and rotational accelerations than collisions along the perimeter (Mihalik, Blackburn, et al., 2010). Moreover, anticipated head impacts were nearly six times more common, but just as severe as unanticipated head impacts. In male youth hockey, head accelerations were also greater during collisions that were penalized, but only 15-17% of head impacts resulted in penalties (Mihalik, Greenwald, et al., 2010). No study has analyzed the specific object that impacts the head (e.g. boards vs glass; shoulder vs elbow or hand) and how this influences head impact severity. Furthermore, no study has examined how head impact severity associates with playing zone, puck possession, and visible signs of concussion.

In this observational cohort study, we combined helmet-mounted sensor measures with video footage of head impacts captured over five seasons of home games (**Chapter 2**) to address the following questions: (1) What are the most common circumstances for head impacts in ice hockey? (2) How do the most common scenarios differ in terms of peak head linear accelerations and rotational velocities?

3.3. Materials and methods

3.3.1. Participants

Sixty-eight members (46 forwards and 22 defensemen) of the Simon Fraser University (SFU) Men's Ice Hockey team (British Columbia Intercollegiate Hockey League) participated in the study over five consecutive seasons from 2014-19. Forty-six players (33 forwards and 13 defensemen) were enrolled in the study across three consecutive seasons from 2016-19. Written informed consent was obtained from each player and the study was approved SFU's Research Ethics Board.

3.3.2. Instrumentation

Participants were instrumented with helmet-mounted GForceTracker^{TM} sensors (GFT; version 3.s.19; Artaflex, Markham, Canada) to measure the severity of the head impact (Figure 3.1.). The GFT contains a triaxial accelerometer and a triaxial gyroscope, which measures linear accelerations (g) and rotational velocities (degrees per second or °/s). Linear accelerations were sampled at 3000 Hz (range of ± 200 g and 1 g resolution for each axis) and rotational velocities were sampled at 800 Hz (range of ± 2000°/s for each axis). Linear and rotational data were low pass filtered on-board with a 300Hz and 100Hz anti-aliasing filter, respectively. The GFT sensors recorded, time stamped, and stored data in 40 millisecond segments (8 milliseconds pre-trigger, 32 milliseconds post-trigger), when any axis of the linear acceleration exceeded a user-defined threshold—which was set to 10 g for this study (King et al., 2016).

The GFT was recommended as a valuable tool for field studies measuring head kinematics (Allison et al., 2015; Campbell et al., 2016; Knowles et al., 2017). Previous studies compared peak resultant head kinematics from raw GFT measures—placed inside the top, lateral aspect of hockey helmets—to "gold standard" 50th percentile, male Hybrid-III headform measures. Allison et al. (2015) and Knowles et al. (2017) found that mean absolute percent differences in linear acceleration for raw GFT measures were 97% and 54%, while differences in rotational velocity were 15% and 21%, respectively. Helmet type and sensor location effected the magnitude of sensor error (Allison et al. 2015; Knowles et al. 2017). In the current thesis, efforts were made with the team to ensure players consistently wore the same helmet model (CCM Vector 08), normalizing the effect of helmet type and sensor location on the recorded sensor measures. According to the manufacturer, our GFT measures were also corrected to the center of gravity of the head through built-in, proprietary sensor algorithms, which likely minimizes the large differences between (untransformed) raw GFT and Hybrid-III head kinematic measures previously reported by Allison et al. (2015) and Knowles et al. (2017).

3.3.3. Sensor data of head impacts

At the first home game every season, each player was assigned a GFT sensor. The sensor was calibrated at the beginning of each season for the player's helmet and used for that specific individual every home game of the season. If there was an issue with the sensor (e.g., faulty battery), a new sensor was calibrated for that individual. The sensor was secured to the top right inside of the helmet's shell using double sided foam tape (VHB, 3M, London, Canada), where the protective foam liner would not interfere. Approximately 30 minutes before the pre-game warm-up started, the sensor was turned on and the real time was noted. Impact data were stored on-board. At the end of each game, the sensor was turned off, removed from the helmet, and the data were downloaded to the device's software (gManager 1.8) via USB connection.

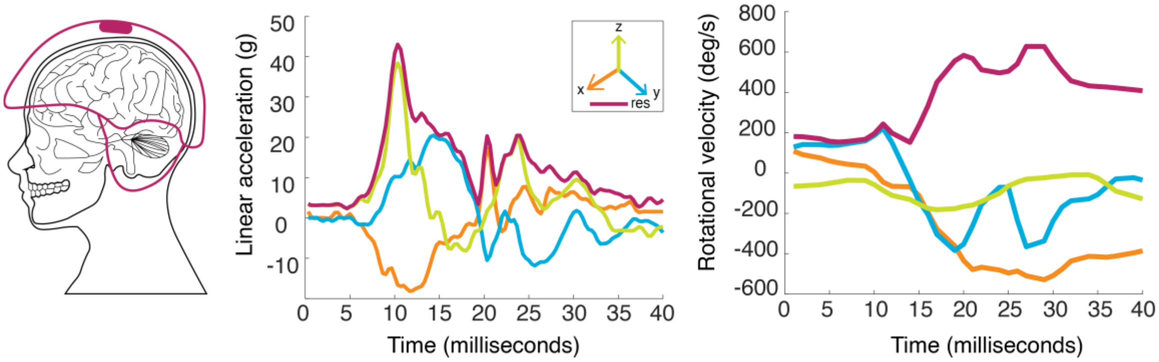


Figure 3.1. **GForceTracker^{TM} sensor placement in the helmet (left) and raw traces for linear acceleration (centre) and rotational velocity (right).**

3.3.4. Video footage of head impacts

Five video camcorders (2 Sony HDR-CX330 and 3 Sony HDR-CX405BKIT), recording at 60 fps and 1920 x 1080p resolution, were stationed around the ice surface at various positions on the concourse, allowing for multiple angles and full-ice coverage to record the play (Figure 3.2.). Six trained research assistants turned on the camera and noted the real time at the start of each game (where ‘start’ was defined as the referees’ audible whistle). A member of the research team then flashed a laptop (used to calibrate and sync the sensors) with the real time and date in front of each of the cameras. During the game, the six research assistants watched from different angles around the rink, and noted the time, location, and jersey number for observed head impacts.

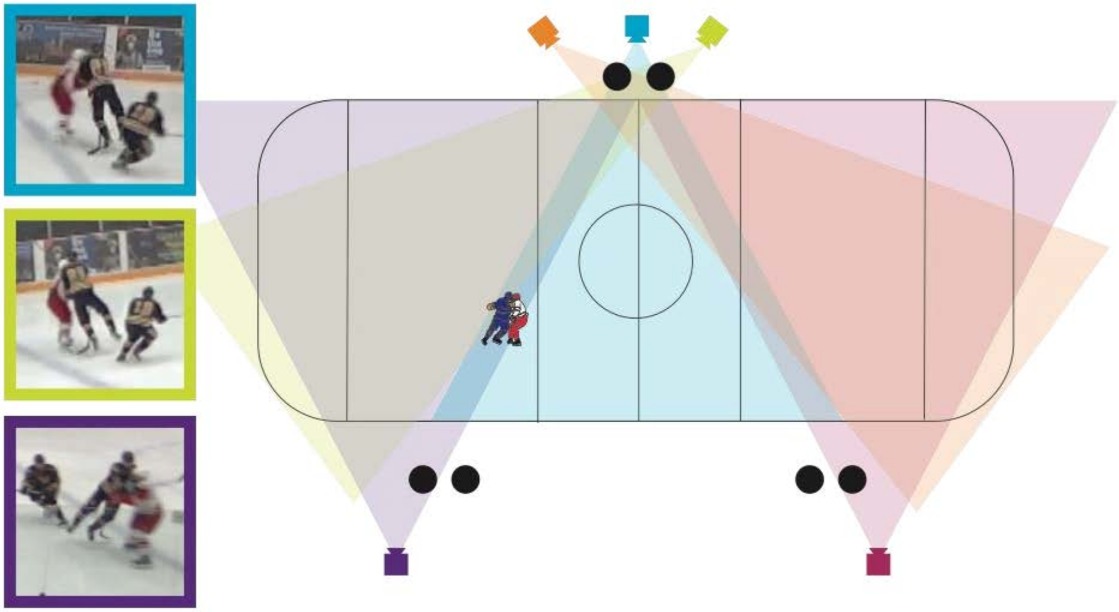


Figure 3.2. **Camera set-up with screenshots of a captured head impact event.**

3.3.5. Synchronization of sensor and video data

We used these game notes and corresponding time stamps to search the video footage and confirm the occurrence of head impacts. In this study, head impact events were defined as any visible contact applied directly to the player’s head. If an event was verified on video as a head impact, we used the laptop time displayed in the video (reference time) and time stamps from the game notes to synchronize the video with the time-stamped sensor data. We then identified candidate sensor data within ± 90 seconds of the time stamps from game notes (five seasons, 2014-19), as well as ± 60 and ± 10 seconds of the reference time (three seasons, 2016-19). If the video-sensor pairing met the criteria, we extracted the peak head linear accelerations and rotational velocities from raw impact data. Rotational velocities were converted from °/s to rad/s for comparison to other literature. We included head-impact events that resulted in a peak linear acceleration ≥ 10g. If no sensor data was present or timestamps were outside the desired time windows, the head impact was excluded from our analysis. Video footage of verified head impacts were clipped and edited in Adobe Premier Pro CS4 (San Jose, USA) for further analysis.

3.3.6. Head impact video analysis

Each head impact video was analyzed individually by three trained raters using a reliable and validated questionnaire (**Appendix A**). **Chapter 2** provides a detailed description of our training procedures, and **Appendix B** describes the development of the questionnaire and our inter-rater reliability analysis. For the eight questionnaire items examined in this study, the total percent agreement (TPA) and free marginal kappa (Brennan & Prediger, 1981) ranged between 67-93% and 0.33-0.90, respectively. In particular, the TPA and kappa for puck possession were 50% and 0.33, respectively. By collapsing from four categories (clear possession, attempting to gain possession, just released puck, no possession) into two (clear or no possession), near perfect agreement was achieved (TPA=97%, kappa=0.93). At least 2 of the 3 raters had to reach consensus to obtain the final answer for a questionnaire item. If no consensus was reached, a fourth rater selected the best perceived response. All clipped videos were analyzed in Quicktime (up to v10.4; Apple, Cupertino, USA) or VLC Media Players (up to v3.0.8; VideoLAN, Paris, France).

We used the questionnaire to probe observable situational factors before, during and after impact to the head. We classified the following factors before the collision: the playing zone, location on the ice where the head impact occurred, whether the player receiving the head impact was in possession of the puck and whether the player was looking in the direction of the collision. For location on the ice, the rink was divided into “perimeter” (compromised of the side boards, corners, end boards), “open ice” (interior portion of ice not accounted for by perimeter), and “near the net” (circumference surrounding the net— including the crease area). “No puck possession” included cases where the player just released the puck, was attempting to gain puck possession or had no possession of the puck.

We also used the questionnaire to classify the following factors during the head impact event: the specific body part or object contacting the head, the aspect of the head that was struck, and whether the head was the initial site of contact. The object striking the head was classified as “hand,” “elbow/forearm,” “shoulder/upper arm,” “glass,” “board/caprail,” “ice,” “puck,” “net,” “head,” “torso,” or “lower limb.”

Finally, we classified the outcome of the head impact based on: whether the player who received the head impact exhibited one or more visible signs of concussion and whether the referee penalized the head impact event. We classified visible signs of concussion based on definitions by Echemendia et al. (2018) (e.g., “slow to get up,” “clutching of head,” “motor incoordination,” “loss of consciousness,” “blank or vacant look,” “disorientation,” “visible facial injury in combination with any sign.”). We also examined the video to determine whether referees signaled for a penalty after the resulting impact event. We matched box score data from the league’s website to volunteer game notes (jersey numbers, clock time, rink location) to identify the infraction type and duration for the opposing player. A “minor infraction” was defined as two minutes in the penalty box whereas a “major infraction” was defined as more than two minutes. This study did not involve monitoring of diagnosed concussions.

3.3.7. Statistical analysis

We calculated descriptive statistics (counts, percentages) to describe the counts of each response category for verified head impacts ≥10g. We then used Generalized Linear Mixed Models to examine whether the severity of the head impact (as measured by linear acceleration or rotational velocity) differed among situational (explanatory) variables. We fit the model for a gamma error distribution with a log-link function, to correct for positive skewness of the sensor data. Participant code was treated as a random effect, to account for repeated head impacts by a given individual. Tukey post-hoc tests were used to examine pairwise comparisons when significant effects were observed between the response categories for linear acceleration and rotational velocity. Reported means and confidence intervals were back-transformed for interpretation of the results. The significance level was set to alpha=0.05. Statistical analyses were performed in JMP v16.0 for Macintosh (SAS Institute Inc., Cary, USA)—including the Generalized Linear Mixed Model Add-in (Dong, 2020).

3.4. Results

We captured and verified 535 head impact events (video footage paired with helmet-sensor data) within ± 90 seconds of the time stamps from our game notes, across 45 games (2014-19). Across the 25 games with a reference time (2016-19), 289 head impacts events were captured within ± 60 seconds of the reference time, and 234 head impacts within ± 10 seconds of the reference time. The means (standard deviations) and medians for GFT measures of linear acceleration and rotational were relatively consistent across the different time windows (Table 3.1.).

Table 3.1. Sample sizes, means, standard deviations (SD), and medians for GFT peak measures of linear acceleration (LA) and rotational velcoities (RV), where the video and sensor data were time matched with various windows.

	90s or less*	60s or less	45s or less	30s or less	20s or less	10s or less	5s or less	2s or less
Number of games	45	25	25	25	25	25	25	23
Sample size	535	289	276	265	246	234	221	162
Mean LA	38.8	36.1	36.1	36.2	35.8	36.1	36.1	35.7
SD LA	31.6	30.3	30.5	30.2	28.8	29.4	29.6	28.8
Median LA	26.2	24.1	23.8	24.0	24.2	24.0	23.9	24.0
Mean RV	15.2	14.6	14.6	14.5	14.5	14.6	14.7	14.8
SD RV	8.3	8.6	8.5	8.3	8.2	8.2	8.3	8.6
Median RV	13.7	13.0	12.9	13.1	13.1	13.2	13.3	13.2

* We identified candidate sensor data within ± 90 seconds of the time stamps from game notes, as well as ± 60, ± 45, ± 30, ± 20, ± 10, ± 5, and ± 2 seconds of the reference time.

In the Results and Discussion of this chapter, we refer to head impact frequencies and severities from the dataset within ± 10 seconds of the reference (laptop) time. We conducted the same statistical analyses for data within ± 90 seconds of the impact time from our game notes and ± 60 seconds of the reference (laptop) time, which are provided in **Appendix D** and **Appendix E**, respectively. Across each of the three datasets, the main effects and post-hoc analyses were the same except for statistically significant differences in (1) rotational velocity between upper limb contact site, (2) linear acceleration between visible signs of concussion, and (3) rotational velocity between playing zones. **Appendix F.** provides mean peak head linear accelerations (resultant, medial-lateral, anterior-posterior, superior-inferior components) and rotational velocities (resultant, roll, pitch, yaw components) for 48 head impacts experienced by a single player.

3.4.1. Overview of observed head impacts

Over the 25 home games, we captured and verified 234 head impact events (video footage paired with helmet-sensor data) within ± 10 seconds of the reference time. Head impacts were experienced by 30 unique, instrumented players, including 9 defensemen (41 events), and 21 forwards (193 events). The average number of head impacts per player per game was 0.31 (range=0.04-1.84). The mean body mass and height of player receiving the head impact were 80.6 kg (SD=8.6, range=68.0-96.1) and 178.9 cm (SD=7.5, range=167.6-198.1). The mean body mass and height of the player delivering the head impact were 85.8 kg (SD=7.7, range=72.7-111.4) and 183.8 cm (SD=5.6, range=165.1-198.1).

The distributions of peak head linear accelerations and rotational velocities were positively skewed, due to the 10g recording threshold, as observed in other studies (Mihalik, Blackburn, et al., 2010; Wilcox, Beckwith, et al., 2014). The median peak linear acceleration and rotational velocity were 24.1 g (25th-75th percentile = 16.4-45.8 g) and 13.2 rad/s (25th-75th percentile = 9.1-18.3 rad/s), respectively. The mean peak linear acceleration and rotational velocity data were 36.1 g (SD=29.4) and 14.6 rad/s (SD=8.2), respectively.

3.4.2. Situational factors preceding impact to the head

Playing zone and location on the ice. In total, 55% (n=128/234) of head impacts occurred in the offensive zone, 32% occurred in the defensive zone and 13% occurred in the neutral zone. 77% of head impacts were observed along the “perimeter” of the rink (n=181/234). “Open ice” and “near the net” accounted for 18% and 5% of head impacts, respectively. There were no differences in peak head kinematics between playing zones or locations on the ice (Table 3.2.).

Puck possession and direction of gaze. Players without puck possession experienced a 6.8-fold greater number of head impacts (n=204/234) than those with possession (n=30/234). There were no differences in the impact severity for the player with (versus without) puck possession. In 60% of cases, the player was looking in the direction of the impeding collision (n=141/234). There were no differences in the impact severity for the player looking (versus not looking) in the direction of the impending collision (Table 3.2.).

Table 3.2. Estimated means and confidence intervals (CI) for peak linear accelerations and rotational velocities with respect to situational factors preceding head impact (playing zone, location on ice, puck possession, and direction of gaze), within ± 10 seconds of the reference time.

	Frequency	Linear acceleration (g)		Rotational velocity (rad/s)	
	Count (% of head impacts captured)	Mean (95% CI)	p value	Mean (95% CI)	p value
Playing zone*	n = 234	n = 234	0.468	n = 234	0.096
Offensive zone	128 (54.7%)	38.2 (25.3-57.7)		14.4 (13.9-14.9)	
Defensive zone	76 (32.5%)	31.6 (25.7-38.8)		13.6 (12.1-15.3)	
Neutral zone	30 (12.8%)	36.8 (26.5-51.2)		17.5 (14.5-21.2)	
Location on ice	n = 234	n = 234	0.385	n = 234	0.273
Perimeter	181 (77.4%)	34.6 (31.8-37.6)		14.4 (13.6-15.2)	
Open ice	41 (17.5%)	32.6 (26.5-40.2)		14.1 (12.3-16.2)	
Near the net (crease)	12 (5.1%)	47.6 (30.1-75.4)		18.8 (13.8-25.6)	
Puck possession*	n = 234	n = 234	0.987	n = 234	0.580
Clear possession	30 (12.8%)	35.2 (26.8-46.1)		14.0 (11.7-16.8)	
No possession	204 (87.2%)	35.1 (33.1-37.2)		14.9 (14.3-15.5)	
Looking in direction of collision*	n = 234	n = 234	0.706	n = 234	0.919
Yes	141 (60.3%)	34.5 (31.7-37.6)		14.7 (13.9-15.6)	
No	93 (39.7%)	36.0 (31.2-41.5)		14.6 (13.3-16.1)	

*Relative to the player receiving the head impact.

3.4.3. Situational factors observed at the instant of head impact

Objects associated with head impact. 60% of head impacts were caused by contact with another players' body part, whereas 40% were caused by contact with the environment (defined as glass, boards, ice). Impact severity was plotted as a function of the prevalence (percent of all head impacts) for each of the nine impacting objects in Figure 3.3. There were no differences between impacting objects for mean peak head rotational velocity and linear acceleration (p=0.636 and p=0.758, respectively).

With respect to upper limb-to-head impacts, the number of "shoulder/upper arm" and "hand" impacts to the head were nearly 2.2-fold greater than "elbow/forearm." As for "glass" versus "board/caprail" impacts to the head, the number of head impacts associated with "glass" was 3.7-fold greater than impacts to "board/caprail." There were no differences in impact severity between upper limb contact sites, or the glass and board/caprail (Table 3.3.).

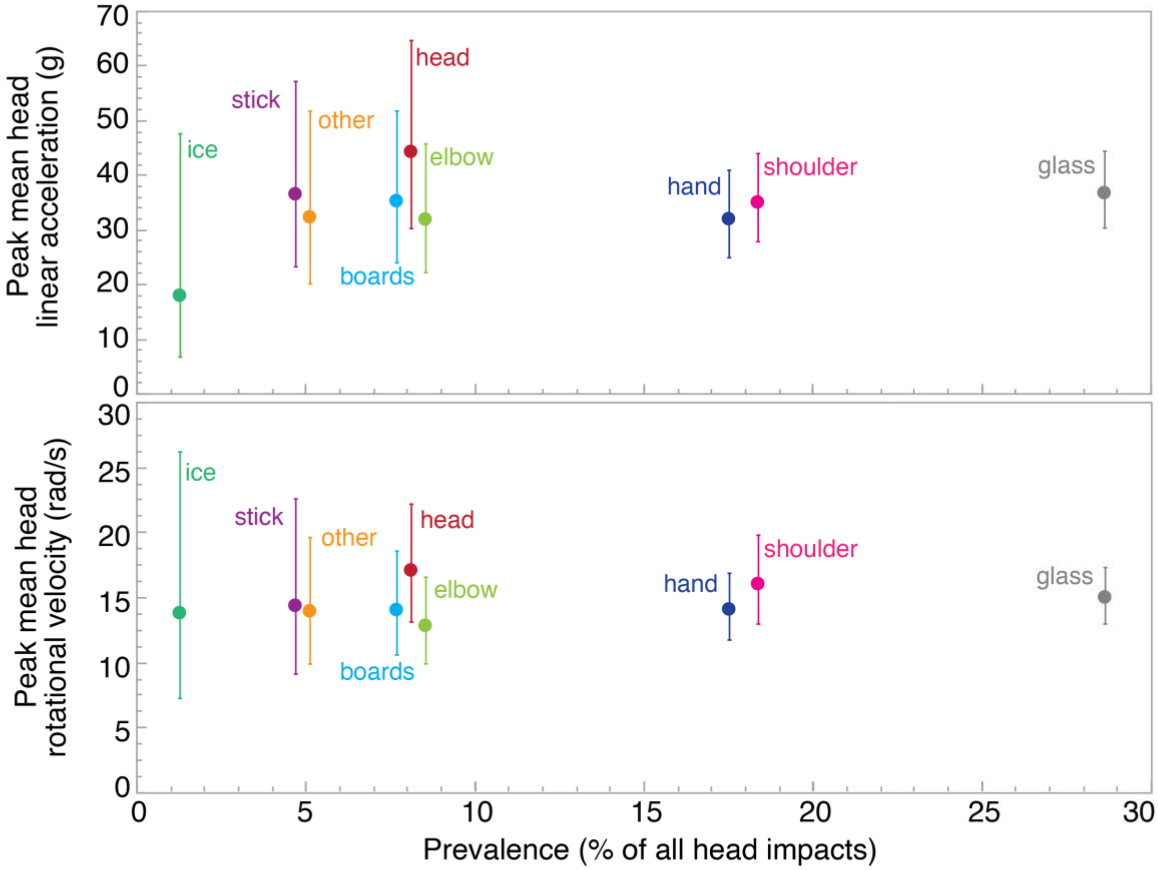


Figure 3.3. **Mean peak head linear accelerations and rotational velocities as a function of the prevalence (percent of all head impacts) for each impacting object. The bars represent 95% confidence intervals. "Other" consists of the "net," "torso," and "lower limb".**

Impact location on head and head as the initial point of contact. In 62% of cases, players experienced an impact to the side of the head. 21% of cases occurred to the front of the head, 12% to the back, and 5% to the top, and there were no differences in impact severity between impact locations on the head. The head was the initial point of contact in 54 of 233 (24%) of cases involving contact with another player. There were no differences in impact severity for cases where the head was not (versus was) the initial site of contact (Table 3.3.).

Table 3.3. Estimated means and confidence intervals (CI) for peak linear accelerations and rotational velocities with respect to situational factors at the instant of head impact (objects striking the head, location of impact on the head, and whether the head was the initial point of contact), within ± 10 seconds of the reference time.

	Frequency	Linear acceleration (g)		Rotational velocity (rad/s)	
	Count (% of head impacts captured)	Mean (95% CI)	p value	Mean (95% CI)	p value
Object impacting head	n = 234	n = 234	0.636	n = 234	0.758
Board/ caprail/ glass	85 (36.3%)	36.4 (31.0-42.7)		14.9 (12.8-20.2)	
Elbow/ forearm/ hand	61 (26.0%)	31.9 (26.3-38.7)		13.7 (11.7-16.1)	
Shoulder/ upper arm	43 (18.4%)	35.0 (22.9-43.9)		16.1 (12.8-20.2)	
Head	19 (8.1%)	44.3 (30.3-64.6)		17.1 (13.1-22.3)	
Other*	12 (5.1%)	32.2 (20.2-51.6)		14.1 (9.9-19.9)	
Stick	11 (4.7%)	36.5 (23.3-57.0)		14.6 (8.8-24.0)	
Ice	3 (1.3%)	17.9 (6.8-47.4)		13.8 (7.3-26.2)	
Impact to environment object versus another player	n = 222	n = 222	0.922	n = 222	0.821
Body part	134 (60.4%)	35.5 (32.7-38.7)		14.5 (13.8-15.5)	
Environmental object**	88 (39.6%)	35.9 (30.7-42.0)		14.3 (12.9-15.8)	
Upper limb contact site***	n = 104	n = 104	0.860	n = 104	0.254
Hand	41 (39.4%)	34.0 (25.3-45.7)		13.5 (11.3-16.1)	
Shoulder/ upper arm	43 (41.3%)	37.0 (29.2-46.6)		15.9 (13.9-18.3)	
Elbow/ forearm	20 (19.2%)	31.5 (20.2-49.3)		12.1 (9.2-15.7)	
Glass versus boards/caprail impacting head	n = 85	n = 85	0.742	n = 85	0.477
Glass	67 (78.8%)	37.4 (30.5-46.1)		14.7 (13.0-16.8)	
Board/ caprail	18 (21.2%)	35.1 (24.4-50.5)		13.5 (10.8-16.8)	
Location of impact on head	n = 234	n = 234	0.171	n = 234	0.680

	Frequency	Linear acceleration (g)		Rotational velocity (rad/s)	
	Count (% of head impacts captured)	Mean (95% CI)	p value	Mean (95% CI)	p value
Side	146 (62.4%)	36.5 (22.5-39.8)		15.2 (14.3-16.1)	
Front	49 (20.9%)	28.7 (23.5-34.9)		13.8 (12.0-15.8)	
Back	28 (12.0%)	35.6 (26.6-47.5)		13.9 (11.3-17.0)	
Top (crown)	11 (4.7%)	48.2 (30.0-77.4)		15.7 (11.3-21.9)	
Head initial point of contact†	n = 223	n = 223	0.939	n = 223	0.812
No	169 (75.8%)	36.1 (31.0-42.0)		14.5 (13.6-15.4)	
Yes	54 (24.2%)	36.4 (28.3-46.9)		14.8 (13.2-16.6)	

*Where "other" consists of the "net," "torso," or "lower limb." There were no cases of "puck."; **Where "environment" consists of the "boards/caprail," "glass," and "ice." Excludes n=12 where n=11 for stick and n=1 for net; ***Upper limb contact site of player delivering the hit; †Only includes cases involving another player (opponent or teammate)

3.4.4. Situational factors observed after head impact

Visible signs of concussion. We observed visible signs of concussion in 25 of 234 (11%) of cases. "Slow to get up" was observed 21 times and "clutching of head" was observed 5 times. "Loss of consciousness," "motor incoordination," "blank or vacant look," and "visible facial injury" were not observed. Of these cases, "board/caprail/glass" was the most common impacting object (n=10/25), followed by the "shoulder/upper arm" (n=4), "elbow/forearm/hand" (n=4), and "stick" (n=3). The mean peak rotational velocity (p=0.049) was 1.3-fold greater when the player was (versus was not) visibly affected by the head impact, but there was no difference in the mean peak linear acceleration (p=0.678; Table 3.4.).

Infraction. 8% of the 223 head impacts involving a collision with another player were penalized. 75% of infractions were minor penalties. Only 4% of cases where the head was the initial point of contact were penalized. The mean peak rotational velocity was 2.0-fold higher for major infractions (penalties more than two minutes) than no infractions (p=0.038), but there was no difference in rotational velocity between cases with minor infractions versus no infractions (p=0.988) or major infractions (p=0.074). There was no difference in mean peak linear acceleration for cases with (versus) without penalization of the head impact (p=0.838; Table 3.4.)

Table 3.4. Estimated means and confidence intervals (CI) for peak linear accelerations and rotational velocities with respect to situational factors proceeding head impact (visible signs of concussion, penalty), within ± 10 seconds of the reference time.

	Frequency	Linear acceleration (g)		Rotational velocity (rad/s)	
	Count (% of head impacts captured)	Mean (95% CI)	p value	Mean (95% CI)	p value
Presence of visible sign(s) of concussion	n = 234	n = 234	0.678	n = 234	0.049
No	209 (89.3%)	34.7 (32.4-37.2)		14.0 (13.4-14.7)	
Yes	25 (10.7%)	37.3 (28.2-49.2)		17.6 (14.6-21.2)	
Penalization of head impact†	n = 223	n = 223	0.821	n = 223	0.152
No	204 (92.7%)	36.0 (30.8-42.2)		14.2 (13.7-14.8)	
Yes	16 (7.3%)	37.8 (24.7-57.9)		17.6 (13.6-22.7)	
Penalty type*,†	n = 223	n = 223	0.838	n = 223	0.049
No infraction	207 (92.8%)	36.0 (30.8-42.2)		14.2 (13.7-14.8)	
Minor infraction	12 (5.4%)	35.1 (21.7-59.7)		13.9 (10.2-18.9)	
Major infraction	4 (1.8%)	46.1 (19.9-106.6)		28.3 (16.8-47.6)	

†Only includes cases involving another player (opponent or teammate); *Where "minor infraction" was defined as less than two minutes in the penalty box and "major infraction" was defined as more than two minutes.

3.5. Discussion

In this study, we combined helmet-sensor measures with video footage to classify and examine how head impact severity depended on the circumstances of head impacts in men's university ice hockey. We collected 234 head impact events and examined observable situational factors before, during and after the collision.

More head impacts occurred in the offensive zone, but there were no differences in head kinematics between playing zones. Swenson et al. (2022) examined how player speed influences head kinematics in youth ice hockey, reporting that athletes reached higher speeds in the neutral zone resulting in greater head linear accelerations and rotational velocities at impact. Moreover, in professional hockey, Hutchison et al. (2015a) found that concussive impacts most often occurred in the injured player's defensive zone (45%), followed by the offensive (34%) and neutral (21%) zones. Further investigation on the role of playing zone with respect to head impact and concussion risk is required.

We found no differences in the severity of impacts to the head from being struck by an opponent’s “shoulder/upper arm,” “elbow/forearm,” or “hand.” Injury risk may depend on padding over each of the three upper limb contact sites. Potvin et al. (2019) examined the severity and duration of linear and rotational head accelerations when players delivered shoulder-, elbow-, and hand-to-head impacts to an instrumented kickboxing dummy. They found that mean peak linear and rotational head accelerations were up to 2.1-fold greater for the hand and 1.9-fold greater for the elbow than shoulder. Modifications to shoulder padding may provide a promising avenue for reducing the severity of shoulder-to-head impacts. Virani et al. (2017) showed that the addition of 2-cm-thick polyurethane foam over existing shoulder caps decreases peak head linear accelerations and rotational velocities up to 25% and 12%, respectively. Kendall et al. (2014) and Richards et al. (2016) have also shown that design features of shoulder pads influence head accelerations and consequently risk for brain injury during shoulder-to-head impacts in hockey.

In addition, players who exhibited visible signs of concussion experienced 1.3-fold greater peak head rotational velocities. The most common signs were “slow to get up” and “clutching of head.” Echemendia et al. (2018) and Bruce et al. (2018) examined the use of visible signs to predict subsequent concussion diagnosis in professional ice hockey. They found that, despite being frequently observed, “slow to get up” and “clutching of head” were poor predictors of concussion. Bruce et al. (2018) speculated that “slow to get up” and “clutching of head” may arise due to the player’s behavioral response to receiving an impact, (e.g., an attempt to draw a penalty) or indicate an injury other than concussion. Although injury diagnosis in the current study was unknown, we showed that players with visible signs experience greater head kinematics. Our findings suggest that if any visible sign of concussion is observed, players should be removed from play and receive appropriate medical attention.

We found that signs of anticipating the collision did not associate with head impact severity. Mihalik, Blackburn, et al. (2010) also reported no differences in mean head accelerations between anticipated and unanticipated head impacts in youth hockey (aged 14). Furthermore, Eliason et al. (2022) found that more experience in performing body checks did not protect minor hockey players (aged 15-17) against injury, including concussion. Future research is required to evaluate the protective value of anticipatory responses and player training in reducing the frequency and severity of head impacts and injury in hockey.

We also found that head-to-glass collisions were just as severe, and much more common, than head-to-board collisions. Previous studies showed that modifications to the rink may reduce impact severity and injury risk (Schmitt et al., 2018; Tuominen et al., 2017). Our findings suggest that additional studies are required to evaluate the stiffness of the glass/boards and its effect on head accelerations.

Our results have implications for new rules, as well as enforcement of existing rules. Of 289 head impacts, the head was the initial site of contact in only 21% of cases. Furthermore, the severity of impacts did not depend on whether the head was the initial site of contact. This suggests that rules that focus on primary targeting of the head, while important, offer a limited solution. Only 4% of these events where the head was the initial site of contact were penalized (n=2 of 55). Player-on-player collisions resulting in “major infractions” (penalties of longer than two minutes in the box) experienced 2.0-fold higher head rotational velocities than cases involving “no infraction.” Similarly, Mihalik, Greenwald, et al. (2010) found that 17% of impacts resulted in infractions, and that penalized impacts resulted in higher linear accelerations. Collectively, our findings suggest that, while the most severe impacts tend to result in penalties, 95% of collisions that involve clear rule infractions are not called. In male youth hockey, body checking restrictions were found to reduce concussion rates during game play (Black et al., 2017; C. Emery et al., 2020; C. A. Emery et al., 2022), but not the incidence of direct head contact (Krolikowski et al., 2017). Future studies should examine whether Hockey Canada’s Head Contact rule (*Hockey Canada Playing Rules 2022-2024*, 2022) effectively reduces the frequency *and* severity of head impacts in men’s university ice hockey.

Our study has important limitations. We only analyzed data from the home games of a single men’s university ice hockey team. Therefore, results from this study may not apply to other contexts (e.g., practices; women’s ice hockey; other teams, leagues and levels of play). Moreover, we observed substantial to perfect inter-rater reliability ($k_n > 0.60$) for most questionnaire items used in our analysis. However, caution should be used when interpreting “looking in the direction of the collision,” as only fair agreement was achieved (TPA=0.67, k_n=0.33). In addition, we estimated that we captured ~62% of all head impact events experienced during game play with available sensor data (**Appendix C**). Based on the distribution of data across games and seasons (Table 3.1.), we have no reason to believe that the head impacts analyzed in the current thesis are not representative of all head impacts in hockey.

In addition, our findings are also specific to the sensor used (GForceTracker^{TM}). Previous validation studies compared peak head kinematics from raw GFT measures to "gold standard" 50th Hybrid-III headform measures (Allison et al., 2015; Campbell et al., 2016; Knowles et al., 2017). Mean absolute percent differences of raw GFT measures for linear accelerations and rotational velocities were up to 96.8% and 14.5%, respectively. The errors were attributed, in part, to the data not being transformed from the helmet location to the centre of gravity of the head and relative movement (or vibration) of the helmet. Previous studies also found that helmet type, sensor location, and impact location affect the accuracy of GFT measures (Allison et al., 2015; Campbell et al., 2016; Knowles et al., 2017). In the current thesis, we used transformed GFT measures as well as standardized the helmet model and sensor placement (except for three participants who required accommodations due to gear availability and personal comfort), to minimize sensor error.

We also rarely observed differences for impact severity and were more often seen in rotational velocity than linear acceleration. The following considerations may explain challenges in detecting "statistically significant" differences. First, we used Tukey post-hoc analysis to detect differences, which is sensitive to unequal variance across each category but allowed us to compare more than two categories at a time — minimizing the occurrence of type I errors (Tukey, 1949). Second, impact magnitude calculations may be influenced by classification of false-negatives and -positives, especially if these errors varied over a range of impact magnitudes (Eckner et al., 2018). To minimize the number of false-negatives and -positives classified by the sensor, impacts were first verified on video then paired with sensor data (Patton et al., 2020). Third, the sensitivity and resolution of helmet-mounted sensors to measure head kinematics when impacted by diverse objects (e.g., glass, ice, boards, body parts) in uncontrolled, sporting environments is unknown (Aguiar et al., 2022; Zacharias et al., 2022). Previous studies which found differences in impact severity either (1) reported small differences in mean magnitudes (< 2g or <200 rad/s), where the clinical significance is unclear, or (2) examined factors at high impact magnitudes (e.g., > 20 g threshold or at the 95th percentile), excluding common low-magnitude impact events (Brainard et al., 2012; Mihalik, Blackburn, et al., 2010; Mihalik et al., 2012; Wilcox, Machan, et al., 2014). Further studies are required to improve the accuracy of head kinematic measurements by sensor technologies for impacts in sport (Le Flao et al., 2022).

We examined the circumstances and severity of 234 direct head impact events in men's university ice hockey. Shoulder-to-head impacts and impacts delivered to players in their offensive zone were more common, but there were no differences in the head kinematics between upper limb contact sites and playing zones. Most players were not visibly affected by the head impact, but those who were visibly affected experienced greater peak rotational velocities and must be assessed by a medical professional. Head impacts most often occurred to players along the boards, without puck possession, and to the lateral aspect of their head. Modifications to the stiffness of shoulder padding and shielding (glass and boards) provide a promising avenue for decreasing the severity of head impacts in hockey. Further investigation of player training (e.g., checking or anticipatory strategies) and rule modification/enforcement are required to reduce the incidence of head impacts in men's university ice hockey.

Chapter 4.

Impact characteristics of the body during laboratory simulations of shoulder checks in ice hockey

The following chapter was accepted for publication in the following peer-reviewed journal:

Aguiar, OMG., et al. (2021), “Effective stiffness, damping and mass of the body during laboratory simulations of shoulder checks in ice hockey.” Sports Biomechanics; https://doi.org/10.1080/14763141.2021.1951828

In this chapter, the publication is presented verbatim (with permission from the publisher).

4.1.1. Abstract

Ice hockey is a fast-paced sport with a high incidence of collisions between players. Shoulder checks are especially common, accounting for a large portion of injuries including concussions. The forces generated during these collisions depend on the inertial and viscoelastic characteristics of the impacting bodies. Furthermore, the effect of shoulder pads in reducing peak force depends on the baseline (unpadded) properties of the shoulder. We conducted experiments with nine men’s ice hockey players (aged 19-26) to measure their effective shoulder stiffness, damping and mass during the impact stage of a shoulder check. Participants delivered a style of check commonly observed in men’s university ice hockey, involving lateral impact to the deltoid region, with the shoulder brought stationary by the collision. The effective stiffness and damping coefficient of the shoulder averaged 12.8 kN/m and 377 N-s/m at 550N, and the effective mass averaged 47% of total body mass. The damping coefficient and stiffness increased with increasing force, but there was no significant difference in the damping coefficient above 350N. Our results provide new evidence on the dynamics of shoulder checks in ice hockey, as a starting point for designing test systems for evaluating and improving the protective value of shoulder pads.

4.2. Introduction

Ice hockey is a fast-paced sport with a high incidence of collisions between players. Player-to-player contact accounts for up to 58% of injuries to hockey players across all age levels, sexes and divisions of play (Agel & Harvey, 2010; Flik et al., 2005; Lynall et al., 2018). Shoulder checks are responsible for a large portion of the injury burden (C. A. Emery et al., 2010; Pauelsen et al., 2017; Tator et al., 2016), including up to 38% of upper extremity injuries (Melvin et al., 2018) and 42% of concussions in elite-level hockey (Hutchison et al., 2015b). Insight on the dynamics of shoulder checks in hockey can improve player safety by informing advances in the design and evaluation of protective equipment, including shoulder pads.

The forces generated during shoulder checks (and the related risk for injury) will depend on the change in kinetic energy during the collision, and the elastic and damping properties of the impacting body parts. The simplest model for describing these interactions is a single-degree-of-freedom, mass-spring-damper model (Mertz, 1984; Nikooyan & Zadpoor, 2011; Robinovitch et al., 1991, 1997), where the mass is the effective (moving) mass with respect to the contact site, and the spring and damper represent the effective stiffness and damping coefficient of the body during impact. For lateral impact to the shoulder of seated cadavers, the effective mass averaged 24.0 kg or 32% of total body mass (Bolte & Hines, 2000; Mertz, 1984). Shoulder stiffness increased with increasing force but plateaued in magnitude around 400-600 N, at a value between 35 and 108 kN/m (Bolte & Hines, 2000; Compigne et al., 2004; Ono et al., 2005), following the well-known "J-shaped" compressive force-deflection characteristics of soft biological materials (Bennett & Ker, 1990). Ono et al. (2005) also observed that unlike seated cadavers, shoulder stiffness of seated living volunteers continued to increase above 400 N.

To our knowledge, no study has examined the effective stiffness and damping of living humans during shoulder checks in hockey. Furthermore, the effective mass of the shoulder has been examined only for laboratory simulations of impacts to the head occurring in "open ice," as opposed to along the boards (Rousseau & Hoshizaki, 2015). In that study, players delivered shoulder checks to a freely moving headform suspended by an overhead cable, while skating through the collision.

While high-speed, open-ice hits may create the greatest risk for injury, hits along the boards are more common and account for a considerable portion of the injury burden. 53% of concussions in the NHL occurred along the perimeter of the ice (Hutchison et al., 2015a). Furthermore, in 37% of concussions in the NHL, and 26% of concussions in men's university hockey, the head of the injured player contacted the glass or boards (Delaney et al., 2014; Hutchison et al., 2015a). Moreover, there is growing concern regarding the potential long-term neurological consequences of repeated sub-concussive head impacts in hockey (Karton & Hoshizaki, 2018). In our studies of men's university hockey, shoulder checks resulting in head impact were most often delivered along the periphery of the rink to opponents who were contacting or near the boards/glass (**Chapters 2-3**) . Moreover, checks were often delivered in a lateral direction, from slow speeds, with the shoulder brought stationary by the collision (Potvin et al., 2019).

The goal of this study was to measure the effective stiffness, damping and mass of the body during laboratory experiments where hockey players delivered shoulder checks, without padding, to an instrumented, spring-mounted dome, simulating an opponent sandwiched against the boards or glass shielding. We hypothesized that the effective stiffness and damping coefficient of the shoulder would increase at low force levels, but plateau in magnitude at higher force levels. We also hypothesized that the effective mass of the shoulder would average close to 15% of total body mass, as observed by Rousseau and Hoshizaki (2015) in their simulations of open-ice shoulder-to-head impacts.

4.3. Materials and methods

4.3.1. Participants

Nine men participated in the study, of mean age 22.0 years (SD=2.4, range=19-26), mean height 1.77 m (SD=0.08, range=1.65-1.88) and mean body mass 85.2 kg (SD=10.2, range=73.2-102.5). At the time of data collection, all participants were active players in competitive hockey leagues that permit body checking. Five played on the SFU Men's Hockey Team (British Columbia Intercollegiate Hockey League) while the remaining four played at the Junior-A level (British Columbia Hockey League). None reported shoulder injuries within six months of the experimental trials. Each participant provided written informed consent. The Research Ethics Committee of Simon Fraser University approved the experimental protocol.

4.3.2. Experimental procedure

During the experiment trials, players delivered checks to a mechanical representation of the struck player, consisting of a 3.46 kg solid wood dome of diameter 19 cm, mounted on four identical linear springs (Figure 4.1.). The dome-spring arrangement was designed to (a) provide a reasonable representation of the contact area and resistance to deformation of an opponent's shoulder, torso or head when sandwiched against the glass shielding, and (b) be simple enough to accurately model (as an undamped mass-spring system) in our approach for extracting the effective stiffness, damping and mass of the shoulder. The springs were of length 10 cm, and were rigidly attached at one end to the dome, and at the other end to a force plate (4060-15, Bertec Corporation, Columbus, USA), which was secured to metal studs in the laboratory wall. The springs provided a total stiffness of 81.1 kN/m, measured from the period of free vibration after striking the dome with a mallet, which demonstrated essentially zero damping.

Participants delivered shoulder checks to the dome from an initially stationary position (Figure 4.1.A.), with the lateral edge of their closest foot located a horizontal distance of 10 cm from the apex of the dome. The dome height was adjusted for each participant, so the apex was 5 cm higher than the deltoid tuberosity, identified through palpation. Participants did not wear padding or clothing on their upper limbs and were instructed to deliver shoulder checks to the dome "straight on with no rotation", to allow for uniform compression of the four springs supporting the dome (Figure 4.1.C.).

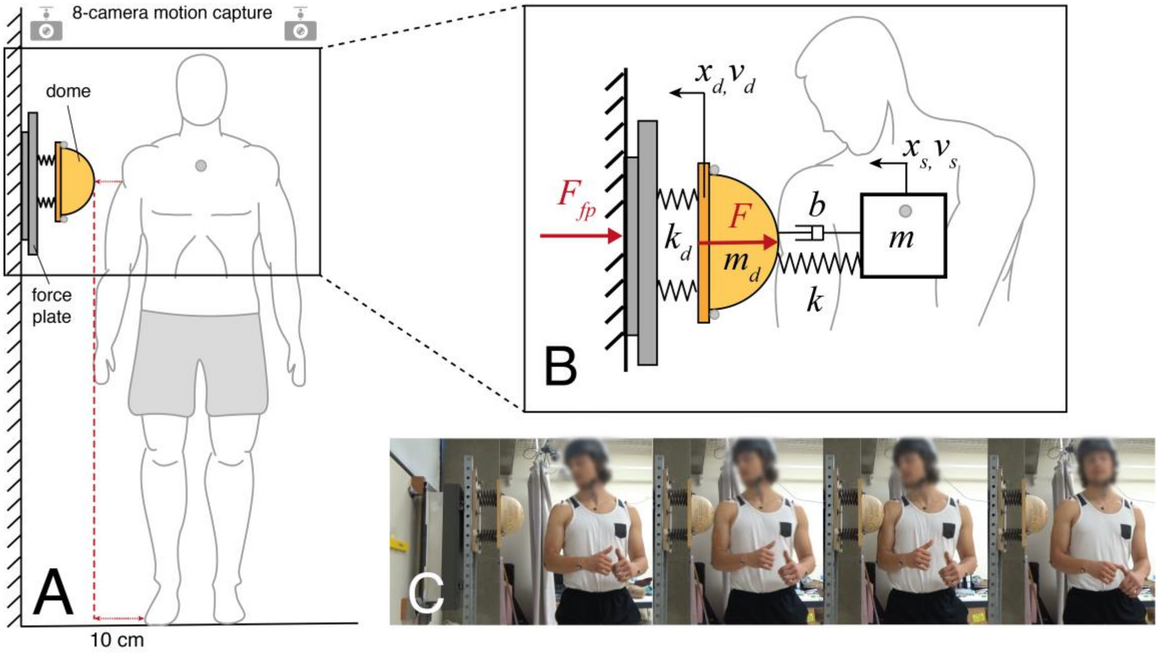


Figure 4.1. **(A) Experimental schematic and (B) mathematical model of shoulder-to-dome impacts. In (B), the parameters m_d and k_d represent the mass and stiffness of the dome, and m, k and b represent the effective mass, stiffness, and damping coefficient of the shoulder. (C) Example of a participant delivering a shoulder check at the medium hitting intensity (600 N).**

Each participant was given three practice trials to become familiar with the resistance and contact force provided by the dome. We acquired trials at three hitting intensities (low, medium, and high), presented in random order, and involving different acceptable ranges in the peak horizontal force measured by the force plate. The acceptable range in peak force was 300 ± 50 N for low intensity checks, 600 ± 50 N for medium intensity checks, and 900 ± 50 N for high intensity checks. The 900 N peak force for the high intensity condition was based on safety considerations for unpadded impacts (Compigne et al., 2004) and perceived player comfort from early pilot trials. During the trials, players alternated between right and left side impacts, and had a rest break of 60 seconds between trials, to allow tissue recovery. We monitored the peak force in real-time and provided feedback to participants on whether it was less than, greater than or within the target range. Early pilot trials with three participants revealed right shoulder and left shoulder impacts yielded equivalent force-time, force-deflection, and force-velocity behaviour (Figure 4.2.). We therefore pooled data from right side and left side impacts, and halted trials at a given hitting intensity once four of the acquired trials met the target peak force range.

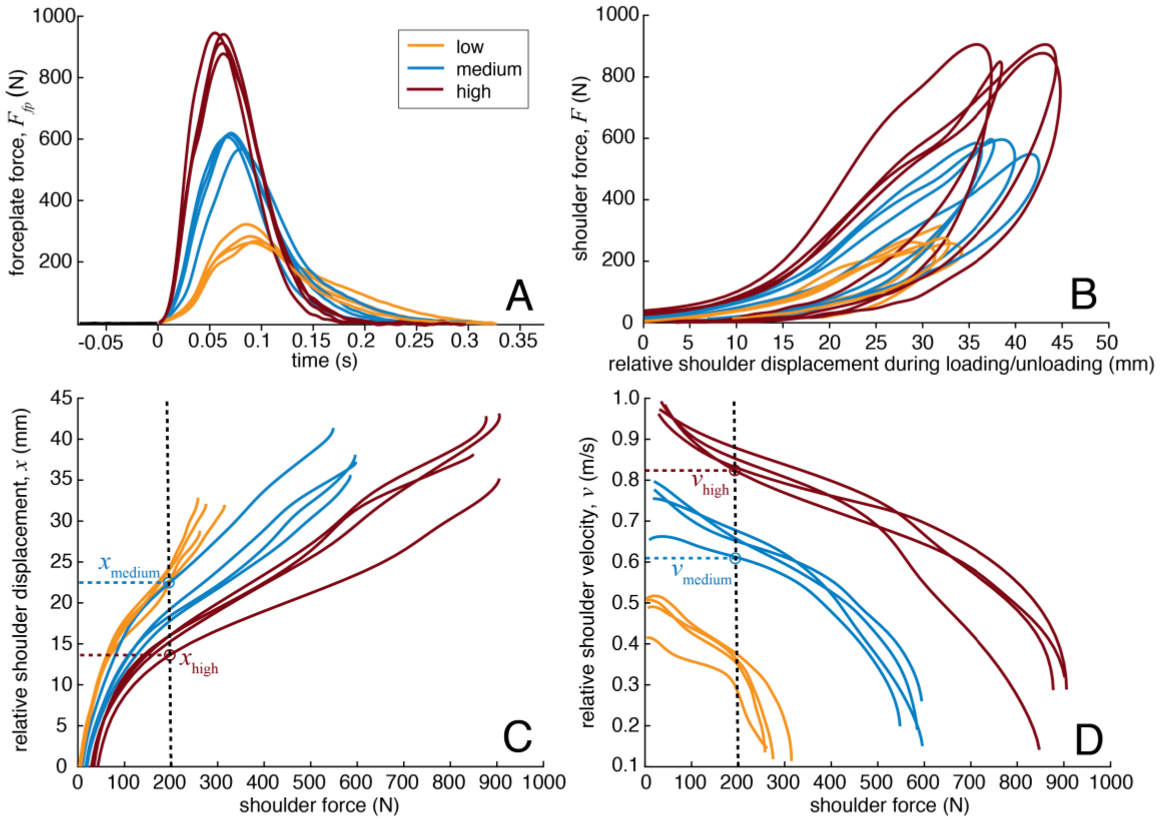


Figure 4.2. Raw data for a typical participant (SS03). (A) Horizontal force measured by the force plate in low, medium and high intensity trials, where the target peak force was 300 ± 50 N, 600 ± 50 N, and 900 ± 50 N, respectively. (B) Force applied to the shoulder versus relative displacement of the shoulder with respect to dome. Note the small non-zero value of shoulder force at t=0 is due to acceleration of the dome mass. (C) and (D) highlight values of relative shoulder displacement (x_{high} and x_{medium}) and velocity (v_{high} and v_{medium}) for different intensity trials at a force level of 200N. Note that $x_{high} < x_{medium}$, while $v_{high} > v_{medium}$ reflecting higher damping force and lower spring force in the high intensity trial. We utilized the difference across trials in x and v at specific force levels to calculate effective stiffness and damping coefficient in 50N increments, across all pairwise comparisons of trials at different intensities.

In each trial, position data were captured using an eight-camera motion capture system (Miqus M3, Qualisys, Gothenburg, Sweden) surrounding the apparatus and participant. The time-varying position of the shoulder was approximated from a reflective marker placed on the skin over the manubrium of the sternum. The sternum marker was selected since it was close in height to the shoulder contact point, and, unlike a marker placed over the acromion, experienced minimal occlusion and skin motion artifact during the trials. We also placed markers around the circumference of the dome. Force and motion capture data were sampled at 640 Hz and 2560 Hz respectively, using Qualisys Track Manager (v2.14). Power analysis indicated that 98% of the energy content for both displacement and force data was below 15 Hz. Accordingly, we used MATLAB (vR2019b, MathWorks, Natick, USA) to filter displacement data with a fourth-order, dual pass, low-pass Butterworth filter at a cut-off frequency of 20 Hz, and force data with a 100 Hz cut-off frequency for accurate determination of the onset of loading. This approach is consistent with previous studies analyzing upper limb impact (Davidson et al., 2005).

4.3.3. Mathematical model of impact

We modeled the body during impact with a single-degree-of-freedom horizontally translating mass, and an in-parallel arrangement of elastic (spring) and viscous (damping) elements (Figure 4.1.B.). In this model, m is the effective mass of the body with respect to the shoulder, k is the effective stiffness of the shoulder, b is the effective damping coefficient of the shoulder, and $x = (x_s - x_d)$ and $v = (v_s - v_d)$ are the displacement and velocity of the shoulder relative to the dome.

Preliminary observations confirmed the appropriateness of this model. The contact force measured during the trials tended to rise and fall with a single dominant frequency (Figure 4.2.A), suggesting translation of a single effective mass. We also noted the role of damping in causing substantial hysteresis in force-displacement traces (Fig 4.2.B.). Finally, we observed at a given level of shoulder compression (relative to the dome), both shoulder force and shoulder velocity tended to increase with increases in the intensity of the trials (Figure 4.2.C and 4.2.D.). This behaviour cannot be explained without the presence of damping, and provided us with the basis for extracting the magnitudes of k and b.

4.3.4. Measures of effective shoulder stiffness and damping coefficient

We assumed the magnitude of k and b depended on F, and that F was given by the sum of force in the shoulder spring and damper ($F = k \cdot x + b \cdot v$), as reflected in our model (Figure 4.1.B.). We determined k and b from simultaneous solution of two of the following three equations, for F varying in 50 N increments from 50 to 550 N:

$$F = k \cdot x_{high} + b \cdot v_{high} \qquad (1)$$

$$F = k \cdot x_{med} + b \cdot v_{med} \qquad (2)$$

$$F = k \cdot x_{low} + b \cdot v_{low} \qquad (3)$$

where x and v are interpolated values corresponding to the value of F of interest (Figure 4.2.C. and 4.2.D.). For example, in comparing low and high intensity trials, we first solved for b using Equation (1):

$$b = \left(F - k \cdot x_{high}\right)/v_{high} \qquad (4)$$

We then inserted this expression into Equation (3) to yield:

$$k = F \cdot (v_{high} - v_{low})/(v_{high} \cdot x_{low} - v_{low} \cdot x_{high}) \qquad (5)$$

We applied a similar approach to calculate k and b by comparing low versus medium intensity trials, and medium versus high intensity trials. At each force level, we examined all possible comparisons from the four trials acquired at each intensity, yielding between 16 and 48 estimates at a given force level, from which we derived average values of k and b for a given participant.

4.3.5. Measures of effective shoulder mass

We estimated the effective mass (m) of the shoulder based on impulse-momentum principles, modeling the body as a single mass located at the shoulder moving with an absolute horizontal velocity (v_s). We then considered that m is given by the ratio of the horizontal impulse ($\int F \cdot dt$) applied to the shoulder over the interval between the onset of force (t_1) and the instant of peak force (t_2), divided by the change in horizontal velocity (Δv_s) over the same time period:

$$m = \left(\int_{t_2}^{t_1} F \cdot dt\right)/\triangle\, v_s \qquad (6)$$

where the shoulder force F was calculated as the sum of the normal (horizontal) force measured by the force plate (F_{fp}) and the inertial force ($m_d \cdot a_d$) associated with the dome acceleration in the same direction. The dome acceleration was determined from double differentiation of the average horizontal position of the four dome markers.

We applied Equation 6 to the four trials acquired at each hitting intensity for a given participant, and reported the average m at each intensity. An assumption inherent to our approach is that, during the interval between t_1 and t_2, the horizontal force applied to the feet provided a negligible contribution to the overall impulse applied to the body, when compared to the force applied to the shoulder. This assumption is supported by a previous study which examined shoulder tackles in rugby, and showed that the net foot contact force, while having a strong horizontal component leading up to contact, is nearly vertical throughout the impact event (Seminati et al., 2017).

4.3.6. Statistical analysis

We used generalized linear mixed models for repeated-measures in JMP v14 for Macintosh (SAS Institute Inc., Cary, USA), to determine differences in k and b at different levels of F, and differences in m at different hitting intensities. When significant effects were observed, we used Tukey post-hoc tests to examine paired comparisons. For all analyses, participant code was treated as a random effect and the significance level was set to α=0.05.

4.4. Results

All participants completed the protocol. Table 4.1. shows peak magnitudes of force, times to peak force (based on the interval between t_1 and t_2), and shoulder impact velocities for low, medium and high intensity trials.

Table 4.1. Mean peak shoulder force, time to peak force, impact velocity and effective mass (± standard deviations) for shoulder impacts at each hitting intensity

Hitting intensity	Peak shoulder force (N)	Time to peak force (ms)	Impact velocity (m/s)	Mean effective mass	
				kg	% of body mass
low	297 ± 25	88.6 ± 15.8	0.50 ± 0.08	36.3 ± 8.6	42.5 ± 8.5
medium	574 ± 23	74.9 ± 8.6	0.77 ± 0.10	40.5 ± 9.7	47.3 ± 8.1
high	874 ± 25	63.9 ± 7.4	0.99 ± 0.12	43.1 ± 8.4	50.3 ± 6.2

The effective stiffness of the shoulder (k) varied with force level ($p<0.0001$), increasing more than 4-fold between 50 and 550 N (Figure 4.3.). The magnitude of k increased between 50 and 200 N (from an average of 3.06 to 7.46 kN/m; $p<0.05$), was constant between 200 and 450 N ($p \geq 0.05$), and increased between 450 and 550 N (from 9.85 to 12.8 kN/m; $p<0.05$).

The effective damping coefficient (b) of the shoulder also varied with force level ($p<0.0001$), increasing more than 9-fold between 50 and 550 N (Figure 4.3.). The magnitude of b was constant between 50 and 250 N ($p \geq 0.05$), increased between 250 and 350 N (from 153 to 274 N-s/m; $p<0.05$), and did not statistically differ in magnitude between 350 and 550 N (averaging 377 N-s/m at 550 N; $p \geq 0.05$).

Effective shoulder mass (m) averaged 40.0 kg (SD=9.3), or 46.7% (SD=8.2%) of body mass (Table 4.1.). There was a significant association between m and hitting intensity ($p=0.002$). The magnitude of m increased 12% between low and medium intensity impacts ($p<0.05$) and 19% between low vs high intensity impacts ($p<0.05$). There was no significant difference in effective mass between medium and high intensity impacts ($p \geq 0.05$).

4.5. Discussion

We analyzed the body’s dynamic response in experiments where players delivered shoulder checks to an instrumented, spring-mounted dome. The experiments mimicked a common type of shoulder check in ice hockey, where the feet are planted in a stationary position, and the shoulder is accelerated laterally to contact an opponent, with sufficient impact force to halt the forward momentum of the player delivering the check. By simultaneously measuring shoulder contact force, and shoulder displacement and velocity, we determined the effective stiffness, damping, and mass characteristics of the body during the impact stage of the shoulder check.

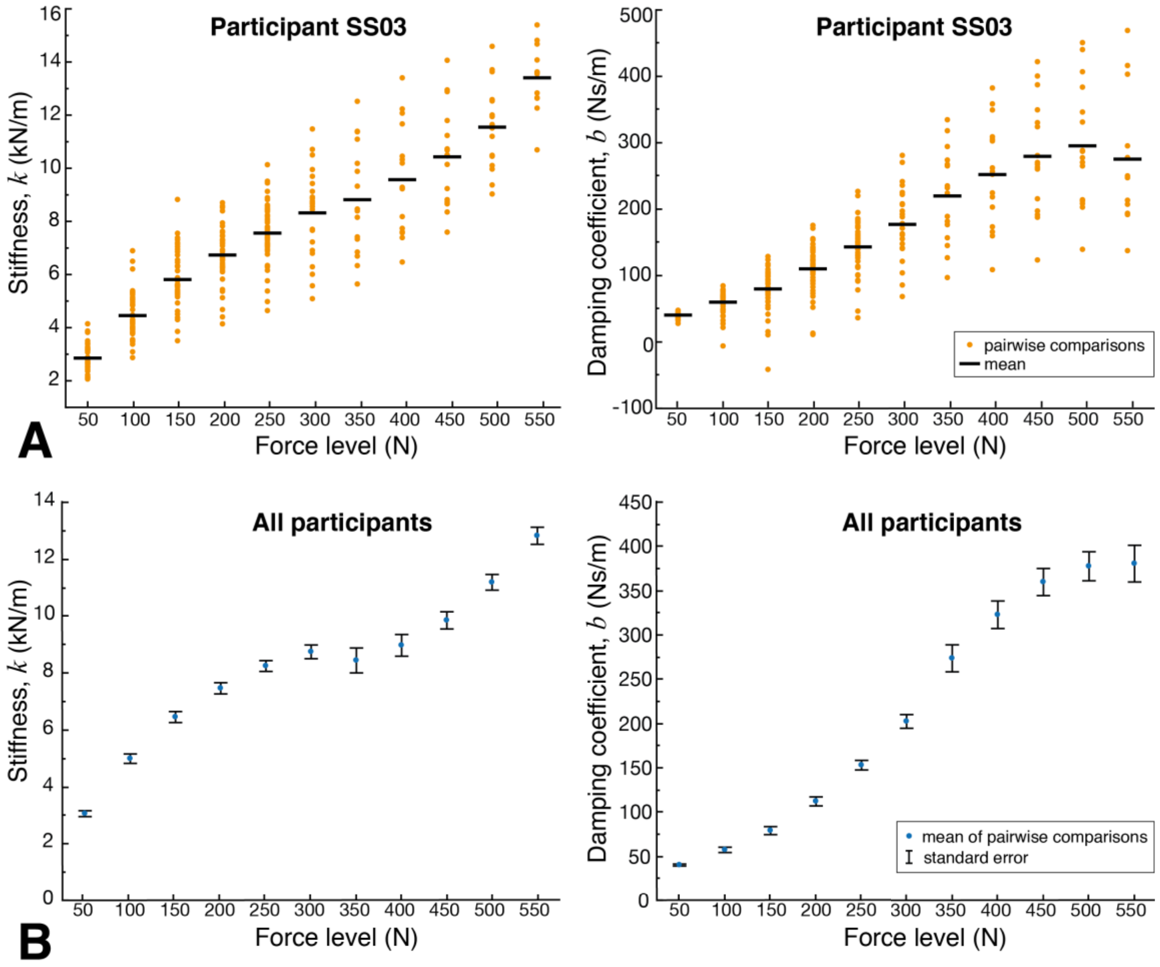


Figure 4.3. **Effective shoulder stiffness and damping coefficient measured at shoulder force levels between 50 and 550 N. (A) shows all values measured for a typical participant (SS03). (B) shows mean values measured across all nine participants with error bars showing ± 1 standard error.**

At the highest measured force level (550 N), the effective stiffness of the shoulder averaged 12.8 kN/m and the damping coefficient averaged 377 Ns/m. We hypothesized the magnitudes of stiffness and damping would increase with increasing contact force, and plateau in magnitude at higher forces, following the previously documented “J-shape” of the force-deflection curve for lateral impact to the shoulder (Bolte & Hines, 2000; Compigne et al., 2004). However, we observed plateauing in only damping and not stiffness. Furthermore, our mean shoulder stiffness of 12.8 kN/m (at 550 N) is approximately 3-fold lower than the range of 35 to 108 kN/m reported by Bolte and Hines (2000) for cadavers. These differences are consistent with the results reported by Ono et al. (2005) who found during lateral shoulder impacts, the stiffness of cadavers was higher than living volunteers, and plateaued at 400 N, while the stiffness of live volunteers continued to increase above 400 N. These authors surmised the differences might be due to rigor mortis causing a greater baseline stiffness for cadavers, and the role of muscle activation in increasing the high-force stiffness of living humans.

We found the effective mass of the shoulder averaged 47% of body mass, which was 3.2-fold greater than hypothesized based on results from open-ice shoulder-to-head impacts in hockey (Rousseau & Hoshizaki, 2015). We see two possible reasons for the difference between our values of effective mass and those reported by Rousseau and Hoshizaki (2015). First, the studies simulated common but distinct impact scenarios in hockey that involve substantially different initial and boundary conditions. In our experiments, checks were delivered in a lateral direction to a spring-mounted dome that halted the checking player's momentum. In the experiment conducted by Rousseau and Hoshizaki, players struck a freely-moving headform (suspended by an overhead cable) with a "glancing blow" that did not halt their horizontal momentum. The smaller momentum transfer, and combination of anterior and lateral momentum, may have contributed to a smaller effective mass. Second, Rousseau and Hoshizaki modeled the collision as perfectly inelastic in their impulse-momentum analysis of effective mass. This assumption seems questionable in light of our findings that the body exhibits substantial elasticity as well as damping during a shoulder check. Our analysis of effective mass utilized experimental measures of both shoulder kinematics and contact force, and involved no assumptions regarding the viscoelastic nature of the body during the impact event. We defined the effective mass as the mass that, when multiplied by the measured change in lateral shoulder velocity, equaled the measured laterally-directed impulse applied to the shoulder over this interval. Conceptually, any body part moving with a non-zero lateral velocity will contribute to effective mass, in an amount that depends on their velocity as well as their mass. Given we observed movement of the thighs, pelvis, torso, head and upper limbs in the same direction as the shoulder leading up to impact, we were not surprised the effective mass averaged 47% of total body mass.

Out values of effective shoulder mass are also larger than values reported from simulated motor vehicle collisions. Bolte and Hines (2000) measured the effective mass during lateral impacts to the shoulder of seated cadavers, and reported 1.7-fold smaller values of average effective mass than observed in the current study (24 vs 40 kg). This is likely due to differences in torso and lower limb contributions to the effective mass when delivering a shoulder check versus receiving an impact in a seated position. When delivering a shoulder check, players are likely to “put more of their weight” into the impact. We observed this behavior when participants delivered checks at higher intensities; the effective mass increased by 19% between low intensity and high intensity impacts.

Our study had important limitations. Our measures of effective shoulder stiffness, damping and mass are specific to the population of young adult male hockey players that participated in this study. Furthermore, our results are specific to the style of shoulder checking we simulated, which involves impact to a braced opponent’s shoulder or torso, or head sandwiched against the glass shielding. As shown in **Chapter 2**, such checks are a common cause of head impact in men’s university hockey (Aguiar et al., 2020; Potvin et al., 2019), and contribute up to 53% of concussions in the NHL (Delaney et al., 2014; Hutchison et al., 2015a). However, future experiments should characterize shoulder stiffness, damping and mass for different impact scenarios and player populations. To guide such efforts, improved evidence is required on the frequency and risk for injury created by different types of checks in hockey.

In calculating effective mass, we assumed the horizontal force between the feet and the ground was negligible during the (~70 ms) interval between the instant of impact and the instant of peak shoulder force. We did not acquire measures of foot contact forces to verify this assumption. However, our approach is supported by the results of Seminati et al. (2017), who examined foot reaction forces during rugby tackles, and found while participants generated horizontal forces at the feet prior to contact, foot reaction forces at the instant of contact were closely aligned with the vertical.

In our experiments, participants delivered checks to the dome without wearing shoulder pads. This approach allowed us to measure baseline (unpadded) values of shoulder stiffness, damping, and mass. Furthermore, due to safety precautions, we limited peak forces in our experiments to target values of 900 N (Compigne et al., 2004), and analyzed stiffness and damping at force levels between 50 and 550 N. However, real-life shoulder checks in hockey are delivered while wearing shoulder pads, and this may influence the style in which players deliver shoulder checks, and the peak force generated during these events. For example, Post et al. (2019) reconstructed concussive and non-concussive shoulder-to-head impacts in professional men's hockey, and observed peak translational head accelerations averaging 29.6 g and 23.9 g, respectively. For a 5 kg head, this corresponds to peak forces of 1451 and 1173 N. Peak contact forces during unpadded shoulder tackles in rugby were found to exceed 1600 N (Seminati et al., 2017; Usman et al., 2011). However, the contact area involved in rugby tackles is spread over a considerably larger area of the torso, shoulders and arms, and the portion of load generated at the shoulder is unclear.

In conclusion, we conducted experiments to measure the dynamic response of the body when delivering a style of shoulder check commonly observed in men's university ice hockey. The effective stiffness and damping coefficient of the shoulder averaged 12.8 kN/m and 377 N-s/m at 550 N, and the effective mass averaged 40.0 kg, or 47% of total body mass. Previous studies have shown that design features of shoulder pads influence the risk for head injury during shoulder-to-head impacts in ice hockey (Kendall et al., 2014; Richards et al., 2016; Virani et al., 2017). More work is required to determine how stiffness, damping and mass depend on the initial and boundary conditions of the impact, and to rank the importance of different types of checks, in terms of the frequency and severity of injuries. However, our results provide a useful starting point towards the development of biofidelic test systems for evaluating and optimizing the protective value of shoulder pads in ice hockey (Hughes et al., 2020; Payne et al., 2013, 2014).

Chapter 5.

Conclusions

This final chapter summarizes key findings from the current thesis. I provide a general summary, which ties in literature from the Introduction to the objectives and our results. I then discuss the implications and limitations of our findings and provide directions for future research.

5.1. General summary

In this thesis research, we used novel approaches to improve our understanding of the characteristics and risk factors for head impacts in men's university hockey. Specifically, we identified the circumstances surrounding the most common and severe types of head impacts and characterized the dynamic response of the body during shoulder checking—a leading cause of head impact and concussion in men's hockey (Figure 5.1.).

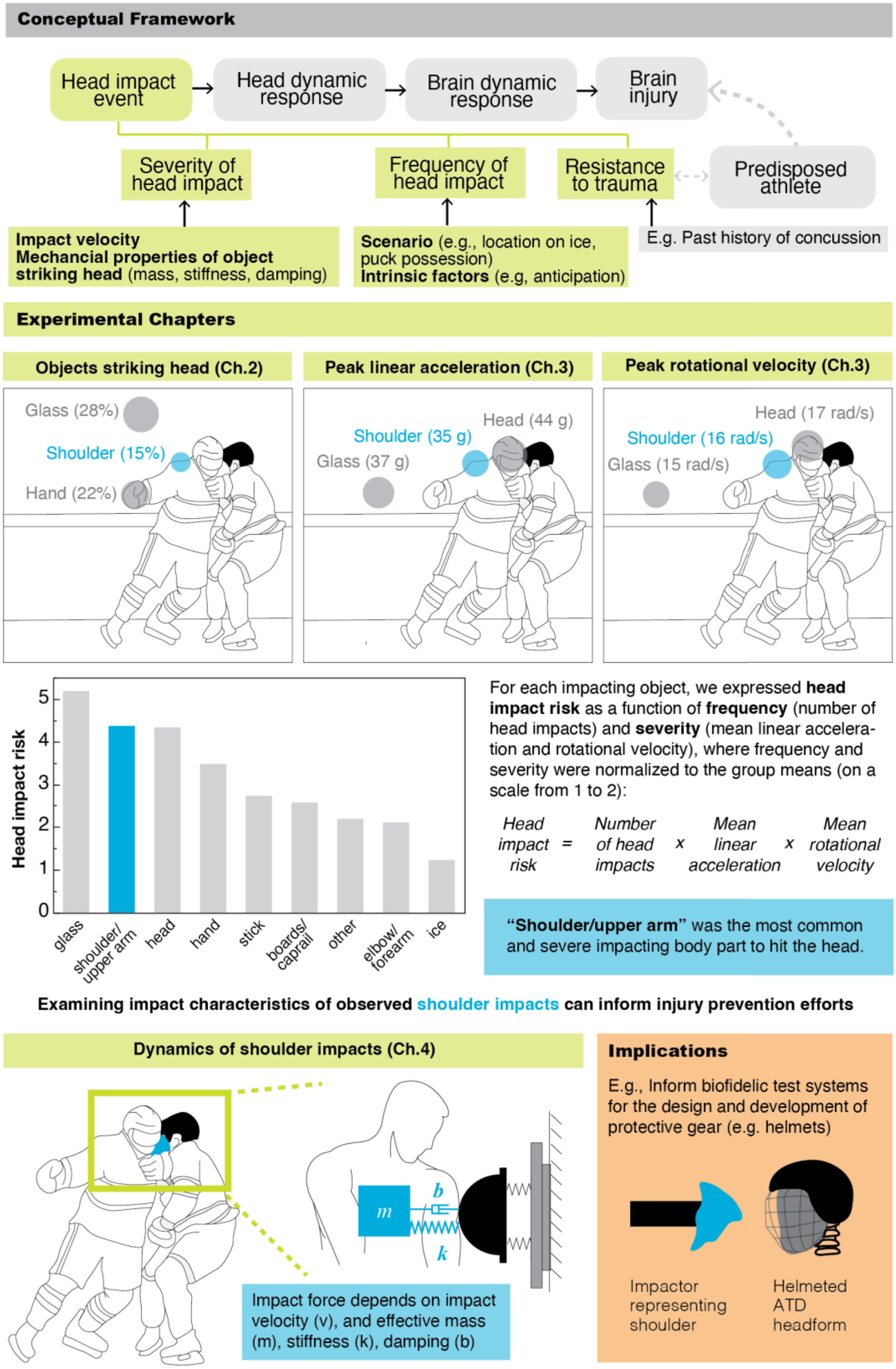
Ice hockey players often experience impact to the head. Previous studies in men's hockey have primarily focused on investigating head impact exposure during game play (Brainard et al., 2012; Mihalik et al., 2008, 2020; Wilcox, Beckwith, et al., 2014). However, these studies did not combine sensor measures with video capture and analysis of the impact event (Table 1.1.). Accordingly, it is unclear how head impacts occurred, how they depended on the playing situation, and which opponents' body parts and environmental objects most often impact the head—each of which provide specific opportunities for prevention (e.g., modifications to the boards or glass, or padding of the shoulder, elbow, or hand). Moreover, previous studies did not use video and/or observer confirmation to verify the recorded head impact event (e.g., true-positive). Thus, these estimates of head impact exposure (frequency, severity, and location of impact) from sensor-recorded events in men's hockey were likely inconsistent, overestimated, and consequently may misinform prevention efforts (Cortes et al., 2017; Kuo et al., 2018; Patton et al., 2020; L. C. Wu et al., 2018). A small number of studies have combined head sensor measures with systematic video analysis of head impacts in hockey. For example, in male university and youth hockey, previous studies examined how infractions, location on the ice, anticipation of the collision and the impacting object associate with impact severity (Mihalik, Blackburn, et al., 2010; Mihalik, Greenwald, et al., 2010; Wilcox, Machan, et al., 2014), but no study has examined risk factors such as playing zone, puck possession, and visible signs of concussion. The combined use of wearable sensors, systematic video analysis, and anthropometric test device reconstruction can address these limitations and gaps in knowledge while improving our understanding of head impact events (Tierney, 2021).

In **Chapter 2**, we identified the most common scenarios for head impacts in men's university ice hockey, through collection and analysis of video footage with a structured questionnaire. We captured and analyzed 836 head impacts from the SFU Men's Ice Hockey team across five seasons of home games (2014-19), using a five-camera system which provide multiple angles of the impact from different vantage points. Our results indicated that head impacts in men's university ice hockey occur most often to players in their offensive zone, who did not have puck possession, and were checked along the boards by an opposing player moving obliquely from their side. The impact event most often caused the lateral aspect of the head to strike the glass or be struck by the opponent's hand. In 24% of collisions involving another player, the head was the first site of contact. In 30% of events, the head experienced two or more successive impacts. Less than 15% of events led to infractions. Further investigation is required on the potential of modifications to the stiffness of the glass and gloves (C. A. Emery et al., 2017; Schmitt et al., 2018; Tuominen et al., 2017), as well as improved detection and enforcement of infractions by referees (Krolikowski et al., 2017; Mihalik, Greenwald, et al., 2010), to reduce the frequency and severity of head impacts in men's university ice hockey.

In **Chapter 3**, we expanded on approaches by Wilcox, Machan, et al. (2014) to determine how the impact scenario (measured in **Chapter 2**) associated with the severity of direct head impacts in men's university ice hockey, as measured from helmet-mounted sensors. We combined the video evidence with high-resolution data collected on head kinematics from helmet-mounted sensors, within ± 10 seconds of the reference (laptop) time, for 234 head impact events. Impacts to the head by the "shoulder/upper arm" and "hand" were more common than the "elbow/forearm," and there were no differences in the head kinematics between upper limb contact sites. Head impacts resulting in visible signs of concussion and player-on-player collisions resulting in "major infraction" (longer than two minutes) were associated with higher head rotational velocities. Head impacts occurred most often to the side of the head, along the boards to players in their offensive zone without puck possession. Glass-to-head impacts were nearly four times more common, but just as severe as board-to-head impacts. Impacting object, playing zone, direction of gaze, head initial contact, puck possession, location on ice, and head impact location did not influence impact severity. Our results provide further evidence on the most severe and common types of head impact to guide improvements in protective gear, rink modification, player training, and rules to preserve brain health (Bahr & Krosshaug, 2005).

When considering frequency and severity as a function of head impact risk, from **Chapter 2-3**, we observed that shoulder checks were the most common and severe body part to impact the head in men's university hockey (Figure 5.1.). These events occurred most often along the periphery of the rink to players who were contacting or near the boards/glass, and resulted in higher head rotational velocities than elbow or hand impacts to the head. Furthermore, shoulder checks were often delivered in a lateral direction, from slow speeds, with the shoulder brought stationary by the collision (Potvin et al., 2019). Despite that, there is limited research on the impact dynamics governing head collisions in ice hockey (Rousseau & Hoshizaki, 2015). No study prior to this thesis has measured the impact characteristics (e.g., effective mass, stiffness, and damping) of the body in delivering these common and severe shoulder checks.

In **Chapter 4**, we conducted experiments to measure the dynamic response of the body when delivering the style of shoulder check commonly observed in men's university ice hockey. Of particular interest was understanding the effective mass, stiffness, and damping of the body in delivering a shoulder check. We found that the effective stiffness and damping coefficient of the shoulder averaged 12.8 kN/m and 377 N-s/m, and the effective mass averaged 40.0 kg, or 47% of total body mass. Our results provide new evidence on the dynamics of shoulder checks in ice hockey, as a starting point for designing test systems for evaluating and improving the protective value of shoulder pads (Funk et al., 2022; Kendall et al., 2014; Payne et al., 2016).



For each impacting object, we expressed **head impact risk** as a function of **frequency** (number of head impacts) and **severity** (mean linear acceleration and rotational velocity), where frequency and severity were normalized to the group means (on a scale from 1 to 2):

Head impact risk = *Number of head impacts* x *Mean linear acceleration* x *Mean rotational velocity*

"Shoulder/upper arm" was the most common and severe impacting body part to hit the head.

Examining impact characteristics of observed shoulder impacts can inform injury prevention efforts

Impact force depends on impact velocity (v), and effective mass (m), stiffness (k), damping (b)

Implications

E.g., Inform biofidelic test systems for the design and development of protective gear (e.g. helmets)

Figure 5.1. Summary of thesis findings with respect to the conceptual framework and implications.

5.2. Implications

In this section, I expand on the implications of the current thesis with respect to experimental design and research methods, innovation, injury prevention, rules/policy and sideline screening.

This thesis contributes knowledge on the loading conditions of sub-concussive head impacts, which is an essential piece of the understanding the relationship between collisions in sports and brain tissue damage. Our findings may be used to inform the "biofidelity" of biomechanical approaches (e.g., finite element models, anthropometric test device reconstructions) in research, test standards and protective gear innovations (e.g., helmets), aimed at reducing cumulative brain strain from head impacts. For example, our observational and quantitative results in **Chapters 2-4** may be used as input parameters in the design of future case studies or laboratory reconstructions, facilitating the evaluation of head impact dynamics in hockey under "real world" test conditions and scenarios (Funk et al., 2022). The data from **Chapters 2-3** may also be used to guide the development of head impact detection algorithms, improving the validity of wearable sensor measures.

Our results also provide evidence to guide improvements in rules of play to preserve brain health. In **Chapters 2-3**, we found that the vast majority of player-on-player contacts resulting in head impact are not penalized, including events that involve clear rule infractions (e.g., initial contact to the head). The complex and subjective nature of the head contact rule, which requires referees to judge (a) the severity of the impact, (b) whether it was avoidable, and (c) whether it resulted in apparent injury, may in part explain this discrepancy. In male youth hockey, body checking restrictions were found to reduce concussion rates during game play (Black et al., 2017; C. Emery et al., 2020; C. A. Emery et al., 2022), but not the incidence of direct head contact (Krolikowski et al., 2017). Clearly, changes are required both in the nature and enforcement of rules in hockey to reduce the frequency and severity of head impacts.

In **Chapter 2**, we also found that hand-to-head impacts were more common than "shoulder/upper arm" and "elbow/forearm." Previous studies have not reported specific body parts (e.g., shoulder versus elbow versus hand) striking the head in sub-concussive impacts in ice hockey. The high number of observed gloved hand-to-head impacts contributing to cumulative loading of the brain in men's university hockey is cause for concern, and highlights the need for further research on modifications to the padding of gloves to reduce the severity of these common impacts. Moreover, modification of rules and/or stricter enforcement of penalties, such as roughing, may reduce the incidence of head impacts in these scenarios.

While the glass shielding serves an essential role for puck containment and travel, it is associated with a high prevalence of head impact in men's university ice hockey. In **Chapter 2**, players were just as likely to experience at least one event where the head impacted an environmental object (most often the glass) as an opponents' body part (most often the hand). Other studies have reported a similarly high number of head impacts to the glass/boards, but have not separated impacts to the glass versus boards (Hutchison et al., 2015a; Wilcox, Machan, et al., 2014). In **Chapter 3**, we found that head-to-glass collisions were just as severe, and much more common, than head-to-board collisions. Reductions to the stiffness of the glass resulted in lower magnitudes of head accelerations in laboratory-based simulations (Schmitt et al., 2018), and a reduced rate of concussions in International and Olympic ice hockey (Tuominen et al., 2017). The high number of observed head-to-glass impacts in our study reinforces the need for further research on design, implementation and evaluation of low-stiffness glass/boards and its effect on head accelerations (C. A. Emery et al., 2017).

In **Chapters 2-3**, players often experienced head impacts to the side of the head—an observation relevant to evaluating the brain dynamic response from finite element models (Post, Kendall, et al., 2018; Tiernan & Byrne, 2019) and the design and evaluation of helmets (B. Rowson et al., 2015). These findings contradict Brainard et al. (2012) and Wilcox, Beckwith, et al. (2014), who reported that men's university hockey players sustained impacts equally to the side, back, and front of the head. Methodological difference may have contributed to contrasting results between the current and previous studies. For example, Brainard et al. (2012) and Wilcox, Beckwith, et al. (2014) relied on signals from helmet-mounted sensors without video review to compute the head impact locations, which may lead to imprecise quantification of impact location frequencies (Cortes et al., 2017; Patton et al., 2020). Caution should be used when comparing impact counts and magnitudes across studies involving video and/or sensor technologies.

Our results also provide new evidence on the dynamics of shoulder checks in ice hockey, as a starting point for designing test systems for evaluating and improving the protective value of shoulder pads. In **Chapter 2-3**, we found that shoulder-to-head impacts were most often delivered along the periphery of the rink to opponents who were contacting or near the boards/glass. Moreover, in **Chapter 4**, we measured the effective stiffness, stiffness and damping during these common and severe shoulder checks to the head. Previous studies have shown that design features of shoulder pads influence the risk for head injury during shoulder-to-head impacts in ice hockey (Kendall et al., 2014; Richards et al., 2016; Virani et al., 2017). Our results provide a useful starting point towards the development of biofidelic test systems for evaluating and optimizing the protective value of shoulder pads in ice hockey (Hughes et al., 2020; Payne et al., 2013, 2014).

Our results may also inform injury detection strategies. In **Chapter 3**, players who exhibited visible signs of concussion experienced 1.6-fold greater peak head rotational velocities. The most common signs were “slow to get up” and “clutching of head.” Echemendia et al. (2018) and Bruce et al. (2018) examined the use of visible signs to predict subsequent concussion diagnosis in professional ice hockey. They found that, despite being frequently observed, “slow to get up” and “clutching of head” were poor predictors of concussion. Bruce et al. (2018) speculated that “slow to get up” and “clutching of head” may arise due to the player’s behavioral response to receiving an impact, (e.g., an attempt to draw a penalty) or indicate an injury other than concussion. Although injury diagnosis in the current study was unknown, we showed that players with visible signs experienced greater impact severities. Our findings suggest that if any visible sign of concussion is observed, players should be removed from play and receive appropriate medical attention.

Some of our negative results have important implications for prevention through training programs. In **Chapters 2-3**, we found that anticipating the collision did not reduce the severity or number of observed head impact events. Mihalik, Blackburn, et al. (2010) also reported no differences in head accelerations between anticipated and unanticipated head impacts in youth hockey (aged 14). Furthermore, Eliason et al. (2022) found that more experience in performing body checks did not protect minor hockey players (aged 15-17) against injury, including concussion. Although visual and sensorimotor training are promising avenues for injury prevention (C. A. Emery et al., 2017; Kiefer et al., 2018; Kung et al., 2020), more research is required to evaluate the protective value of anticipatory responses and player training in reducing the frequency and severity of head impacts and injury in hockey.

5.3. Limitations

In the current section, I discuss important limitations to this thesis—which are crucial for the interpretation of our results and considerations for future studies.

First, our results in **Chapters 2-4** are specific to direct head impacts observed in men's university ice hockey games and may not apply to other contexts (e.g., practices; other teams, leagues, levels of play; female ice hockey players) involving different rules, skill levels, and levels of physicality/aggression (Abbott, 2014). In **Chapters 2-3**, we observed substantial to perfect inter-rater reliability ($k_n > 0.60$) for most questionnaire items used in our analysis. However, caution should be used when interpreting "looking in the direction of the collision," as only fair agreement was achieved (TPA=0.67%, $k_n = 0.33$). In **Chapters 2-4**, we also focused on describing the circumstances and severity of head impacts in hockey and not the clinical consequences of the impacts we observed. Few studies have captured and described concussive impacts in ice hockey (Wilcox et al., 2015). More research is required to understand the playing situations and biomechanics surrounding head impacts leading to diagnosed concussion. At the same time, the growing evidence on the long-term neurological effects of sub-concussive head impacts leads credibility to our analysis of all head impacts.

Second, it is unlikely that we captured every head impact sustained by each player during game play. In **Chapters 2-3**, the accuracy of our outcomes may have been limited by occlusions and sub-optimal camera angles, which created challenges to video analysis. However, we used five cameras to capture head impacts occurring in all regions of the ice, reducing the probability of missed impacts (Cortes et al., 2017), when compared to previous video-based studies of head impact in hockey, which used a single camera that followed the puck (Mihalik, Blackburn, et al., 2010; Mihalik, Greenwald, et al., 2010; Wilcox, Machan, et al., 2014). In addition, in **Chapter 3**, impact magnitude calculations may be influenced by classification of false-negatives and -positives, especially if these errors varied over a range of impact magnitudes (Eckner et al., 2018). For example, Wilcox, Machan, et al. (2014) used helmet-mounted sensors

(HIT system) and recorded 1965 impact events across 12 home games in a single season, yet only 270 head impacts were captured on video. To minimize the number of false-positives classified by the sensor, impacts were first identified by observers at the rink, then verified on video and paired with available sensor data (Patton et al., 2020). We estimated that 60-70% of all head impact events experienced during game play were captured in this analysis (**Appendix C**). Based on the distribution of data across games and seasons (see Table 3.1. in **Chapter 3**), we have no reason to believe that the head impacts analyzed in the current thesis are not representative of all head impacts in hockey. However, some of the head impacts were captured on video not by the sensor. This may be due to: (1) the impact not exceeding 10 g; (2) the impacted player not wearing a sensor; (3) misclassification of the impact event by proprietary algorithms built into the sensor; and/or (4) inability to synchronize the video and sensor time stamps.

Third, our findings in **Chapter 3** are specific to the sensor used—GForceTracker™. Since the GFT is adhered to the helmet shell, it may capture helmet movement rather than kinematics experienced by the head (Cummiskey et al., 2017; Jadischke et al., 2013). Moreover, in laboratory-based validation studies, helmet type, sensor location, and impact location affect the accuracy of GFT measures (Allison et al., 2015; Campbell et al., 2016; Knowles et al., 2017). However, the accuracy of helmet-mounted sensors to measure head kinematics when impacted by diverse objects (e.g., glass, ice, boards, body parts) in uncontrolled, sporting environments is poorly understood (Aguiar et al., 2022; Zacharias et al., 2022). Interestingly, we more often observed differences across scenarios in rotational velocity than linear acceleration (see **3.4. Results** and **Appendices D-E**). Previous studies which found differences in impact severity either (1) reported small differences in mean magnitudes (< 2 g or <200 rad/s), where the clinical significance is unclear, or (2) examined factors at high impact magnitudes (e.g., > 20 g threshold or at the 95th percentile), excluding common low-magnitude impact events (Brainard et al., 2012; Wilcox, Beckwith, et al., 2014). Further studies are required to improve the accuracy of head kinematic measurements by sensor technologies for impacts in sport (Le Flao et al., 2022; Tierney, 2021). For example, advanced machine learning algorithms may facilitate impact detection methods in wearable technologies for accurate exposure monitoring (L. C. Wu et al., 2018). Future work should also consider using mouthguard-mounted sensors, which are less error-prone (Cummiskey et al., 2017; Tierney, 2021).

Lastly, our results in **Chapter 4** are specific to the style of shoulder checking we stimulated, which involves impact to a braced opponent's shoulder or torso, or head sandwiched against the glass shielding. Such checks are a common cause of head impact in men's university hockey, as shown in **Chapters 2-3** and Potvin et al. (2019), and contribute up to 53% of concussions in the NHL (Delaney et al., 2014; Hutchison et al., 2015a). However, future experiments should characterize shoulder stiffness, damping and mass for different impact scenarios and player populations, and determine how these impact characteristics depend on the initial and boundary conditions of the impact. To guide such efforts, more evidence is required on the frequency and risk for injury created by different types of checks in hockey.

5.4. Future directions

In this section, I propose directions for future research investigations in the field of head impact biomechanics related to hockey and other collision sports.

First, future studies may adopt approaches used in the current thesis, to understand the circumstances and severity of head impacts experienced by other populations in collision sports. For example, studies of women are underrepresented in the sports concussion and head impact biomechanics fields. A recent review found that 22% of 185 head impact studies in sport included one or more female participants (less than 15% of the overall investigated population) (Le Flao et al., 2022). When comparing males and females in hockey studies that used the same sensor and methods, females experienced fewer head impacts and lower magnitude rotational head accelerations than males (Brainard et al., 2012; Eckner et al., 2018; Mihalik et al., 2020; Wilcox, Beckwith, et al., 2014; Wilcox, Machan, et al., 2014). Despite that, women/females tend to be more sensitive to the negative effects of head impacts than males, and are at a higher risk of concussion (Prien et al., 2018; Resch et al., 2017), with higher symptom severity (Resch et al., 2017), and longer recovery periods (Gallagher et al., 2018) than males. More studies are needed to understand the circumstances and risk factors of head impacts in female athletes. Furthermore, more biofidelic testing systems and models are necessary to reconstruct head impacts in female collision sports under realistic conditions.

Second, further research is warranted to determine the dynamics of head impacts, and the risk for brain injury, across different scenarios in hockey. In a high-speed, collision sport like ice hockey, the head can be impacted in many ways. In the current thesis, we focused on the most common and severe scenarios that led to head impact. However, as stated by Meeuwisse et al. (2007), “one can imagine an almost infinite number of scenarios based on the combination of intrinsic and extrinsic risk factors and the number of events, cycles, and time that passes before an injury actually occurs.” Additional investigation of other common and severe head impact scenarios in hockey is needed. For instance, as discussed in Section 5.1., future studies may examine the head dynamics during collisions with the glass/boards, to inform the design, development, and test standards of shielding systems. In addition, the integration of other biomechanical and computational approaches to detect head impact events (e.g., artificial intelligence such as Computer Vision) and understand the head or brain dynamic response during a range of impact scenarios (e.g., finite element models, multibody model simulations), may uncover which conditions provide the greatest risk for brain tissue damage and injury. The data from **Chapter 4** provides a scientific basis for selecting mass, stiffness and damping for shoulder-to-head simulations. This may lead to the development of biofidelic mechanical systems for assessing and optimizing the protective value of padding and helmets.

Third, standardized data collection methods and better reporting of the uses and set-up of devices is essential to advance future research in sport impact biomechanics. Moreover, collaboration between researchers and companies, independent validation protocols based on consensus agreement, and improvements in hardware/software development are needed to improve the accuracy of biomechanical measures during head impacts (Le Flao et al., 2022; Patton et al., 2020; Tierney, 2021). Collectively, these effects would improve the validity of measures from wearable sensors and lab reconstructions, and improve efforts to gather large human datasets of accurately measured head impact kinematics, from which brain tissue deformation parameters can be simulated with computational models (Le Flao et al., 2022; Tierney, 2021; L. Wu, 2020). In 2022, the Consensus Head Acceleration Measurement Practices (CHAMP) group published recommendations and best practices for the on-field deployment and laboratory validation of wearable head kinematic devices (Gabler et al., 2022; Kuo et al., 2022), conducting laboratory reconstructions of head impacts (Funk et al., 2022), and use of brain biomechanical models (Ji et al., 2022) in contact sports. Many of these recommendations were used in the current thesis, such as video confirmation and reporting of trigger/inclusion thresholds. Standardized recording, processing, and reporting will considerably aid in data and signal processing and allow for meaningful cross-study comparisons (Arbogast et al., 2022; Patton et al., 2020; Tierney, 2021).

Lastly, in addition to biomechanical characteristics and playing situation, player perceptions on the causes and consequences of the head impact should be evaluated. As discussed, research to date has focused on analysis of sensor-based measures of head kinematics during head impact events in hockey (Brainard et al., 2012; Eckner et al., 2018; Mihalik et al., 2008, 2020; Wilcox, Machan, et al., 2014). While these studies have improved our understanding of head impact severity, they provide limited insight on how head impacts occur, and how this depends on behavioural factors (e.g., risk-taking, playing style, perceptions of the cause and consequences of head impacts). Todd et al. (2019) found that hockey players, coaches and parents believe player contact maintains social order of the game and can be performed in a sportsmanlike manner (Todd et al., 2019). Consequently, if players do not feel the head impact event was serious/severe, they often will not seek medical attention and continue to play – even if symptoms are present (Delaney et al., 2015; Kaut et al., 2003; Lininger et al., 2017; McCrea et al., 2004). Despite these findings, researchers have yet to examine what factors players perceive as contributing to the cause, consequence, and prevention of head impacts in hockey. The design and implementation of improved brain injury prevention strategies in hockey requires an integrated approach that considers biomechanical, situational, and behavioural factors related to head impact events (Bahr & Krosshaug, 2005; Verhagen et al., 2010). Qualitative descriptions of head impact events from interviews with players can overcome these gaps in knowledge and facilitate the development and adoption of new prevention initiatives to protect brain health in hockey, such as educational tools, player training, and user-centred environmental/gear design (Malagon-Maldonado, 2014; Todd et al., 2019).

5.5. Concluding remarks

In summary, this thesis provides evidence on the circumstances and severity of head impacts in men’s university hockey. Although most observed events resulting in head impact involved contact with another player, the head was just as likely to experience impact with an environmental object, as with an opposing player’s body part. When considering frequency and severity as a function of head impact risk, we observed that shoulder checks were the most common and severe body part to strike the head in men’s university hockey. These findings provide insight into how head impacts occur, and which scenarios lead to the most common and severe head impacts. By improving our knowledge on the mechanism of head impacts in hockey, this thesis provides an evidence base to inform the design of improved strategies (e.g., player training, rink design, equipment, and rules of player) to reduce the number and severity of head impacts and brain injuries, and ultimately create a safer game for athletes. Further research is warranted to examine the head and brain dynamic response from impacts to the glass/boards and other body parts (e.g., hand), as well as determine the characteristics and risk factors for head impacts in underrepresented populations in sport collision research (e.g., female hockey players).

References

Abbott, K. (2014). Injuries in women's ice hockey: Special considerations. *Current Sports Medicine Reports*, *13*(6), 377–382. https://doi.org/10.1249/JSR.0000000000000102

Abrahams, S., Fie, S. M., Patricios, J., Posthumus, M., & September, A. V. (2014). Risk factors for sports concussion: An evidence-based systematic review. *British Journal of Sports Medicine*, *48*(2), 91–97. https://doi.org/10.1136/bjsports-2013-092734

Agel, J., Dompier, T. P., Dick, R., & Marshall, S. W. (2007). Descriptive epidemiology of collegiate men's ice hockey injuries: National Collegiate Athletic Association injury surveillance system, 1988–1989 through 2003–2004. *Journal of Athletic Training*, *42*(2), 241–248.

Agel, J., & Harvey, E. J. (2010). A 7-year review of men's and women's ice hockey injuries in the NCAA. *Canadian Journal of Surgery*, *53*(5), 319–323.

Aguiar, O. M. G., Potvin, B. M., Yang, Y., Hua, K. N., Bruschetta, M. L., Virani, S., & Robinovitch, S. N. (2020). American society of biomechanics journal of biomechanics award 2019: Circumstances of head impacts in men's university ice hockey. *Journal of Biomechanics*, *108*, 109882. https://doi.org/10.1016/j.jbiomech.2020.109882

Aguiar, O. M. G., Zacharias, J., Vakili, O., & Robinovitch, S. N. (2022). Agreement between GFT & Hybrid-III head kinematics for different impact scenarios in ice hockey. *North American Congress on Biomechanics Conference Proceedings*. NACOB 2022, Ottawa, Canada. https://nacob.org/wp-content/uploads/2022/08/MondayTuesdayUpdate.pdf

Al-Bsharat, A. S., Hardy, W. N., Yang, K. H., Khalil, T. B., Tashman, S., & King, A. I. (1999, October 10). Brain/skull relative displacement magnitude due to blunt head impact: New experimental data and model. *SAE Technical Paper 99SC22*. Stapp Car Crash Conference. https://doi.org/10.4271/99SC22

Allison, M. A., Kang, Y. S., Bolte, J. H. I., Maltese, M. R., & Arbogast, K. B. (2014). Validation of a helmet-based system to measure head impact biomechanics in ice hockey. *Medicine & Science in Sports & Exercise*, *46*(1), 115–123. https://doi.org/10.1249/MSS.0b013e3182a32d0d

Allison, M. A., Kang, Y. S., Maltese, M. R., Bolte, J. H., & Arbogast, K. B. (2015). Measurement of Hybrid III head impact kinematics using an accelerometer and gyroscope system in ice hockey helmets. *Annals of Biomedical Engineering*, *43*(8), 1896–1906. https://doi.org/10.1007/s10439-014-1197-z

Andersen, T. E., Larsen, Ø., Tenga, A., Engebretsen, L., & Bahr, R. (2003). Football incident analysis: A new video based method to describe injury mechanisms in professional football. *British Journal of Sports Medicine*, *37*(3), 226–232. https://doi.org/10.1136/bjsm.37.3.226

Arbogast, K. B., Caccese, J. B., Buckley, T. A., McIntosh, A. S., Henderson, K., Stemper, B. D., Solomon, G., Broglio, S. P., Funk, J. R., & Crandall, J. R. (2022). Consensus head acceleration measurement practices (CHAMP): Origins, methods, transparency and disclosure. *Annals of Biomedical Engineering*. https://doi.org/10.1007/s10439-022-03025-9

Bahr, R., & Krosshaug, T. (2005). Understanding injury mechanisms: A key component of preventing injuries in sport. *British Journal of Sports Medicine*, *39*(6), 324–329. https://doi.org/10.1136/bjsm.2005.018341

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

Bain, A. C., & Meaney, D. F. (2000). Tissue-level thresholds for axonal damage in an experimental model of central nervous system white matter injury. *Journal of Biomechanical Engineering*, *122*(6), 615–622. https://doi.org/10.1115/1.1324667

Bangsbo, J., Blackwell, J., Boraxbekk, C.-J., Caserotti, P., Dela, F., Evans, A. B., Jespersen, A. P., Gliemann, L., Kramer, A. F., Lundbye-Jensen, J., Mortensen, E. L., Lassen, A. J., Gow, A. J., Harridge, S. D. R., Hellsten, Y., Kjaer, M., Kujala, U. M., Rhodes, R. E., Pike, E. C. J., … Viña, J. (2019). Copenhagen consensus statement 2019: Physical activity and ageing. *British Journal of Sports Medicine*, *53*(14), 856–858. https://doi.org/10.1136/bjsports-2018-100451

Bari, S., Svaldi, D. O., Jang, I., Shenk, T. E., Poole, V. N., Lee, T., Dydak, U., Rispoli, J. V., Nauman, E. A., & Talavage, T. M. (2019). Dependence on subconcussive impacts of brain metabolism in collision sport athletes: An MR spectroscopic study. *Brain Imaging and Behavior*, *13*(3), 735–749. https://doi.org/10.1007/s11682-018-9861-9

Bayly, P. V., Cohen, T. S., Leister, E. P., Ajo, D., Leuthardt, E. C., & Genin, G. M. (2005). Deformation of the human brain induced by mild acceleration. *Journal of Neurotrauma*, *22*(8), 845–856. https://doi.org/10.1089/neu.2005.22.845

BC Intercollegiate Hockey League. (2022). https://www.bcihl.ca/leagues/front_pagePro.cfm?clientID=3692&leagueID=11139

Bennett, M. B., & Ker, R. F. (1990). The mechanical properties of the human subcalcaneal fat pad in compression. *Journal of Anatomy*, *171*, 131–138.

Black, A. M., Hagel, B. E., Palacios-Derflingher, L., Schneider, K. J., & Emery, C. A. (2017). The risk of injury associated with body checking among Pee Wee ice hockey players: An evaluation of Hockey Canada's national body checking policy change. *British Journal of Sports Medicine*, *51*(24), 1767–1772. https://doi.org/10.1136/bjsports-2016-097392

Bland, M. L., McNally, C., & Rowson, S. (2018). Differences in impact performance of bicycle helmets during oblique impacts. *Journal of Biomechanical Engineering*, *140*(9). https://doi.org/10.1115/1.4040019

Bolte, J. H., & Hines, M. H. (2000, November 1). Shoulder response characteristics and injury due to lateral glenohumeral joint impacts. *SAE Technical Paper 2000-01-SC18*. Stapp Car Crash Conference. https://doi.org/10.4271/2000-01-SC18

Brainard, L. L., Beckwith, J. G., Chu, J. J., Crisco, J. J., Mcallister, T. W., Duhaime, A.-C., Maerlender, A. C., & Greenwald, R. M. (2012). Gender differences in head impacts sustained by collegiate ice hockey players. *Medicine & Science in Sports & Exercise*, *44*(2), 297–304. https://doi.org/10.1249/MSS.0b013e31822b0ab4

Breedlove, E. L., Robinson, M., Talavage, T. M., Morigaki, K. E., Yoruk, U., O'Keefe, K., King, J., Leverenz, L. J., Gilger, J. W., & Nauman, E. A. (2012). Biomechanical correlates of symptomatic and asymptomatic neurophysiological impairment in high school football. *Journal of Biomechanics*, *45*(7), 1265–1272. https://doi.org/10.1016/j.jbiomech.2012.01.034

Brennan, R. L., & Prediger, D. J. (1981). Coefficient kappa: Some uses, misuses, and alternatives. *Educational and Psychological Measurement*, *41*(3), 687–699. https://doi.org/10.1177/001316448104100307

Bruce, J. M., Echemendia, R. J., Meeuwisse, W., Hutchison, M. G., Aubry, M., & Comper, P. (2018). Development of a risk prediction model among professional hockey players with visible signs of concussion. *British Journal of Sports Medicine*, *52*(17), 1143–1148. https://doi.org/10.1136/bjsports-2016-097091

Budday, S., Sommer, G., Birkl, C., Langkammer, C., Haybaeck, J., Kohnert, J., Bauer, M., Paulsen, F., Steinmann, P., Kuhl, E., & Holzapfel, G. A. (2017). Mechanical characterization of human brain tissue. *Acta Biomaterialia*, *48*, 319–340. https://doi.org/10.1016/j.actbio.2016.10.036

Campbell, K. R., Warnica, M. J., Levine, I. C., Brooks, J. S., Laing, A. C., Burkhart, T. A., & Dickey, J. P. (2016). Laboratory evaluation of the gForce Tracker^{TM}, a head impact kinematic measuring device for use in football helmets. *Annals of Biomedical Engineering*, *44*(4), 1246–1256. https://doi.org/10.1007/s10439-015-1391-7

Caswell, S. V., Lincoln, A. E., Almquist, J. L., Dunn, R. E., & Hinton, R. Y. (2012). Video incident analysis of head injuries in high school girls' lacrosse. *The American Journal of Sports Medicine*, *40*(4), 756–762. https://doi.org/10.1177/0363546512436647

Chandran, A., Boltz, A. J., Morris, S. N., Robison, H. J., Nedimyer, A. K., Collins, C. L., & Register-Mihalik, J. K. (2022). Epidemiology of concussions in National Collegiate Athletic Association (NCAA) sports: 2014/15-2018/19. *The American Journal of Sports Medicine*, *50*(2), 526–536. https://doi.org/10.1177/03635465211060340

Clark, J. M., Post, A., Hoshizaki, T. B., & Gilchrist, M. D. (2016). Protective capacity of ice hockey helmets against different impact events. *Annals of Biomedical Engineering*, *44*(12), 3693–3704. https://doi.org/10.1007/s10439-016-1686-3

Cohen, J. (1960). A coefficient of agreement for nominal scales. *Educational and Psychological Measurement*, *20*(1), 37–46. https://doi.org/10.1177/001316446002000104

Compigne, S., Caire, Y., Quesnel, T., & Verries, J.-P. (2004, November 1). Non-injurious and injurious impact response of the human shoulder three-dimensional analysis of kinematics and determination of injury threshold. *SAE Technical Paper 2004-22-0005*. Stapp Car Crash Conference. https://doi.org/10.4271/2004-22-0005

Cortes, N., Lincoln, A. E., Myer, G. D., Hepburn, L., Higgins, M., Putukian, M., & Caswell, S. V. (2017). Video analysis verification of head impact events measured by wearable sensors. *The American Journal of Sports Medicine*, *45*(10), 2379–2387. https://doi.org/10.1177/0363546517706703

Crisco, J. J., Wilcox, B. J., Beckwith, J. G., Chu, J. J., Duhaime, A.-C., Rowson, S., Duma, S. M., Maerlender, A. C., McAllister, T. W., & Greenwald, R. M. (2011). Head impact exposure in collegiate football players. *Journal of Biomechanics*, *44*(15), 2673–2678. https://doi.org/10.1016/j.jbiomech.2011.08.003

Cummiskey, B., Schiffmiller, D., Talavage, T. M., Leverenz, L., Meyer, J. J., Adams, D., & Nauman, E. A. (2017). Reliability and accuracy of helmet-mounted and head-mounted devices used to measure head accelerations. *Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology*, *231*(2), 144–153. https://doi.org/10.1177/1754337116658395

Cusimano, M. D., Cho, N., Amin, K., Shirazi, M., McFaull, S. R., Do, M. T., Wong, M. C., & Russell, K. (2013). Mechanisms of team-sport-related brain injuries in children 5 to 19 years old: Opportunities for prevention. *PLoS One*, *8*(3), e58868. https://doi.org/10.1371/journal.pone.0058868

Damji, F., & Babul, S. (2018). Improving and standardizing concussion education and care: A Canadian experience. *Concussion*, *3*(4), CNC58. https://doi.org/10.2217/cnc-2018-0007

Davidson, P. L., Mahar, B., Chalmers, D. J., & Wilson, B. D. (2005). Impact modeling of gymnastic back-handsprings and dive-rolls in children. *Journal of Applied Biomechanics*, *21*(2), 115–128. https://doi.org/10.1123/jab.21.2.115

Delaney, J. S., Al-Kashmiri, A., & Correa, J. A. (2014). Mechanisms of injury for concussions in university football, ice hockey, and soccer. *Clin J Sport Med*, *24*(3), 233–237.

Delaney, J. S., Lamfookon, C., Bloom, G. A., Al-Kashmiri, A., & Correa, J. A. (2015). Why university athletes choose not to reveal their concussion symptoms during a practice or game. *Clinical Journal of Sport Medicine*, *25*(2), 113–125. https://doi.org/10.1097/JSM.0000000000000112

Donaldson, L., Li, B., & Cusimano, M. D. (2014). Economic burden of time lost due to injury in NHL hockey players. *Injury Prevention*, *20*(5), 347–349. https://doi.org/10.1136/injuryprev-2013-041016

Dong, M. (2020, August 6). *Generalized linear mixed model add-in*. JMP User Community. https://community.jmp.com/t5/JMP-Add-Ins/Generalized-Linear-Mixed-Model-Add-in/ta-p/284627

Echemendia, R. J., Bruce, J. M., Meeuwisse, W., Hutchison, M. G., Comper, P., & Aubry, M. (2018). Can visible signs predict concussion diagnosis in the National Hockey League? *British Journal of Sports Medicine*, *52*(17), 1149–1154. https://doi.org/10.1136/bjsports-2016-097090

Eckner, J. T., O'Connor, K. L., Broglio, S. P., & Ashton-Miller, J. A. (2018). Comparison of head impact exposure between male and female high school ice hockey athletes. *The American Journal of Sports Medicine*, *46*(9), 2253–2262. https://doi.org/10.1177/0363546518777244

Eliason, P. H., Hagel, B. E., Palacios-Derflingher, L., Warriyar, V., Bonfield, S., Black, A. M., Mrazik, M., Lebrun, C., & Emery, C. A. (2022). Bodychecking experience and rates of injury among ice hockey players aged 15–17 years. *Canadian Medical Association Journal*, *194*(24), E834–E842. https://doi.org/10.1503/cmaj.211718

Emery, C. A., Black, A. M., Kolstad, A., Martinez, G., Nettel-Aguirre, A., Engebretsen, L., Johnston, K., Kissick, J., Maddocks, D., Tator, C., Aubry, M., Dvořák, J., Nagahiro, S., & Schneider, K. (2017). What strategies can be used to effectively reduce the risk of concussion in sport? A systematic review. *British Journal of Sports Medicine*, *51*(12), 978–984. https://doi.org/10.1136/bjsports-2016-097452

Emery, C. A., Eliason, P., Warriyar, V., Palacios-Derflingher, L., Black, A. M., Krolikowski, M., Spencer, N., Sick, S., Kozak, S., Schneider, K. J., Babul, S., Mrazik, M., Lebrun, C., Goulet, C., Macpherson, A., & Hagel, B. E. (2022). Body checking in non-elite adolescent ice hockey leagues: It is never too late for policy change aiming to protect the health of adolescents. *British Journal of Sports Medicine*, *56*(1), 12–17. https://doi.org/10.1136/bjsports-2020-103757

Emery, C. A., Hagel, B., Decloe, M., & Carly, M. (2010). Risk factors for injury and severe injury in youth ice hockey: A systematic review of the literature. *Injury Prevention*, *16*(2), 113–118. https://doi.org/10.1136/ip.2009.022764

Emery, C., Palacios-Derflingher, L., Black, A. M., Eliason, P., Krolikowski, M., Spencer, N., Kozak, S., Schneider, K. J., Babul, S., Mrazik, M., Lebrun, C. M., Goulet, C., Macpherson, A., & Hagel, B. E. (2020). Does disallowing body checking in non-elite 13- to 14-year-old ice hockey leagues reduce rates of injury and concussion? A cohort study in two Canadian provinces. *British Journal of Sports Medicine*, *54*(7), 414–420. https://doi.org/10.1136/bjsports-2019-101092

Fernandes, F. A., & Sousa, R. J. A. de. (2015). Head injury predictors in sports trauma – A state-of-the-art review. *Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine*, *229*(8), 592–608. https://doi.org/10.1177/0954411915592906

Fice, J. B., Siegmund, G. P., & Blouin, J.-S. (2018). Neck muscle biomechanics and neural control. *Journal of Neurophysiology*, *120*(1), 361–371. https://doi.org/10.1152/jn.00512.2017

Fickling, S. D., Smith, A. M., Stuart, M. J., Dodick, D. W., Farrell, K., Pender, S. C., & D'Arcy, R. C. N. (2021). Subconcussive brain vital signs changes predict head-impact exposure in ice hockey players. *Brain Communications*. https://doi.org/10.1093/braincomms/fcab019

Flik, K., Lyman, S., & Marx, R. G. (2005). American collegiate men's ice hockey: An analysis of injuries. *The American Journal of Sports Medicine*, *33*(2), 183–189. https://doi.org/10.1177/0363546504267349

Funk, J. R., McIntosh, A. S., Withnall, C., Wonnacott, M., & Jadischke, R. (2022). Best practices for conducting physical reconstructions of head impacts in sport. *Annals of Biomedical Engineering*. https://doi.org/10.1007/s10439-022-03024-w

Gabler, L., Patton, D., Begonia, M., Daniel, R., Rezaei, A., Huber, C., Siegmund, G., Rooks, T., & Wu, L. (2022). Consensus head acceleration measurement practices (champ): Laboratory validation of wearable head kinematic devices. *Annals of Biomedical Engineering*. https://doi.org/10.1007/s10439-022-03066-0

Galbraith, J. A., Thibault, L. E., & Matteson, D. R. (1993). Mechanical and electrical responses of the squid giant axon to simple elongation. *Journal of Biomechanical Engineering*, *115*(1), 13–22. https://doi.org/10.1115/1.2895464

Gallagher, V., Kramer, N., Abbott, K., Alexander, J., Breiter, H., Herrold, A., Lindley, T., Mjaanes, J., & Reilly, J. (2018). The effects of sex differences and hormonal contraception on outcomes after collegiate sports-related concussion. *Journal of Neurotrauma*, *35*(11), 1242–1247. https://doi.org/10.1089/neu.2017.5453

Gardner, A. J., Howell, D. R., & Iverson, G. L. (2018). A video review of multiple concussion signs in National Rugby League match play. *Sports Medicine - Open*, *4*(1), 5. https://doi.org/10.1186/s40798-017-0117-9

Gennarelli, T. A. (1993). Mechanisms of brain injury. *The Journal of Emergency Medicine*, *11 Suppl 1*, 5–11.

Giza, C., Greco, T., & Prins, M. L. (2018). Concussion: Pathophysiology and clinical translation. In *Handbook of Clinical Neurology* (Vol. 158, pp. 51–61). Elsevier. https://doi.org/10.1016/B978-0-444-63954-7.00006-9

Goldsmith, W., & Plunkett, J. (2004). A biomechanical analysis of the causes of traumatic brain injury in infants and children. *American Journal of Forensic Medicine & Pathology*, *25*(2), 89–100. https://doi.org/10.1097/01.paf.0000127407.28071.63

Goulet, C., Roy, T.-O., Nadeau, L., Hamel, D., Fortier, K., & Emery, C. (2016). The incidence and types of physical contact associated with body checking regulation experience in 13–14 year old ice hockey players. *International Journal of Environmental Research and Public Health*, *13*(7), 668. https://doi.org/10.3390/ijerph13070668

Gurdjian, E. S. (1975). Re-evaluation of the biomechanics of blunt impact injury of the head. *Surgery, Gynecology & Obstetrics*, *140*(6), 845–850.

Gurdjian, E. S., Lissner, H. R., Hodgson, V. R., & Patrick, L. M. (1964). Mechanism of head injury. *Clinical Neurosurgery*, *12*, 112–128. https://doi.org/10.1093/neurosurgery/12.cn_suppl_1.112

Gurdjian, E. S., Lissner, H. R., Latimer, F. R., Haddad, B. F., & Webster, J. E. (1953). Quantitative determination of acceleration and intracranial pressure in experimental head injury: Preliminary report. *Neurology*, *3*(6), 417–417. https://doi.org/10.1212/WNL.3.6.417

Gurdjian, E. S., Roberts, V. L., & Thomas, L. M. (1966). Tolerance curves of acceleration and intracranial pressure and protective index in experimental head injury. *The Journal of Trauma*, *6*(5), 600–604. https://doi.org/10.1097/00005373-196609000-00005

Guskiewicz, K. M., Marshall, S. W., Bailes, J., McCrea, M., Cantu, R. C., Randolph, C., & Jordan, B. D. (2005). Association between recurrent concussion and late-life cognitive impairment in retired professional football players. *Neurosurgery*, *57*(4), 719–726. https://doi.org/10.1227/01.NEU.0000175725.75780.DD

Guskiewicz, K. M., Mihalik, J. P., Shankar, V., Marshall, S. W., Crowell, D. H., Oliaro, S. M., Ciocca, M. F., & Hooker, D. N. (2007). Measurement of head impacts in collegiate football players: Relationship between head impact biomechanics and acute clinical outcome after concussion. *Neurosurgery*, *61*(6), 1244–1253. https://doi.org/10.1227/01.neu.0000306103.68635.1a

Hardy, W. N., Foster, C. D., King, A. I., & Tashman, S. (1997). *Investigation of brain injury kinematics: Introduction of a new technique*. 241–254. https://doi.org/10.1115/IMECE1997-1201

Hardy, W. N., Foster, C. D., Mason, M. J., Yang, K. H., King, A. I., & Tashman, S. (2001, November 1). Investigation of head injury mechanisms using neutral density technology and high-speed biplanar X-ray. *SAE Technical Paper 2001-22-0016*. Stapp Car Crash Conference. https://doi.org/10.4271/2001-22-0016

Harris, A. W., Jones, C. A., Rowe, B. H., & Voaklander, D. C. (2012). A population-based study of sport and recreation-related head injuries treated in a Canadian health region. *Journal of Science and Medicine in Sport*, *15*(4), 298–304. https://doi.org/10.1016/j.jsams.2011.12.005

Hockey Canada playing rules 2022-2024. (2022). Hockey Canada. https://cdn.hockeycanada.ca/hockey-canada/Hockey-Programs/Officiating/Downloads/rulebook_casebook_e.pdf

Hodgson, V. R., Gurdjian, E. S., & Thomas, L. M. (1966). Experimental skull deformation and brain displacement demonstrated by flash x-ray technique. *Journal of Neurosurgery*, *25*(5), 549–552. https://doi.org/10.3171/jns.1966.25.5.0549

Holbourn, A. H. S. (1943). Mechanics of head injuries. *The Lancet*, *242*(6267), 438–441. https://doi.org/10.1016/S0140-6736(00)87453-X

Hoshizaki, T. B., Post, A., Kendall, M., Cournoyer, J., Rousseau, P., Gilchrist, M. D., Brien, S., Cusimano, M., & Marshall, S. (2017). The development of a threshold curve for the understanding of concussion in sport. *Trauma*, *19*(3), 196–206. https://doi.org/10.1177/1460408616676503

Hughes, A., Driscoll, H., & Carré, M. (2020). Development of silicone elastomer for use in the assessment of padded clothing in rugby union. *Proceedings*, *49*(1), Article 1. https://doi.org/10.3390/proceedings2020049077

Hutchison, M. G., Comper, P., Meeuwisse, W. H., & Echemendia, R. J. (2014). An observational method to code concussions in the National Hockey League (NHL): The heads-up checklist. *British Journal of Sports Medicine*, *48*(2), 125–129. https://doi.org/10.1136/bjsports-2012-092059

Hutchison, M. G., Comper, P., Meeuwisse, W. H., & Echemendia, R. J. (2015a). A systematic video analysis of National Hockey League (NHL) concussions, part I: Who, when, where and what? *British Journal of Sports Medicine*, *49*(8), 547–551. https://doi.org/10.1136/bjsports-2013-092234

Hutchison, M. G., Comper, P., Meeuwisse, W. H., & Echemendia, R. J. (2015b). A systematic video analysis of National Hockey League (NHL) concussions, part II: How concussions occur in the NHL. *British Journal of Sports Medicine*, *49*(8), 552–555. https://doi.org/10.1136/bjsports-2013-092235

Jadischke, R., Viano, D. C., Dau, N., King, A. I., & McCarthy, J. (2013). On the accuracy of the Head Impact Telemetry (HIT) System used in football helmets. *Journal of Biomechanics*, *46*(13), 2310–2315. https://doi.org/10.1016/j.jbiomech.2013.05.030

Ji, S., Ghajari, M., Mao, H., Kraft, R. H., Hajiaghamemar, M., Panzer, M. B., Willinger, R., Gilchrist, M. D., Kleiven, S., & Stitzel, J. D. (2022). Use of brain biomechanical models for monitoring impact exposure in contact sports. *Annals of Biomedical Engineering*. https://doi.org/10.1007/s10439-022-02999-w

Ji, S., Zhao, W., Li, Z., & McAllister, T. W. (2014). Head impact accelerations for brain strain-related responses in contact sports: A model-based investigation. *Biomechanics and Modeling in Mechanobiology*, *13*(5), 1121–1136. https://doi.org/10.1007/s10237-014-0562-z

Karton, C., & Hoshizaki, T. B. (2018). Concussive and subconcussive brain trauma: The complexity of impact biomechanics and injury risk in contact sport. In B. Hainline & R. A. Stern (Eds.), *Handbook of Clinical Neurology* (Vol. 158, pp. 39–49). Elsevier. https://doi.org/10.1016/B978-0-444-63954-7.00005-7

Kaut, K. P., DePompei, R., Kerr, J., & Congeni, J. (2003). Reports of head injury and symptom knowledge among college athletes: Implications for assessment and educational intervention. *Clinical Journal of Sport Medicine*, *13*(4), 213–221.

Kendall, M., Oeur, A., Brien, S. E., Cusimano, M., Marshall, S., Gilchrist, M. D., & Hoshizaki, T. B. (2020). Accident reconstructions of falls, collisions, and punches in sports. *Journal of Concussion*, *4*, 2059700220936957. https://doi.org/10.1177/2059700220936957

Kendall, M., Post, A., Rousseau, P., & Hoshizaki, T. B. (2014). The effect of shoulder pad design on reducing peak resultant linear and rotational acceleration in shoulder-to-head impacts. In A. Ashare & M. Ziejewski (Eds.), *Mechanism of Concussion in Sports* (pp. 1–11). https://doi.org/10.1520/STP155220120150

Kerr, Z. Y., Register-Mihalik, J. K., Marshall, S. W., Evenson, K. R., Mihalik, J. P., & Guskiewicz, K. M. (2014). Disclosure and non-disclosure of concussion and concussion symptoms in athletes: Review and application of the socio-ecological framework. *Brain Injury*, *28*(8), 1009–1021. https://doi.org/10.3109/02699052.2014.904049

Kiefer, A. W., DiCesare, C., Nalepka, P., Foss, K. B., Thomas, S., & Myer, G. D. (2018). Less efficient oculomotor performance is associated with increased incidence of head impacts in high school ice hockey. *Journal of Science and Medicine in Sport*, *21*(1), 4–9. https://doi.org/10.1016/j.jsams.2017.06.016

Kindschi, K., Higgins, M., Hillman, A., Penczek, G., & Lincoln, A. (2017). Video analysis of high-magnitude head impacts in men's collegiate lacrosse. *BMJ Open Sport & Exercise Medicine*, *3*(1), e000165. https://doi.org/10.1136/bmjsem-2016-000165

King, D., Hume, P., Gissane, C., Brughelli, M., & Clark, T. (2016). The influence of head impact threshold for reporting data in contact and collision sports: Systematic review and original data analysis. *Sports Medicine*, *46*(2), 151–169. https://doi.org/10.1007/s40279-015-0423-7

Kleiven, S. (2007). Predictors for traumatic brain injuries evaluated through accident reconstructions. *SAE Technical Paper 2007-22-0003*. Stapp Car Crash Conference. https://doi.org/10.4271/2007-22-0003

Kleiven, S. (2013). Why most traumatic brain injuries are not caused by linear acceleration but skull fractures are. *Frontiers in Bioengineering and Biotechnology*, *1*. https://www.frontiersin.org/articles/10.3389/fbioe.2013.00015

Kleiven, S., & Hardy, W. N. (2002). Correlation of an FE Model of the Human Head with Local Brain Motion—Consequences for Injury Prediction. *Stapp Car Crash Journal*, *46*, 123–144. https://doi.org/10.4271/2002-22-0007

Knowles, B. M. K., Yu, H., & Dennison, C. R. (2017). Accuracy of a wearable sensor for measures of head kinematics and calculation of brain tissue strain. *Journal of Applied Biomechanics*, *33*, 2–11. http://dx.doi.org/10.1123/jab.2016-0026

Krolikowski, M. P., Black, A. M., Palacios-Derflingher, L., Blake, T. A., Schneider, K. J., & Emery, C. A. (2017). The effect of the “zero tolerance for head contact” rule change on the risk of concussions in youth ice hockey players. *The American Journal of Sports Medicine*, *45*(2), 468–473. https://doi.org/10.1177/0363546516669701

Krosshaug, T., Andersen, T. E., Olsen, O.-E. O., Myklebust, G., & Bahr, R. (2005). Research approaches to describe the mechanisms of injuries in sport: Limitations and possibilities. *British Journal of Sports Medicine*, *39*(6), 330–339. https://doi.org/10.1136/bjsm.2005.018358

Kung, S. M., Suksreephaisan, T. K., Perry, B. G., Palmer, B. R., & Page, R. A. (2020). The effects of anticipation and visual and sensory performance on concussion risk in sport: A review. *Sports Medicine - Open*, *6*(1), 54. https://doi.org/10.1186/s40798-020-00283-6

Kuo, C., Patton, D., Rooks, T., Tierney, G., McIntosh, A., Lynall, R., Esquivel, A., Daniel, R., Kaminski, T., Mihalik, J., Dau, N., & Urban, J. (2022). On-field deployment and validation for wearable devices. *Annals of Biomedical Engineering*. https://doi.org/10.1007/s10439-022-03001-3

Kuo, C., Wu, L., Loza, J., Senif, D., Anderson, S. C., & Camarillo, D. B. (2018). Comparison of video-based and sensor-based head impact exposure. *PLoS One*, *13*(6), e0199238. https://doi.org/10.1371/journal.pone.0199238

Landis, J. R., & Koch, G. G. (1977). The measurement of observer agreement for categorical data. *Biometrics*, *33*(1), 159–174. https://doi.org/10.2307/2529310

Laplaca, M. C., Lee, V. M.-Y., & Thibault, L. E. (1997). An in vitro model of traumatic neuronal injury: Loading rate-dependent changes in acute cytosolic calcium and lactate dehydrogenase release. *Journal of Neurotrauma*, *14*(6), 355–368. https://doi.org/10.1089/neu.1997.14.355

Lawrence, D. W., Hutchison, M. G., Cusimano, M. D., Singh, T., & Li, L. (2014). Interrater agreement of an observational tool to code knockouts and technical knockouts in mixed martial arts. *Clinical Journal of Sport Medicine*, *24*(5), 397–402. https://doi.org/10.1097/JSM.0000000000000047

Le Flao, E., Siegmund, G. P., & Borotkanics, R. (2022). Head impact research using inertial sensors in sport: A systematic review of methods, demographics, and factors contributing to exposure. *Sports Medicine*, *52*(3), 481–504. https://doi.org/10.1007/s40279-021-01574-y

Lininger, M. R., Wayment, H. A., Huffman, A. H., Craig, D. I., & Irving, L. H. (2017). An exploratory study on concussion-reporting behaviors from collegiate student athletes' perspectives. *Athletic Training & Sports Health Care*, *9*(2), 71–80. https://doi.org/10.3928/19425864-20161116-01

Lynall, R. C., Mihalik, J. P., Pierpoint, L. A., Currie, D. W., Knowles, S. B., Wasserman, E. B., Dompier, T. P., Comstock, R. D., Marshall, S. W., & Kerr, Z. Y. (2018). The first decade of web-based sports injury surveillance: Descriptive epidemiology of injuries in us high school boys' ice hockey (2008–2009 through 2013–2014) and National Collegiate Athletic Association men's and women's ice hockey (2004–2005 through 2013–2014). *Journal of Athletic Training*, *53*(12), 1129–1142. https://doi.org/10.4085/1062-6050-176-17

Mackay, D. F., Russell, E. R., Stewart, K., MacLean, J. A., Pell, J. P., & Stewart, W. (2019). Neurodegenerative disease mortality among former professional soccer players. *New England Journal of Medicine*, *381*(19), 1801–1808. https://doi.org/10.1056/NEJMoa1908483

Malagon-Maldonado, G. (2014). Qualitative research in health design. *Health Environments Research & Design*, *7*(4), 120–134. https://doi.org/10.1177/193758671400700411

Malenfant, S., Goulet, C., Nadeau, L., Hamel, D., & Emery, C. A. (2012). The incidence of behaviours associated with body checking among youth ice hockey players. *Journal of Science and Medicine in Sport*, *15*(5), 463–467. https://doi.org/10.1016/j.jsams.2012.03.003

Manley, G., Gardner, A. J., Schneider, K. J., Guskiewicz, K. M., Bailes, J., Cantu, R. C., Castellani, R. J., Turner, M., Jordan, B. D., Randolph, C., Dvořák, J., Hayden, K. A., Tator, C. H., McCrory, P., & Iverson, G. L. (2017). A systematic review of potential long-term effects of sport-related concussion. *British Journal of Sports Medicine*, *51*(12), 969–977. https://doi.org/10.1136/bjsports-2017-097791

McCrea, M., Hammeke, T., Olsen, G., Leo, P., & Guskiewicz, K. (2004). Unreported concussion in high school football players: Implications for prevention. *Clinical Journal of Sport Medicine*, *14*(1), 13–17.

McCrory, P., Meeuwisse, W., Dvorak, J., Aubry, M., Bailes, J., Broglio, S., Cantu, R. C., Cassidy, D., Echemendia, R. J., Castellani, R. J., Davis, G. A., Ellenbogen, R., Emery, C., Engebretsen, L., Feddermann-Demont, N., Giza, C. C., Guskiewicz, K. M., Herring, S., Iverson, G. L., … Vos, P. E. (2017). Consensus statement on concussion in sport—The 5th international conference on concussion in sport held in Berlin, October 2016. *British Journal of Sports Medicine*, *51*(11), 838–847. https://doi.org/10.1136/bjsports-2017-097699

Meeuwisse, W. H. (2009). What is the mechanism of no injury (MONI)? *Clinical Journal of Sport Medicine*, *19*(1), 1–2. https://doi.org/10.1097/JSM.0b013e3181979c1d

Meeuwisse, W. H., Tyreman, H., Hagel, B., & Emery, C. (2007). A dynamic model of etiology in sport injury: The recursive nature of risk and causation. *Clinical Journal of Sport Medicine*, *17*(3), 215–219. https://doi.org/10.1097/JSM.0b013e3180592a48

Melvin, P. R., Souza, S., Mead, R. N., Smith, C., & Mulcahey, M. K. (2018). Epidemiology of upper extremity injuries in NCAA men’s and women’s ice hockey. *The American Journal of Sports Medicine*, *46*(10), 2521–2529. https://doi.org/10.1177/0363546518781338

Mertz, H. J. (1984, April 1). A procedure for normalizing impact response data. *SAE Technical Paper 840884*. SAE Government Industry Meeting and Exposition. https://doi.org/10.4271/840884

Mihalik, J. P., Blackburn, J. T., Greenwald, R. M., Cantu, R. C., Marshall, S. W., & Guskiewicz, K. M. (2010). Collision type and player anticipation affect head impact severity among youth ice hockey players. *Pediatrics*, *125*(6), e1394–e1401. https://doi.org/10.1542/peds.2009-2849

Mihalik, J. P., Greenwald, R. M., Blackburn, J. T., Cantu, R. C., Marshall, S. W., & Guskiewicz, K. M. (2010). Effect of infraction type on head impact severity in youth ice hockey. *Medicine & Science in Sports & Exercise*, *42*(8), 1431–1438. https://doi.org/10.1249/MSS.0b013e3181d2521a

Mihalik, J. P., Guskiewicz, K. M., Jeffries, J. A., Greenwald, R. M., & Marshall, S. W. (2008). Characteristics of head impacts sustained by youth ice hockey players. *Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology*, *222*(1), 45–52. https://doi.org/10.1243/17543371JSET4

Mihalik, J. P., Guskiewicz, K. M., Marshall, S. W., Blackburn, J. T., Cantu, R. C., & Greenwald, R. M. (2012). Head impact biomechanics in youth hockey: Comparisons across playing position, event types, and impact locations. *Annals of Biomedical Engineering*, *40*(1), 141–149. https://doi.org/10.1007/s10439-011-0405-3

Mihalik, J. P., Guskiewicz, K. M., Marshall, S. W., Greenwald, R. M., Blackburn, J. T., & Cantu, R. C. (2011). Does cervical muscle strength in youth ice hockey players affect head impact biomechanics? *Clinical Journal of Sport Medicine*, *21*(5), 416–421. https://doi.org/10.1097/JSM.0B013E31822C8A5C

Mihalik, J. P., Wasserman, E. B., Teel, E. F., & Marshall, S. W. (2020). Head impact biomechanics differ between girls and boys youth ice hockey players. *Annals of Biomedical Engineering*, *48*(1), 104–111. https://doi.org/10.1007/s10439-019-02343-9

Montenigro, P. H., Alosco, M. L., Martin, B. M., Daneshvar, D. H., Mez, J., Chaisson, C. E., Nowinski, C. J., Au, R., McKee, A. C., Cantu, R. C., McClean, M. D., Stern, R. A., & Tripodis, Y. (2017). Cumulative head impact exposure predicts later-life depression, apathy, executive dysfunction, and cognitive impairment in former high school and college football players. *Journal of Neurotrauma*, *34*(2), 328–340. https://doi.org/10.1089/neu.2016.4413

Muise, D. P., MacKenzie, S. J., & Sutherland, T. M. (2016). Frequency and magnitude of head accelerations in a Canadian interuniversity sport football team’s training camp and season. *International Journal of Athletic Therapy and Training*, *21*(5), 36–41. https://doi.org/10.1123/ijatt.2016-0005

Myer, G. D., Yuan, W., Barber Foss, K. D., Smith, D., Altaye, M., Reches, A., Leach, J., Kiefer, A. W., Khoury, J. C., Weiss, M., Thomas, S., Dicesare, C., Adams, J., Gubanich, P. J., Geva, A., Clark, J. F., Meehan, W. P., Mihalik, J. P., & Krueger, D. (2016). The effects of external jugular compression applied during head impact exposure on longitudinal changes in brain neuroanatomical and neurophysiological biomarkers: A preliminary investigation. *Frontiers in Neurology*, *7*(74). https://doi.org/10.3389/fneur.2016.00074

Nauman, E. A., Breedlove, K. M., Breedlove, E. L., Talavage, T. M., Robinson, M. E., & Leverenz, L. J. (2015). Post-season neurophysiological deficits assessed by ImPACT and fMRI in athletes competing in American football. *Developmental Neuropsychology*, *40*(2), 85–91. https://doi.org/10.1080/87565641.2015.1016161

Nauman, E. A., & Talavage, T. M. (2018). Subconcussive trauma. In *Handbook of Clinical Neurology* (Vol. 158, pp. 245–255). Elsevier. https://doi.org/10.1016/B978-0-444-63954-7.00024-0

Naunheim, R. S., Standeven, J., Richter, C., & Lewis, L. M. (2000). Comparison of impact data in hockey, football, and soccer. *The Journal of Trauma: Injury, Infection, and Critical Care*, *48*(5), 938–941. https://doi.org/10.1097/00005373-200005000-00020

Nguyen, J. V. K., Brennan, J. H., Mitra, B., & Willmott, C. (2019). Frequency and magnitude of game-related head impacts in male contact sports athletes: A systematic review and meta-analysis. *Sports Medicine*, *49*(10), 1575–1583. https://doi.org/10.1007/s40279-019-01135-4

Nikooyan, A. A., & Zadpoor, A. A. (2011). Mass–spring–damper modelling of the human body to study running and hopping – an overview. *Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine*, *225*(12), 1121–1135. https://doi.org/10.1177/0954411911424210

Ommaya, A. K., Faas, F., & Yarnell, P. (1968). Whiplash injury and brain damage: An experimental study. *Journal of the American Medical Association*, *204*(4), 285–289. https://doi.org/10.1001/jama.1968.03140170001001

Ommaya, A. K., Fisch, F. J., Mahone, R. M., Corrao, P., & Letcher, F. (1970, February 1). Comparative tolerances for cerebral concussion by head impact and whiplash injury in primates. *SAE Technical Paper 700401*. International Automobile Safety Conference. https://doi.org/10.4271/700401

Ommaya, A. K., & Gennarelli, T. A. (1974). Cerebral concussion and traumatic unconsciousness: Correlation of experimental and clinical observations on blunt head injuries. *Brain*, *97*(1), 633–654. https://doi.org/10.1093/brain/97.1.633

Ommaya, A. K., & Hirsch, A. E. (1971). Tolerances for cerebral concussion from head impact and whiplash in primates. *Journal of Biomechanics*, *4*(1), 13–21. https://doi.org/10.1016/0021-9290(71)90011-X

Ommaya, A. K., Hirsch, A. E., Flamm, E. S., & Mahone, R. H. (1966). Cerebral concussion in the monkey: An experimental model. *Science*, *153*(3732), 211–212.

Ommaya, A. K., Hirsch, A. E., & Martinez, J. L. (1966, February 1). The role of whiplash in cerebral concussion. *SAE Technical Paper 660804*. Stapp Car Crash Conference. https://doi.org/10.4271/660804

Ono, K., Ejima, S., Kaneoka, K., Fukushima, M., Yamada, S., Ujihashi, S., & Compigne, S. (2005). Biomechanical responses of head/neck/torso to lateral impact loading on shoulders of male and female volunteers. *2005 International Research Council on the Biomechanics of Injury Conference Proceedings*, 14.

Patton, D. A. (2016). A review of instrumented equipment to investigate head impacts in sport. *Applied Bionics and Biomechanics*, *2016*, 1–16. https://doi.org/10.1155/2016/7049743

Patton, D. A., Huber, C. M., Jain, D., Myers, R. K., McDonald, C. C., Margulies, S. S., Master, C. L., & Arbogast, K. B. (2020). Head impact sensor studies in sports: A systematic review of exposure confirmation methods. *Annals of Biomedical Engineering*, *48*(11), 2497–2507. https://doi.org/10.1007/s10439-020-02642-6

Pauelsen, M., Nyberg, G., Tegner, C., & Tegner, Y. (2017). Concussion in ice hockey—A cohort study across 29 seasons. *Clinical Journal of Sport Medicine*, *27*(3), 283–287. https://doi.org/10.1097/JSM.0000000000000347

Payne, T., Mitchell, S., & Bibb, R. (2013). Design of human surrogates for the study of biomechanical injury: A review. *Critical Reviews in Biomedical Engineering*, *41*(1). https://doi.org/10.1615/CritRevBiomedEng.2013006847

Payne, T., Mitchell, S., Bibb, R., & Waters, M. (2014). Initial validation of a relaxed human soft tissue simulant for sports impact surrogates. *Procedia Engineering*, *72*, 533–538. https://doi.org/10.1016/j.proeng.2014.06.092

Payne, T., Mitchell, S., Halkon, B., & Bibb, R. (2016). A systematic approach to the characterisation of human impact injury scenarios in sport. *BMJ Open Sport & Exercise Medicine*, *2*(1), e000017. https://doi.org/10.1136/bmjsem-2015-000017

Poole, V. N., Breedlove, E. L., Shenk, T. E., Abbas, K., Robinson, M. E., Leverenz, L. J., Nauman, E. A., Dydak, U., & Talavage, T. M. (2015). Sub-concussive hit characteristics predict deviant brain metabolism in football athletes. *Developmental Neuropsychology*, *40*(1), 12–17. https://doi.org/10.1080/87565641.2014.984810

Post, A., Dawson, L., Hoshizaki, T. B., Gilchrist, M. D., & Cusimano, M. D. (2019). The influence of impact source on variables associated with strain for impacts in ice hockey. *Computer Methods in Biomechanics and Biomedical Engineering*, *22*(7), 713–726. https://doi.org/10.1080/10255842.2019.1588255

Post, A., Hoshizaki, T. B., Karton, C., Clark, J. M., Dawson, L., Cournoyer, J., Taylor, K., Oeur, R. A., Gilchrist, M. D., & Cusimano, M. D. (2019). The biomechanics of concussion for ice hockey head impact events. *Computer Methods in Biomechanics and Biomedical Engineering*, *22*(6), 631–643. https://doi.org/10.1080/10255842.2019.1577827

Post, A., Kendall, M., Cournoyer, J., Karton, C., Oeur, R. A., Dawson, L., & Hoshizaki, T. B. (2018). Brain tissue analysis of impacts to American football helmets. *Computer Methods in Biomechanics and Biomedical Engineering*, *21*(3), 264–277. https://doi.org/10.1080/10255842.2018.1445229

Post, A., Koncan, D., Kendall, M., Cournoyer, J., Michio Clark, J., Kosziwka, G., Chen, W., de Grau Amezcua, S., & Blaine Hoshizaki, T. (2018). Analysis of speed accuracy using video analysis software. *Sports Engineering*, *21*(3), 235–241. https://doi.org/10.1007/s12283-018-0263-4

Post, A., Oeur, A., Walsh, E., Hoshizaki, B., & Gilchrist, M. D. (2014). A centric/non-centric impact protocol and finite element model methodology for the evaluation of American football helmets to evaluate risk of concussion. *Computer Methods in Biomechanics and Biomedical Engineering*, *17*(16), 1785–1800. https://doi.org/10.1080/10255842.2013.766724

Potvin, B. M., Aguiar, O. M. G., Komisar, V., Sidhu, A., Elabd, K., & Robinovitch, S. N. (2019). A comparison of the magnitude and duration of linear and rotational head accelerations generated during hand-, elbow- and shoulder-to-head checks delivered by hockey players. *Journal of Biomechanics*, *91*, 43–50. https://doi.org/10.1016/j.jbiomech.2019.05.002

Prien, A., Grafe, A., Rössler, R., Junge, A., & Verhagen, E. (2018). Epidemiology of head injuries focusing on concussions in team contact sports: A systematic review. *Sports Medicine*, *48*(4), 953–969. https://doi.org/10.1007/s40279-017-0854-4

Public Health Agency of Canada. (2020). *Injury in review, 2020 edition: Spotlight on traumatic brain injuries across the life course*. https://epe.lac-bac.gc.ca/100/201/301/weekly_acquisitions_list-ef/2020/20-25/publications.gc.ca/collections/collection_2020/aspc-phac/HP15-6-2020-eng.pdf

Reed, N., Taha, T., Greenwald, R., & Keightley, M. (2017). Player and game characteristics and head impacts in female youth ice hockey players. *Journal of Athletic Training*, *52*(8), 771–775. https://doi.org/10.4085/1062-6050-52.5.04

Reed, N., Taha, T., Keightley, M., Duggan, C., McAuliffe, J., Cubos, J., Baker, J., Faught, B., McPherson, M., & Montelpare, W. (2010). Measurement of head impacts in youth ice hockey players. *International Journal of Sports Medicine*, *31*(11), 826–833. https://doi.org/10.1055/s-0030-1263103

Resch, J. E., Rach, A., Walton, S., & Broshek, D. K. (2017). Sport concussion and the female athlete. *Clinics in Sports Medicine*, *36*(4), 717–739. https://doi.org/10.1016/j.csm.2017.05.002

Richards, D., Ivarsson, B. J., Scher, I., Hoover, R., Rodowicz, K., & Cripton, P. (2016). Ice hockey shoulder pad design and the effect on head response during shoulder-to-head impacts. *Sports Biomechanics*, *15*(4), 385–396. https://doi.org/10.1080/14763141.2016.1163414

Robinovitch, S. N., Hayes, W. C., & McMahon, T. A. (1991). Prediction of femoral impact forces in falls on the hip. *Journal of Biomechanical Engineering*, *113*(4), 366–374. https://doi.org/10.1115/1.2895414

Robinovitch, S. N., Hayes, W. C., & McMahon, T. A. (1997). Distribution of contact force during impact to the hip. *Annals of Biomedical Engineering*, *25*(3), 499–508. https://doi.org/10.1007/BF02684190

Robinson, M. E., Shenk, T. E., Breedlove, E. L., Leverenz, L. J., Nauman, E. A., & Talavage, T. M. (2015). The role of location of subconcussive head impacts in fmri brain activation change. *Developmental Neuropsychology*, *40*(2), 74–79. https://doi.org/10.1080/87565641.2015.1012204

Rousseau, P., & Hoshizaki, T. B. (2015). Defining the effective impact mass of elbow and shoulder strikes in ice hockey. *Sports Biomechanics*, *14*(1), 57–67. https://doi.org/10.1080/14763141.2015.1025236

Rowson, B., Rowson, S., & Duma, S. M. (2015). Hockey STAR: A methodology for assessing the biomechanical performance of hockey helmets. *Annals of Biomedical Engineering*, *43*(10), 2429–2443. https://doi.org/10.1007/s10439-015-1278-7

Rowson, S., Bland, M. L., Campolettano, E. T., Press, J. N., Rowson, B., Smith, J. A., Sproule, D. W., Tyson, A. M., & Duma, S. M. (2016). Biomechanical perspectives on concussion in sport. *Sports Medicine and Arthroscopy Review*, *24*(3), 100–107. https://doi.org/10.1097/JSA.0000000000000121

Ruhe, A., Gänsslen, A., & Klein, W. (2014). The incidence of concussion in professional and collegiate ice hockey: Are we making progress? A systematic review of the literature. *British Journal of Sports Medicine*, *48*(2), 102–106. https://doi.org/10.1136/bjsports-2012-091609

Russell, E. R., Mackay, D. F., Stewart, K., MacLean, J. A., Pell, J. P., & Stewart, W. (2021). Association of field position and career length with risk of neurodegenerative disease in male former professional soccer players. *JAMA Neurology*, *78*(9), 1057–1063. https://doi.org/10.1001/jamaneurol.2021.2403

Schmidt, J. D., Pierce, A. F., Guskiewicz, K. M., Register-Mihalik, J. K., Pamukoff, D. N., & Mihalik, J. P. (2016). Safe-play knowledge, aggression, and head-impact biomechanics in adolescent ice hockey players. *Journal of Athletic Training*, *51*(5), 366–372. https://doi.org/10.4085/1062-6050-51.5.04

Schmitt, K.-U., Muser, M. H., Thueler, H., & Bruegger, O. (2018). Crash-test dummy and pendulum impact tests of ice hockey boards: Greater displacement does not reduce impact. *British Journal of Sports Medicine*, *52*(1), 41–46. https://doi.org/10.1136/bjsports-2017-097735

Schneider, K. J., Emery, C. A., Black, A., Yeates, K. O., Debert, C. T., Lun, V., & Meeuwisse, W. H. (2019). Adapting the dynamic, recursive model of sport injury to concussion: An individualized approach to concussion prevention, detection, assessment, and treatment. *Journal of Orthopaedic & Sports Physical Therapy*, *49*(11), 799–810. https://doi.org/10.2519/jospt.2019.8926

Schwab, N., Wennberg, R., Grenier, K., Tartaglia, C., Tator, C., & Hazrati, L.-N. (2021). Association of position played and career duration and chronic traumatic encephalopathy at autopsy in elite football and hockey players. *Neurology*, *96*(14), e1835–e1843. https://doi.org/10.1212/WNL.0000000000011668

Seminati, E., Cazzola, D., Preatoni, E., & Trewartha, G. (2017). Specific tackling situations affect the biomechanical demands experienced by rugby union players. *Sports Biomechanics*, *16*(1), 58–75. https://doi.org/10.1080/14763141.2016.1194453

Siegmund, G. (2001). *The reflex response of human neck muscles to whiplash-like perturbations* [Doctoral dissertation]. University of British Columbia.

Siegmund, G. P., Guskiewicz, K. M., Marshall, S. W., DeMarco, A. L., & Bonin, S. J. (2016). Laboratory validation of two wearable sensor systems for measuring head impact severity in football players. *Annals of Biomedical Engineering*, *44*(4), 1257–1274. https://doi.org/10.1007/s10439-015-1420-6

Sim, J., & Wright, C. C. (2005). The kappa statistic in reliability studies: Use, interpretation, and sample size requirements. *Physical Therapy*, *85*(3), 257–268. https://doi.org/10.1093/ptj/85.3.257

Singh, A., Kallakuri, S., Chen, C., & Cavanaugh, J. M. (2009). Structural and functional changes in nerve roots due to tension at various strains and strain rates: An in-vivo study. *Journal of Neurotrauma*, *26*(4), 627–640. https://doi.org/10.1089/neu.2008.0621

Stemper, B. D., Shah, A. S., Harezlak, J., Rowson, S., Mihalik, J. P., Duma, S. M., Riggen, L. D., Brooks, A., Cameron, K. L., Campbell, D., DiFiori, J. P., Giza, C. C., Guskiewicz, K. M., Jackson, J., McGinty, G. T., Svoboda, S. J., McAllister, T. W., Broglio, S. P., McCrea, M., & the CARE Consortium Investigators. (2019). Comparison of head impact exposure between concussed football athletes and matched controls: Evidence for a possible second mechanism of sport-related concussion. *Annals of Biomedical Engineering*, *47*(10), 2057–2072. https://doi.org/10.1007/s10439-018-02136-6

Swenson, A. G., Schunicht, B. A., Pritchard, N. S., Miller, L. E., Urban, J. E., & Stitzel, J. D. (2022). Head kinematics in youth ice hockey by player speed and impact direction. *Journal of Applied Biomechanics*, *38*(4), 201–209. https://doi.org/10.1123/jab.2021-0331

Takhounts, E. G., Craig, M. J., Moorhouse, K., McFadden, J., & Hasija, V. (2013, November 11). Development of Brain Injury Criteria (BrIC). *SAE Technical Paper 2013-22-0010*. Stapp Car Crash Conference. https://doi.org/10.4271/2013-22-0010

Talavage, T. M., Nauman, E. A., Breedlove, E. L., Yoruk, U., Dye, A. E., Morigaki, K. E., Feuer, H., & Leverenz, L. J. (2014). Functionally-detected cognitive impairment in high school football players without clinically-diagnosed concussion. *Journal of Neurotrauma*, *31*(4), 327–338. https://doi.org/10.1089/neu.2010.1512

Tator, C. H., Provvidenza, C., & Cassidy, J. D. (2016). Update and overview of spinal injuries in canadian ice hockey, 1943 to 2011: The continuing need for injury prevention and education. *Clinical Journal of Sport Medicine*, *26*(3), 232–238. https://doi.org/10.1097/jsm.0000000000000232

Tiernan, S., & Byrne, G. (2019). The effect of impact location on brain strain. *Brain Injury*, *33*(4), 427–434. https://doi.org/10.1080/02699052.2019.1566834

Tierney, G. (2021). Concussion biomechanics, head acceleration exposure and brain injury criteria in sport: A review. *Sports Biomechanics*, 1–29. https://doi.org/10.1080/14763141.2021.2016929

Todd, R. A., Soklaridis, S., Treen, A. K., Bhalerao, S. U., & Cusimano, M. D. (2019). Understanding the resistance to creating safer ice hockey: Essential points for injury prevention. *Injury Prevention*, *25*, 211–216. https://doi.org/10.1136/injuryprev-2016-042272

Trosseille, X., Tarriére, C., Lavaste, F., Guillon, F., & Domont, A. (1992, November 1). Development of a F.E.M. of the human head according to a specific test protocol. *SAE Technical Paper 922527*. Stapp Car Crash Conference. https://doi.org/10.4271/922527

True Sport. (2022). *Power of sport: The true sport report* (p. 72). Canadian Centre for Ethics in Sport. https://cces.ca/true-sport

Tukey, J. W. (1949). Comparing Individual Means in the Analysis of Variance. *Biometrics*, *5*(2), 99–114. https://doi.org/10.2307/3001913

Tuominen, M., Hänninen, T., Parkkari, J., Stuart, M. J., Luoto, T., Kannus, P., & Aubry, M. (2017). Concussion in the international ice hockey World Championships and Olympic Winter Games between 2006 and 2015. *British Journal of Sports Medicine*, *51*(4), 244–252. https://doi.org/10.1136/bjsports-2016-097119

Usman, J., McIntosh, A. S., & Fréchède, B. (2011). An investigation of shoulder forces in active shoulder tackles in rugby union football. *Journal of Science and Medicine in Sport*, *14*(6), 547–552. https://doi.org/10.1016/j.jsams.2011.05.006

Verhagen, E. A. L. M., van Stralen, M. M., & van Mechelen, W. (2010). Behaviour, the key factor for sports injury prevention. *Sports Medicine*, *40*(11), 899–906. https://doi.org/0112-1642/10/0011-0899

Virani, S., Russell, C. N., Bruschetta, M. L., Hua, K. N., Potvin, B. M., Cox, D. N., & Robinovitch, S. N. (2017). The effect of shoulder pad design on head impact severity during checking. *Medicine & Science in Sports & Exercise*, *49*(3), 573–580. https://doi.org/10.1249/MSS.0000000000001136

Weaver, A. A., Danelson, K. A., & Stitzel, J. D. (2012). Modeling Brain Injury Response for Rotational Velocities of Varying Directions and Magnitudes. *Annals of Biomedical Engineering*, *40*(9), 2005–2018. https://doi.org/10.1007/s10439-012-0553-0

Wennberg, R. (2004). Collision frequency in elite hockey on North American versus international size rinks. *The Canadian Journal of Neurological Sciences*, *31*(3), 373–377. https://doi.org/10.1017/s0317167100003474

Wennberg, R. (2005). Effect of ice surface size on collision rates and head impacts at the World Junior Hockey Championships, 2002 to 2004. *Clinical Journal of Sport Medicine*, *15*(2), 67–72. https://doi.org/10.1097/01.jsm.0000152712.27968.fe

Wilcox, B. J., Beckwith, J. G., Greenwald, R. M., Chu, J. J., McAllister, T. W., Flashman, L. A., Maerlender, A. C., Duhaime, A.-C., & Crisco, J. J. (2014). Head impact exposure in male and female collegiate ice hockey players. *Journal of Biomechanics*, *47*(1), 109–114. https://doi.org/10.1016/j.jbiomech.2013.10.004

Wilcox, B. J., Beckwith, J. G., Greenwald, R. M., Raukar, N. P., Chu, J. J., McAllister, T. W., Flashman, L. A., Maerlender, A. C., Duhaime, A.-C., & Crisco, J. J. (2015). Biomechanics of head impacts associated with diagnosed concussion in female collegiate ice hockey players. *Journal of Biomechanics*, *48*(10), 2201–2204. https://doi.org/10.1016/j.jbiomech.2015.04.005

Wilcox, B. J., Machan, J. T., Beckwith, J. G., Greenwald, R. M., Burmeister, E., & Crisco, J. J. (2014). Head-impact mechanisms in men's and women's collegiate ice hockey. *Journal of Athletic Training*, *49*(4), 514–520. https://doi.org/10.4085/1062-6050-49.3.19

Williamson, R. A., Kolstad, A. T., Nadeau, L., Goulet, C., Hagel, B., & Emery, C. A. (2022). Does increasing the severity of penalties assessed in association with the "zero tolerance for head contact" policy translate to a reduction in head impact rates in youth ice hockey? *Clinical Journal of Sport Medicine*, *Publish Ahead of Print*. https://doi.org/10.1097/JSM.0000000000001063

Wu, L. (2020). Sports concussions: Can head impact sensors help biomedical engineers to design better headgear? *British Journal of Sports Medicine*, *54*(7), 370–371. https://doi.org/10.1136/bjsports-2019-101300

Wu, L. C., Kuo, C., Loza, J., Kurt, M., Laksari, K., Yanez, L. Z., Senif, D., Anderson, S. C., Miller, L. E., Urban, J. E., Stitzel, J. D., & Camarillo, D. B. (2018). Detection of American football head impacts using biomechanical features and support vector machine classification. *Scientific Reports*, *8*(1), 855. https://doi.org/10.1038/s41598-017-17864-3

Wu, L. C., Nangia, V., Bui, K., Hammoor, B., Kurt, M., Hernandez, F., Kuo, C., & Camarillo, D. B. (2016). In vivo evaluation of wearable head impact sensors. *Annals of Biomedical Engineering*, *44*(4), 1234–1245. https://doi.org/10.1007/s10439-015-1423-3

Yang, Y., Schonnop, R., Feldman, F., & Robinovitch, S. N. (2013). Development and validation of a questionnaire for analyzing real-life falls in long-term care captured on video. *BMC Geriatrics*, *13*(1), 40. https://doi.org/10.1186/1471-2318-13-40

Zacharias, J., Aguiar, O. M. G., Vakili, O., & Robinovitch, S. N. (2022). Effects of filtering on the agreement between GFT helmet-mounted sensors and Hybrid-III measures of head kinematics body-to-head impacts in hockey. *North American Congress on Biomechanics Conference Proceedings*. NACOB 2022, Ottawa, Canada. https://nacob.org/wp-content/uploads/2022/08/WednesdayThursday.pdf

Zhan, X., Li, Y., Liu, Y., Domel, A. G., Alizadeh, H. V., Raymond, S. J., Ruan, J., Barbat, S., Tiernan, S., Gevaert, O., Zeineh, M. M., Grant, G. A., & Camarillo, D. B. (2021). The relationship between brain injury criteria and brain strain across different types of head impacts can be different. *Journal of The Royal Society Interface*, *18*(179), 20210260. https://doi.org/10.1098/rsif.2021.0260

Zhang, L., Yang, K. H., & King, A. I. (2004). A proposed injury threshold for mild traumatic brain injury. *Journal of Biomechanical Engineering*, *126*(2), 226–236. https://doi.org/10.1115/1.1691446

Zuckerman, S. L., Kerr, Z. Y., Yengo-Kahn, A., Wasserman, E., Covassin, T., & Solomon, G. S. (2015). Epidemiology of sports-related concussion in NCAA athletes from 2009-2010 to 2013-2014: Incidence, recurrence, and mechanisms. *The American Journal of Sports Medicine*, *43*(11), 2654–2662. https://doi.org/10.1177/0363546515599634

Appendix A.

Head Impact Video Evaluation (HIVE) questionnaire

A subset (12 out of 34 items) of the Head Impact Video Evaluation (HIVE) was published as supplementary data in the following peer-reviewed journal:

Aguiar, OMG., et al., (2020), “American Society of Biomechanics Journal of Biomechanics Award 2019: Circumstances of head impacts in men’s university ice hockey.” Journal of Biomechanics, https://doi.org/10.1016/j.jbiomech.2020.109882

The full, 34-item questionnaire is provided below.

INTRODUCTION TO THE HIVE VIDEO ANALYSIS PROCEDURES

The HIVE is a tool for reviewing video footage to identify the circumstance of head impacts in ice hockey. An individual rater will analyze various characteristics of the impact, probed through the HIVE. For each question, instructions are included that provide definitions, interpretations, and guidelines to assist the rater in completing the question.

In completing the HIVE, the rater should view the video footage on a high-quality computer screen (or LCD projector). The analysis should be completed in a quiet, private room. In analyzing the impact, the rater may view the video footage as many times as desired at any speed desired.

GENERAL GUIDELINES FOR COMPLETING THE HIVE

These general guidelines should be followed while completing the HIVE:

- Select the single most appropriate answer to each question.
- There are no “can’t tell” answers. Instead, identify the single best answer to each question, and provide an estimate of the percent probability (between 1-100%) of that answer being correct. This probability will sometimes be quite low, as in the case, for example of substantial occlusion of body parts from the camera view. Select the probability in 5% increments.

Here is a guide to help you determine what percentage to choose:

- 100%: confident of the answer without a doubt;
- 90%: confident of the answer with only a slight doubt;
- 80%: confident of the answer with some doubt;
- 70%: confident of the answer with reasonable doubt;
- 60%: confident of the answer with considerable doubt;
- 50%: confident of the answer but another answer or combination of answers could be equally plausible;
- <40%: this is your best guess to the answer, in cases where you really can't identify a single most probable answer.
- At the start of the session, play the video file through completely. Then play desired segments of the video as many times as desired to answer each question. Although the rater will likely wish to focus on only the few seconds surrounding the impact, the video may contain footage before and after the impact.
- Always play the video clip with the sound off. Video clips may include a narrated commentary. Please ensure the sound is off, to ensure the commentary does not influence the way you answer the questions.

DETAILED INSTRUCTIONS AND DEFINITIONS FOR EACH ITEM IN THE HIVE

Please note: Questions marked with an asterisk (*) or cross (†) were used in Chapters 2 and 3, respectively.

Part 1: Head loading characteristics

All questions in this section focus on the player RECEIVING the head impact.

1. Was the head the first body site to be impacted in the collision (initial point of contact)? *,†

Instructions: Describe whether or not the player's head was the initial point of meaningful contact during the primary impact.

a) Yes

b) No

Probability:__________

2. What body part or object struck the head during the PRIMARY contact? *,†, [1]

---

[1] Combined categories for the statistical analyses in Chapters 2 and 3 (described in methods section of each chapter).

Instructions: Answer this question even if you specified "no" to Question (2) above. Specify the body part of the checker, or the object, that first contacted the player's head in a significant manner. If "other" is selected, clearly describe in writing the body part or object. If there was no contact to the head, choose option (m). Note: The "caprail" is the ledge between the boards and the glass.

a) Shoulder

b) Upper arm

c) Elbow

d) Forearm

e) Hands

f) Hip

g) Stick

h) Boards / Caprail

i) Glass

j) Ice

k) Net

l) Other: ____

m) No primary contact to the head

Probability:__________

3(a). Was there a second contact to the head? (i.e., after the first head contact) [*]

Instructions: Describe whether the head experienced a second significant impact (occurring after the first significant impact to the head).

a) Yes

b) No

Probability:__________

3(b). What body part or object struck the head in the SECOND contact? [*, 1]

Instructions: Specify the body part of the checker, or the object, that contacted the player's head during the second impact. If "other" is selected, clearly describe in writing the body part or object. If there was no second contact to the head, choose option (m). Note: The "caprail" is the ledge between the boards and the glass.

a) Shoulder

b) Upper arm

c) Elbow

d) Forearm

e) Hands

f) Hip

g) Stick

h) Boards / Cap rails

i) Glass

j) Ice

k) Net

l) Other: ____

m) No second contact to the head

Probability:__________

4(a). Was there a third contact to the head? (i.e., after the primary and secondary collisions) [*]

Instruction: Describe whether the head experienced a third significant impact (occurring after the second significant impact to the head).

a) Yes

b) No

Probability:__________

4(b). What body part or object struck the head in the THIRD contact? [*, 1]

Instructions: Specify the body part of the checker, or the object, that contacted the player's head during the third impact. If "other" is selected, clearly describe in writing the body part or object. If there was no second contact to the head, choose option (m). Note: The "caprail" is the ledge between the boards and the glass.

a) Shoulder

b) Upper arm

c) Elbow

d) Forearm

e) Hands

f) Hip

g) Stick

h) Boards / Cap rails

i) Glass

j) Ice

k) Net

l) Other: ____

m) No third contact to the head

Probability:__________

5(a). What aspect of the head received the impact in the PRIMARY contact? [*,†,2]

Instructions: Specify the aspect of the head that was impacted during the primary contact to the head. The letters in the diagrams below point to the aspects that correspond to each answer below.

a) Left lateral aspect of the head

b) Right lateral aspect of the head

c) Top (crown) of the head

d) Back of the head

e) Front of the head

f) No contact to the head

Probability:__________

5(b). What vertical level of the head received the impact in the PRIMARY contact?

Instructions: Specify the vertical level where the head was contacted during the primary contact to the head. Referring to the picture at right, "Chin" represents the bottom third of the head (from the lower lip downward), "Face" represents the middle third of the head (from lower lip to top of nose), and "Forehead" represents the top third of the head (above the nose). If multiple levels were contacted, select the level that was impacted most severely.

a) Chin level

b) Face level

c) Forehead level

d) No contact to the head

Probability:__________

6(a). Was the player's head turned left or right, relative to their shoulders, just before PRIMARY contact to the head?

Instructions: Specify whether the player's head was rotated right or left just before the occurrence of primary contact to the head. The orientation should be described relative to the player's shoulders. Referring to the figure at right, which shows a top (bird's-eye) view of the player. The horizontal axis is the line between the right and left shoulders. Rotation of the head (relative to the shoulders) is shown in degrees. Select (a) if the

---

[2] Combined (a) left and (b) right lateral into "side" for statistical analyses in Chapters 2 and 3.

player's head was turned so the player was facing towards the dark grey area (-45.1º to 180º). Select (b) if the player's head was turned to face the white are (45.1º to 180º). Select (c) if the player's head was directed toward the light grey area (-45º to 45º). No matter how the player's body is positioned, answer this question as if their shoulders were running along the horizontal line shown in the diagram.

a) Head was turned to the left

b) Head was turned to the right

c) Head was in neutral position

Probability:__________

6(b). Was the player's head oriented up or down, relative to the ice, just before PRIMARY contact to the head?

Instructions: Specify whether the player's head was turned up or down just before the occurrence of primary contact to the head. The orientation should be described relative to the ice. Refer to the figure at right, which shows the head in a neutral position, so a straight-ahead gaze would be directed at 0º. Select option (a) if the player's head was angled upwards (so a straight-ahead gaze would be directed to the dark grey region). Select option (b) if the player's head was angled downward (so a straight-ahead gaze would be directed to the white region). Select option (c) if the player's head was in a neutral position (so a straight-ahead gaze would be directed to light grey region).

a) Head was turned up

b) Head was turned down

c) Head was in neutral position

Probability:__________

7(a). Did the player's head accelerate to rotate left or right upon receiving the PRIMARY contact to the head?

Instructions: Specify whether the player's head accelerated upon receiving the primary contact, to rotate more rapidly left or right, relative to their shoulders (i.e., the movement made when shaking the head "no").

a) Head rotated rapidly left

b) Head rotated rapidly right

c) No rotation left or right (or no increase in the baseline rate of rotation)

Probability:__________

7(b). Did the player's head accelerate to rotate up or down upon receiving the PRIMARY contact to the head?

Instructions: Specify whether the player's head accelerated upon receiving the PRIMARY contact, to rotate more rapidly up or down (i.e., the movement made when shaking the head "yes").

a) Head rotated rapidly upward

b) Head rotated rapidly downward

c) No rotation up or down (or no increase in the baseline rate of rotation)

Probability:__________

Part 2: Anticipation of Collision

All questions in this section focus on the player RECEIVING the head impact.

8. Did the player appear to be looking in the direction of the impending (initial) collision? [*,†]

Instructions: Specify whether the player who received the check appeared to be looking in the direction of the checking player (or object) just before the primary contact to the head (initial collision), and therefore could have seen the impending collision.

a) Yes (player was looking towards impending collision)

b) No (player was not looking towards impending collision)

Probability:__________

9. Were the player's knees flexed to > 30º at the time of initial collision with the checking player or object?

Instructions: Referring to the figure at right, specify whether the player's knees were bent more than 30º at the moment of initial collision. This should be based on the relative angle between the thigh and shin. If one or both knees were bent more than 30º, select option (a). If neither of the knees were bent more than 30º, select option (b).

a) Yes (one or both knees were flexed more than 30º)

b) No (neither knee was flexed more than 30º)

Probability:__________

10. Was the player's trunk flexed greater than 45º at the time of initial collision with the checking player or object?

Instructions: Referring to the figure at right, specify whether the player's trunk was flexed (i.e., bent forward at the waist) more than 45º at the moment of initial collision. This should be based on the absolute angle of the trunk relative to the vertical.

a) Yes (trunk was flexed more than 45º)

b) No (trunk was not flexed more than 45º)

Probability:__________

11. Were the player's feet at least shoulder-width apart (in the lateral direction) at the time of the initial collision with the checking player or object?

Instructions: Specify whether the player's feet were spaced more than shoulder-width apart at the moment of the initial collision. Only consider the distance between the feet in the lateral direction (side to side), and not in the fore-aft direction.

a) Yes (feet were spaced at least shoulder-width apart)

b) No (feet were less than shoulder-width apart)

Probability:__________

12. Did the player use the shoulder to intentionally drive into the initial collision with the checking player or object?

Instructions: Specify whether the player who received the check drove into the impact with their shoulder, in a motion intended to oppose the initial, oncoming check/impact that caused the primary contact to the head. This could involve leaning into, or forcefully driving into the collision with the upper body. Only consider movements that appear to be intended to oppose the oncoming collision.

a) Yes (player drove shoulder into the collision)

b) No (player did not drive shoulder into the collision)

Probability:__________

13. Did the player use the legs to intentionally drive into the initial collision with the checking player or object?

Instructions: Specify whether the player who received the check forcefully drove into the impact or initial collision with their hip or knee, in a motion intended to oppose the oncoming check/impact that caused the primary contact to the head. Only consider movements that appear to be intended to oppose the oncoming collision.

a) Yes (player drove hip or knee into the collision)

b) No (player did not drive hip or knee into the collision)

Probability:__________

14(a). Did the player further alter their body position in an attempt to avoid or lessen the impact of the collision that caused the PRIMARY contact to the head?

Instructions: Specify whether the player further altered their body position in a significant manner in an apparent attempt to oppose, avoid or lessen the severity of the oncoming check/impact that caused the primary contact to the head. This question is referring to *movements other then the "shoulder driving" and "leg driving" movements addressed in Questions 13 and 14. You will be asked to describe this movement in Question 15(b).*

a) Yes

b) No

Probability:__________

14(b). How did the player further alter their position?

Instructions: Specify the option that best describes how the player further altered their body position in an apparent attempt to oppose, avoid or lessen the severity of the oncoming check/impact that caused the primary contact to the head. If you select "other", write down exactly how the player changed their body position. If no change in body position occurred, select option (h).

a) Lowered their centre of mass in preparation for the impact

b) Contacted the boards in preparation for the impact

c) Countered the check by checking the opposing player first

d) Attempted to maneuver out of the path of the opposing player

e) Braced themselves in preparation for the impact

f) Raised their arm(s) to block the impending impact

g) Other: ____

h) Player did not further alter their position

Probability:__________

Part 3: Relationship between the Two Players

Answer this section **only** if the primary head contact was caused by a collision between two players.

15. What was the relative trajectory of movement between the two players just before the collision that caused the primary head contact? *

Instructions: Select the option that best describes the trajectory of the players just before the collision that caused the primary head contact. The trajectory should be described relative to the shoulders of the player who receives the head impact. Referring to the figure at right, which shows a top (bird's-eye) view of the player. Select (a) if the checking player approaches from the front (white region). Select (b) if the checking player approaches at an angle from the front (either of the two dark grey regions). Select (c) if the checking player approaches directly laterally. Select (d) if the checking player approaches at an angle from the back (light grey regions). Select (e) if the checking player approaches directly from the back (black region).

a) Checking player approaches receiving player directly from the front (white region)

b) Checking player approaches receiving player at an angle from the front (dark grey region)

c) Checking player approaches receiving player directly from the side (90 deg or -90 deg)

d) Checking player approaches receiving player at an angle from the back (light grey region)

e) Checking player approaches receiving player directly from the back (black region)

f) No head impact occurred

Probability:__________

16. What was the horizontal speed of the player receiving the check?

Instructions: Specify the option that best describes the horizontal speed of the player receiving the check at the moment just before the collision that caused the primary head contact. Be sure that your decision is based on viewing the video at normal speed (not slow motion or sped up). It can be helpful to consider the speed the player would have continued at, if the collision never occurred. Select (a) if the player is standing still, slowly gliding or turning in place. Select (b) if the player is moving relatively slowly (e.g., in the first stride after a forceful push-off from stationary). Select (c) if the player is moving at moderate speed. Select (d) if the player is moving fast.

a) Player receiving check was at a standstill or gliding in place

b) Player receiving check was moving slowly

c) Player receiving check was moving at a moderate speed

d) Player receiving check was moving at a high speed

Probability:__________

17. What was the horizontal speed of the player delivering the check?

Instructions: Specify the option that best describes the horizontal speed of the player delivering the check at the moment just before the collision that caused the primary head contact. Be sure that your decision is based on viewing the video at normal speed (not slow motion or sped up). It can be helpful to consider the speed the player would have continued at, if the collision never occurred. Select (a) if the player is standing still, slowly gliding or turning in place. Select (b) if the player is moving relatively slowly (e.g., in the first stride after a forceful push-off from stationary). Select (c) if the player is moving at moderate speed. Select (d) if the player is moving fast.

a) Player delivering check was at a standstill or gliding in place

b) Player delivering check was moving slowly

c) Player delivering check was moving at a moderate speed

d) Player delivering check was moving at a high speed

Probability:__________

18. Were the checking player's skates off the ice at the time of the collision?

Instructions: Specify whether the checking player's skates left the ice in delivering the check that caused the primary head contact. Consider the position of the skates only at the moment of initial impact. If one or both of the skates were off the ice, select option (a). If both skates remained on the ice, select option (b).

a) Yes (one or both skates were off the ice)

b) No (neither right or left skates were off the ice)

Probability:__________

Part 4: Role of the Arm of the Checker.

All questions in this section focus on the player DELIVERING the check that caused the head contact.

19. Did the shoulder play a functionally significant role in the head impact?

Instructions: Specify whether the checking player delivered force in a meaningful way with the right or left shoulder during the collision that caused the primary head contact.

a) Yes, the right shoulder delivered force causing head contact

b) Yes, the left shoulder delivered force causing head contact

c) No, the shoulders did not play a significant role in causing head contact

Probability:__________

20. Did the elbow play a functionally significant role in the head impact?

Instructions: Specify whether the checking player delivered force in a meaningful way with the right or left elbow during the collision that caused the primary head contact.

a) Yes, the right elbow delivered force causing head contact

b) Yes, the left elbow delivered force causing head contact

c) No, the elbow did not play a significant role in causing head contact

Probability:__________

21. What part of the checker's upper limb had the first point of contact with the head?

Instructions: Specify the part of the checker's upper limb that made FIRST contact with the receiving player's head. This may be different that the body parts that made later, and perhaps more significant contact to the head. If no part of the checker's upper limb *impacted the head, select option (f). Note: "upper arm" is the segment from the elbow to the shoulder, and "forearm" is the segment from the elbow to the wrist.*

a) Shoulder made first contact with head

b) Upper arm made first contact with head

c) Elbow made first contact with head

d) Forearm made first contact with head

e) Hand / Glove made first contact with head

f) No part of the upper limb impacted the head

Probability:__________

22. What part of the checker's upper limb had the last point of contact with the head?

Instructions: Specify the part of the checker's upper limb that made LAST contact with the receiving player's head. This may be different that the body parts that made earlier, and perhaps more significant contact to the head. If no part of the checker's upper limb impacted the head, select option (f). Note: "upper arm" is the segment from the elbow to the shoulder, and "forearm" is the segment from the elbow to the wrist.

a) Shoulder made last contact with head

b) Upper arm made last contact with head

c) Elbow made last contact with head

d) Forearm made last contact with head

e) Hand / Glove made last contact with head

f) No part of the upper limb impacted the head

Probability:__________

23(a). What was the direction of outward movement of the upper limb in delivering contact force to the head?

Instructions: Specify how the upper limb moved just before it contacted the head. This question is tricky. We are asking you to consider the upper limb's direction of movement just before it contacts the receiving player's head. The direction is in relation to the torso of the player delivering the check. Referring to the figure at right, describe whether the upper arm's movement was (a) primarily in a posterior direction, (b) primarily in an anterior direction, or (c) primarily in a lateral direction. If the upper limb appears to be moving in different directions, choose the last direction just before head impact. If the upper limb did not move relative to the trunk, select (d). If the upper limb did not contact the head, select (e).

a) Movement of upper limb was directed posteriorly

b) Movement of upper limb was directed anteriorly

c) Movement of upper limb was directed laterally

d) No outward movement of arm

e) No part of the upper limb impacted the head

Probability:__________

23(b). What was the direction of up/ down movement of the upper limb in delivering contact force to the head?

Instructions: Specify whether the upper limb moved up or down just before it contacted the head. Referring to the figure at right, describe whether the movement was (a) in an upward direction, (b) in a horizontal path (with no appreciable upward or downward component to the movement), or (c) primarily in a downward direction. If the upper limb appears to be moving in different directions, choose the last direction just before head impact. If the upper limb did not contact the head, select (d).

a) Arm travelled upward

b) Arm travelled in horizontal path (moved in horizontal plane)

c) Arm travelled downward

d) No part of the upper limb impacted the head

Probability:__________

Part 5: Game Situation and Player Information

All questions in this section focus on the player who RECEIVED the head contact.

24. In what area of the ice did the head impact occur? *,†,[3]

Instructions: Select the option that best describes the location on the ice of the player at the time of the initial collision that resulted in primary head contact.

a) Along the side boards

b) Near but not contacting the side boards

c) At the corner boards

d) Near but not contacting the corner boards

e) Open ice

f) Near the net (crease)

g) At the end board/behind the net

Probability:__________

---

[3] Collapsed categories for the statistical analyses in Chapters 2 and 3 (described in methods of each chapter).

25. In what playing zone did the initial collision occur with the checking player or object? *,†

Instructions: Select the option that best describes the location on the ice of the player at the time of the initial collision that resulted in primary head contact. The defensive zone refers to the area of the ice that contains the net of the checked player's team, up to the blue line. The neutral zone refers to the area of ice between the blue lines. The offensive zone refers to the area of ice that contains the opposing team's net, up to the blue line. If the check occurs right on the blue line, select the region where the puck was headed). Note: the figure on the right labels each zone assuming the net for the checked player's team is on the left side.

a) The defensive zone of the checked player's team

b) The neutral zone

c) The offensive zone of the checked player's team

Probability:__________

26. Did the player receiving the check have possession of the puck when the initial collision occurred with the checking player or object? *,†[4]

Instructions: Select the option that best describes the relationship of the checked player to the puck at the time of the initial collision that resulted in primary head contact. Select "yes" if the player definitely had control of the puck. Select "attempting to gain possession of the puck" if the player is reaching or attempting to control the puck (e.g., in a struggle for the puck along the boards, or about to receive a pass). Select "had just released the puck" if the player had definite control of the puck prior to the impact but had lost or released the puck before the impact occurred (e.g., they had just passed the puck to another player). "No" would refer to a situation where the player did not have control of the puck and was not attempting to gain possession of it nor did they just release it (e.g., tipping a pass or shot, chipping a loose puck out).

a) Yes (receiving player had possession of the puck at the time of the collision causing primary head contact)

b) No (receiving player did not have possession of the puck at the time of the collision causing primary head contact)

c) Receiving player was attempting to gain possession of the puck at the time of the collision causing primary head contact

d) Receiving player had just released the puck at the time of the collision causing primary head contact

Probability:__________

27. Did the checked player appear affected by the head impact? †

---

[4] Collapsed categories for the statistical analyses in Chapters 2 and 3 (described in methods of each chapter).

Instructions: Select the option that best describes if the player appeared affected by the head impact and note the probability.

a) Yes, the head impact caused a noticeable effect on player (visible signs of concussion, pain or being "shaken up," may or may not return to play immediately)

b) No, the head impact caused little or no discernible effect on the player (no visible signs of concussion, pain or being "shaken up," returned to play immediately)

Probability:_________

--END OF QUESTIONNAIRE--------------------------------------

Appendix B.

Development and reliability of the HIVE questionnaire

BACKGROUND

Video footage of sports events is widely available and provides a potentially rich source of information on the circumstances of head impacts. Observation tools exist for analyzing head impacts from video footage in sports such as mixed martial arts (Lawrence et al., 2014), rugby (Gardner et al., 2018), soccer (Andersen et al., 2003), and lacrosse (Caswell et al., 2012). Two tools exist in ice hockey: the Heads Up Checklist (HUC) (Hutchison et al., 2014) and the Carolina Hockey Evaluation of Children's Checking List (CHECC) (Mihalik, Blackburn, et al., 2010). However, the HUC and CHECC do not provide a complete picture of the biomechanical factors (i.e. contact sites, player speeds and head orientation at impact) that influence the magnitude and nature of head accelerations and corresponding brain tissue stresses and strains (Post, Dawson, et al., 2019; Post et al., 2014). In addition, most concussions in hockey occur from begin struck by another player (Chandran et al., 2022; Delaney et al., 2014; Hutchison et al., 2015b; Zuckerman et al., 2015), yet current tools do not probe the role of the striker's upper limb during head impacts, trajectory of the impact, nor the speed of the impact. Although these published tools address video quality as a limitation to the ability of the tool to reliably perform, no previous research has quantified the effect of video quality on the reliability of an observational tool. The lack of biomechanical information and potential technological limitations is a barrier to improvements in the design of testing conditions for helmets and other protective gear, and safer rules of play.

To address these limitations, we developed a comprehensive questionnaire, the Head Impact Video Evaluation (HIVE), that is completed by trained raters based on review of video footage of the collision. The HIVE incorporates elements of existing tools (Hutchison et al., 2014; Mihalik, Blackburn, et al., 2010) and new questions related to head loading characteristics, anticipation of collision, player positions and speeds at impact, checking style, and game situation. In the current study, we describe the evolution of the HIVE and the inter-rater reliability of the tool based on comparing responses from two independent raters in reviewing 30 videos of head impacts in professional hockey and 30 videos of head impacts from an on-going study with a collegiate ice hockey team.

DEVELOPMENT OF THE HEAD IMPACT VIDEO EVALUATION (HIVE) TOOL

In developing the HIVE, we considered existing evidence on the nature of concussive and non-concussive head impacts (Agel & Harvey, 2010; Cusimano et al., 2013; Hutchison et al., 2014; Wilcox, Machan, et al., 2014), and the biomechanical factors that should influence brain tissue stresses and strains such as impact site, type and velocity (Post, Dawson, et al., 2019; Post et al., 2014). We compared this to the information gathered by (and missing from) existing tools for analyzing video footage of head collisions in ice hockey, which consist of the HUC (Hutchison et al., 2014) and CHECC (Mihalik, Blackburn, et al., 2010). We also viewed numerous examples of video footage of head impacts in ice hockey and used iterative loops to refine the clarity and relevance of our questions and response categories.

The first version of the HIVE tool was structed into five sections, as described below.

(1) Head loading characteristics. Questions in this section focus on the object contacting the head (i.e., the specific body part or environmental object), where on the head the force was applied, and head movements occurring immediately after impact (which reflect the direction of the force). We included questions from the HUC (Hutchison et al., 2014) examining the number of head collisions during the event and the corresponding object(s) that contacted the head, the aspect of the head that was contacted (e.g., front, back or side), and the nature of head motion (rotational acceleration) just after impact. We expanded on the HUC by separately examining left-right motion (“nodding no” movement) and up-down motion (“nodding yes” movement) and modified the former question to distinguish head impacts to the dasher boards versus the glass—an issue important to environmental design. We introduced new questions probing whether the head was the first site of impact, the level of the head that was first contacted (chin, forehead, or mid-level), and the orientation of the player’s head just prior to head impact (turned left or right, angled up or down, or in the neutral anatomic position).

(2) Anticipation of collision. This section examines preparatory actions by the player receiving the head impact that may affect the severity of the collision. We included six questions from the CHECC List focusing on the position of the player receiving the head impact (i.e. positioning of the feet at the time of collision; and flexion of the knees and trunk at the moment of impact), whether the player was looking in the direction of the impending collision, and whether they “drove” into the collision (Mihalik et al., 2010). We added new questions on additional anticipatory actions, including raising the arms, maneuvering into a more protective position or leaning into the boards.

(3) Player positions and speeds at impact. This entirely novel section of the HIVE examines the speeds and relative trajectory of the players at the moment of impact, which should affect momentum transfer and impact severity. We included questions concerning the trajectory of the player delivering the body check with respect to the player receiving the body check (approach from front, back or side), and the speed of each player at impact (fast, moderate, slow speed, standstill). We also included a question on whether the checking player’s skates left the ice at the time of the impact, a penalty in hockey (Hockey Canada Playing Rules 2022-2024, 2022).

(4) Role of the arm of the hitter. This section focuses on the nature of impacts to the head by the upper limb (hand, elbow or shoulder) of the opposing player as it was found that 62% of this category of hits end in concussion at the professional level of play (Hutchison et al., 2015b). We included one question from the CHECC List, examining whether the elbow contacted the head (Mihalik, Blackburn, et al., 2010). We added novel questions concerning the particular site(s) on the upper limb that initiated and ended the head contact, and the position and motion of the upper limb while delivering the body check.

(5) Game situation and player information. This section examines situational aspects of the head collision that may be important to skills training or rules of play. In particular, we adapted questions from the HUC (Hutchison et al., 2014) and CHECC List (Mihalik, Blackburn, et al., 2010) concerning puck possession at the time of the collision, and the playing zone where the impact occurred.

After the first iteration of the questionnaire (32-items) was used to analyze 30 head impacts from videos in professional hockey, two additional questions were added to the second iteration (total of 34-items). The first question probed whether or not the player appeared to be visibly affected by the hit (e.g., exhibit visible signs of concussion). The second question focused on where the head occurred in the rink (i.e. along or near the boards, open ice, or near the net). The final version of the HIVE can be found in **Appendix A.**

ADDITIONAL ANALYSES NOT INCLUDED IN THE HIVE

After the second iteration of the questionnaire (34-items) was used to analyze 30 head impacts from videos in university-level hockey, two additional questions were examined but not included in the questionnaire. No inter- or intra-rater reliability testing were performed for these analyses.

The first question probed whether the head impact resulted in a penalty. A single rater examined the video, to determine whether the on-ice officials signalled for a penalty related to the impact event (based on the referee's hand signals from the Hockey Canada official case/rule book). If a penalty call was observed, game notes (jersey number, game clock time, rink location) were matched to box score data from the league's website (*BC Intercollegiate Hockey League*, 2022) to confirm and identify the type and duration of the infraction. A "minor infraction" was defined as two minutes in the penalty box whereas a "major infraction" was defined as more than two minutes.

The second question probed which visible sign of concussions were exhibited by the checked player. A single rater examined a subset of videos, where the player appeared to be visibly affected by the impact event (e.g., Question 27 of the HIVE in **Appendix A.** was answered "(a) Yes…"). If one or more visible signs were observed, the rater classified each type of visible sign of concussion based on the following descriptions from Echemendia et al. (2018, pp. 2, Table 1.):

1. Loss of consciousness or lying motionless (a player who is not moving or fails to reflexively protect or brace himself while falling after contact)
2. Slow to get up (a player who is hit in the head and takes longer than is typical to get up to his skates)

3. Motor incoordination or balance problems (a player who is hit in the head and takes longer than is typical to get up to his skates)
4. Blank or vacant look (a player who exhibits a vacant look or abnormalities are observed in eye position)
5. Disorientation (a player appears to be unsure of where he is on the ice or bench).
6. Clutching of the head (a player makes a distinct and sustained motion to grab/clutch his head (including face) or helmet with one or both hands after a contact. This does not include the player fixing or correcting placement of the helmet following contact).
7. Visible facial injury in combination with any of the above signs (a player suffers a visible facial injury in which blood is observed and one of the other six visible signs is present)

RELIABILITY TESTING

We initially assessed the inter-rater reliability of the HIVE using video footage of 30 body checks that resulted in head impact during National Hockey League (NHL) games. Videos of 18 body checks were downloaded from the NHL Department of Player Safety website, which maintains database of publicly accessible videos for all body checks delivered by NHL players resulting in supplementary discipline (i.e. suspension). Twelve additional videos of body checks involving head impact, but not resulting in supplementary discipline, were downloaded from YouTube. Our selection criteria were: (a) the body check resulted in head impact (but not necessarily a confirmed concussion), and (b) the event occurred between 2011-2015. Each video was randomly distributed to two raters, who independently used the 32-item version of the HIVE to analyze the event.

Our secondary analysis of inter-rater reliability of the HIVE included video footage of 30 head impacts from an on-going video collection with the Simon Fraser University Men’s Ice Hockey team (British Columbia Intercollegiate Hockey League) during home games over the 2014-15, 2015-16 and 2017-18 seasons. Five video camcorders (2xSony HDR-CX330 and 3x Sony HDR-CX405BKIT) were used to record video footage of the games at 1080p and 60 frames per second. The camcorders were stationed at various positions around the rink to provide full ice coverage and multiple vantage points. During each game, six trained research assistants watched the games from different angles around the rink and noted the details and time of each identified head impact. From these lists, head impacts were identified on relevant video files and cut into short video clips using Adobe Premier Pro CS4 for further analysis. We noted time stamps, player jersey numbers (checking and checked player) as well as a brief description of the game and impact situation. Similarly to the primary analysis, each video was randomly distributed to two raters, who individually used the 34-item version of the HIVE to analyze the event.

All raters were undergraduate students in Kinesiology at Simon Fraser University, who volunteered to participate in the reliability testing. The experimental protocol was approved by the SFU Office of Research Ethics, and all raters provided informed consent. The raters experience with ice hockey ranged from none to some experience either playing and/or coaching hockey. Each rater was trained by members of the research team on how to complete the HIVE. During training, each rater worked with the trainer to complete eight practice videos of head impacts from professional and/or collegiate hockey games. The eight training videos presented a range of impact scenarios, similar in nature to the 30 separate videos used for reliability testing. The rater was assessed after the eighth video, having to justify their answers to each question of the HIVE, and after this both the research team and the rater felt confident in their ability to correctly use the tool.

The videos were played using VLC Media Player (v2.2.1, VideoLAN, Paris, France) and Quicktime Player (v7.78.80.95, Apple, Cupertino, USA). Raters began each session viewing the body check in its entirety at regular speed. They then had the option to view the clip as many times as desired, at any playback speed and degree of zoom necessary to accurately complete the questions. The raters were not allowed to leave any questions blank and instead characterized the confidence they had in their answer using an estimated probability from 1-100% (Yang et al., 2013).

STATISTICAL ANALYSIS

We characterized the inter-rater reliability of each question based on the total percent agreement (TPA), defined by the ratio of number of ratings where the two raters agree divided by total number of ratings, and two kappa values: Cohen's coefficient kappa (k) and Brennan-Prediger's kappa (k_n). Cohen's k (Cohen, 1960) is commonly used as a measure of inter-rater reliability as it provides the proportion of agreement between two raters while accounting for the expected proportion of chance agreement. However, Cohen's k has been criticized for misinterpreting weak symmetrical margins (uneven distribution of responses in the respective categories) as high chance agreement (Sim & Wright, 2005). For example, in cases where raters consistently select the same response category rather than distributing their responses throughout the available categories, TPA will be high however Cohen's k will be low due interpreting weak symmetrical margins as "guessing." As the raters in this study were not asked to response to a given category a fixed number of times, kappa values computed should not be penalized based on marginal symmetry. To resolve this limitation of Cohen's k, we computed Brennan-Prediger's k_n, which assumes all categories have an equal or "free" chance of being selected (Brennan & Prediger, 1981). Therefore, the resulting k_n reflects the agreement between both raters while incorporating the expected probability of selecting an available category, rather than if the proportions of responses of the raters were distributed equally amongst the available categories.

Statistical analysis was performed using JMP v13.0 for Macintosh (SAS Institute Inc., Cary, USA) and Microsoft Excel (version 16.16.1). Brennan-Prediger's k_n values were used for classification and interpreted based on the recommendations of Landis and Koch (1977), where a kappa value of 0.00-0.20 is classified as having "slight" agreement, 0.21-0.40 as "fair," 0.41-0.60 as "moderate," 0.61-0.80 as "substantial" and 0.81-1.00 as "almost perfect."

RESULTS

For the first phase of reliability testing involving the NHL videos, all 32 questions of the HIVE had a TPA of 70% or higher (Table B.1.). The average TPA was 85% (SD=9.0%). Cohen's k was calculated for 30 questions whereas Brennan-Prediger's k_n was calculated for all 32 questions. Cohen's k could not be calculated for the remaining two questions (shoulder driving and leg driving) since there were zero values in at least one cell of the corresponding contingency tables. The average Cohen's k was 0.68 (SD=0.15), with a minimum value of 0.38. The average Brennan-Prediger's k_n was 0.78 (SD=0.14), with all questions having values of 0.40 or larger. Based on k_n and classification recommendations (Landis & Koch, 1977), thirteen of the 32 questions were classified as having "almost perfect" agreement, 16 as "substantial," 2 as "moderate," and 1 as "fair." Rater confidence (in their answers to individual questions being correct, ranged from 81% to 98% and averaged 88%.

Table B.1. Inter-rater reliability for 32 questions of the HIVE, based on analysis of 30 instances of head impact in NHL, 2011-2015.

Question	TPA	k	k 95% CI	k_n	k_n 95% CI	Rater
Head loading characteristics (12 items)						
Initial point of contact was head	97	0.91	0.74-1.00	0.93	0.80-1.00	91
Primary object contacting head [H]	87	0.84	0.69-0.98	0.86	0.72-0.99	86
Secondary contact with head [H]	97	0.89	0.68-1.00	0.93	0.80-1.00	89
Secondary object contacting head	97	0.9	0.70-1.00	0.96	0.89-1.00	96
Tertiary contact with head [H]	97	0.65	0.02-1.00	0.93	0.80-1.00	96
Tertiary object contacting head	97	0.66	0.03-1.00	0.96	0.89-1.00	98
Aspect of head [H]	70	0.57	0.33-0.80	0.64	0.44-0.84	87
Level of head	80	0.55	0.24-0.86	0.73	0.54-0.93	84
Head orientation with shoulders	73	0.54	0.28-0.80	0.60	0.36-0.84	86
Head orientation with ice	77	0.55	0.26-0.83	0.65	0.42-0.88	84
Acceleration left or right [H]	77	0.64	0.41-0.87	0.65	0.42-0.88	84
Acceleration up or down	73	0.49	0.21-0.78	0.60	0.36-0.84	81
Anticipation of collision (8 items)						
Looking towards impending collision [H,M]	83	0.67	0.40-0.93	0.67	0.40-0.94	87
Knee flexion [M]	90	0.71	0.40-1.00	0.80	0.58-1.00	86
Trunk flexion [M]	87	0.43	-0.03-0.89	0.73	0.49-0.98	87
Feet position [M]	70	0.38	0.05-0.72	0.40	0.07-0.73	87
Shoulder driving [M]	100	n/a	n/a	1.00	1.00-1.00	88
Leg driving [M]	97	n/a	n/a	0.93	0.80-1.00	89
Use of alternative anticipatory strategies	83	0.59	0.27-0.91	0.67	0.40-0.94	87
Nature of anticipatory strategy	80	0.54	0.24-0.83	0.77	0.61-0.94	90
Player positions and speeds at impact (4 items)						
Relative trajectory of checking player (with respect to the player receiving head impact)	77	0.67	0.46-0.88	0.72	0.54-0.90	87
Speed of player receiving check	83	0.72	0.50-0.94	0.78	0.60-0.96	86
Speed of player delivering check	73	0.58	0.33-0.83	0.64	0.43-0.86	85
Skates off ice	90	0.61	0.21-1.00	0.80	0.58-1.00	84
Role of the arm of the checker (6 items)						
Shoulder played a significant role	93	0.86	0.67-1.00	0.90	0.76-1.00	92
Elbow played a significant role [M]	93	0.72	0.36-1.00	0.90	0.76-1.00	92
Upper limb initial contact point	87	0.83	0.67-0.98	0.84	0.69-0.99	90
Upper limb final contact point	83	0.78	0.62-0.95	0.80	0.64-0.96	88
Direction of outward movement of upper limb	87	0.82	0.65-0.98	0.83	0.68-0.99	85

Question	TPA	k	k 95% CI	k_n	k_n 95% CI	Rater
Direction of up/down movement of upper limb	77	0.65	0.44-0.87	0.69	0.48-0.89	86
Game situation (2 items)						
Playing zone [H]	97	0.95	0.84-1.00	0.95	0.85-1.00	97
Puck possession [H]	80	0.72	0.53-0.91	0.73	0.54-0.93	91

TPA = Total percent agreement; k = Cohen's kappa; CI = Upper and lower 95th confidence interval; k_n = Brennan-Prediger's (free-marginal) kappa; [H] = question adapted from Hutchison et al.'s HUC questionnaire (2014); [M] = question adapted from Mihalik, Blackburn et al.'s CHECC List questionnaire (2010); Rater = Self-reported rater confidence in answering the questionnaire item

For the second phase of reliability testing involving the collegiate videos, 24 out of the 34 questions (71%) in the HIVE had a TPA of 70% or higher (Table B.2.). The remaining 10 questions had TPA ranging between 50% to 67%. Cohen's k was not computed for three of the 34 questions (secondary object to contact the head, tertiary impact and tertiary object to contact the head), since there were zero values in at least one cell of the corresponding contingency tables. However, Brennan-Prediger's k_n was calculated for all of the HIVE questions. The average Cohen's k for the collegiate video analysis was 0.39 (SD=0.24, range=-0.11-0.88), respectively and the average k_n value was 0.62 (SD=0.19, range=0.20-1.00) respectively. Based on the k_n and classification recommendations, six of the 34 questions were classified as "near perfect," 12 as "substantial," 12 as "moderate," and 4 as "fair." Rater confidence ranged between 78% to 99%, and averaged 86%. By collapsing from four categories (clear possession, attempting to gain possession, just released puck, no possession) into two (clear or no possession), near perfect agreement was achieved (TPA=97%, kappa=0.93).

Table B.2. Inter-rater reliability for 34 questions of the HIVE, based on analysis of 30 instances of head impact in collegiate ice hockey, 2014-2017.

Question	TPA	k	k 95% CI	kn	k_n 95% CI	Rater
Head loading characteristics (12 items)						
Initial point of contact was head *†	77	0.47	0.14-0.80	0.53	0.23-0.84	84
Primary object contacting head [H] *†	70	0.62	0.43-0.82	0.67	0.49-0.86	85
Secondary contact with head [H] *	87	-0.05	-0.13-0.03	0.73	0.49-0.98	90
Secondary object contacting head *	83	n/a	n/a	0.82	0.67-0.97	90
Tertiary contact with head [H] *	100	n/a	n/a	1.00	1.00-1.00	94
Tertiary object contacting head *	100	n/a	n/a	1.00	1.00-1.00	95
Aspect of head [H] *†	70	0.58	0.37-0.79	0.64	0.44-0.84	83

Question	TPA	k	k 95% CI	kn	k_n 95% CI	Rater
Level of head	67	0.06	-0.24-0.36	0.56	0.33-0.78	78
Head orientation with shoulders	70	0.22	-0.11-0.55	0.55	0.30-0.80	80
Head orientation with ice	77	0.53	0.23-0.84	0.65	0.42-0.88	79
Acceleration left or right [H]	63	0.44	0.18-0.71	0.45	0.19-0.71	81
Acceleration up or down	50	0.22	-0.07-0.51	0.25	-0.02-0.52	81
Anticipation of collision (8 items)						
Looking towards impending collision [H,M] *†	67	0.31	0.02-0.60	0.33	0.01-0.68	85
Knee flexion [M]	83	0.44	0.04-0.85	0.67	0.40-0.94	83
Trunk flexion [M]	87	0.27	-0.24-0.77	0.73	0.49-0.98	87
Feet position [M]	73	0.46	0.14-0.78	0.47	0.14-0.79	83
Shoulder driving [M]	80	-0.11	-0.20-0.02	0.60	0.31-0.89	82
Leg driving [M]	80	-0.11	-0.20- -0.02	0.60	0.31-0.89	84
Use of alternative anticipatory strategies	60	0.23	-0.09-0.54	0.20	-0.16-0.56	79
Nature of anticipatory strategy	53	0.29	0.06-0.53	0.47	0.26-0.67	82
Player positions and speeds at impact (4 items)						
Relative trajectory of checking player (with respect to the player receiving head impact) *	70	0.59	0.37-0.81	0.64	0.44-0.84	80
Speed of player receiving check	80	0.61	0.34-0.88	0.73	0.54-0.93	85
Speed of player delivering check	73	0.38	0.02-0.73	0.64	0.43-0.86	83
Skates off ice	93	0.71	0.33-1.00	0.87	0.69-1.00	88
Role of the arm of the checker (6 items)						
Shoulder played a significant role	90	0.62	0.23-1.00	0.85	0.69-1.00	90
Elbow played a significant role [M]	83	0.24	-0.19-0.67	0.75	0.55-0.95	89
Upper limb initial contact point	67	0.47	0.26-0.68	0.60	0.39-0.81	87
Upper limb final contact point	63	0.43	0.22-0.63	0.56	0.35-0.77	87
Direction of outward movement of upper limb	73	0.52	0.27-0.77	0.67	0.47-0.87	85
Direction of up/down movement of upper limb	63	0.35	0.13-0.57	0.51	0.28-0.74	87
Game situation (2 items)						
Playing zone [H] *†	93	0.88	0.72-1.00	0.90	0.76-1.00	99
Puck possession [H] *†	50	0.33	0.08-0.58	0.33	0.09-0.58	87
Additional questions (2 items)						
Visibly shaken up from the impact†	77	0.23	-0.17-0.63	0.53	0.23-0.84	85
Location on the ice [H,M] *†	77	0.71	0.53-0.88	0.73	0.55-0.91	93

TPA = Total percent agreement; k = Cohen's kappa; CI = Upper and lower 95th confidence interval; k_n = Brennan-Prediger's (free-marginal) kappa; [H] = question adapted from Hutchison et al.'s HUC questionnaire (2014); [M] = question adapted from Mihalik, Blackburn et al.'s CHECC List questionnaire (2010); Rater = Self-reported rater confidence in answering the questionnaire item; * = Used in Chapter 2; † = Used in Chapter 3

Appendix C.

Head impact identification by observers and video review

We compared the head impacts identified by six observers at the rink to those captured by a single rater who independently reviewed video from five cameras of a single period of play (Table C.1.). The observers identified 10 head impacts occurring in this period. Five of those 10 cases had sensor data within ±10 seconds of the window threshold for inclusion. There were no sensor data available for the 5 remaining cases (e.g., players did not wear a sensor, impact did not exceed 10 g, or data were not recorded). The video reviewer identified 14 head impacts. Ten of those 14 cases were also identified by the observers, which suggests that 31% (n=4/14) of head impacts were missed by the observers. Eight of the 14 cases identified by the video reviewer had sensor within ±10 seconds of the window threshold for inclusion. Three of these eight cases were missed by the observers. This suggests that 38% of head impacts (n=3/8) with available sensor data were missed by the observers.

Table C.1. Head impacts from one period of play, identified by six observers and one independent video reviewer.

Impact number	Captured by observers	Captured by video review	Available sensor data
1	Yes	Yes	No
2	No	Yes	Yes
3	Yes	Yes	No
4	Yes	Yes	No
5	No	Yes	Yes
6	Yes	Yes	No
7	Yes	Yes	Yes
8	Yes	No	Yes
9	Yes	Yes	Yes
10	Yes	Yes	Yes
11	No	Yes	No
12	Yes	Yes	No
13	No	Yes	Yes
14	Yes	Yes	Yes

Appendix D.

Associations between the scenario and severity of head impacts for events within a 90 second time window

OVERVIEW OF OBSERVED HEAD IMPACTS

Over the 45 home games, we captured and verified 535 head impact events (video footage paired with helmet-sensor data) within ± 90 seconds of the impact time in our game notes. Head impacts were experienced by 50 unique, instrumented players, including 15 defensemen (110 events), and 35 forwards (425 events). The average number of head impacts per player per game was 0.24 (range=0.02-1.18). The mean body mass and height of player receiving the head impact were 82.1 kg (SD=7.6, range=68.0-96.1) and 180.0 cm (SD=6.2, range=167.6-198.1). The mean body mass and height of the player delivering the head impact were 86.4 kg (SD=7.8, range=72.7-111.4) and 184.1 cm (SD=6.1, range=165.1-198.1).

The distributions of peak head linear acceleration (n=535) and rotational velocity (n=533) were positively skewed, due to the 10g recording threshold, as observed in other studies (Mihalik, Blackburn, et al., 2010; Wilcox, Beckwith, et al., 2014). The median peak linear acceleration and rotational velocity were 26.2 g (25th-75th percentile = 17.8-49.2 g) and 13.7 rad/s (25th-75th percentile = 9.7-19.4 rad/s), respectively. The mean peak linear acceleration and rotational velocity data were 38.8 g (SD=31.6) and 15.2 rad/s (SD=8.3), respectively.

SITUATIONAL FACTORS PRECEDING IMPACT TO THE HEAD

Playing zone and location on the ice. In total, 56% (n=298/535) of head impacts occurred in the offensive zone, 34% occurred in the defensive zone and 11% occurred in the neutral zone. Head impacts in the neutral zone were up to 1.3-fold greater in the mean peak rotational velocity of the head than those in the offensive or defensive zones (p=0.020 and p=0.017, respectively). 76% of head impacts were observed along the “perimeter” of the rink (n=409/535). “Open ice” and “near the net” accounted for 15% and 9% of head impacts, respectively. There were no differences in peak linear acceleration between playing zones, and no difference in impact severity between locations on the ices (Table D.1.).

Puck possession and direction of gaze. Players without puck possession experienced a 7.2-fold greater number of head impacts (n=470/535) than those with possession (n=65/535). There were no differences in the impact severity for the player with (versus without) puck possession. In 50% of cases, the player was looking in the direction of the impeding collision (n=268/535). There were no differences in the impact severity for the player looking (versus not looking) in the direction of the impending collision (Table D.1.).

Table D.1. Estimated means and confidence intervals (CI) for peak linear accelerations and rotational velocities with respect to situational factors preceding head impact (playing zone, location on ice, puck possession, and direction of gaze), within ± 90 seconds of the impact time in our game notes.

	Frequency	**Linear acceleration (g)**		**Rotational velocity (rad/s)**	
	Count (% of head impacts captured)	**Mean (95% CI)**	**p value**	**Mean (95% CI)**	**p value**
Playing zone*	n = 535	n = 535	0.407	n = 533	0.012
Offensive zone	298 (55.7%)	37.7 (33.8-42.2)		14.9 (13.9-15.9)	
Defensive zone	176 (32.9%)	39.3 (34.3-45.0)		14.6 (13.5-15.9)	
Neutral zone	61 (11.4%)	44.0 (35.7-54.2)		18.3 (15.9-21.0)	
Location on ice	n = 535	n = 535	0.331	n = 533	0.982
Perimeter	409 (76.4%)	39.4 (35.9-43.4)		15.2 (14.4-16.1)	
Open ice	79 (14.8%)	34.6 (28.7-41.7)		15.2 (13.4-17.2)	
Near the net (crease)	47 (8.8%)	42.1 (33.3-53.2)		15.0 (12.8-17.6)	
Puck possession*	n = 535	n = 535	0.235	n = 533	0.136
Clear possession	65 (12.2%)	34.7 (28.3-42.6)		13.8 (12.1-15.8)	
No possession	470 (87.9%)	39.5 (36.1-43.2)		15.4 (14.6-16.2)	
Looking in direction of collision*	n = 535	n = 535	0.253	n = 533	0.499
Yes	268 (50.1%)	37.4 (33.4-41.9)		15.4 (14.4-16.5)	
No	267 (49.9%)	40.5 (36.4-45.2)		14.9 (14.0-16.0)	

SITUATIONAL FACTORS OBSERVED AT THE INSTANT OF HEAD IMPACT

Objects associated with head impact. 59% of head impacts were caused by contact with another players' body part, whereas 42% were caused by contact with the environment (defined as glass, boards, ice). Impact severity was plotted as a function of the prevalence (percent of all head impacts) for each of the eight impacting object in Figure C.1. There were differences between impacting object in rotational velocity of the head (p=0.013), but not for linear acceleration (p=0.290). "Shoulder/upper arm" impacts were 1.3-fold greater in the mean peak rotational velocity of the head than "elbow/forearm/hand" (p=0.012; Table D.2.).

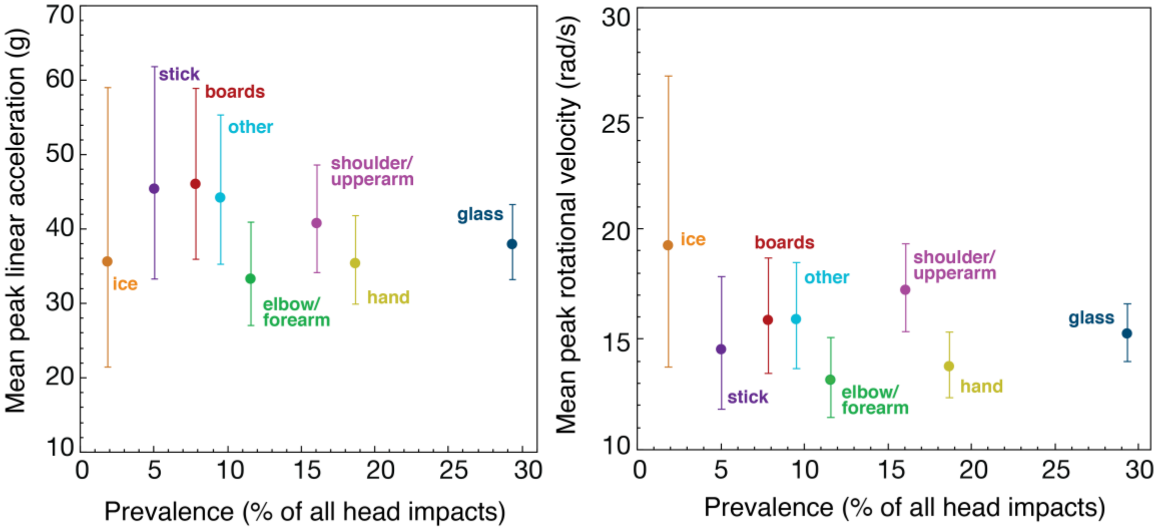


Figure D.1. **Mean peak head linear accelerations and rotational velocities as a function of the prevalence (percent of all head impacts) for each impacting object. The bars represent 95% confidence intervals. "Other" consists of the "puck," "net," "head," "torso," and "lower limb".**

With respect to upper limb-to-head impacts, the number of "hand" impacts to the head were up to 1.6-fold greater than "shoulder/upper arm" and "elbow/forearm." While linear acceleration of the head did not differ between categories (p=0.301), the peak rotational velocity was 1.3-fold greater for "shoulder/upper arm" than "elbow/forearm" (p=0.017) and "hand" (p=0.025) impacts to the head. As for "glass" versus "board/caprail" impacts to the head, the number of head impacts associated with "glass" was 3.7-fold greater than impacts to "board/caprail." There were no differences in impact severity between the glass and board/caprail (Table D.2.).

Impact location on head and head as the initial point of contact. In 63% of cases, players experienced an impact to the side of the head. 17% of cases occurred to the front of the head, 16% to the back, and 4% to the top, and there were no differences in impact severity between impact locations on the head. The head was the initial point of contact in 120 of 502 (24%) of cases involving contact with another player. There were no differences in impact severity and for cases where the head was not (versus was) the initial site of contact (Table D.2.).

Table D.2. Estimated means and confidence intervals (CI) for peak linear accelerations and rotational velocities with respect to situational factors at the instant of head impact (objects striking the head, location of impact on the head, and whether the head was the initial point of contact), within ± 90 seconds of the impact time in our game notes.

	Frequency	Linear acceleration (g)		Rotational velocity (rad/s)	
	Count (% of head impacts captured)	Mean (95% CI)	p value	Mean (95% CI)	p value
Object impacting head	n = 535	n = 535	0.290	n = 533	0.013
Board/ caprail/ glass	199 (37.2%)	39.6 (35.1-44.7)		15.4 (14.2-16.6)	
Elbow/ forearm/ hand	162 (30.3%)	34.5 (30.1-39.5)		13.5 (12.4-14.7)	
Shoulder/ upper arm	86 (16.1%)	40.8 (34.1-48.7)		17.2 (15.3-19.3)	
Other*	51 (9.5%)	44.2 (35.2-55.4)		15.9 (13.7-18.5)	
Stick	27 (5.0%)	45.2 (33.1-61.8)		14.5 (11.8-17.8)	
Ice	10 (1.9%)	35.5 (21.3-59.1)		19.2 (13.7-26.9)	
Impact to environment object versus another player	n = 504	n = 504	0.550	n = 502	0.511
Body part	295 (58.5%)	37.9 (33.9-42.3)		15.0 (14.1-16.1)	
Environmental object**	209 (41.5%)	39.5 (35.0-44.6)		15.6 (14.4-16.8)	
Upper limb contact site***	n = 248	n = 248	0.301	n = 247	0.008
Hand	100 (40.3%)	34.8 (29.1-41.6)		13.8 (12.2-15.5)	
Shoulder/ upper arm	86 (34.7%)	40.0 (33.17-48.1)		17.2 (15.2-19.5)	

	Frequency	Linear acceleration (g)		Rotational velocity (rad/s)	
	Count (% of head impacts captured)	Mean (95% CI)	p value	Mean (95% CI)	p value
Elbow/ forearm	62 (25.0%)	32.8 (26.4-40.7)		13.2 (11.3-15.3)	
Glass versus boards/caprail impacting head	n = 199	n = 199	0.175	n = 199	0.677
Glass	157 (78.9%)	37.9 (33.2-43.3)		15.3 (14.2-16.4)	
Board/ caprail	42 (21.1%)	45.8 (35.8-58.7)		15.8 (13.7-18.2)	
Location of impact on head	n = 535	n = 535	0.318	n = 533	0.960
Side	337 (63.0.%)	38.5 (34.8-42.6)		15.0 (14.1-16.0)	
Front	93 (17.4%)	35.7 (30.1-42.3)		15.4 (13.8-17.3)	
Back	83 (15.5%)	42.6 (35.6-50.9)		15.4 (13.7-17.4)	
Top (crown)	22 (4.1%)	47.4 (33.7-66.8)		15.5 (12.3-19.5)	
Head initial point of contact†	n = 502		0.502		0.395
No	382 (76.1%)	37.9 (34.5-41.6)		14.9 (14.0-15.8)	
Yes	120 (23.9%)	40.1 (34.4-46.7)		15.6 (14.1-17.3)	

*Where “other” consists of the puck, net, head, torso, or lower limb; **Where “environment” consists of the boards/caprail, glass, and ice. Excludes n=57 where n=52 for stick, n=2 for puck and n=3 for net; ***Upper limb contact site of player delivering the hit; †Only includes cases involving another player (opponent or teammate)

SITUATIONAL FACTORS OBSERVED AFTER HEAD IMPACT

Visible signs of concussion. We observed visible signs of concussion in 57 of 535 (11%) of cases. “Slow to get up” was observed 44 times, “clutching of head” 19 times, and “motor incoordination” 4 times. “Loss of consciousness,” “blank or vacant look,” and “visible facial injury” were not observed. Of these cases, “stick” was the most common impacting object (n=13/57), followed by the “board/caprail” (n=9), “glass” (n=8), and “shoulder/upper arm” (n=6). The mean peak linear acceleration (p=0.006) and rotational velocity (p=0.001) were both 1.3-fold greater when the player was (versus was not) visibly affected by the head impact (Table D.3.).

Infraction. 11% of the 502 head impacts involving a collision with another player were penalized. 73% of infractions were minor penalties. Only 10% of cases where the head was the initial point of contact were penalized. The mean peak rotational velocity was 1.6-fold higher for major infractions (penalties more than two minutes) than for minor infractions or no infractions (p=0.009), but there were no differences in mean peak linear acceleration (p=0.612) (Table D.3.)

Table D.3. Estimated means and confidence intervals (CI) for peak linear accelerations and rotational velocities with respect to situational factors proceeding head impact (visible signs of concussion, penalty), within ± 90 seconds of the impact time in our game notes.

	Frequency	**Linear acceleration (g)**		**Rotational velocity (rad/s)**	
	Count (% of head impacts captured)	**Mean (95% CI)**	**p value**	**Mean (95% CI)**	**p value**
Presence of visible sign(s) of concussion	n = 535	n = 535	0.006	n = 533	0.001
No	478 (89.3%)	37.8 (34.4-41.6)		14.7 (13.9-15.5)	
Yes	57 (10.7%)	51.4 (41.4-63.9)		19.2 (16.6-22.2)	
Penalization of head impact[†]	n = 502	n = 502	0.338	n = 500	0.159
No	447 (89.0%)	37.9 (34.7-41.5)		14.9 (14.0-15.8)	
Yes	55 (11.0%)	42.4 (34.0-52.8)		16.6 (14.3-19.3)	
Penalty type[*,†]	n = 502	n = 502	0.612	N = 500	0.009
No infraction	447 (89.0%)	37.9 (34.6-41.5)		14.9 (14.1-15.7)	
Minor infraction	40 (8.0%)	41.7 (32.2-53.8)		14.3 (12.0-16.9)	
Major infraction	15 (3.0%)	44.4 (29.3-67.1)		22.9 (17.4-30.3)	

[†] Only includes cases involving another player (opponent or teammate); [*] Where “minor infraction” was defined as less than two minutes in the penalty box and “major infraction” was defined as more than two minutes.

Appendix E.

Associations between the scenario and severity of head impacts for events within a 60 second time window

OVERVIEW OF OBSERVED HEAD IMPACTS

Over the 25 home games, we captured and verified 289 head impact events (video footage paired with helmet-sensor data) within ± 60 seconds of the reference time. Head impacts were experienced by 35 unique, instrumented players, including 10 defensemen (46 events), and 25 forwards (243 events). The average number of head impacts per player per game was 0.33 (range=0.04-1.92). The mean body mass and height of player receiving the head impact were 80.7 kg (SD=8.2, range=68.0-96.1) and 179.1 cm (SD=7.2, range=167.6-198.1). The mean body mass and height of the player delivering the head impact were 85.3 kg (SD=7.3, range=72.7-111.4) and 183.8 cm (SD=5.6, range=165.1-198.1).

The distributions of peak head linear acceleration (n=289) and rotational velocity (n=288) were positively skewed, due to the 10g recording threshold, as observed in other studies (Mihalik, Blackburn, et al., 2010; Wilcox, Beckwith, et al., 2014). The median peak linear acceleration and rotational velocity were 24.1 g (25th-75th percentile = 16.4-44.9 g) and 13.0 rad/s (25th-75th percentile = 9.0-18.2 rad/s), respectively. The mean peak linear acceleration and rotational velocity data were 36.1 g (SD=30.3) and 14.6 rad/s (SD=8.6), respectively.

SITUATIONAL FACTORS PRECEDING IMPACT TO THE HEAD

Playing zone and location on the ice. In total, 55% (n=160/289) of head impacts occurred in the offensive zone, 33% occurred in the defensive zone and 12% occurred in the neutral zone. Head impacts in the neutral zone were up to 1.5-fold greater in the mean peak rotational velocity of the head than those in the offensive or defensive zones (p=0.015 and p=0.004, respectively). 78% of head impacts were observed along the “perimeter” of the rink (n=226/289). “Open ice” and “near the net” accounted for 16% and 6% of head impacts, respectively. There were no differences in peak linear acceleration between playing zones, and no difference in impact severity between locations on the ices (Table E.1.).

Puck possession and direction of gaze. Players without puck possession experienced a 7.5-fold greater number of head impacts (n=255/289) than those with possession (n=34/289). There were no differences in the impact severity for the player with (versus without) puck possession. In 61% of cases, the player was looking in the direction of the impeding collision (n=176/289). There were no differences in the impact severity for the player looking (versus not looking) in the direction of the impending collision (Table E.1.).

Table E.1. Estimated means and confidence intervals (CI) for peak linear accelerations and rotational velocities with respect to situational factors preceding head impact (playing zone, location on ice, puck possession, and direction of gaze), within ± 60 seconds of the reference time.

	Frequency	Linear acceleration (g)		Rotational velocity (rad/s)	
	Count (% of head impacts captured)	Mean (95% CI)	p value	Mean (95% CI)	p value
Playing zone*	n = 289	n = 289	0.247	n = 288	0.005
Offensive zone	160 (55.4%)	35.2 (33.4-37.0)		14.3 (12.3-16.6)	
Defensive zone	94 (32.5%)	32.6 (27.7-38.5)		13.2 (11.7-15.0)	
Neutral zone	35 (12.1%)	43.4 (32.7-57.4)		19.5 (16.0-23.7)	
Location on ice	n = 289	n = 289	0.652	n = 288	0.681
Perimeter	226 (78.2%)	35.7 (33.1-38.4)		14.6 (13.2-16.1)	
Open ice	46 (15.9%)	33.2 (27.2-40.6)		14.0 (11.6-17.0)	
Near the net (crease)	17 (5.9%)	41.6 (27.9-62.1)		16.3 (12.2-21.9)	
Puck possession*	n = 289	n = 289	0.759	n = 288	0.292
Clear possession	34 (11.8%)	34.4 (26.6-44.4)		13.2 (10.7-16.2)	
No possession	255 (88.2%)	36.1 (34.2-38.0)		14.8 (13.5-16.2)	
Looking in direction of collision*	n = 289	n = 289	0.850	n = 288	0.695
Yes	176 (60.9%)	35.4 (32.6-38.4)		14.8 (13.3-16.4)	
No	113 (39.1%)	36.1 (31.8-40.9)		14.3 (12.7-16.2)	

*Relative to the player receiving the head impact.

SITUATIONAL FACTORS OBSERVED AT THE INSTANT OF HEAD IMPACT

Objects associated with head impact. 61% of head impacts were caused by contact with another players' body part, whereas 39% were caused by contact with the environment (defined as glass, boards, ice). Impact severity was plotted as a function of the prevalence (percent of all head impacts) for each of the nine impacting objects in Figure E.1. There were no differences between impacting objects for mean peak head rotational velocity and linear acceleration (p=0.728 and p=0.712, respectively).

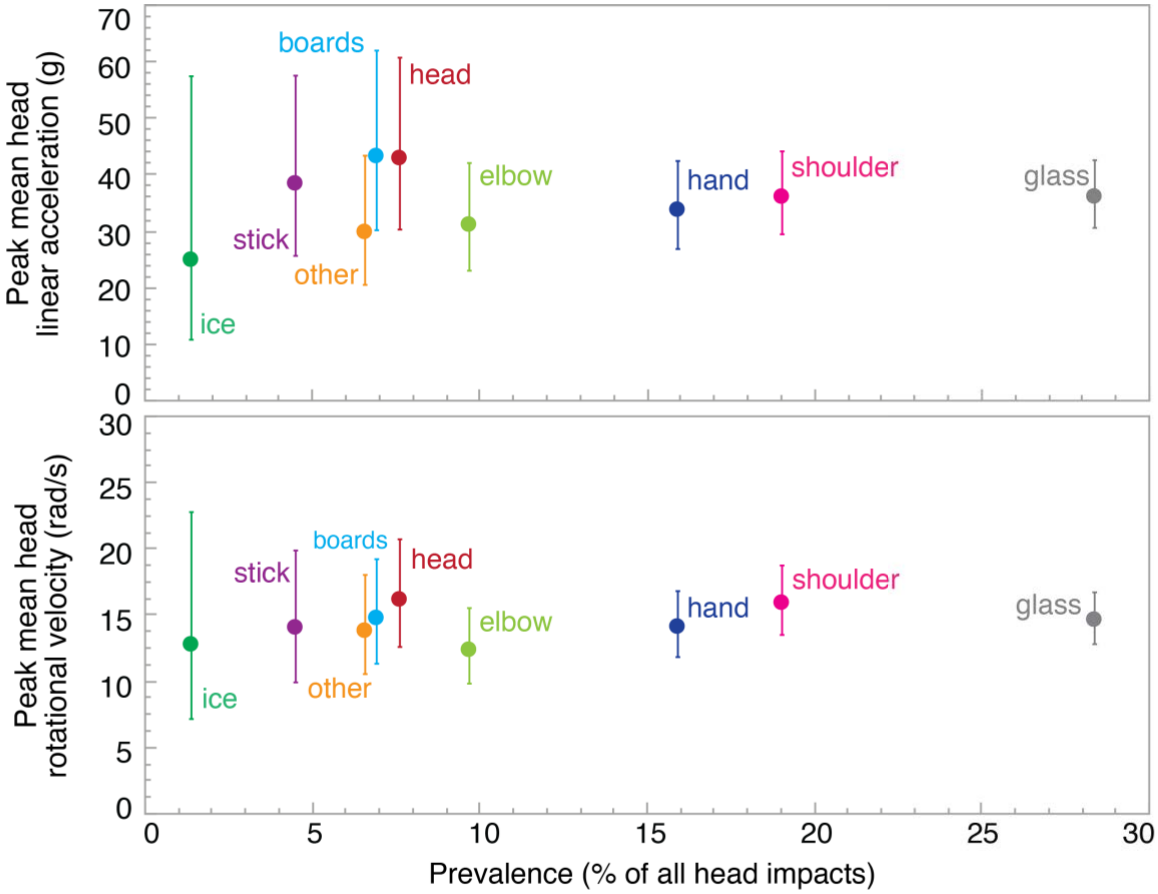


Figure E.1. Mean peak head linear accelerations and rotational velocities as a function of the prevalence (percent of all head impacts) for each impacting object. The bars represent 95% confidence intervals. "Other" consists of the "net," "torso," and "lower limb".

With respect to upper limb-to-head impacts, the number of "shoulder/upper arm" and "hand" impacts to the head were up to 2.0-fold greater than "elbow/forearm." As for "glass" versus "board/caprail" impacts to the head, the number of head impacts associated with "glass" was 4.1-fold greater than impacts to "board/caprail." There were no differences in impact severity between upper limb contact sites, or the glass and board/caprail (Table E.2.).

Impact location on head and head as the initial point of contact. In 62% of cases, players experienced an impact to the side of the head. 20% of cases occurred to the front of the head, 14% to the back, and 5% to the top, and there were no differences in impact severity between impact locations on the head. The head was the initial point of contact in 58 of 265 (22%) of cases involving contact with another player. There were no differences in impact severity for cases where the head was not (versus was) the initial site of contact (Table E.2.).

Table E.2. Estimated means and confidence intervals (CI) for peak linear accelerations and rotational velocities with respect to situational factors at the instant of head impact (objects striking the head, location of impact on the head, and whether the head was the initial point of contact), within ± 60 seconds of the reference time.

	Frequency	Linear acceleration (g)		Rotational velocity (rad/s)	
	Count (% of head impacts captured)	**Mean (95% CI)**	**p value**	**Mean (95% CI)**	**p value**
Object impacting head	n = 289	n = 289	0.712	n = 288	0.728
Board/ caprail/ glass	102 (35.3%)	37.4 (32.4-43.1)		14.7 (13.0-16.6)	
Elbow/ forearm/ hand	74 (25.6%)	32.7 (27.5-39.0)		13.5 (11.7-15.5)	
Shoulder/ upper arm	55 (19.0%)	35.9 (29.3-44.1)		15.9 (13.5-18.7)	
Head	22 (7.6%)	42.9 (30.1-61.1)		16.2 (12.6-20.7)	
Other*	19 (6.6%)	29.7 (20.3-43.4)		13.8 (10.5-18.1)	
Stick	13 (4.5%)	38.2 (25.3-57.6)		14.0 (9.9-19.9)	
Ice	4 (1.4%)	24.8 (10.6-58.1)		12.8 (7.1-22.8)	
Impact to environment object versus another player	n = 274	n = 274	0.705	n = 273	0.866
Body part	168 (61.3%)	35.2 (28.5-43.4)		14.7 (13.2-16.5)	
Environmental object**	106 (38.7%)	36.6 (30.0-44.7)		14.6 (12.9-16.5)	
Upper limb contact site***	n = 129	n = 129	0.502	n = 128	0.128
Hand	46 (35.7%)	36.5 (28.4-46.9)		13.9 (11.6-16.6)	
Shoulder/ upper arm	55 (42.6%)	38.3 (31.9-46.0)		16.5 (12.8-21.4)	

	Frequency	Linear acceleration (g)		Rotational velocity (rad/s)	
	Count (% of head impacts captured)	Mean (95% CI)	p value	Mean (95% CI)	p value
Elbow/ forearm	28 (21.7%)	29.5 (21.0-41.3)		11.6 (9.1-14.8)	
Glass versus boards/caprail impacting head	n = 102	n = 102	0.447	n = 102	0.921
Glass	82 (80.4%)	35.9 (29.3-43.9)		14.7 (11.7-18.3)	
Board/ caprail	20 (19.6%)	41.9 (28.8-60.9)		14.5 (12.9-16.3)	
Location of impact on head	n = 289	n = 289	0.286	n = 288	0.915
Side	180 (62.2%)	36.1 (33.3-39.1)		14.9 (13.4-16.5)	
Front	57 (19.7%)	30.5 (25.2-36.8)		14.2 (12.0-16.7)	
Back	39 (13.5%)	41.0 (32.0-52.7)		14.0 (11.5-16.9)	
Top (crown)	13 (4.5%)	42.9 (27.4-67.3)		14.5 (10.5-20.1)	
Head initial point of contact†	n = 265	n = 265	0.922	n = 264	0.582
No	207 (78.1%)	35.3 (31.0-40.2)		14.2 (12.9-15.6)	
Yes	58 (21.2%)	34.9 (28.1-43.5)		14.8 (12.6-17.4)	

*Where "other" consists of the "net," "torso," or "lower limb." There were no cases of "puck."; **Where "environment" consists of the "boards/caprail," "glass," and "ice." Excludes n=15 where n=13 for stick and n=2 for net; ***Upper limb contact site of player delivering the hit; †Only includes cases involving another player (opponent or teammate)

SITUATIONAL FACTORS OBSERVED AFTER HEAD IMPACT

Visible signs of concussion. We observed visible signs of concussion in 30 of 289 (10%) of cases. "Slow to get up" was observed 25 times and "clutching of head" was observed 6 times. "Loss of consciousness," "motor incoordination," "blank or vacant look," and "visible facial injury" were not observed. Of these cases, "board/caprail/glass" was the most common impacting object (n=12/30), followed by the "stick" (n=4), and "shoulder/upper arm" (n=4). The mean peak rotational velocity (p=0.021) was 1.3-fold greater when the player was (versus was not) visibly affected by the head impact, but there was no difference in the mean peak linear acceleration (p=0.187; Table E.3.).

Infraction. 6% of the 265 head impacts involving a collision with another player were penalized. 76% of infractions were minor penalties. Only 5% of cases where the head was the initial point of contact were penalized. The mean peak rotational velocity was 1.9-fold higher for major infractions (penalties more than two minutes) than no infractions (p=0.029), but there was no difference in rotational velocity between cases with minor infractions versus no infractions (p=0.958). There was no difference in mean peak linear acceleration for cases with (versus) without penalization of the head impact (p=0.755; Table E.3.)

Table E.3. Estimated means and confidence intervals (CI) for peak linear accelerations and rotational velocities with respect to situational factors proceeding head impact (visible signs of concussion, penalty), within ± 60 seconds of the reference time.

	Frequency	Linear acceleration (g)		Rotational velocity (rad/s)	
	Count (% of head impacts captured)	Mean (95% CI)	p value	Mean (95% CI)	p value
Presence of visible sign(s) of concussion	n = 289	n = 288	0.187	n = 288	0.021
No	259 (89.6%)	34.6 (32.4-37.0)		14.2 (12.8-15.6)	
Yes	30 (10.4%)	42.6 (33.2-54.6)		18.6 (14.7-23.4)	
Penalization of head impact†	n = 265	n = 265	0.755	n = 264	0.087
No	248 (93.6%)	35.2 (30.9-39.9)		14.1 (12.8-15.5)	
Yes	17 (6.4%)	37.3 (25.6-54.5)		17.9 (13.6-23.5)	
Penalty type*,†	n = 265	n = 265	0.779	n = 264	0.038
No infraction	248 (93.6%)	35.1 (30.9-39.9)		14.1 (12.8-15.5)	
Minor infraction	13 (4.9%)	34.6 (22.5-53.1)		14.7 (10.9-19.9)	
Major infraction	4 (1.5%)	46.2 (21.4-99.8)		28.6 (16.6-49.2)	

†Only includes cases involving another player (opponent or teammate); *Where "minor infraction" was defined as less than two minutes in the penalty box and "major infraction" was defined as more than two minutes.

Appendix F.

Peak mean head kinematics measured from a single player

We examined the peak mean linear accelerations and rotational velocities for 48 head impacts experienced by a single player across two seasons (2017-18, 2018-19). Peak mean head kinematics were obtained within ± 10 seconds of the reference (laptop) time (Figure F.1.). Head impacts resulted in a wide range of loading conditions, magnitudes, and directions of linear acceleration and rotational velocity (Figure F.2.). Mean values over the 48 trials for peak magnitudes of head linear accelerations (and 95th percentile confidence intervals) were 30.1 g (25.1-36.1 g) for resultant, 22.2 g (18.0-26.4 g) for medial-lateral, 17.0 g (13.6-20.5 g) for anterior-posterior, and 18.6 g (14.5-22.7 g) for superior-inferior components. Peak mean head rotational velocities (and 95th percentile confidence intervals) were 818.3 deg/s (705-932 rad/s) for resultant, 393.2 deg/s (321-468 deg/s) for roll, 494.7 deg/s (398-591 deg/s) for pitch, and 490.7 deg/s (381.6-599.7 deg/s) for yaw components (Figure F.1.).

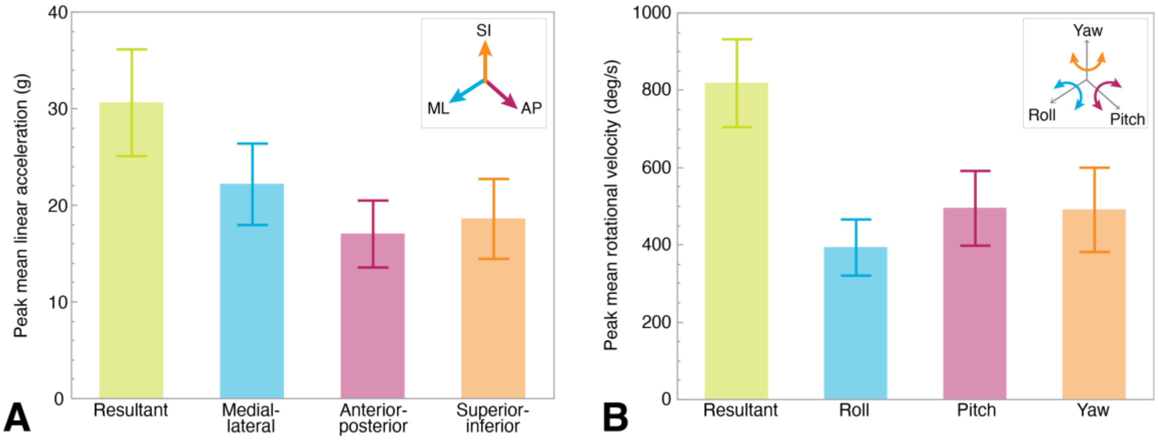


Figure F.1. (A) Peak magnitudes of mean head linear accelerations (resultant, medial-lateral, anterior-posterior, superior-inferior components) and (B) rotational velocities (resultant, roll, pitch, yaw components) for 48 head impacts experienced by a single player.

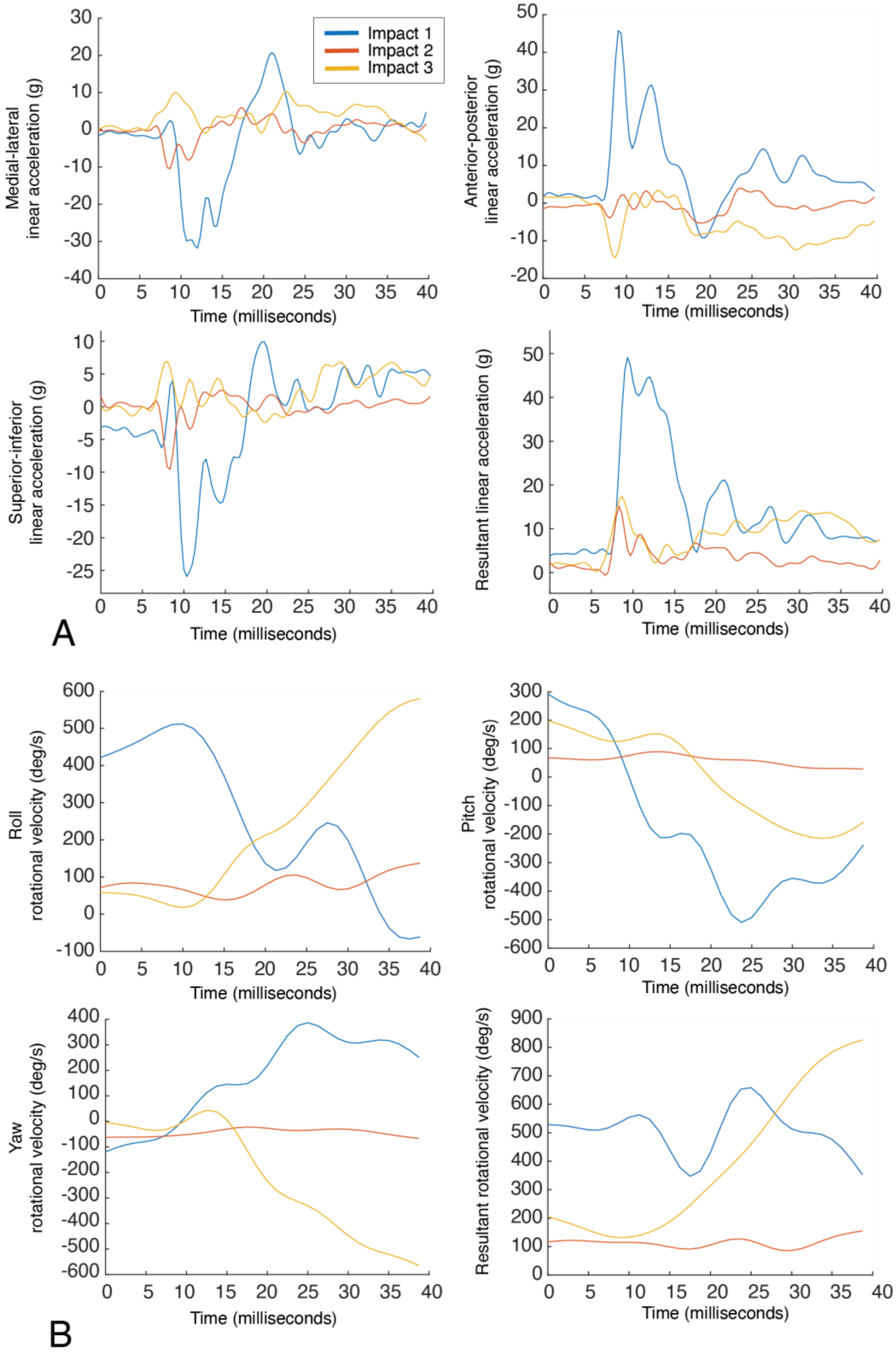


Figure F.2. **Traces of the three-dimensional linear accelerations and rotational velocities for three different head impact events (shown in blue, orange, and yellow) experienced by a single player.**