Comparing Brain Trauma Profiles for U15 Ice Hockey Leagues With Standard and Modified Body Contact Rules

Benjamin Peter Krbavac

Advisor
T. Blaine Hoshizaki, PhD

Committee
Michael Robidoux, PhD
Andrew Post, PhD

Thesis submitted to the University of Ottawa

In partial fulfillment of the requirements for
the Master of Science Degree in Human Kinetics

School of Human Kinetics
Faculty of Health Sciences
University of Ottawa

Acknowledgements

I want to dedicate all my work in the memory of Zoë King, and to the entire King family. This Master's thesis began as an appreciation from the game of hockey, one that has brought myself and many of those close to me so much joy and passion and excitement, yet also pain. It was created due to struggles with brain injuries for myself and those around me, most especially my three siblings. As motivated and passionate as I am, it would have been impossible to do this without the support of everyone around me. To everyone who cheered me on through the highs and picked me up throughout the lows, thank you.

I want to first thank my supervisor, Dr. Blaine Hoshizaki, for the opportunity to follow my passions and to allow me to be part of the world-renowned research that runs through your lab. From the moment I walked into the Neurotrauma Impact Science Laboratory in 2018 you have given me every reason to trust in you to help me achieve my passions and goals – while also telling great stories after hockey on Friday afternoons. I would also like to thank Dr. Robidoux (Robes) and Dr. Post for their expertise and time while being part of my committee; I really appreciate you both being there for this entire journey. Thank you to CCM for providing me with the helmets to conduct my research, and to Connor McFaul of Dr. Robidoux's research team for analyzing some games in advance for me.

I also want to thank all my lab colleagues for their support and input through my time in the NISL: Jarett, Amy, Stephanie, Luc, Jasmine, Kayla, Klara, Amir, Parisa, Karen, and Bianca. I would particularly like to thank Clara Karton, Andrew Post (again), and Janie Cournoyer for their support and guidance throughout my journey. Each one of you has provided comradery, insight and support that has brought out my best work.

Thank you to all my friends throughout my years at uOttawa for always being there to give me the push that I need or being there to comfort me when needed. Specifically thank you to Jake & Paul Collie, and to Dan Fazari. I couldn't have asked for better friends along the way. I also want to thank Will Simpson, Bill Simspon, and Dawna McDonald for always having a home for me when I need the support of family but couldn't go back to Hamilton.

Thank you to Steve and Andrea Alvi. To my love and best friend, Julia Alvi, thank you for always being my rock and seeing me in a way that I even struggle to see myself in. I am so proud of you, and I am so excited to start the next chapter of our lives together. Finally, I would like to thank my family for their unwavering support throughout this journey, and my entire life. Thank you to my Mom and Dad, for always pushing me to do more and be the best that I can be, while always ensuring that my finances and visits home are never to be worried about. It's really special to have parents who have always put their four children first, and I am so grateful that I've never had to worry about your support wavering. Thank you to my siblings, Julia, Nat, and Zak; to my grandmothers, Nanny and Nona, as well as my late grandfathers, and all my extended family (blood related and not), I could not have done this without your love and support. From the bottom of my heart, thank you all!

Abstract

In youth hockey the act of bodychecking is used to separate the opponent from possession of the puck by contacting the body. In one form or another bodychecking has been an integral part of hockey, especially competitive hockey. Bodychecking is associated with a high risk for concussion symptoms with a number of studies reporting a significant decrease in concussion symptom presentation when bodychecking is removed from the game (Black et al., 2016). To decrease the incidence of concussion symptom presentation and maintain body checking in the game, some leagues have introduced modified body contact rules. This study compared the brain trauma profiles, characterized by frequency and magnitude, of players playing with modified body contact rules to a standard bodychecking hockey league. U15 AAA adhered to standard bodychecking, while M15 minor only allowed shoulder-to-shoulder contact while keeping sticks on the ice and travelling in the same direction along the boards.

16 U15 AAA and 16 M15 minor hockey games were analyzed documenting head impacts, and head impact conditions that were reconstructed to examine the differences by comparing frequency and magnitudes of head impact events. There were 76 and 101 impacts in AAA and M15 minor, respectively. Most common events in AAA were head-to-glass, shoulder, and other; and in M15 minor were head-to-shoulder, head, and other. Magnitudes were grouped into very low, low, medium, high, and very high. The only magnitude levels that were significantly different when comparing total head impacts were more very low magnitude head impacts in M15 minor. Most common frequencies of magnitude levels for events in AAA were low glass, and in M15 minor were very low head, and low shoulder events.

Changing the body contact rules increased the frequency of very low magnitude events and did not change the frequency of individual events between the medium and very high magnitude events. The low magnitude displayed a shift from head-to-glass to shoulder-to-head events when body contact rules were modified. These findings suggest that modifying body contact rules can result in differences in the frequencies and magnitudes of head impacts in U15 ice hockey. Changing body contact rules resulted in changes of most common events, though the frequency of magnitudes of brain trauma did not decrease with modified contact. It is important to understand the risks associated with the frequencies of events and magnitudes in both divisions.

Table of Contents

CHAPTER 1: INTRODUCTION

1.1 PROBLEM STATEMENT

There were 429,173 registered minor hockey players in Canada prior to the coronavirus pandemic (IIHF, 2020). Hockey is a collision sport, and some divisions allow players to initiate physical collisions with other players as a means of playing defence and retaining possession of the puck (Cusimano et al., 2011; *Rule Book - Hockey Canada 2020-21*, 2020). This practice is known as *bodychecking* and, in Canada, is permitted starting at competitive levels of U15 hockey. Bodychecking has risks, as the physical contact between players and the speed of hockey can result in head impacts and subsequent injury (Emery & Meeuwisse, 2006; Hoshizaki et al., 2013; Hunter et al., 2019; Post et al., 2019). Bodychecking is not to be confused with *body contact*, as body contact is allowed in leagues where bodychecking is prohibited. Body contact involves any player-to-player contact and includes bodychecking. Bodychecking rules are standard, whereas body contact rules are modifiable.

At the ages of 13 and 14 years-old, known as U15, players' brains are still developing and the risk of mild traumatic (mTBI) and traumatic brain injury (TBI) comes with associated risk of long-term developmental issues (Halstead et al., 2013; Wasserman et al., 2016). In addition to concussion, repeated sub-concussive impacts throughout a collision sport season has been shown to result in players' cognitive abilities being below their preseason baseline, which can compound and lead to long-term cognitive health implications, in addition to physical and metabolic changes to brain tissue (Abbas et al., 2015; Bazarian et al., 2012; Gavett et al., 2011; McCrory, 2011; Nauman & Talavage, 2018). Athletes are, consequently, at risk for academic problems when they suffer symptomatic injury, or repetitive head impacts at this age (Baillargeon et al., 2012; Ransom et al., 2015; Sim et al., 2008; Wasserman et al., 2016). Evidence in collision sports, such as football and hockey, have demonstrated that rule changes can help reduce incidence of concussion and injury; rule changes for kickoffs in football have been effective in reducing rates of concussion in college football; and in minor hockey, eliminating bodychecking from leagues has resulted in a decreased incidence of concussion (Black et al., 2016; Emery et al., 2020; Wiebe et al., 2018). While concussions and injury rates are useful measures, they are limited by inconsistent symptom presentation and diagnosis (McAllister et al., 2014). Measuring brain trauma profiles provides a more objective measure of damage to brain tissue (Karton et al., 2016). The increased exposure to brain trauma associated with bodychecking in youth hockey calls for an examination of an alternative approach to bodychecking in hockey (Emery et al., 2010; Emery & Meeuwisse, 2006).

The Ligue de Hockey Préparatoire Scolaire (LHPS) is an intermediate skill level hockey league in Québec that takes a modified approach to body contact. In the LHPS, physical contact as means of separating an opponent from the puck is permitted, though bodychecking is illegal (*Réglementation spécifique 2020-21*, 2020). Defending players must be travelling in the same direction as the attacker, keep their stick on the ice, and make shoulder-to-shoulder contact against the boards. The efficacy of this approach to body contact on brain trauma had never been examined, and this study aimed to determine if the LHPS modified contact rules are a safer alternative to standard bodychecking at the U15 age.

1.2 PURPOSE

To examine the effect of modifying body contact rules on brain trauma in ice hockey.

1.3 RESEARCH QUESTION

What is the effect of using modifying contact rules on frequency and magnitude of head impacts in U15 minor hockey?

1.4 OBJECTIVES

i. Compare the frequency of head impacts between M15 minor and U15 AAA hockey.

ii. Compare the frequency of head impact events between M15 minor and U15 AAA hockey.

iii. Compare the frequency of MPS levels of head impacts between M15 minor and U15 AAA hockey.

iv. Compare the frequency-magnitude of head impact events between M15 minor and U15 AAA hockey.

1.5 INDEPENDENT VARIABLES

- Division characterized by body contact rules (n=2)
  - **Québec M15 Minor →** LHPS contact rules: shoulder-to-shoulder contact against the boards, with the defender's stick remaining on the ice and both players travelling in the same direction. Players are not allowed to follow through and create a high energy collision, beyond trying to separate an opponent from the puck (*Réglementation spécifique 2020-21*, 2020);

    Ontario U15 AAA → standard bodychecking rules: players can travel in any direction and may make contact from the front or side, but cannot leave their feet, use their stick, make contact with the head area, or hit an opponent in a vulnerable position (*Checking Resource Guide*, n.d.).
- Impact events (to describe the total frequency of impact events and the frequency of impact events within each MPS magnitude bin) (n=10)
  - Shoulder-to-Head
  - Elbow-to-Head
  - Head-to-Head
  - Head-to-Boards
  - Head-to-Glass

  - Head-to-Ice
  - Glove-to-Head
  - Punch
  - Puck
  - Other

1.6 DEPENDENT VARIABLES

- Head Impact frequency
  - Head impact frequency
  - Head impact frequency for each event
  - Head impact frequency for each MPS magnitude level
  - Head impact frequency for each MPS magnitude level for each event

Magnitude Maximum Principal Strain (MPS)

  - Very low (< .080)
  - Low, (.080 – .169)
  - Medium (.170 - .259)
  - High (.260 – .349)
  - Very high (>.350)

1.7 EXPERIMENTAL HYPOTHESES (full list of hypotheses in appendix)

i. There will be significant differences in frequency of total head impacts between M15 minor and AAA.

ii. There will be significant differences in the frequency of head impact event types between M15 minor and AAA.

iii. There will be significant differences in frequency of MPS levels of head impacts between M15 minor and AAA.

iv. There will be significant differences in frequency-magnitude of head impact events between M15 minor and AAA.

1.8 NULL HYPOTHESES

i. There will be no significant differences in frequency of total head impacts between M15 minor and AAA.

ii. There will be no significant differences in the frequency of head impact event types between M15 minor and AAA.

iii. There will be no significant differences in frequency of MPS levels of head impacts between M15 minor and AAA.

iv. There will be no significant differences in frequency-magnitude of head impact events between M15 minor and AAA.

1.9 LIMITATIONS

Games will be analyzed from pre-recorded video footage, which may have obstructed views, poor quality, or impacts outside of the field of view, potentially underrepresenting the number of confirmed head impacts. Hybrid III headform is partially biofidelic and might not fully represent the response to head impacts in this demographic but has been used in literature as an appropriate surrogate for a human head, as it has been partially validated (Walsh et al., 2018). While partially validated in adults, the finite element (FE) model, UCDBTM V2 and scaled 95% it may not fully represent the adolescent aged brain in question in this study (Nellhaus, 1968). AAA hockey is the highest level of minor hockey, whereas M15 minor is an intermediate competitive level, meaning that the comparison is not comparing 2 equivalent skill levels. Game times were not consistent between divisions, AAA was 55 minutes and M15 minor was 45 minutes. Games are analyzed on a per game basis, if normalized per minute, the M15 minor frequencies would be higher.

1.10 DELIMITATIONS

Only in-game footage from Ontario and Québec was used and might not fully representative of all minor hockey in Canada, or elsewhere in the world. Only confirmed head impact events were reconstructed and analyzed. Due to differences in game lengths, the frequencies of head impacts were analyzed on a per game basis. Impact events other than those defined (such as head to chest, back/torso, stick, etc.), see IVs, were logged as *other*. Adolescent brain is smaller than what UCDBTM V2 represents. This was accounted for in the usage of UCDBTM V2 by using a 95% scaled version of the model (Nellhaus, 1968). There is no equivalent level to M15 minor with standard bodychecking, so the AAA level in Ontario was selected to be compared, as players in this level likely represent the most skilled and experienced population with bodychecking experience. M15 minor is unique to the LHPS, and encompasses a wider range of skill levels, with some players having played at levels as high as AAA hockey, and others having less competitive hockey experience.

1.11 SIGNIFICANCE

U15 aged bodychecking hockey players have some of the highest levels of brain trauma in ice hockey (Emery & Meeuwisse, 2006; Karton et al., 2021; Robidoux et al., 2020). Eliminating bodychecking has been effective in reducing injury rates, however the effect of using modified body contact rules on brain trauma in U15 hockey has not previously been investigated. By examining brain trauma, this study will provide a better understanding of the risk of brain trauma associated with different body contact rules (McAllister et al., 2014). The results of this study will provide a better understanding whether an alternative to bodychecking in youth ice hockey is a viable option for reducing brain trauma and have a positive effect on the health of youth athletes in the future.

CHAPTER 2: LITERATURE REVIEW

2.1 EPIDEMIOLOGY OF INJURY

2.1.1 MINOR HOCKEY INJURY RISK

Ice hockey is a collision sport, which puts players at higher risk of repetitive head impacts (RHI) (Hunter et al., 2019). In a study encompassing bodychecking and non-bodychecking leagues, Emery and Meeuwisse (2006) report that head injuries make up the highest rate of injuries in hockey, followed by shoulder sprains/dislocations, knee sprains/strains and arm fractures. It is estimated that 18-24% of all injuries in minor hockey are head injuries (Emery & Meeuwisse, 2006; Marar et al., 2012; Meehan et al., 2011; Willer et al., 2005). Injuries can be the result of body contact, whether intentional or not, or non-body contact events (Brust, 1992; Emery & Meeuwisse, 2006). It is estimated that 14.2% of injuries in minor hockey are caused by initiated collisions and subsequent contact against the boards or glass (Emery & Meeuwisse, 2006).

2.1.2 U15 HOCKEY REPORTED INJURY RATES

In Canada, bodychecking is introduced to players in the U15 age group, 13 and 14 years old. Bodychecking was previously legal in intermediate divisions but is now legal at only competitive levels of hockey for U15 and above. U15 aged players are also the most likely of all ages to sustain injuries that result in a loss of play time of greater than 14 days (Emery & Meeuwisse, 2006). Among all high school sports in the United States, boys hockey was only second to football in rate of concussion, at 54-61.9 per 100 000 athletic exposures (AEs) (Guerriero et al., 2012). Kontos and colleagues (2016) report a rate of 1.58 per 1000 AEs. Emery and Meeuwisse (2006) report that at the U15 age level, concussions are sustained at a rate of 0.97 per 1000 player hours, which is the highest of all divisions. When measuring brain injury risk, it is important to consider that concussion statistics do not entirely represent risk of injury as the diagnosis is symptom based recognition (Karton et al., 2016, 2021). Brain trauma profiling was used in this study, as objectively quantifies the brain trauma associated with individual events, by simulating the magnitude of events based on the impact parameters (Karton et al., 2016, 2021).

At this age, 50th percentile American 13 and 14 year-old males can range in weight from 54.45-60.0kg, with differences in weight as great as 61.91kg recorded, and in height from 163.6-170.0cm tall, with differences as great as 30.1cm recorded (Fryar et al., 2021). Such large disparities in size have been shown to contribute to increased symptomatic brain injury risk in minor hockey (Brust, 1992; Emery et al., 2010; Emery & Meeuwisse, 2006; Mölsä et al., 2003; Stuart et al., 1995). In addition to the size disparity, the differences due to puberty and hormone levels may contribute to risk of high energy collisions. Despite U15 players sustaining 6.3 head impacts per game, and they average the highest percentage of reported concussion symptom presentation, at 0.33% (Karton et al., 2021; Robidoux et al., 2020). U15 aged players also sustain a significantly higher frequency of medium velocity (4.00-5.99m/s) impacts than all other divisions, putting them at higher risk of sustaining higher levels of brain trauma (Karton et al., 2021).

2.2 BODYCHECKING IN ICE HOCKEY

2.2.1 STANDARD BODYCHECKING RULES AND INJURY RATES

Most studies that compare bodychecking to non-bodychecking hockey compare the rates of injury, based on diagnosis of reported symptoms. When considering the effect of rules on injury risk, it is important to acknowledge that the rates of injury are exclusively based on presence of symptoms, making it a less objective measure. Brain trauma profiling, which will be detailed in section 2.4, was used in this study to quantify injury risk (Bazarian et al., 2012; McAllister et al., 2014). Brain trauma profiles provide an objective measure of brain trauma by using measurable parameters to quantify the strain to brain tissue resulting from head impact events.

Bodychecking in hockey has been linked to increased overall risk of injury, with concussion symptom presentation rates being greater when bodychecking is allowed, compared to after its removal (Cusimano et al., 2011; Emery et al., 2010, 2020; Emery & Meeuwisse, 2006). In a study by Emery and Meeuwisse (2006), bodychecking accounted for 44.6% of all injuries, with the player receiving the bodycheck being injured on 97% of these occasions. Bodychecking hockey leagues have a sixfold increased risk of injury in comparison to non-bodychecking leagues of the same age and competition level, and rates of injury are higher in bodychecking leagues of all levels (Darling et al., 2011; Willer et al., 2005). Among injuries sustained, it is reported that bodychecking leagues have a threefold increase in the rate of concussion symptom presentation when compared to non-bodychecking equivalents (Black et al., 2016). Bodychecking collisions are associated with increased concussion symptom incidence at the U15 age group (Emery et al., 2010, 2022; Emery & Meeuwisse, 2006). Emery and colleagues (2020) found that eliminating bodychecking led to a 40% reduction in rates of concussion symptom presentation. Emery and colleagues (2006, 2022) also asserted the importance of examining and testing preventative strategies to make hockey safer, which should include re-examining the practice of bodychecking.

In 2011, Hockey Canada modified a rule aimed at eliminating all head contact (intentional or accidental) by assessing a penalty to any player who contacts an opponent's head. The "zero tolerance" rule has not been determined to be effective in reducing concussion symptom presentation risk in bodychecking leagues (Krolikowski et al., 2017). This was followed by Hockey Canada universally raising the introduction age of bodychecking in games from the U13 age group (11-12 years-old) to the U15 age group (13-14 years-old). Following this policy change was a threefold decrease in incidence of concussion symptom presentation in U13 leagues which previously allowed bodychecking (Black et al., 2016). The examination of an alternative form of body contact on brain trauma has yet to be performed. The alternative body contact rule was the LHPS contact rules in this study. Such a comparison can provide insight into whether or not modifying body contact rules is effective in reducing the level of brain trauma in U15 hockey.

2.2.2 STANDARD BODYCHECKING RULES AND BRAIN TRAUMA

In youths aged 13-16, concussion symptom presentation is most likely to be the result of body collisions (Willer et al., 2005). Head impact events change with age, as head-to-head impacts are frequent in younger divisions, such as IP, U9, and U11, but less frequent in U13, U15, and U18 (Karton et al., 2021). Conversely, head-to-glass impacts are rare in the former three divisions, but much more common in U15, and especially U18, where head-to-glass events represent almost a quarter of all head impact events (Karton et al., 2021). Chen and colleagues (2020) also showed that, when compared to U13 players, U15 players sustained higher frequencies of head-to-glass impacts, and fewer head-to-boards and elbow-to-head impacts.

2.2.2 INTRODUCTION TO LHPS CONTACT RULES

The Ligue de Hockey Préparatoire Scolaire (LHPS) takes a modified approach to body contact, as they do not allow full bodychecking at the M15 minor (intermediate level within U15 age) level. The LHPS allows for shoulder-to-shoulder contact as means of separating players from the puck (*Réglementation spécifique 2020-21*, 2020). Modified body contact rules are used as an alternative to bodychecking, as modified contact rules are created with the intention of allowing body contact, whilst not allowing bodychecking, such that collisions can occur, without the high energy of bodychecks. Contact is to be made when players are traveling in the same direction, the stick of the defender must remain on the ice, and the player cannot follow through with force to make a bodycheck (*Réglementation spécifique 2020-21*, 2020). Contact must be made against the boards (i.e. “angling the opponent off the puck”) (*Réglementation spécifique 2020-21*, 2020). For simplicity, this rule was referred to as the *LHPS contact rules* in this paper.

2.3 HEALTH IMPLICATIONS

2.3.1 SYMPTOMS OF BRAIN INJURY

Concussions are diagnosed based on the presence of a variety of symptoms. The term "concussion" is used, though note that concussion refers to presentation of symptoms, and is not an objective diagnosis of brain trauma. Concussion can lead to long-term cognitive impairment, motor control dysfunction and mental health concerns in later life, specifically for people with a history of multiple concussions (De Beaumont et al., 2007, 2009; Manley et al., 2017). Martini and Broglio (2018) found that the long-term effects of concussion cannot be attributed to a specific number of concussions, or age at time of injury, and that a longitudinal study focussing on different athletes (combat, collision, contact, and non-contact) would be well suited to quantify specific risks associated with acute and repetitive concussion.

One limitation with concussion epidemiology research is that concussions are diagnosed using symptoms and return to play guidelines for athletes and are subject to interpretation based on the clinician, as observable functional disruption is used to diagnose because structural damage is harder to observe (Putukian, 2011; West & Marion, 2014). mTBIs are underreported, and athletes can sustain multiple concussions without recall, as they can ignore the presence of symptoms (Martini & Broglio, 2018). Despite this, U15 players in bodychecking leagues are reported to have a threefold risk of concussion compared to players in non-bodychecking leagues, with many concussions in minor hockey going unreported (Cusimano et al., 2017; Emery et al., 2010; Emery & Meeuwisse, 2006). High concussion incidences show that the differences in injury risk between bodychecking and non-bodychecking hockey likely exist, but when reporting injury risk, brain trauma is a more objective measure, detailed in 2.4 (Karton et al., 2016). Frequency and magnitude are useful measures, as by using these it is possible to quantify the exposure to brain trauma, while focussing on event specific parameters. Analyzing frequency and magnitude allows for a relationship to be established between how events take place, and how the damage to brain tissue is expressed (Karton et al., 2020).

2.3.2 HIGH FREQUENCIES OF NON-SYMPTOMATIC BRAIN TRAUMA

Non-symptomatic brain trauma is defined as head impacts that do not cause observable functional disruption. RHIs at lower magnitudes presents clinical risk for young athletes. Despite not presenting with symptoms of concussion, sub-concussive impacts can cause trauma to brain tissue, resulting in physical and metabolic changes to brain tissue (Bazarian et al., 2012; Gavett et al., 2011; McCrory, 2011; Nauman & Talavage, 2018). When comparing football players in-season to non-contact sport athletes, football players demonstrated short-term changes in memory recall inferior to their baseline abilities prior to the season, due to high frequency of very low magnitude head impacts (Abbas et al., 2015). Former football players who had played for multiple years also presented with an accumulation of neurological changes hypothesized to have been associated with playing football for multiple years (Abbas et al., 2015). Chronic traumatic encephalopathy (CTE) is a neurodegenerative disease that can present in contact and collision sport athletes who have been exposed to repetitive sub-concussive impacts. This disease is caused by neuronal loss and brain white matter (WM) atrophy in brain structures (Gavett et al., 2011; McKee et al., 2013; Omalu et al., 2005, 2006). As with other contact and collision sport athletes, hockey players face risks of CTE and long-term neural damage (Schwab et al., 2021).

Despite not sustaining symptoms of concussion through the course of a season, WM changes are still detected in contact sport athletes (Bazarian et al., 2012; Davenport et al., 2014; McAllister et al., 2014). The measure of changes in brain WM is through diffusivity, as higher diffusivity values represent a higher amount of WM changes to the brain. Studies have reported RHI lead to changes in WM over the course of a collision sport season that resemble changes experienced by athletes reporting concussive injury (Bazarian et al., 2012; Davenport et al., 2014; McAllister et al., 2014). The effects of sub-concussive trauma are associated with MPS levels starting around 8% (Bazarian et al., 2012; Davenport et al., 2014; Karton, 2019; McAllister et al., 2014). Over the course of a season, these changes can represent long-term changes to brain health and potential public health implications (McCrory, 2011; Sollmann et al., 2018). The implications of changes in brain health on developing brains demonstrates the importance of examining potential causes of such changes and working to limit exposure.

2.4 BIOMECHANICAL INJURY PREDICTORS

Brain trauma results from movement of the brain within the skull caused by collisions with external objects and expressed differently based on the energy of the collisions. Damage to the axons of grey and white matter result in a wide variety of symptoms. Forces resulting from head impacts can cause swelling of axons, alterations in metabolic processes, and blood-barrier disruptions. Repetitive events causing these effects create a risk for brain disease, specifically neurodegeneration. At strain levels as low as 5%, there is potential for disruption of the brain, though the risk of long-term damage is low at low frequencies (Karton, 2019; Yuen et al., 2009).

Comparing rates of concussion between hockey leagues with different body contact rules is the most common approach used to establish the effectiveness of the rule changes (Black et al., 2016; Emery et al., 2020, 2022; Emery & Meeuwisse, 2006). Reported concussion rates rely on self-reporting and diagnosis using signs and symptoms making them less objective. This research compared the effect of rule changes involving body contact and bodychecking by using magnitude levels and frequency of brain trauma. Brain trauma measures do not rely on the interpretation of symptoms providing a more objective measure. Measuring frequency and magnitude of tissue deformation (MPS) for the two different divisions provides a better understanding of the risks associated with the different body contact rules (Bazarian et al., 2012; McAllister et al., 2014).

Helmet test standards are created to protect against TBI, and such injuries have become less frequent in hockey. Current standards do not mandate protection against mTBI or sub-concussive trauma and the increasing prevalence of such injury as a result of head impact events requires further examination (Post et al., 2013). Current helmets are designed to protect against high linear accelerations, but brain strain levels are connected to rotational acceleration measures, which current standards do not mandate protection against, so the risk of mTBI and sub-concussive trauma remains in hockey (Hoshizaki et al., 2013; Post et al., 2013, 2019).

2.4.1 FREQUENCY AND EVENT TYPE

RHI can lead to damage to brain tissue, resulting in long-term mental health deficits in athletes (Bazarian et al., 2012; Davenport et al., 2014; McAllister et al., 2014). The frequency of potentially concussive impacts can indicate more acute health risks associated with playing minor hockey at these levels (Ji et al., 2015; McAllister et al., 2012). Younger athletes who sustain RHI at a high frequency are susceptible to long-term health deficits, that may present as a public health issue if not addressed (McCrory, 2011; Sollmann et al., 2018).

Robidoux and colleagues (2020) found that 62% of head impacts in U15 are caused by collisions to a body segment, with a further 19% of head impacts caused by collisions, followed by the head hitting the boards or glass, and 5% of head impacts resulting from a collision, followed by head-to-ice. Glove-to-head, shoulder-to-head, elbow-to-head, head-to-boards, head-to-glass, and head-to-ice are the events which most commonly result in brain trauma in hockey (Emery et al., 2022; Emery & Meeuwisse, 2006; Hutchison, 2012; Kendall et al., 2012; Wilcox et al., 2014).

Low compliant surfaces, such as the glass, boards, and ice, can elicit high linear accelerations. Highly compliant surfaces, such as elbow, glove, and shoulder elicit lower linear accelerations, but higher rotational accelerations, which contribute to a high MPS level (Post et al., 2019).

2.4.2 MAGNITUDE – MAXIMUM PRINCIPAL STRAIN (MPS)

There is no way to measure an in-vivo brain response for head impacts, but finite element (FE) modelling based on the material brain characteristics provides a means to calculate the three-dimensional response of brain tissue when exposed to loading of the head, known as MPS (Horgan & Gilchrist, 2003; Kleiven, 2006; Post et al., 2012; Trotta et al., 2020). The definition of MPS is the highest tensile strain that occurs along the 3 axes in the brain when tissues are stretched along their principal axes, and is a percentage of elongation compared to original length (Bain & Meaney, 2000; Cournoyer & Hoshizaki, 2021; Karton et al., 2016; Patton et al., 2013; Zanetti et al., 2013; Zhang et al., 2004). Linear and rotational accelerations from head impacts are obtained using event reconstructions followed by FE modelling to calculate MPS (Hoshizaki et al., 2013; Kimpara & Iwamoto, 2012; Post & Hoshizaki, 2015; Zhang et al., 2004). At the sub-concussive level, FE modelling determined MPS represents potential for nerve tissue disruption (Bain & Meaney, 2000; Hoshizaki et al., 2013). When measured with diffuse tensor imaging (DTI), used to help determine WM diffusivity, MPS determined by FE modelling is shown to be correlated with WM diffusivity to predict injury (McAllister et al., 2012). Maximum principal strain (MPS) provides an objective measure of neural injury (Karton et al., 2016).

CHAPTER 3: METHODOLOGY

3.1 OVERVIEW

Video footage of 16 U15 AAA hockey games from Ontario and Québec was obtained using HockeyTV, and 16 U15 M15 minor games from Québec was obtained using a source from the LHPS. All head impact events were logged and clipped using WM Capture software. AAA games were 55 minutes in length, and M15 minor games were 45 minutes in length, with no overtime. Head impacts that occurred after the whistle as the result of scrums or fights were included in this study. The event characteristics were logged, and a frequency of confirmed events was logged. The characteristics of events were used to reconstruct events, with the kinematic data from reconstructions inputted into FE modelling to determine MPS.

3.2 VIDEO ANALYSIS

3.2.1 INCLUSION/EXCLUSION CRITERIA

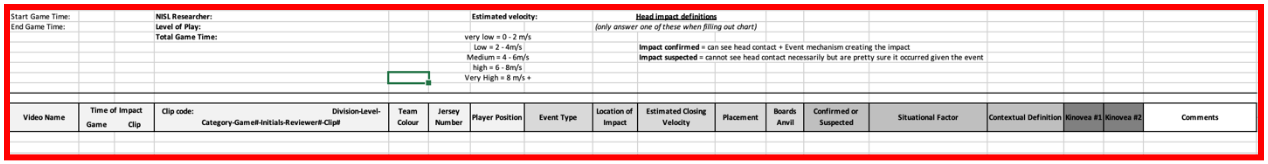
The games included league play, playoffs, and tournament games. The camera in each game focused on the puck while trying to maintain the largest field of view of the ice. Head impacts were identified as confirmed impacts. Confirmed impacts involve events in which the head contact and event type being clearly visible (Chen et al., 2020; Rahnama, 2002). The frame rate used for clipping and analysis was 25 frames per second (fps). Analysis at 25fps allowed for velocity to be calculated by dividing the distance prior to impact, by the time until impact.

$$\text{velocity} = \frac{\text{distance travelled}}{\text{time to impact}}$$

The full inclusion/exclusion criteria for Kinovea were as follows: (1) Head impacts are each singular impact to the head; (2) Head is initial point of contact; (3) Head impact and impact event must be clearly visible; (4) Dimensions of rink must be known; and (5) Enough markings on rink must be in camera view. If one or more of these criteria was/were not fulfilled, visual estimation using an approximation of the head's distance from the impacting surface prior to impact was used as the velocity. The visual estimation process is approximately 85.5 percent accurate when compared to events calculated using Kinovea (Cronbach alpha =.923) (Cournoyer et al., 2021). 36 impacts in AAA and 75 impacts in M15 minor were estimated.

3.2.2 DATA COLLECTION

Each game was analyzed by 2 reviewers who logged confirmed head impact events and characteristics according to the template below. A third, experienced reviewer reviewed the logged impacts and confirmed that a head impact occurred. Kinovea analysis was performed, with 2 calculations per impact being completed and the average velocity being recorded. If the calculated velocities were >1m/s apart, a third velocity calculation was completed, and averaged with the closer of the two previous calculations.



Start Game Time:
End Game Time:

NISL Researcher:
Level of Play:
Total Game Time:

Estimated velocity:
very low = 0 - 2 m/s
Low = 2 - 4m/s
Medium = 4 - 6m/s
high = 6 - 8m/s
Very High = 8 m/s +

Head impact definitions
(only answer one of these when filling out chart)
Impact confirmed = can see head contact + Event mechanism creating the impact
Impact suspected = cannot see head contact necessarily but are pretty sure it occurred given the event

Video Name	Time of Impact Game	Time of Impact Clip	Clip code: Division-Level-Category-Game#-Initials-Reviewer#-Clip#	Team Colour	Jersey Number	Player Position	Event Type	Location of Impact	Estimated Closing Velocity	Placement	Boards Anvil	Confirmed or Suspected	Situational Factor	Contextual Definition	Kinovea #1	Kinovea #2	Comments

Figure 1. Excel template used to track head impacts.

3.3 PRESCRIBED IMPACT CONDITIONS

3.3.1 EQUIPMENT

3.3.1.1 HYBRID III HEADFORM

Head impact events were reconstructed by striking a helmeted and caged Hybrid III 5th percentile headform equipped with accelerometers in a 3-2-2-2 array attached to an unbiased neckform, for all conditions except the flat and angled boards conditions (Chen et al., 2020; Post et al., 2019). The boards conditions employed a free-drop protocol. The helmet used was a size small CCM Tacks 110 with a vinyl nitrile (VN) interior, with a size small FM580 cage attached. The trigger for the headform was set at 1g, and data was the accelerometers were sampled at 20kHz and filtered using CFC 180 low pass filter.

3.3.1.2 IMPACTING EQUIPMENT

A Cadex monorail drop rig and anvil was used to reconstruct head to ice, boards, and glass events; the anvil surface used ice in a steel cylinder (frozen at -25°C for 24+ hours prior to impact, and frozen between impacts), polyethylene boards, and a plexiglass panel for each respective event (Chen et al., 2020; Karton et al., 2021; Kendall et al., 2012; Post et al., 2012, 2019; Post & Hoshizaki, 2015). The monorail drop rig utilized an unbiased neckform for the glass and ice conditions, and a free drop was used for the boards conditions, to stay consistent with the NISL's NSERC Alliance database.

The pendulum drop was used for head-to-head, elbow, punch, and shoulder events (Chen et al., 2020; Karton et al., 2021; Kendall et al., 2012; Post et al., 2012, 2019; Post & Hoshizaki, 2015). Impact masses for shoulder, elbow, head, punch and glove events were 8.76, 3.29, 4.12, 3.09 and 0.45kg respectively (Fryar et al., 2021; Karton et al., 2021). For shoulder impacts a shoulder pad was used on top of the impacting end of the pendulum, while a glove was used on the impacting end for glove impacts (Karton et al., 2021). For punch events, the same glove was used, but additional weight was added to the glove to achieve striking mass (Karton et al., 2021). For head-to-head events, a second headform with a helmet and cage replaced the cylinder of the pendulum system (Karton et al., 2021). For elbow events, a metal attachment was fitted with an elbow pad attachment and outfitted with the necessary additional weights to achieve the striking mass (Karton et al., 2021). Impacting equipment is depicted in Figure 2.

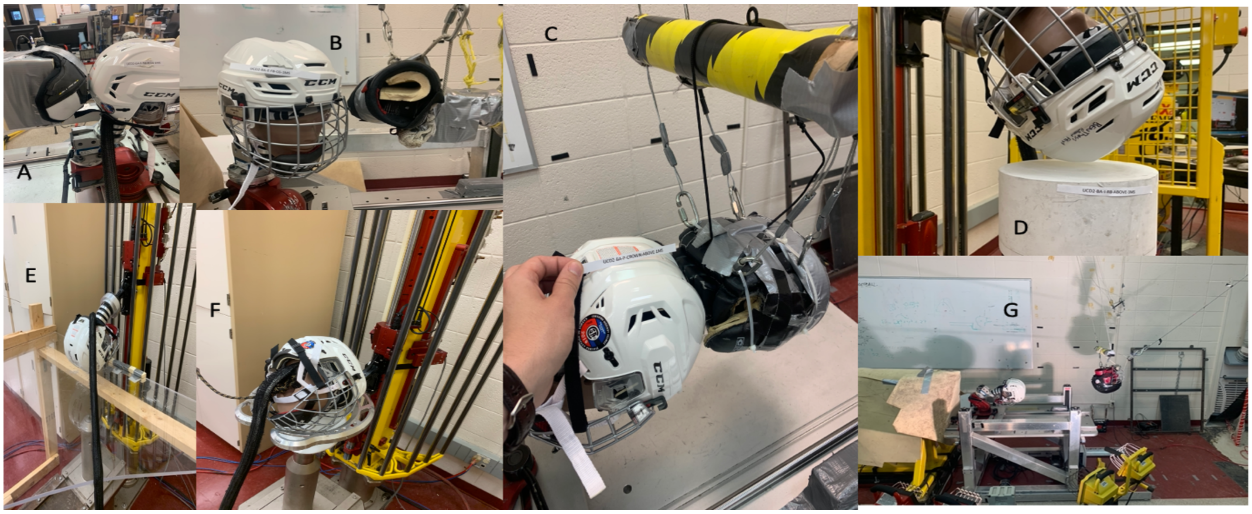


Figure 2. Impacting equipment used for Shoulder (A), Elbow (B), Glove/Punch (C), Ice (D), Glass (E), Boards (F), and Head (G) to head impact event.

3.3.2 IMPACT PARAMETERS

Confirmed events were reconstructed according to their impact parameters. The parameters were inbound velocity, event type, location, and elevation. The inbound velocity was the median velocity at that level (i.e., *Very Low* = 1.00m/s, *Low* = 3.00m/s, Medium = 5.00m/s, High = 7.00m/s) (Chen et al., 2020; Post et al., 2018). These parameters allowed for the dynamic response data of the impact condition to be most representative of the variance in real life impact events.

Impact events were categorized as head-to-*ice, head, shoulder, elbow, boards, glass, glove*, *puck*, *punch* and *other*. *Other* encompassed any events not specified previously (i.e., stick, back, leg, chest, etc.). Puck and other events were not included for reconstructions, though they were included for frequency analysis. For the boards conditions, the anvil was struck at a flat or angled position depending on the geometry of the impact, indicated in the "Boards Anvil" column in the template in figure 1.

Impact location was divided into 6 locations: *Front, Front Boss, Side, Rear, Rear Boss,* and *Crown* (Hutchison, 2012; Kendall, 2016; Rousseau, 2014). The locations are arranged by dividing the head transversely into 8 equal regions of 45°, with the crown being on top of the head on the vertical axis. In addition, the head was divided into 3 elevation locations along the frontal plane: *Above, Middle,* and *Below*, to make dynamic response more representative, as above and below CG elicit different dynamic responses than at CG. The Middle location is within 2.54cm above or below the centre of gravity (cg); above is >2.54cm above cg and below is >2.54cm below cg. For the front boss and rear boss locations, a 45° positive and negative azimuth condition was applied, respectively, to represent the most common documented impact angle at these sites when above or below cg (Walsh et al., 2018).

All impact events were grouped by inbound velocity and defined as *Very Low* (0-1.99m/s), *Low* (2.00-3.99m/s), *Medium* (4.00-5.99m/s), *High* (6.00-7.99m/s), and *Very High* (≥8.00m/s) (Hoshizaki et al., 2013; Karton et al., 2021; Post et al., 2019). There were no reconstructed impacts at the very high velocity level. Velocities were determined using Kinovea analysis, when applicable, and events with no visible geometric markers were determined using visual estimation (defined as *estimated velocity*), as detailed in 3.2.1 (Post et al., 2018).

The other characteristics that were logged included situational factors surrounding the head impact (body collisions, unaided falls, collisions against boards, punches) and the contextual definition of the impact (intentional or incidental) and used for observational purposes and not for analyses.

There were 58 prescribed impact conditions previously reconstructed for the NISL's NSERC Alliance grant that were used in this study. There were 22 conditions not previously reconstructed, so they were reconstructed in the lab. There were 3 impacts reconstructed per condition to ensure consistency of data.

A sample head impact was reconstructed for each impact event, excluding punch and glove events, and compared to an identical pre-existing impact condition to ensure that the researcher's consistency was maintained throughout the data collection process. The impact conditions used were S-FB-CG-3MS (shoulder), E-SIDE-CG-1MS (elbow), H-SIDE-CG-1MS (head), I-SIDE-ABOVE-3MS (ice), BANG-SIDE-ABOVE-1MS (angled boards), B-REAR-CG-3MS (flat boards), and G-FRONT-ABOVE-3MS (ice).

3.4 UNIVERSITY COLLEGE DUBLIN BRAIN TRAUMA MODEL VERSION 2

Linear and rotational acceleration data from impacts were applied to the University College Dublin Brain Trauma Model Version 2 (UCDBTM V2) to determine MPS. This study used a 95% scaled model of UCDBTM V2 to account for the head size of the population (Nellhaus, 1968).

The University College Dublin Brain Trauma Model (UCDBTM) was created through computed tomography and magnetic resonance imaging of a human brain and the model was partially validated through impact tests of cadavers and uses 28 286 hexahedral elements (Doorly & Gilchrist, 2006; Horgan & Gilchrist, 2003; Trotta et al., 2020). UCDBTM has since been improved and a second version, UCDBTM V2, which uses 184 261 hexahedral elements to better replicate the sliding and mechanical properties of the brain (Trotta et al., 2020).

UCDBTM V2 adopted sliding and mechanical properties that are more characteristic of the human scalp. Compared to UCDBTM (V1) the scalp in UCDBTM V2 is not rigidly attached to the skull, allowing for more sliding and mechanical interaction. The mesh components of UCDBTM were refined and allow for more realistic convergence properties in V2. UCDBTM V2 also incorporates elements at three points of connection at the centre of gravity (cg), which is useful for measurements of linear and rotational accelerations when using a Hybrid III headform, as the congruency of accelerometers at cg in the Hybrid III headform coincide with the position of the three elements at points of connections along cg in UCDBTM V2 (Trotta et al., 2020).

This model was partially validated against 3 different data sets using cadavers: Lloyd et al., (2014) to evaluate the response of the head to different impact locations; and Hardy et al., (2001, 2007) to evaluate the response of neutral density targets (NDTs) to impacts (Giordano & Kleiven, 2016; Trotta et al., 2020). There is no data currently that can validate the bio-fidelity of UCDBTM V2 against the brainstem and cerebellum regions, and the anisotropy of the brain has not been validated yet due to computational expense (Trotta et al., 2020). Until such validation is complete, the bio-fidelity of UCDBTM V2 in these regions remains an area for future examination.

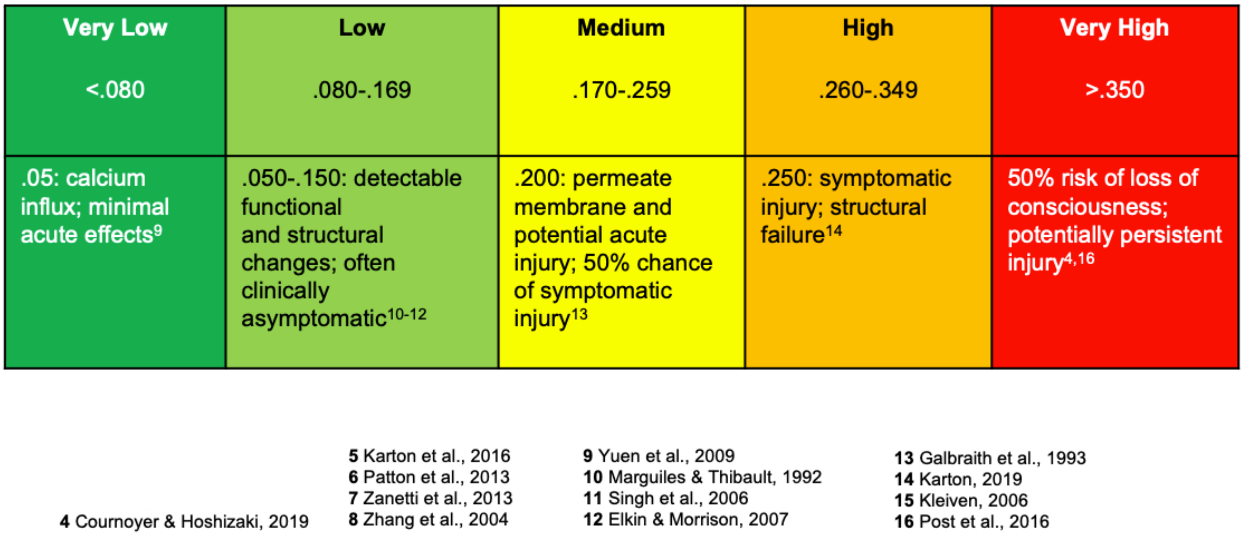
Table 1. Material properties of UCDBTM V2 (Trotta et al., 2020).

Region	**Model**	**Density (kg/m^3)**	**Poisson's Ratio**
Scalp	Hyperelastic (Ogden)	1133	~ 0.5
Cerebellum	Visco-hyperelastic	1060	~ 0.5
Grey matter	Visco-hyperelastic	1060	~ 0.5
Brainstem	Visco-hyperelastic	1060	~ 0.5
Cortical bone	Linear elastic	2000	0.22
Trabecular bone	Linear elastic	1300	0.24
Pia	Linear elastic	1130	0.45
CSF	Linear elastic	1000	~ 0.5
Facial bone	Linear elastic	2100	0.22
Ventricles	Visco-hyperelastic	1040	~ 0.5
White matter	Viscoelastic	1060	~ 0.5
Dura, falx and tentorium	Hyperelastic	1130	~ 0.5

3.5 MPS MAGNITUDE LEVELS

MPS was divided into five levels of magnitude: <8.0 (very low), 8.0-16.99 (low), 17.00-25.99 (medium), 26.00-34.99 (high) and >35.00% (very high), corresponding to an increased risk of symptomatic brain injury (Karton, 2019). Very low MPS magnitudes represent a risk of calcium influx (Yuen et al., 2009). Low MPS magnitudes represent the potential for low functional impairment and repetitive exposure can result in cumulative trauma (Elkin & Morrison, 2007; Margulies & Thibault, 1992; Singh et al., 2006). Medium MPS magnitudes represent potential metabolic changes in the neurons (Galbraith et al., 1993). High MPS magnitudes create structural changes and failure in neurons (Karton, 2019). Very high MPS magnitudes have been associated with loss of consciousness and potential permanent symptoms (Cournoyer & Hoshizaki, 2021).

Table 2. MPS levels and the effects on brain tissues at the various levels.



Very Low <.080	**Low** .080-.169	**Medium** .170-.259	**High** .260-.349	**Very High** >.350
.05: calcium influx; minimal acute effects[9]	.050-.150: detectable functional and structural changes; often clinically asymptomatic[10-12]	.200: permeate membrane and potential acute injury; 50% chance of symptomatic injury[13]	.250: symptomatic injury; structural failure[14]	50% risk of loss of consciousness; potentially persistent injury[4,16]

4 Cournoyer & Hoshizaki, 2019
5 Karton et al., 2016
6 Patton et al., 2013
7 Zanetti et al., 2013
8 Zhang et al., 2004
9 Yuen et al., 2009
10 Marguiles & Thibault, 1992
11 Singh et al., 2006
12 Elkin & Morrison, 2007
13 Galbraith et al., 1993
14 Karton, 2019
15 Kleiven, 2006
16 Post et al., 2016

3.6 STATISTICAL ANALYSIS

Analyses were conducted using *Jamovi 2.3.12.0*. A test for normality was conducted, and the data was found to be not normally distributed. α levels were set at $p \leq 0.05$. Frequency of head impacts and events were collapsed according to both event and magnitude for analyses, to compare between divisions.

3.6.1 FREQUENCY OF HEAD IMPACTS AND EVENTS

Head impacts were logged by frequency per game. A Mann-Whitney U test was conducted to compare the frequency of head impacts between divisions per game. A Mann-Whitney U test was also used to compare the frequency of head impact events per game between divisions.

3.6.2 MPS MAGNITUDE LEVELS BETWEEN DIVISIONS

Frequency between the MPS magnitude levels per game was compared between divisions using a Mann-Whitney U test.

3.6.3 FREQUENCY OF MAGNITUDE AND EVENT TYPE

Frequency of events and magnitudes per game was compared between divisions using a Mann-Whitney U test.

3.6.4 FREQUENCY-MAGNITUDE OF HEAD IMPACT EVENT TYPE

Frequency-magnitude of head impact events was compared between divisions using a series of Mann-Whitney U tests. These tests will compare the frequency of head impacts within the five levels of MPS.

CHAPTER 4: RESULTS

4.1 IMPACT RECONSTRUCTIONS

There was a total of 76 confirmed head impacts in AAA, and 101 confirmed head impacts in M15 minor. On a per game basis, this results in averages of 4.25 (±3.26) and 6.31 (±3.44) per game for AAA and M15 minor respectively.

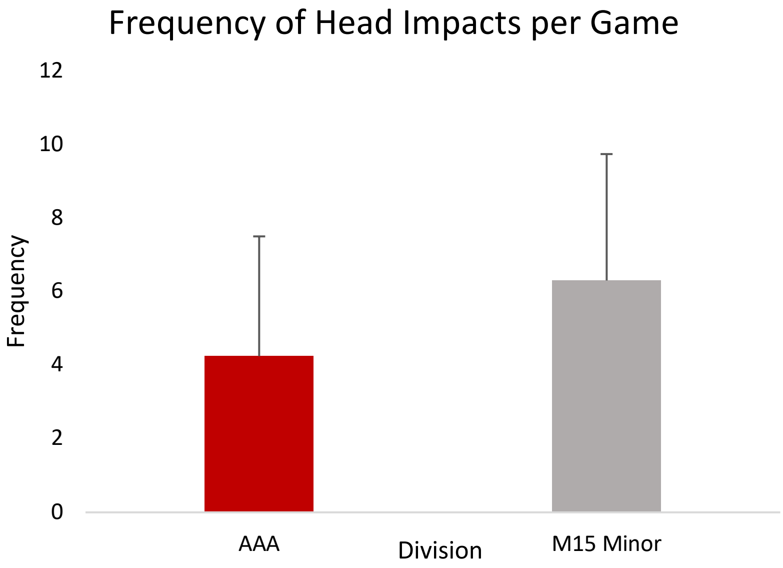


Figure 3. Frequency of head impacts per game.

4.1.1 AAA HEAD IMPACTS

There was a total of 76 confirmed head impacts in AAA: 5 ice, 11 shoulder, 6 elbow, 2 head, 7 boards (4 angled, 3 flat), 18 glass, 10 glove (6 glove to head, 4 punch), 6 puck, and 11 other. The puck impacts and other events were not reconstructed. All other events met prescribed impact conditions. As a result, 59 impacts were simulated using the prescribed conditions.

Table 3. Characteristics of reconstructed head impact events in AAA.

Event	**Location**	**Velocity**	**Elevation**	**Lin Acc. (g)**	**Rot. Acc. (rad/s^2)**	**MPS**
Ice	Rear	Low	Above	84.8	27556.53	0.292
	Rear	Low	CG	66.0	2044.70	0.320

	Side	Low	Above	69.6	13744.72	0.400
	Rear Boss	Low	Above	84.8	27556.53	0.288
Shoulder	Front	Very Low	Above	3.3	239.11	0.035
	Side	Low	CG	17.7	1322.60	0.158
	Front Boss	Low	CG	14.0	1109.84	0.147
	Front Boss	Med	CG	16.8	2481.02	0.185
	Side	Very Low	Below	2.1	231.43	0.032
	Front Boss	Very Low	Above	3.5	199.76	0.043
	Side	Very Low	CG	2.6	140.67	0.034
	Front Boss	Very Low	Below	2.0	235.23	0.029
Elbow	Side	Very Low	CG	2.0	179.99	0.021
	Front Boss	Very Low	CG	2.9	525.53	0.045
	Front Boss	Very Low	Above	2.0	189.91	0.024
	Side	Very Low	Below	1.3	191.76	0.019
Head	Front	Low	CG	10.3	1416.35	0.085
	Side	Low	CG	16.3	1118.84	0.134
BANG	Rear	Very Low	CG	13.3	286.56	0.076
	Side	Very Low	Above	7.9	1144.06	0.078
	Front Boss	Very Low	CG	16.7	1481.09	0.163
	Rear Boss	Very Low	Above	9.4	1024.23	0.075
BFLAT	Side	Very Low	CG	19.5	1084.42	0.155
	Rear	Low	Above	70.9	785.78	0.285
	Rear	Very Low	CG	20.7	146.35	0.123
Punch	Rear	Very Low	Above	2.6	264.36	0.025
	Side	Very Low	CG	3.5	324.98	0.030
	Front Boss	Low	Below	19.5	2114.86	0.136
	Side	Low	CG	11.7	933.48	0.117
Glove	Front Boss	Very Low	Below	4.4	430.04	0.026
	Front Boss	Very Low	CG	1.4	154.61	0.023
	Side	Low	Below	3.8	276.24	0.028
	Rear	Very Low	Above	1.1	220.80	0.012
Glass	Rear	Very Low	Above	7.4	348.34	0.046
	Front Boss	Very Low	Above	4.8	529.45	0.085
	Rear Boss	Very Low	CG	8.0	467.95	0.139
	Rear Boss	Very Low	Above	9.9	675.82	0.090

	Side	Very Low	Above	10.4	856.33	0.159
	Side	Very Low	CG	11.6	782.54	0.124
	Rear	Very Low	CG	10.0	468.36	0.163

Note. BANG = boards angled anvil; BFLAT = boards flat anvil.

4.1.2 M15 MINOR IMPACTS

There was a total of 101 confirmed head impacts in M15 minor: 10 ice, 22 shoulder, 12 elbow, 14 head, 10 boards (3 angled, 7 flat), 7 glass, 7 glove (7 glove to head, 0 punch), 5 puck, and 14 other. The puck and other events were not reconstructed. 3 impact conditions (UCD2-BA-P-CROWN-ABOVE-1MS, UCD2-BA-P-REAR-CG-1MS, and UCD2-BA-P-REAR-BELOW-1MS) did not trigger the headform, as they were below 1g. Consequently, it can reasonably be inferred that the MPS of these impact were below 8% and it can be assigned “very low” magnitude (Chen et al., 2020). 1 impact condition (UCD2-BA-G-CROWN-ABOVE-3MS) could not be reconstructed due to the geometry of the impact. To adjust for this, the condition YO-G-FRONT-ABOVE-3MS was used. Including YO-G-FRONT-ABOVE-3MS, there were a total of 79 impacts simulated using the prescribed conditions. The details of these impacts are outlined in table 4.

Table 4. Characteristics of reconstructed head impact events in M15 Minor.

Event	**Location**	**Velocity**	**Elevation**	**Lin Acc. (g)**	**Rot. Acc. (rad/s^2)**	**MPS**
Ice	Front Boss	Low	CG	33.9	2625.88	0.237
	Rear	Low	CG	66.0	2044.70	0.320
	Rear Boss	Low	CG	43.6	3193.96	0.318
	Front	Low	CG	42.2	3424.38	0.215
	Rear	Very Low	CG	28.7	1158.77	0.163
	Rear Boss	Very Low	CG	16.8	844.37	0.139
	Front Boss	Low	Above	47.0	4287.86	0.354
	Front	Very Low	CG	11.1	619.01	0.092
Shoulder	Rear	Low	CG	10.7	623.49	0.106
	Front	Low	Above	16.0	1194.54	0.125

	Side	Low	Below	16.5	1181.99	0.155
	Rear Boss	Very Low	CG	1.8	172.70	0.024
	Side	Very Low	CG	2.6	140.67	0.034
	Front Boss	Very Low	Above	3.5	199.76	0.043
	Rear Boss	Low	CG	12.6	1003.02	0.132
	Side	Low	CG	17.7	1322.60	0.158
	Front	Low	Below	11.3	948.97	0.103
	Side	Very Low	CG	2.6	140.67	0.034
	Front Boss	Med	CG	16.8	2481.02	0.185
	Front	Very Low	Above	3.3	239.11	0.035
	Front Boss	Very Low	CG	2.5	185.01	0.040
Elbow	Side	Low	Above	12.1	1140.28	0.118
	Rear Boss	Very Low	CG	2.2	160.92	0.025
	Side	Very Low	Below	1.3	191.76	0.019
	Front Boss	Very Low	Above	2.0	189.91	0.024
	Side	Low	CG	11.5	939.01	0.106
	Side	Very Low	CG	2.0	179.99	0.021
	Front	Low	Below	9.6	1076.71	0.077
	Front	Low	CG	13.6	1094.14	0.093
	Side	Very Low	CG	2.0	179.99	0.021
	Side	Very Low	Below	1.3	191.76	0.019
Head	Side	Low	CG	16.3	1118.84	0.134
	Front Boss	Low	Above	21.2	1112.14	0.184
	Front Boss	Very Low	Above	5.2	347.00	0.054
	Rear Boss	Very Low	Above	4.0	400.99	0.043
	Side	Very Low	Above	5.0	391.61	0.041
	Front Boss	Very Low	CG	3.2	341.41	0.028
	Front	Very Low	Above	2.8	334.02	0.027
	Crown	Very Low	Above	5.6	683.28	0.047
	Front	Very Low	CG	3.7	327.17	0.031
BANG	Side	Low	Above	45.9	5636.19	0.316
	Front	Very Low	Above	12.8	313.03	0.088
	Side	Very Low	Above	7.9	1144.06	0.078
BFLAT	Front	Very Low	Above	26.2	431.96	0.137
	Front Boss	Very Low	CG	11.8	1349.36	0.067

	Rear	Very Low	CG	20.7	146.35	0.123
	Crown	Low	Above	80.3	710.20	0.215
	Rear Boss	Low	CG	42.1	1718.64	0.290
	Side	Low	CG	64.7	4103.51	0.374
Glove	Rear[1]	Very Low	CG	NA	NA	0
	Rear[1]	Very Low	Below	NA	NA	0
	Crown[1]	Very Low	Above	NA	NA	0
	Side	Low	Below	3.8	276.24	0.028
	Front Boss	Very Low	Below	4.4	430.04	0.026
	Front	Very Low	Below	1.7	304.55	0.025
	Front Boss	Very Low	Above	1.8	267.82	0.024
Glass	Crown[2]	Low	Above	23.3	1807.49	0.137
	Front	Very Low	Above	4.8	529.45	0.042
	Front Boss	Very Low	CG	3.8	799.18	0.053
	Side	Low	Above	26.2	2073.10	0.174

[1.] Impact did not trigger headform at 1g; [2.] Geometry of impacting equipment made impact impossible (used FB-ABOVE instead of CROWN).

4.2 FREQUENCY OF HEAD IMPACTS

Frequency analyses demonstrated that there were significant differences in the frequencies of head-to-head, and head-to-glass impacts between U15 AAA and M15 Minor hockey divisions. Frequencies shown in figure 4.

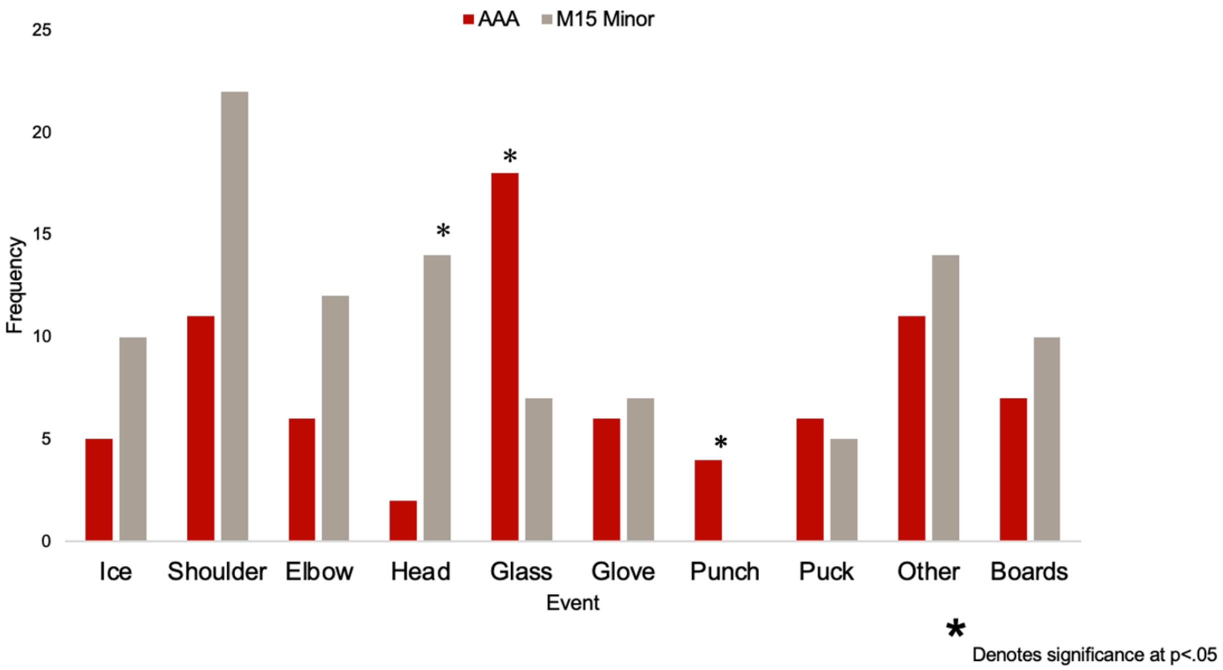


Figure 4. Overall frequency of head impact events.

In addition to the significant differences demonstrated between head (*U*=80.0; p=.017) (M15 minor), punch (*U*=96.0; p=.038), and glass (*U*=72.0; p=.024) events (both AAA), there were notable, but not significant, differences in shoulder events (11 in AAA, 22 in M15 minor) (*U*=80.0; p=.057).

4.3 MAGNITUDES OF HEAD IMPACTS

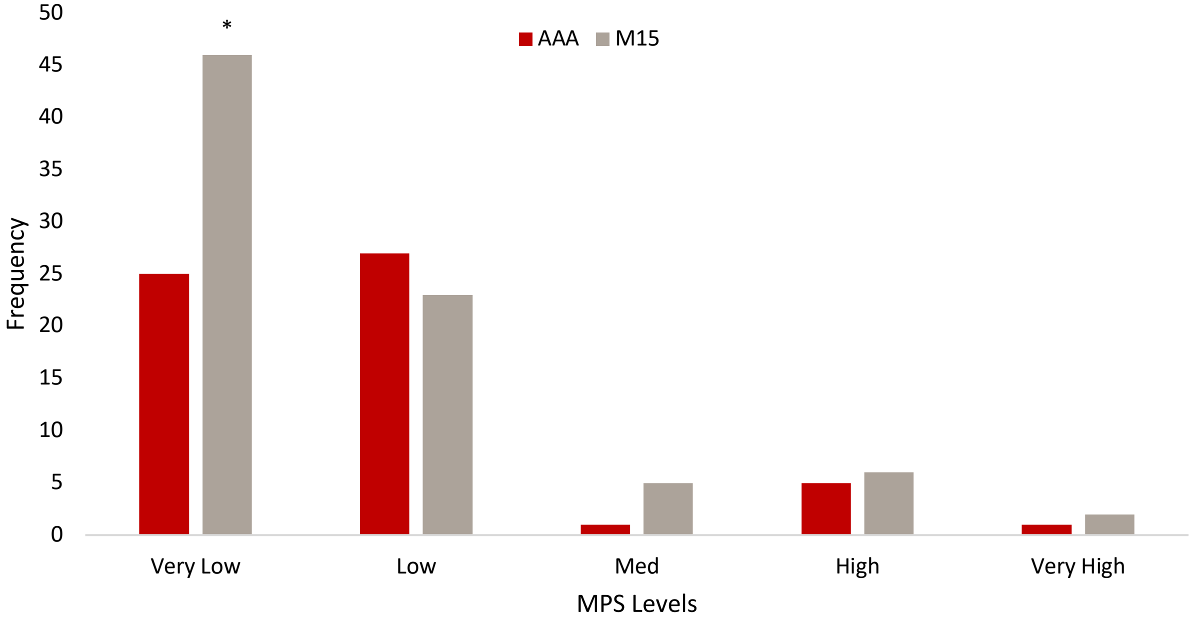


Figure 5. Frequency of MPS magnitudes.

Frequency of overall MPS levels demonstrated that there was a significantly higher frequency of very low MPS impacts in M15 minor compared to AAA (*U*=71.5; p=.030). All other MPS levels had no significant differences.

4.4 FREQUENCY-MAGNITUDE OF HEAD IMPACTS

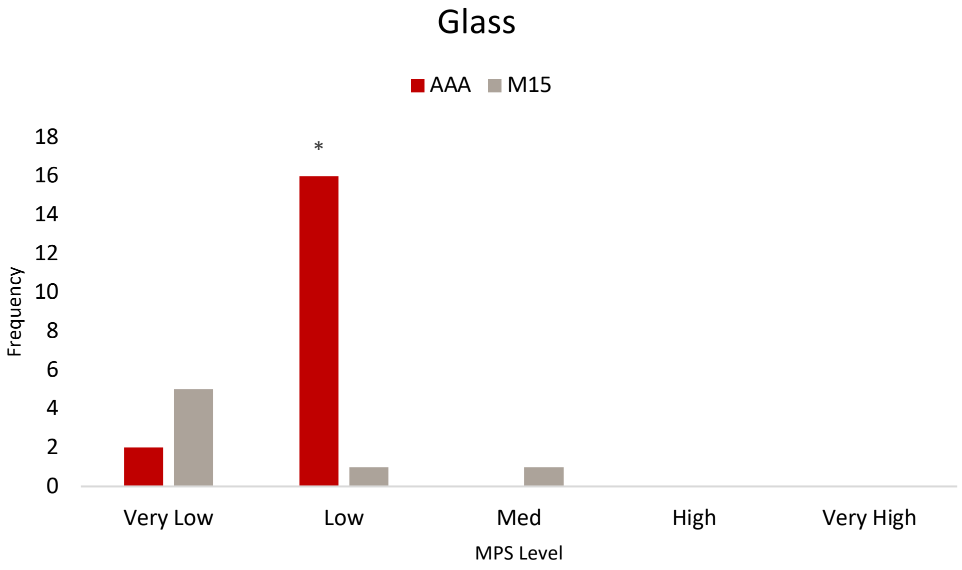


Figure 6. MPS levels of head-to-glass impacts.

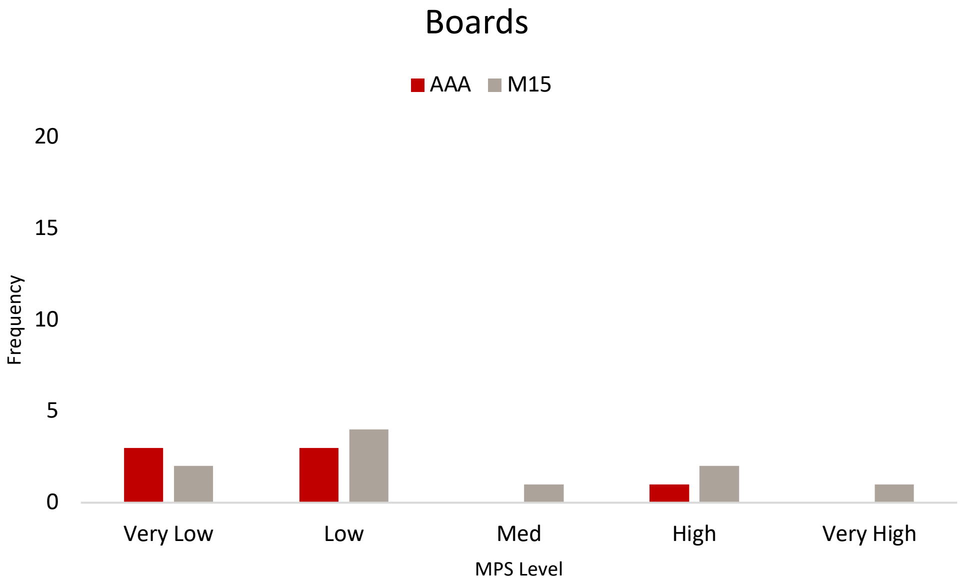


Figure 7. MPS levels of head-to-boards impacts.

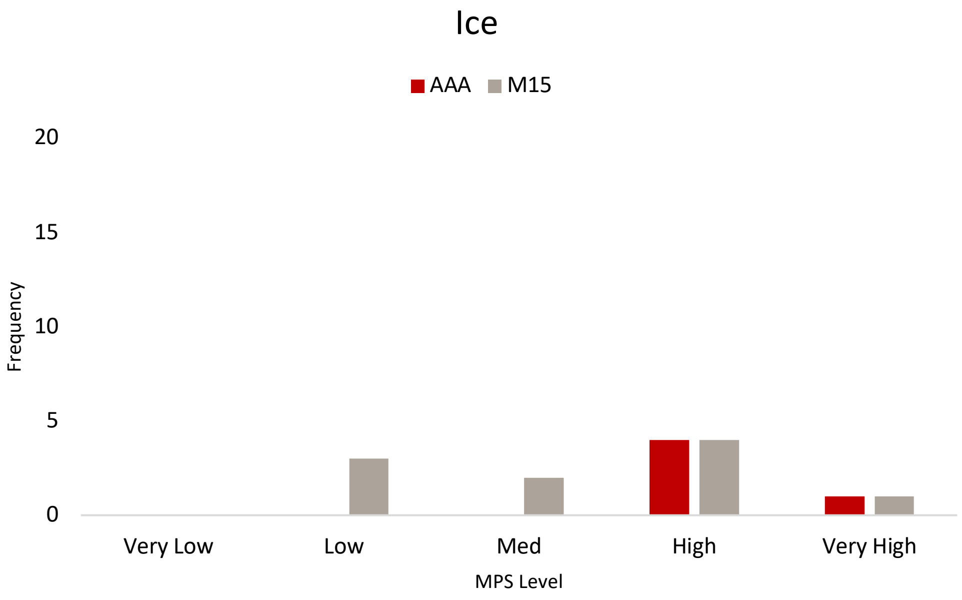


Figure 8. MPS levels of head-to-ice impacts.

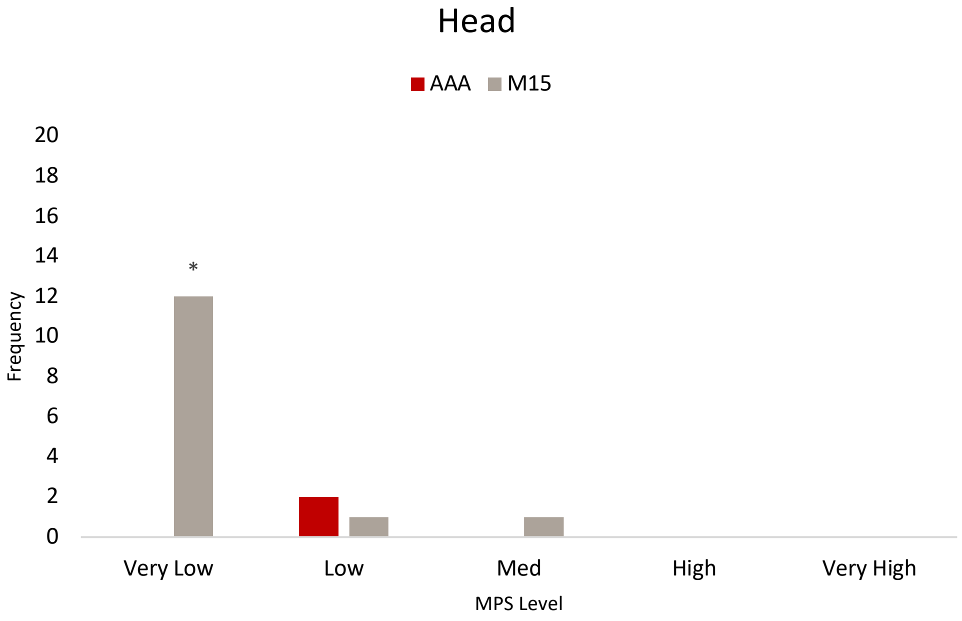


Figure 9. MPS levels of head-to-head impacts.

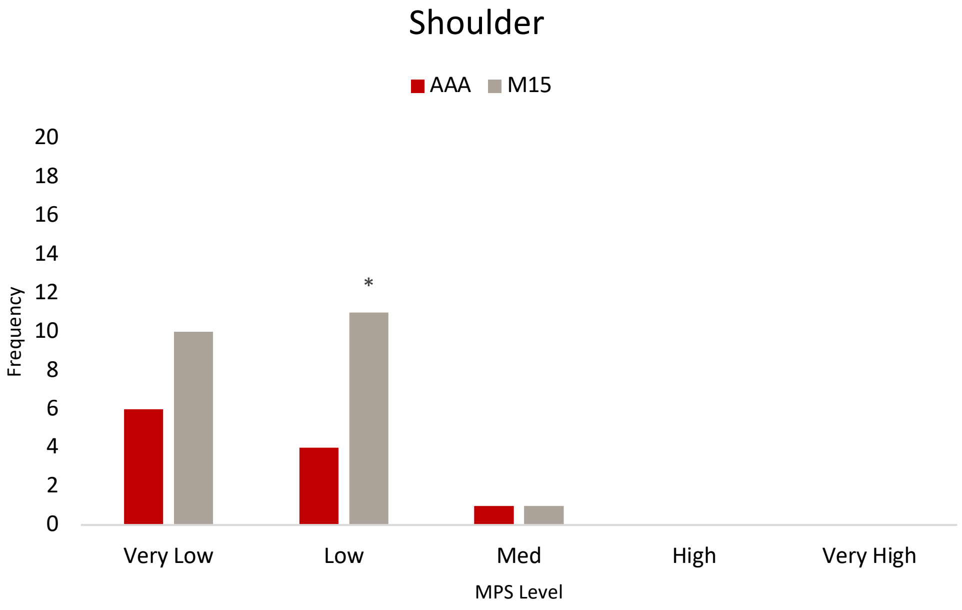


Figure 10. MPS levels of shoulder-to-head impacts.

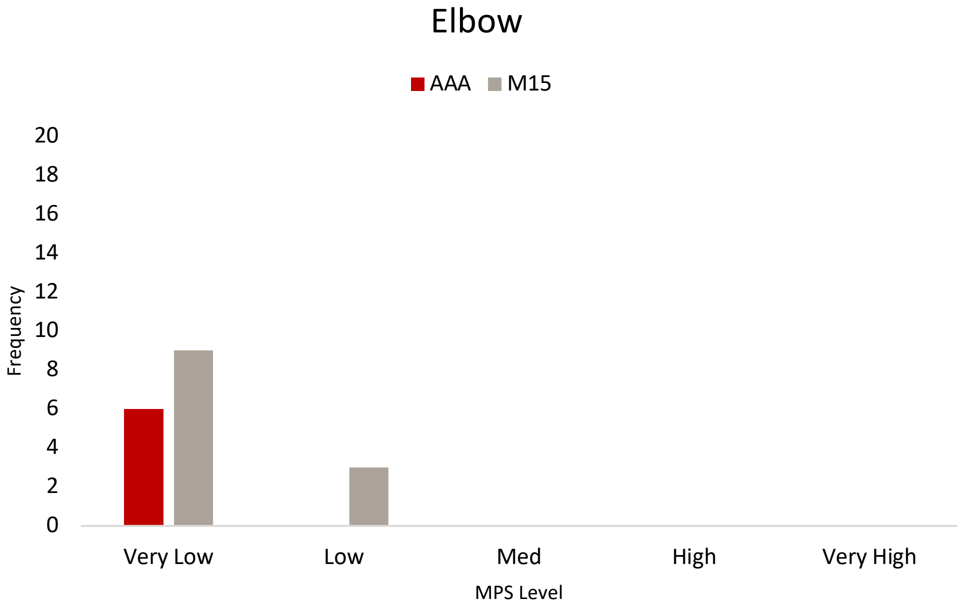


Figure 11. MPS levels of elbow-to-head impacts.

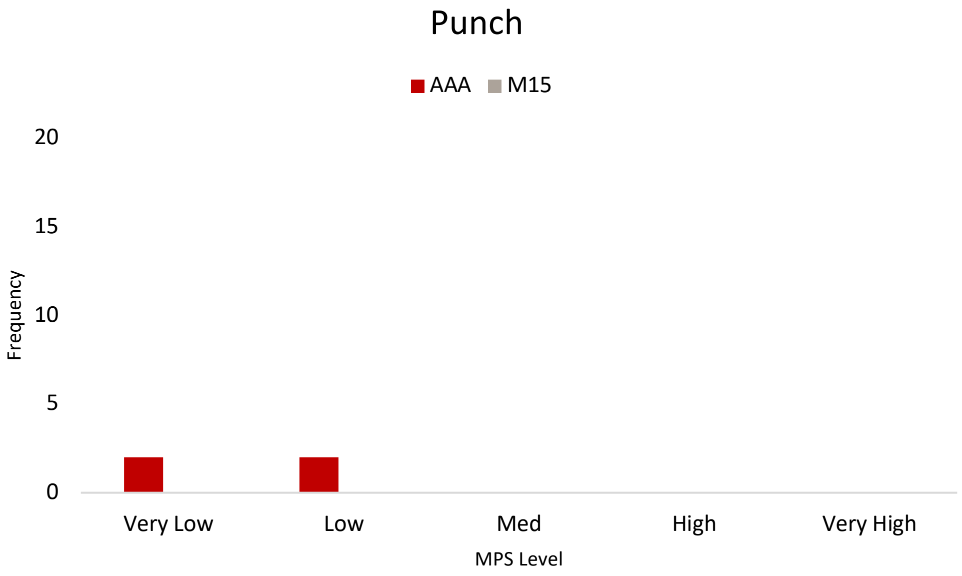


Figure 12. MPS levels of punch-to-head impacts.

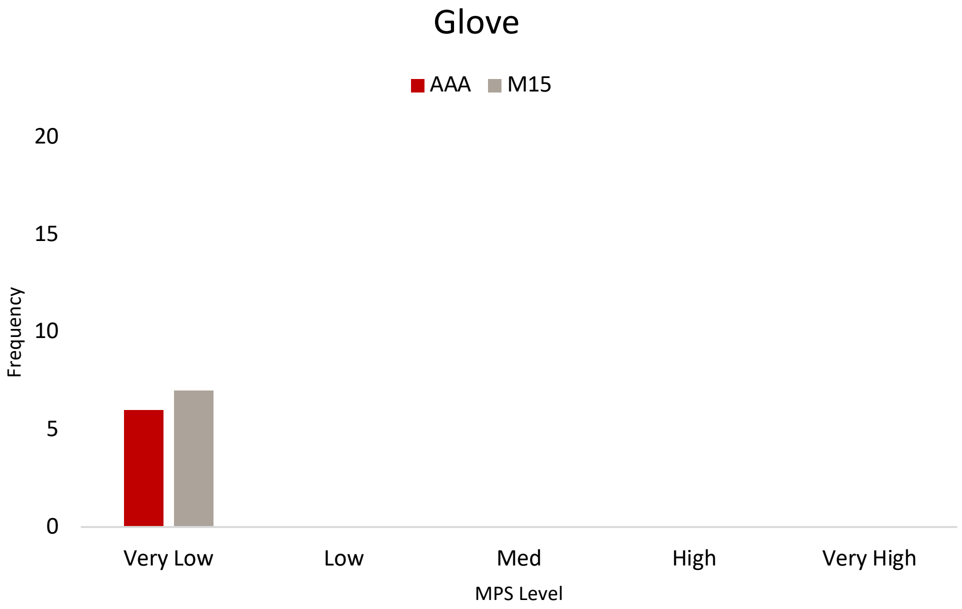


Figure 13. MPS levels of glove-to-head impacts.

Figures 6-13 display the frequency-magnitude levels of each head impact event. Frequency-magnitude of event analyses revealed significant differences in the frequencies between AAA and M15 minor for the following magnitude levels: glass, low magnitude, AAA higher than M15 minor; (*U*=46.0; p<.001) (figure 6), head, very low magnitude M15 significantly higher than AAA (*U*=72.0; p=.004) (figure 9), and for shoulder, low magnitude M15 was significantly higher than AAA (*U*=81.5; p=.043) (figure 10).

CHAPTER 5: DISCUSSION

Quantifying the effectiveness of an alternative approach to body contact, in relation to standard bodychecking was undertaken to help gain an understanding of how well current rules protect players. Bodychecking is primarily a defensive skill in hockey, however it increases the risk of brain trauma, making safer approaches to bodychecking important for protecting young players (Black et al., 2016; Emery et al., 2020; Karton et al., 2021). The purpose of this study was to compare the brain trauma profiles in U15 ice hockey with standard bodychecking rules compared to U15 ice hockey with a modified approach to bodychecking.

5.1 FREQUENCY OF HEAD IMPACTS

5.1.1 TOTAL FREQUENCY OF HEAD IMPACTS

The frequencies of head impacts reported in this study are reflective of the strict inclusion criteria requiring only confirmed head impact events included for analysis. While not statistically significant, M15 minor players experienced more head impacts per game, at 6.31 (±3.44) compared to 4.25 (±3.26) in the AAA division. A further analysis of the video revealed the frequency of head impacts in both divisions to be the result of attempts to initiate contact to separate opponents from the puck. This is consistent with previous studies that report high frequencies of head impacts associated with initiated body contact (Chen et al., 2020; Emery & Meeuwisse, 2006; Karton, 2019; Willer et al., 2005).

5.1.2 FREQUENCY OF HEAD IMPACT EVENTS

There were significantly more head-to-head events in M15 minor, and significantly more head-to-glass and punch events in AAA. The M15 minor contact rules may have contributed to players' heads colliding more frequently, requiring them to be side-by-side and travelling in the same direction to initiate contact. This may have also contributed to the higher, but insignificant, frequency in shoulder-to-head events in M15 minor, as players are only allowed to initiate contact with their shoulder along the boards (*Réglementation spécifique 2020-21*, 2020). Initiating body contact along the boards is the only body contact option in M15 minor (*Rule Book - Hockey Canada 2020-21*, 2020). Despite being legal in all areas of the ice, most bodychecking events resulting in head impacts were observed to take place along the perimeter of the rink (figure 14). The skill difference in the players may have also contributed to the observations, as M15 minor players have a wider range of skill level, and players who are unable to initiate contact may inadvertently contact the head of an opponent.

It is reported in the literature that bodychecking increases the risk of sustaining head impacts due to the head being hit by a body segment (figure 15) (Karton et al., 2021; Robidoux et al., 2020). Most of these events were very low MPS. Less compliant surfaces, head-to-ice and head-to-boards yielded similar frequencies of head impacts. There were significantly more head-to-glass events in AAA. The glass impacts primarily resulted from bodychecks taking place between the faceoff circles at either end of the rink (figure 14).

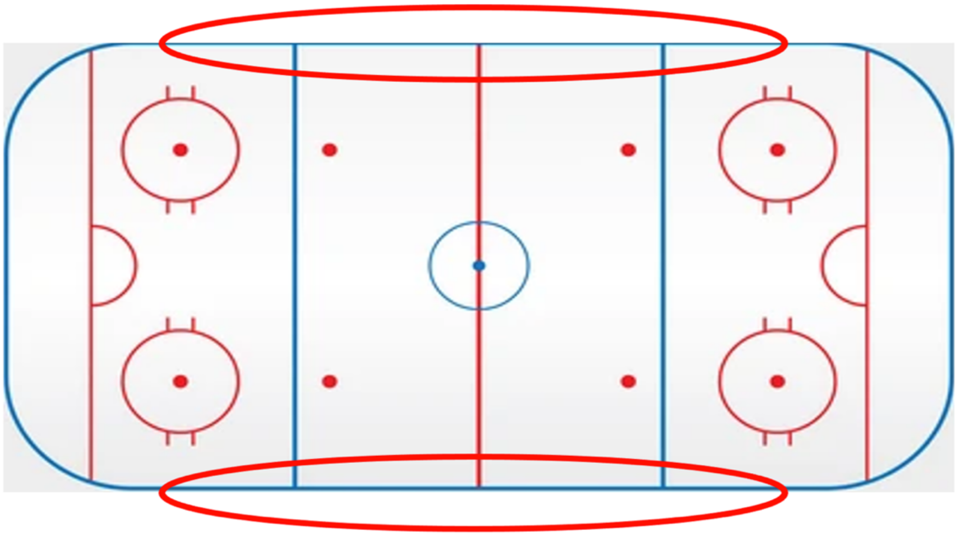


Figure 14. Hockey rink diagram with areas of the ice with most head-to-glass and head-to-shoulder impacts encircled in red.

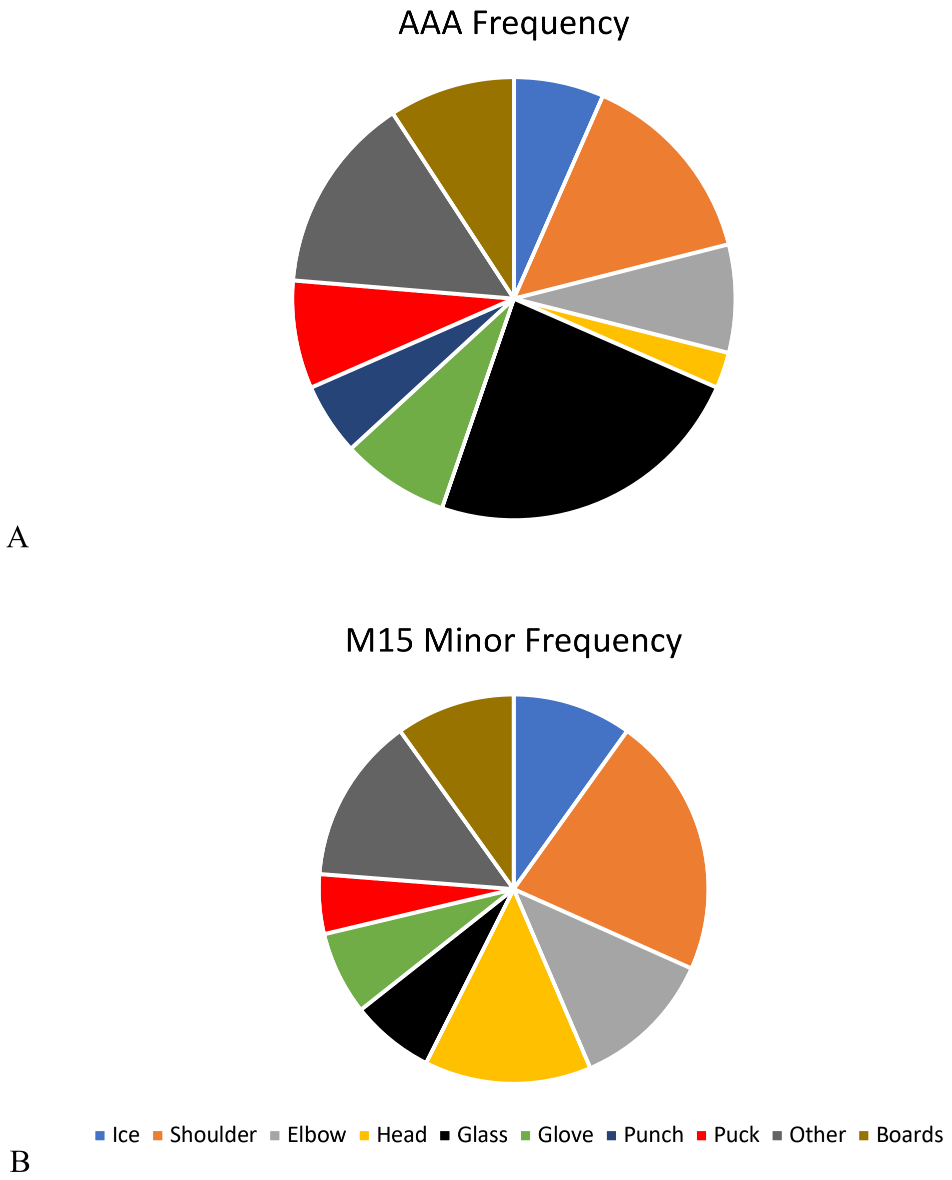


Figure 15. Distribution of head impact events in (A) AAA, and (B) M15 minor.

When compared to Chen and colleagues (2020), the frequency of head-to-glass events in AAA is consistent, as head-to-glass is the most frequent head impact event in U15 bodychecking hockey. While not statistically significant, head-to-shoulder impact events were the most frequent event in M15 minor, which is consistent with the findings of Karton and colleagues (2021). The increase in head-to-head impact events in M15 minor was a finding that has never been ascertained in previous brain trauma profiles for U15 hockey players.

The findings for both divisions are also like those reported by Robidoux and colleagues (2020). Robidoux and colleagues reported that 62% of all impacts in U15 hockey were the result of collisions with body segments. In this study 52% and 68% of head impact events in AAA and M15 minor respectively were the result of collisions with body segments. Robidoux and colleagues reported that 19% of all impacts in U15 hockey were the result of collisions with the boards or glass. In this study 33% and 17% of head impact events in AAA and M15 minor respectively were the result of collisions with the boards or glass.

5.1.3 OTHER EVENTS

There was a total of 10 and 14 head impacts classified as ‘other’ in AAA and M15 minor respectively. Of the 10 impacts in AAA, 4 were back/torso-to-head impacts, 5 were stick-to-head, and 1 was an object on the bench colliding with the head of a player. Of the 14 impacts in M15 minor, 5 were back/torso-to-head impacts, 4 were stick-to-head, 4 were knee-to-head, and 1 forearm-to-head.

5.2.1 FREQUENCY OF MPS MAGNITUDE LEVELS

There were significantly more very low magnitude head impacts in the M15 minor division compared to AAA. No other MPS magnitude levels were significantly different between divisions. Despite having a significantly higher frequency of very low magnitude impacts in M15 minor this level of MPS may not necessarily contribute to a higher level of brain trauma at such low frequencies, but accumulation of these events could result in neurogenerative disease, so the risks should be understood nonetheless (Yuen et al., 2009).

When analyzing frequencies of MPS magnitudes without including very low MPS, there were 34 impacts in AAA and 36 impacts in M15 minor. Comparing individual MPS levels revealed similar frequencies for all MPS magnitudes, with none being significantly different between divisions (figure 16).

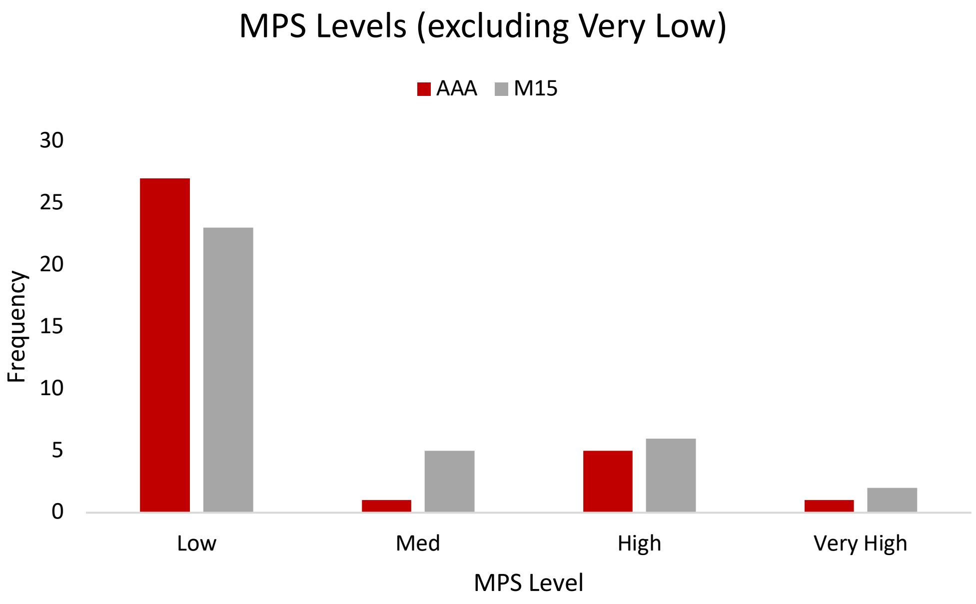


Figure 16. Frequency of MPS magnitudes without including very low level MPS.

There were few head impacts at the high and very high MPS levels, 6 and 8 in AAA and M15 minor respectively, and the plays causing these events were either penalized or unavoidable falls. In such cases, it is important for illegal plays to be penalized to deter players from breaking rules that cause high risk plays in the future (Emery et al., 2020; Krolikowski et al., 2017).

5.2.2 FREQUENCY-MAGNITUDE OF HEAD IMPACT EVENTS

The frequency-magnitude events yielding significantly higher frequencies in M15 minor were very low head-to-head and low shoulder-to-head events; and AAA with a higher frequency of low head-to-glass impacts.

Other than the three significant frequency-magnitudes, all other relationships were found to be not significant. Most head impact events occurred along the sides of the rink, not in open ice, so the frequency of head impacts from body segments were low (Brust, 1992; Emery et al., 2010; Emery & Meeuwisse, 2006; Mölsä et al., 2003; Stuart et al., 1995). This was most evident in elbow impacts where there were only 6 elbow-to-head events in AAA compared to 12 in M15 minor. In AAA, the elbow events only occurred away from the boards, in open ice, and only resulted in very low MPS. In M15 minor, there were 12 elbow-to-head events with 3 above 8% MPS. Boards (1 in AAA, 4 in M15 minor) and ice (5 in AAA, 7 in M15 minor) events were the events that contributed to the medium to very high levels of MPS, with shoulder (1 in each division), head (1 in M15 minor), and glass (1 in M15 minor) contributing to these categories. Every event with MPS levels medium or above was the result of a play observed to have been penalized, or of incidental contact. This would suggest that these were unavoidable events, as they were governed by the rules, or the result of plays that were incidental.

In M15 minor, there was a significantly higher frequency of low magnitude shoulder-to-head impacts. It is worth noting that many of these shoulder impacts occurred as the result of attempts to separate the opponent from the puck, using the modified body contact rules. There were observations of multiple attempts to initiate contact to separate puck carriers from the puck that inadvertently resulted in head impacts. There were fewer of these types of shoulder-to-head impact events observed in the AAA division.

A similar trend was observed when looking at low magnitude head-to-glass events. M15 minor contact rules prohibit completing a bodycheck at all areas of the rink. As depicted in figure 13, most head-to-glass impacts were the result of deliberate bodychecking occurring between the hash marks of the faceoff circles, some were penalized. The low magnitude head impacts in M15 minor primarily involved body contact with the glass, with some events penalized. This may provide policy makers an opportunity to modify the rules of the game to decrease head impact events in this area of the rink.

Very low head-to-head impacts were significantly more common in M15 minor, with 12, compared to 0 in AAA. For shoulder-to-head impacts it was observed that legal attempts to separate opponents from the puck often resulted in head-to-head contact between the puck carrier and the defender. Unlike shoulder-to-head events, these events resulted in very low level MPS, so the risks of sub-concussive brain trauma were less problematic (Karton, 2019; Yuen et al., 2009).

The different body contact rules resulted in a shift in the frequency of head impact events between AAA and M15 minor hockey. The rule changes affected how brain trauma was sustained, however the frequencies of MPS did not significantly change above the very low magnitude. There is opportunity to modify M15 minor, or standard bodychecking rules to reduce brain trauma caused by shoulder-to-head impact events (Black et al., 2016; Emery et al., 2020; Krolikowski et al., 2017). There is also an opportunity to modify standard bodychecking rules to limit head-to-glass impact events. Eliminating bodychecking between the hash marks is one potential example (figure 14).

5.3 IMPLICATIONS

Knowing that the frequency of magnitudes of head impacts did not change beyond the very low magnitude, it is important to examine the differences in the events and examine how brain trauma was sustained between the two divisions. The results of this study provide information to guide future bodychecking rule changes.

The results showed that the significantly higher frequency of low magnitude glass impacts in AAA were replaced by low magnitude shoulder impacts. The rule change may not have been the only factor that led to a change in the frequency of these events, but the analysis of the individual leagues provided insight into where head impacts occurred. The area between the hash marks along the boards was the most frequent location for head impacts (figure 14). Rules targeted at decreasing body contact in this area of the rink could provide an opportunity to reduce brain trauma observed at low levels of MPS caused by glass and shoulder impacts. Through comparison to biomechanical literature, these results suggest that U15 hockey may not pose a large threat to the health of the athletes involved, though it's important to understand the meaning of the frequencies of impact events, and magnitudes of these events. Through understanding the meaning of these events, it can be further understood where areas for improvement lie with respect to brain trauma in U15, and bodychecking hockey. These results also suggest that changing the body contact rules on its own may not be an effective method with respect to reducing brain trauma.

CHAPTER 6: CONCLUSION

The objective of this study was to compare the influence of different body contact rules on brain trauma profiles in youth ice hockey. There were no significant differences in the total frequency of impacts between divisions. There were significantly more head-to-glass and punch events in AAA and more head-to-head events in M15 minor. There were significantly more very low magnitude head impacts in M15 minor; significantly more low magnitude head-to-glass impacts in AAA, and more very low head-to-head and low magnitude shoulder-to-head impacts in M15 minor. This is to suggest that the change from standard bodychecking to the LHPS contact rules resulted in a shift from head-to-glass causing most trauma in AAA, to shoulder-to-head causing the most trauma in M15 minor. These findings suggest that the LHPS contact rules shifted trauma away from head-to-glass events, but consequently resulted in that same level of trauma from shoulder-to-head events. Using rule changes to modify bodychecking resulted in changes in the brain trauma profiles but were not effective in reducing the level of brain trauma. It is important that parents, players, and policy makers understand the importance of limiting frequencies of events that are most common in both levels of U15 hockey, head-to-glass in AAA and shoulder-to-head in M15 minor. It is also important that parents, players, and policy makers understand the importance of reducing the magnitudes of head impacts. In understanding the dangers of playing hockey at these two respective levels from a biomechanical perspective, the rules can be furthered tailored to further protect players involved in U15 hockey.

References

Abbas, K., Shenk, T. E., Poole, V. N., Breedlove, E. L., Leverenz, L. J., Nauman, E. A., Talavage, T. M., & Robinson, M. E. (2015). Alteration of Default Mode Network in High School Football Athletes Due to Repetitive Subconcussive Mild Traumatic Brain Injury: A Resting-State Functional Magnetic Resonance Imaging Study. *Brain Connectivity*, *5*(2), 91–101. https://doi.org/10.1089/brain.2014.0279

Baillargeon, A., Lassonde, M., Leclerc, S., & Ellemberg, D. (2012). Neuropsychological and neurophysiological assessment of sport concussion in children, adolescents and adults. *Brain Injury*, *26*(3), 211–220. https://doi.org/10.3109/02699052.2012.654590

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

Bazarian, J. J., Zhu, T., Blyth, B., Borrino, A., & Zhong, J. (2012). Subject-specific changes in brain white matter on diffusion tensor imaging after sports-related concussion. *Magnetic Resonance Imaging*, *30*(2), 171–180. https://doi.org/10.1016/j.mri.2011.10.001

Black, A. M., Macpherson, A. K., Hagel, B. E., Romiti, M. A., Palacios-Derflingher, L., Kang, J., Meeuwisse, W. H., & Emery, C. A. (2016). Policy change eliminating body checking in non-elite ice hockey leads to a threefold reduction in injury and concussion risk in 11- and 12-year-old players. *British Journal of Sports Medicine*, *50*(1), 55–61. https://doi.org/10.1136/bjsports-2015-095103

Brust, J. D. (1992). Children's Ice Hockey Injuries. *Archives of Pediatrics & Adolescent Medicine*, *146*(6), 741. https://doi.org/10.1001/archpedi.1992.02160180101026

Checking Resource Guide. (n.d.). Hockey Canada.

Chen, W., Post, A., Karton, C., Gilchrist, M. D., Robidoux, M., & Hoshizaki, T. B. (2020). A comparison of frequency and magnitude of head impacts between Pee Wee And Bantam youth ice hockey. *Sports Biomechanics*, 1–24. https://doi.org/10.1080/14763141.2020.1754450

Cournoyer, J., & Hoshizaki, T. B. (2021). Biomechanical comparison of concussions with and without a loss of consciousness in elite American football: Implications for prevention. *Sports Biomechanics*, *20*(6), 751–767. https://doi.org/10.1080/14763141.2019.1600004

Cusimano, M. D., Taback, N. A., McFaull, S. R., Hodgins, R., Bekele, T. M., Elfeki, N., & Canadian Research Team in Traumatic Brain Injury and Violence. (2011). Effect of bodychecking on rate of injuries among minor hockey players. *Open Medicine: A Peer-Reviewed, Independent, Open-Access Journal*, *5*(1), e57-64.

Cusimano, M. D., Topolovec-Vranic, J., Zhang, S., Mullen, S. J., Wong, M., & Ilie, G. (2017). Factors Influencing the Underreporting of Concussion in Sports: A Qualitative Study of Minor Hockey Participants. *Clinical Journal of Sport Medicine*, *27*(4), 375–380. https://doi.org/10.1097/JSM.0000000000000372

Darling, S. R., Schaubel, D. E., Baker, J. G., Leddy, J. J., Bisson, L. J., & Willer, B. (2011). Intentional versus unintentional contact as a mechanism of injury in youth ice hockey. *British Journal of Sports Medicine*, *45*(6), 492–497. https://doi.org/10.1136/bjsm.2009.063693

Davenport, E. M., Whitlow, C. T., Urban, J. E., Espeland, M. A., Jung, Y., Rosenbaum, D. A., Gioia, G. A., Powers, A. K., Stitzel, J. D., & Maldjian, J. A. (2014). Abnormal White Matter Integrity Related to Head Impact Exposure in a Season of High School Varsity

Football. *Journal of Neurotrauma*, *31*(19), 1617–1624. https://doi.org/10.1089/neu.2013.3233

De Beaumont, L., Lassonde, M., Leclerc, S., & Théoret, H. (2007). LONG-TERM AND CUMULATIVE EFFECTS OF SPORTS CONCUSSION ON MOTOR CORTEX INHIBITION. *Neurosurgery*, *61*(2), 329–337. https://doi.org/10.1227/01.NEU.0000280000.03578.B6

De Beaumont, L., Theoret, H., Mongeon, D., Messier, J., Leclerc, S., Tremblay, S., Ellemberg, D., & Lassonde, M. (2009). Brain function decline in healthy retired athletes who sustained their last sports concussion in early adulthood. *Brain*, *132*(3), 695–708. https://doi.org/10.1093/brain/awn347

Doorly, M. C., & Gilchrist, M. D. (2006). The use of accident reconstruction for the analysis of traumatic brain injury due to head impacts arising from falls. *Computer Methods in Biomechanics and Biomedical Engineering*, *9*(6), 371–377. https://doi.org/10.1080/10255840601003551

Elkin, B. S., & Morrison, B. (2007). *Region-Specific Tolerance Criteria for the Living Brain*. 2007-22–0005. https://doi.org/10.4271/2007-22-0005

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, 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, & Meeuwisse, W. H. (2006). Injury Rates, Risk Factors, and Mechanisms of Injury in Minor Hockey. *The American Journal of Sports Medicine*, *34*(12), 1960–1969. https://doi.org/10.1177/0363546506290061

Emery, 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

Fryar, C., Carroll, M., Gu, Q., Afful, J., & Ogden, C. (2021). Anthropometric Reference Data for Children and Adults: United States, 2015–2018. *Vital and Health Statistics. Series 3, Analytical and Epidemiological Studies ; No. 46*.

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

Gavett, B. E., Stern, R. A., & McKee, A. C. (2011). Chronic Traumatic Encephalopathy: A Potential Late Effect of Sport-Related Concussive and Subconcussive Head Trauma. *Clinics in Sports Medicine*, *30*(1), 179–188. https://doi.org/10.1016/j.csm.2010.09.007

Giordano, C., & Kleiven, S. (2016). Development of an unbiased validation protocol to assess the biofidelity of finite element head models used in prediction of traumatic brain injury. *Stapp Car Crash Journal*, *60*, 363–471.

Guerriero, R. M., Proctor, M. R., Mannix, R., & Meehan, W. P. (2012). Epidemiology, trends, assessment and management of sport-related concussion in United States high schools: *Current Opinion in Pediatrics*, *24*(6), 696–701. https://doi.org/10.1097/MOP.0b013e3283595175

Halstead, M. E., McAvoy, K., Devore, C. D., Carl, R., Lee, M., Logan, K., Council on Sports Medicine and Fitness, & Council on School Health. (2013). Returning to Learning Following a Concussion. *Pediatrics*, *132*(5), 948–957. https://doi.org/10.1542/peds.2013-2867

Hardy, W. N., Foster, C. D., Mason, M. J., Yang, K. H., King, A. I., & Tashman, S. (2001). Investigation of Head Injury Mechanisms Using Neutral Density Technology and High-Speed Biplanar X-ray. *Stapp Car Crash Journal*, *45*, 337–368.

Hardy, W. N., Mason, M. J., Foster, C. D., Shah, C. S., Kopacz, J. M., Yang, K. H., King, A. I., Bishop, J., Bey, M., Anderst, W., & Tashman, S. (2007). A study of the response of the human cadaver head to impact. *Stapp Car Crash Journal*, *51*, 17–80.

Horgan, T. J., & Gilchrist, M. D. (2003). The creation of three-dimensional finite element models for simulating head impact biomechanics. *International Journal of Crashworthiness*, *8*(4), 353–366. https://doi.org/10.1533/ijcr.2003.0243

Hoshizaki, B., Post, A., Kendall, M., Karton, C., & Brien, S. E. (2013). The Relationship between Head Impact Characteristics and Brain Trauma. *Journal of Neurology & Neurophysiology*, *05*(01). https://doi.org/10.4172/2155-9562.1000181

Hunter, L. E., Branch, C. A., & Lipton, M. L. (2019). The neurobiological effects of repetitive head impacts in collision sports. *Neurobiology of Disease*, *123*, 122–126. https://doi.org/10.1016/j.nbd.2018.06.016

Hutchison, M. G. (2012). *Concussions in the National Hockey League (NHL): The Video Analysis Project.* Library and Archives Canada = Bibliothèque et Archives Canada.

IIHF. (2020). *Survey of Players*. https://www.iihf.com/en/static/5324/survey-of-players

Ji, S., Zhao, W., Ford, J. C., Beckwith, J. G., Bolander, R. P., Greenwald, R. M., Flashman, L. A., Paulsen, K. D., & McAllister, T. W. (2015). Group-Wise Evaluation and Comparison of White Matter Fiber Strain and Maximum Principal Strain in Sports-Related Concussion. *Journal of Neurotrauma*, *32*(7), 441–454. https://doi.org/10.1089/neu.2013.3268

Karton, C. (2019). *Profiling Brain Trauma in Professional American-style Football and the Implications to Developing Neurological Injury*. https://doi.org/10.20381/RUOR-24220

Karton, C., Hoshizaki, B., & Gilchrist, M. D. (2016). *Frequency, magnitude, and rate of head impacts and risks to neurological disorders in sport.* In Proceedings of the Traumatic Brain Injury: Clinical, Pathological and Translational Mechanisms Conference. Santa Fe NM, USA.

Karton, C., Post, A., Laflamme, Y., Kendall, M., Cournoyer, J., Robidoux, M. A., Gilchrist, M. D., & Hoshizaki, T. B. (2021). Exposure to brain trauma in six age divisions of minor ice hockey. *Journal of Biomechanics*, *116*, 110203. https://doi.org/10.1016/j.jbiomech.2020.110203

Kendall, M. (2016). *Comparison and Characterization of Different Concussive Brain Injury Events*. https://doi.org/10.20381/RUOR-5481

Kendall, M., Post, A., Rousseau, P., Oeur, A., Gilchrist, M. D., & Hoshizaki, B. (2012). A comparison of dynamic impact response and brain deformation metrics within the cerebrum of head impact reconstructions represnting three mechanisms of head injury in ice hockey. *Int. Res. Counc. Biomech*, Impact 430-440.

Kimpara, H., & Iwamoto, M. (2012). Mild Traumatic Brain Injury Predictors Based on Angular Accelerations During Impacts. *Annals of Biomedical Engineering*, *40*(1), 114–126. https://doi.org/10.1007/s10439-011-0414-2

Kleiven, S. (2006). Evaluation of head injury criteria using a finite element model validated against experiments on localized brain motion, intracerebral acceleration, and intracranial pressure. *International Journal of Crashworthiness*, *11*(1), 65–79. https://doi.org/10.1533/ijcr.2005.0384

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

Loyd, A. M., Nightingale, R. W., Song, Y., Luck, J. F., Cutcliffe, H., Myers, B. S., & Bass, C. ‘Dale.’ (2014). The response of the adult and ATD heads to impacts onto a rigid surface. *Accident Analysis & Prevention*, *72*, 219–229. https://doi.org/10.1016/j.aap.2014.06.022

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

Marar, M., McIlvain, N. M., Fields, S. K., & Comstock, R. D. (2012). Epidemiology of Concussions Among United States High School Athletes in 20 Sports: *The American Journal of Sports Medicine*. https://doi.org/10.1177/0363546511435626

Margulies, S. S., & Thibault, L. E. (1992). A proposed tolerance criterion for diffuse axonal injury in man. *Journal of Biomechanics*, *25*(8), 917–923. https://doi.org/10.1016/0021-9290(92)90231-O

Martini, D. N., & Broglio, S. P. (2018). Long-term effects of sport concussion on cognitive and motor performance: A review. *International Journal of Psychophysiology*, *132*, 25–30. https://doi.org/10.1016/j.ijpsycho.2017.09.019

McAllister, T. W., Ford, J. C., Flashman, L. A., Maerlender, A., Greenwald, R. M., Beckwith, J. G., Bolander, R. P., Tosteson, T. D., Turco, J. H., Raman, R., & Jain, S. (2014). Effect of head impacts on diffusivity measures in a cohort of collegiate contact sport athletes. *Neurology*, *82*(1), 63–69. https://doi.org/10.1212/01.wnl.0000438220.16190.42

McAllister, T. W., Ford, J. C., Ji, S., Beckwith, J. G., Flashman, L. A., Paulsen, K., & Greenwald, R. M. (2012). Maximum Principal Strain and Strain Rate Associated with Concussion Diagnosis Correlates with Changes in Corpus Callosum White Matter Indices. *Annals of Biomedical Engineering*, *40*(1), 127–140. https://doi.org/10.1007/s10439-011-0402-6

McCrory, P. (2011). Sports Concussion and the Risk of Chronic Neurological Impairment: *Clinical Journal of Sport Medicine*, *21*(1), 6–12. https://doi.org/10.1097/JSM.0b013e318204db50

McKee, A. C., Stein, T. D., Nowinski, C. J., Stern, R. A., Daneshvar, D. H., Alvarez, V. E., Lee, H.-S., Hall, G., Wojtowicz, S. M., Baugh, C. M., Riley, D. O., Kubilus, C. A., Cormier,

K. A., Jacobs, M. A., Martin, B. R., Abraham, C. R., Ikezu, T., Reichard, R. R., Wolozin, B. L., … Cantu, R. C. (2013). The spectrum of disease in chronic traumatic encephalopathy. *Brain*, *136*(1), 43–64. https://doi.org/10.1093/brain/aws307

Meehan, I. I. I., d'Hemecourt, P., Collins, C. L., & Comstock, R. D. (2011). Assessment and Management of Sport-Related Concussions in United States High Schools: *The American Journal of Sports Medicine*. https://doi.org/10.1177/0363546511423503

Mölsä, J., Kujala, U., Myllynen, P., Torstila, I., & Airaksinen, O. (2003). Injuries to the Upper Extremity in Ice Hockey: Analysis of a Series of 760 Injuries. *The American Journal of Sports Medicine*, *31*(5), 751–757. https://doi.org/10.1177/03635465030310051901

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

Nellhaus, G. (1968). Head circumference from birth to eighteen years: Practical composite and interracial graphs. *Pediatrics*, *41*, 106–114.

Omalu, B. I., DeKosky, S. T., Hamilton, R. L., Minster, R. L., Kamboh, M. I., Shakir, A. M., & Wecht, C. H. (2006). CHRONIC TRAUMATIC ENCEPHALOPATHY IN A NATIONAL FOOTBALL LEAGUE PLAYERPART II. *Neurosurgery*, *59*(5), 1086–1093. https://doi.org/10.1227/01.NEU.0000245601.69451.27

Omalu, B. I., DeKosky, S. T., Minster, R. L., Kamboh, M. I., Hamilton, R. L., & Wecht, C. H. (2005). Chronic Traumatic Encephalopathy in a National Football League Player. *Neurosurgery*, *57*(1), 128–134. https://doi.org/10.1227/01.NEU.0000163407.92769.ED

Patton, D. A., McIntosh, A. S., & Kleiven, S. (2013). The Biomechanical Determinants of Concussion: Finite Element Simulations to Investigate Brain Tissue Deformations During

Sporting Impacts to the Unprotected Head. *Journal of Applied Biomechanics*, *29*(6), 721–730. https://doi.org/10.1123/jab.29.6.721

Post, A., Hoshizaki, B., & Gilchrist, M. D. (2012). Finite element analysis of the effect of loading curve shape on brain injury predictors. *Journal of Biomechanics*, *45*(4), 679–683. https://doi.org/10.1016/j.jbiomech.2011.12.005

Post, A., & Hoshizaki, T. B. (2015). Rotational Acceleration, Brain Tissue Strain, and the Relationship to Concussion. *Journal of Biomechanical Engineering*, *137*(3), 030801. https://doi.org/10.1115/1.4028983

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., 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., Hoshizaki, B., & Gilchrist, M. D. (2013). Examination of the relationship between peak linear and angular accelerations to brain deformation metrics in hockey helmet impacts. *Computer Methods in Biomechanics and Biomedical Engineering*, *16*(5), 511–519. https://doi.org/10.1080/10255842.2011.627559

Putukian, M. (2011). The Acute Symptoms of Sport-Related Concussion: Diagnosis and On-field Management. *Clinics in Sports Medicine*, *30*(1), 49–61. https://doi.org/10.1016/j.csm.2010.09.005

Rahnama, N. (2002). Injury risk associated with playing actions during competitive soccer. *British Journal of Sports Medicine*, *36*(5), 354–359. https://doi.org/10.1136/bjsm.36.5.354

Ransom, D. M., Vaughan, C. G., Pratson, L., Sady, M. D., McGill, C. A., & Gioia, G. A. (2015). Academic Effects of Concussion in Children and Adolescents. *PEDIATRICS*, *135*(6), 1043–1050. https://doi.org/10.1542/peds.2014-3434

Réglementation spécifique 2020-21. (2020). Ligue de Hockey Préparatoire Scolaire. https://www.kreezee.com/files/handler/8337

Robidoux, M. A., Kendall, M., Laflamme, Y., Post, A., Karton, C., & Hoshizaki, T. B. (2020). Comparing concussion rates as reported by hockey Canada with head contact events as observed across minor ice-hockey age categories. *Journal of Concussion*, *4*, 205970022091128. https://doi.org/10.1177/2059700220911285

Rousseau, P. (2014). Analysis of Concussion Metrics of Real-World Concussive and Non-Injurious Elbow and Shoulder to Head Collisions in Ice Hockey. *University of Ottawa*.

Rule Book—Hockey Canada 2020-21. (2020). Hockey Canada.

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

Sim, A., Terryberry-Spohr, L., & Wilson, K. R. (2008). Prolonged recovery of memory functioning after mild traumatic brain injury in adolescent athletes. *Journal of Neurosurgery*, *108*(3), 511–516. https://doi.org/10.3171/JNS/2008/108/3/0511

Singh, I. N., Sullivan, P. G., Deng, Y., Mbye, L. H., & Hall, E. D. (2006). Time Course of Post-Traumatic Mitochondrial Oxidative Damage and Dysfunction in a Mouse Model of Focal Traumatic Brain Injury: Implications for Neuroprotective Therapy. *Journal of Cerebral Blood Flow & Metabolism*, *26*(11), 1407–1418. https://doi.org/10.1038/sj.jcbfm.9600297

Sollmann, N., Echlin, P. S., Schultz, V., Viher, P. V., Lyall, A. E., Tripodis, Y., Kaufmann, D., Hartl, E., Kinzel, P., Forwell, L. A., Johnson, A. M., Skopelja, E. N., Lepage, C., Bouix, S., Pasternak, O., Lin, A. P., Shenton, M. E., & Koerte, I. K. (2018). Sex differences in white matter alterations following repetitive subconcussive head impacts in collegiate ice hockey players. *NeuroImage: Clinical*, *17*, 642–649. https://doi.org/10.1016/j.nicl.2017.11.020

Stuart, M. J., Smith, A. M., Nieva, J. J., & Rock, M. G. (1995). Injuries in Youth Ice Hockey: A Pilot Surveillance Strategy. *Mayo Clinic Proceedings*, *70*(4), 350–356. https://doi.org/10.4065/70.4.350

Trotta, A., Clark, J. M., McGoldrick, A., Gilchrist, M. D., & Annaidh, A. N. (2020). Biofidelic finite element modelling of brain trauma: Importance of the scalp in simulating head impact. *International Journal of Mechanical Sciences*, *173*, 105448. https://doi.org/10.1016/j.ijmecsci.2020.105448

Walsh, E. S., Kendall, M., Post, A., Meehan, A., & Hoshizaki, T. B. (2018). Comparative analysis of Hybrid III neckform and an unbiased neckform. *Sports Engineering*, *21*(4), 479–485. https://doi.org/10.1007/s12283-018-0286-x

Wasserman, E. B., Bazarian, J. J., Mapstone, M., Block, R., & van Wijngaarden, E. (2016). Academic Dysfunction After a Concussion Among US High School and College

Students. *American Journal of Public Health*, *106*(7), 1247–1253. https://doi.org/10.2105/AJPH.2016.303154

West, T. A., & Marion, D. W. (2014). Current Recommendations for the Diagnosis and Treatment of Concussion in Sport: A Comparison of Three New Guidelines. *Journal of Neurotrauma*, *31*(2), 159–168. https://doi.org/10.1089/neu.2013.3031

Wiebe, D. J., D'Alonzo, B. A., Harris, R., Putukian, M., & Campbell-McGovern, C. (2018). Association Between the Experimental Kickoff Rule and Concussion Rates in Ivy League Football. *JAMA*, *320*(19), 2035. https://doi.org/10.1001/jama.2018.14165

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

Willer, B., Kroetsch, B., Darling, S., Hutson, A., & Leddy, J. (2005). Injury Rates in House League, Select, and Representative Youth Ice Hockey: *Medicine & Science in Sports & Exercise*, *37*(10), 1658–1663. https://doi.org/10.1249/01.mss.0000181839.86170.06

Yuen, T. J., Browne, K. D., Iwata, A., & Smith, D. H. (2009). Sodium channelopathy induced by mild axonal trauma worsens outcome after a repeat injury. *Journal of Neuroscience Research*, *87*(16), 3620–3625. https://doi.org/10.1002/jnr.22161

Zanetti, K., Post, A., Karton, C., Hoshizaki, B., & Gilchrist, M. D. (2013). *Identifying risk profiles for three player positions in American football using physical and finite element modeling reconstructions.* In Proceedings of the International Research Council of Biomechanics of Injury Conference, Gothenburg, Sweden.

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

Appendix

Table 5. MPS Magnitude Levels.

Very Low	**<8%**
Low	**8-16.9%**
Medium	**17-25.9%**
High	**26-34.9%**
Very High	**35+%**

Table 6. Inbound Velocity Levels.

Velocity Level	Very Low	Low	Medium	High	Very High
Inbound Velocity (m/s)	<2	2-3.99	4-5.99	6-7.99	>8

Table 7. Impact Mass for Body Collisions.

Collision	Shoulder	Elbow	Head	Glove	Punch
Impact Mass (kg)	8.76	3.29	4.12	0.45	3.09

Figure 17(A) Head Impact Locations; (B) Head Impact Placements.


A.
B.

FULL EXPERIMENTAL HYPOTHESES

i. There will be a significant different frequencies of total head impacts in AAA U15 hockey than M15 minor hockey.

ii. There will be significant differences in the frequency of shoulder-to-head events between M15 minor hockey and AAA U15 hockey.

iii. There will be significant differences in the frequency of elbow-to-head events between M15 minor hockey and AAA U15 hockey.

iv. There will be significant differences in the frequency of head-to-head events between M15 minor hockey and AAA U15 hockey.

v. There will be significant differences in the frequency of head-to-boards events between M15 minor hockey and AAA U15 hockey.

vi. There will be significant differences in the frequency of head-to-glass events between M15 minor hockey and AAA U15 hockey.

vii. There will be significant differences in the frequency of head-to-ice events between M15 minor hockey and AAA U15 hockey.

viii. There will be significant differences in the frequency of glove-to-head events between M15 minor hockey and AAA U15 hockey.

ix. There will be significant differences in the frequency of shoulder-to-head events between M15 minor hockey and AAA U15 hockey.

x. There will be significant differences in the frequency of punch events between M15 minor hockey and AAA U15 hockey.

xi. There will be significant differences in the frequency of puck events between M15 minor hockey and AAA U15 hockey.

xii. There will be significant differences in the frequency of other events between M15 minor hockey and AAA U15 hockey.

xiii. There will be significant differences in frequency of very low level MPS head impacts between M15 minor hockey and AAA U15 hockey.

xiv. There will be significant differences in frequency of low level MPS head impacts between M15 minor hockey and AAA U15 hockey.

xv. There will be significant differences in frequency of medium level MPS head impacts between M15 minor hockey and AAA U15 hockey.

xvi. There will be significant differences in frequency of high level MPS head impacts between M15 minor hockey and AAA U15 hockey.

xvii. There will be significant differences in frequency of very high level MPS head impacts between M15 minor hockey and AAA U15 hockey.

xviii. There will be significant differences in frequency of very low level MPS shoulder-to-head impacts between M15 minor hockey and AAA U15 hockey.

xix. There will be significant differences in frequency of low level MPS shoulder-to-head impacts between M15 minor hockey and AAA U15 hockey.

xx. There will be significant differences in frequency of medium level MPS shoulder-to-head impacts between M15 minor hockey and AAA U15 hockey.

xxi. There will be significant differences in frequency of high level MPS shoulder-to-head impacts between M15 minor hockey and AAA U15 hockey.

xxii. There will be significant differences in frequency of very high level MPS shoulder-to-head impacts between M15 minor hockey and AAA U15 hockey.

xxiii. There will be significant differences in frequency of very low level MPS elbow-to-head impacts between M15 minor hockey and AAA U15 hockey.

xxiv. There will be significant differences in frequency of low level MPS elbow-to-head impacts between M15 minor hockey and AAA U15 hockey.

xxv. There will be significant differences in frequency of medium level MPS elbow-to-head impacts between M15 minor hockey and AAA U15 hockey.

xxvi. There will be significant differences in frequency of high level MPS elbow-to-head impacts between M15 minor hockey and AAA U15 hockey.

xxvii. There will be significant differences in frequency of very high level MPS elbow-to-head impacts between M15 minor hockey and AAA U15 hockey.

xxviii. There will be significant differences in frequency of very low level MPS head-to-head impacts between M15 minor hockey and AAA U15 hockey.

xxix. There will be significant differences in frequency of low level MPS head-to-head impacts between M15 minor hockey and AAA U15 hockey.

xxx. There will be significant differences in frequency of medium level MPS head-to-head impacts between M15 minor hockey and AAA U15 hockey.

xxxi. There will be significant differences in frequency of high level MPS head-to-head impacts between M15 minor hockey and AAA U15 hockey.

xxxii. There will be significant differences in frequency of very high level MPS head-to-head impacts between M15 minor hockey and AAA U15 hockey.

xxxiii. There will be significant differences in frequency of very low level MPS head-to-boards impacts between M15 minor hockey and AAA U15 hockey.

xxxiv. There will be significant differences in frequency of low level MPS head-to-boards impacts between M15 minor hockey and AAA U15 hockey.

xxxv. There will be significant differences in frequency of medium level MPS head-to-boards impacts between M15 minor hockey and AAA U15 hockey.

xxxvi. There will be significant differences in frequency of high level MPS head-to-boards impacts between M15 minor hockey and AAA U15 hockey.

xxxvii. There will be significant differences in frequency of very high level MPS head-to-boards impacts between M15 minor hockey and AAA U15 hockey.

xxxviii. There will be significant differences in frequency of very low level MPS head-to-glass impacts between M15 minor hockey and AAA U15 hockey.

xxxix. There will be significant differences in frequency of low level MPS head-to-glass impacts between M15 minor hockey and AAA U15 hockey.

xl. There will be significant differences in frequency of medium level MPS head-to-glass impacts between M15 minor hockey and AAA U15 hockey.

xli. There will be significant differences in frequency of high level MPS head-to-glass impacts between M15 minor hockey and AAA U15 hockey.

xlii. There will be significant differences in frequency of very high level MPS head-to-glass impacts between M15 minor hockey and AAA U15 hockey.

xliii. There will be significant differences in frequency of very low level MPS head-to-ice impacts between M15 minor hockey and AAA U15 hockey.

xliv. There will be significant differences in frequency of low level MPS head-to-ice impacts between M15 minor hockey and AAA U15 hockey.

xlv. There will be significant differences in frequency of medium level MPS head-to-ice impacts between M15 minor hockey and AAA U15 hockey.

xlvi. There will be significant differences in frequency of high level MPS head-to-ice impacts between M15 minor hockey and AAA U15 hockey.

xlvii. There will be significant differences in frequency of very high level MPS head-to-ice impacts between M15 minor hockey and AAA U15 hockey.

xlviii. There will be significant differences in frequency of very low level MPS glove-to-head impacts between M15 minor hockey and AAA U15 hockey.

xlix. There will be significant differences in frequency of low level MPS glove-to-head impacts between M15 minor hockey and AAA U15 hockey.

l. There will be significant differences in frequency of medium level MPS glove-to-head impacts between M15 minor hockey and AAA U15 hockey.

li. There will be significant differences in frequency of high level MPS glove-to-head impacts between M15 minor hockey and AAA U15 hockey.

lii. There will be significant differences in frequency of very high level MPS glove-to-head impacts between M15 minor hockey and AAA U15 hockey.

liii. There will be significant differences in frequency of very low level MPS punch impacts between M15 minor hockey and AAA U15 hockey.

liv. There will be significant differences in frequency of low level MPS punch impacts between M15 minor hockey and AAA U15 hockey.

lv. There will be significant differences in frequency of medium level MPS punch impacts between M15 minor hockey and AAA U15 hockey.

lvi. There will be significant differences in frequency of high level MPS punch impacts between M15 minor hockey and AAA U15 hockey.

lvii. There will be significant differences in frequency of very high level MPS punch impacts between M15 minor hockey and AAA U15 hockey.

FULL NULL HYPOTHESES

i. There will be no differences in frequency of total head impacts between M15 minor hockey and AAA U15 hockey.

ii. There will be no differences in the frequency of shoulder-to-head events between M15 minor hockey and AAA U15 hockey.

iii. There will be no differences in the frequency of elbow-to-head events between M15 minor hockey and AAA U15 hockey.

iv. There will be no differences in the frequency of head-to-head events between M15 minor hockey and AAA U15 hockey.

v. There will be no differences in the frequency of head-to-boards events between M15 minor hockey and AAA U15 hockey.

vi. There will be no differences in the frequency of head-to-glass events between M15 minor hockey and AAA U15 hockey.

vii. There will be no differences in the frequency of head-to-ice events between M15 minor hockey and AAA U15 hockey.

viii. There will be no differences in the frequency of glove-to-head events between M15 minor hockey and AAA U15 hockey.

ix. There will be no differences in the frequency of shoulder-to-head events between M15 minor hockey and AAA U15 hockey.

x. There will be no differences in the frequency of punch events between M15 minor hockey and AAA U15 hockey.

xi. There will be no differences in the frequency of puck events between M15 minor hockey and AAA U15 hockey.

xii. There will be no differences in the frequency of other events between M15 minor hockey and AAA U15 hockey.

xiii. There will be no differences in frequency of very low level MPS head impacts between M15 minor hockey and AAA U15 hockey.

xiv. There will be no differences in frequency of low level MPS head impacts between M15 minor hockey and AAA U15 hockey.

xv. There will be no differences in frequency of medium level MPS head impacts between M15 minor hockey and AAA U15 hockey.

xvi. There will be no differences in frequency of high level MPS head impacts between M15 minor hockey and AAA U15 hockey.

xvii. There will be no differences in frequency of very high level MPS head impacts between M15 minor hockey and AAA U15 hockey.

xviii. There will be no differences in frequency of very low level MPS shoulder-to-head impacts between M15 minor hockey and AAA U15 hockey.

xix. There will be no differences in frequency of low level MPS shoulder-to-head impacts between M15 minor hockey and AAA U15 hockey.

xx. There will be no differences in frequency of medium level MPS shoulder-to-head impacts between M15 minor hockey and AAA U15 hockey.

xxi. There will be no differences in frequency of high level MPS shoulder-to-head impacts between M15 minor hockey and AAA U15 hockey.

xxii. There will be no differences in frequency of very high level MPS shoulder-to-head impacts between M15 minor hockey and AAA U15 hockey.

xxiii. There will be no differences in frequency of very low level MPS elbow-to-head impacts between M15 minor hockey and AAA U15 hockey.

xxiv. There will be no differences in frequency of low level MPS elbow-to-head impacts between M15 minor hockey and AAA U15 hockey.

xxv. There will be no differences in frequency of medium level MPS elbow-to-head impacts between M15 minor hockey and AAA U15 hockey.

xxvi. There will be no differences in frequency of high level MPS elbow-to-head impacts between M15 minor hockey and AAA U15 hockey.

xxvii. There will be no differences in frequency of very high level MPS elbow-to-head impacts between M15 minor hockey and AAA U15 hockey.

xxviii. There will be no differences in frequency of very low level MPS head-to-head impacts between M15 minor hockey and AAA U15 hockey.

xxix. There will be no differences in frequency of low level MPS head-to-head impacts between M15 minor hockey and AAA U15 hockey.

xxx. There will be no differences in frequency of medium level MPS head-to-head impacts between M15 minor hockey and AAA U15 hockey.

xxxi. There will be no differences in frequency of high level MPS head-to-head impacts between M15 minor hockey and AAA U15 hockey.

xxxii. There will be no differences in frequency of very high level MPS head-to-head impacts between M15 minor hockey and AAA U15 hockey.

xxxiii. There will be no differences in frequency of very low level MPS head-to-boards impacts between M15 minor hockey and AAA U15 hockey.

xxxiv. There will be no differences in frequency of low level MPS head-to-boards impacts between M15 minor hockey and AAA U15 hockey.

xxxv. There will be no differences in frequency of medium level MPS head-to-boards impacts between M15 minor hockey and AAA U15 hockey.

xxxvi. There will be no differences in frequency of high level MPS head-to-boards impacts between M15 minor hockey and AAA U15 hockey.

xxxvii. There will be no differences in frequency of very high level MPS head-to-boards impacts between M15 minor hockey and AAA U15 hockey.

xxxviii. There will be no differences in frequency of very low level MPS head-to-glass impacts between M15 minor hockey and AAA U15 hockey.

xxxix. There will be no differences in frequency of low level MPS head-to-glass impacts between M15 minor hockey and AAA U15 hockey.

xl. There will be no differences in frequency of medium level MPS head-to-glass impacts between M15 minor hockey and AAA U15 hockey.

xli. There will be no differences in frequency of high level MPS head-to-glass impacts between M15 minor hockey and AAA U15 hockey.

xlii. There will be no differences in frequency of very high level MPS head-to-glass impacts between M15 minor hockey and AAA U15 hockey.

xliii. There will be no differences in frequency of very low level MPS head-to-ice impacts between M15 minor hockey and AAA U15 hockey.

xliv. There will be no differences in frequency of low level MPS head-to-ice impacts between M15 minor hockey and AAA U15 hockey.

xlv. There will be no differences in frequency of medium level MPS head-to-ice impacts between M15 minor hockey and AAA U15 hockey.

xlvi. There will be no differences in frequency of high level MPS head-to-ice impacts between M15 minor hockey and AAA U15 hockey.

xlvii. There will be no differences in frequency of very high level MPS head-to-ice impacts between M15 minor hockey and AAA U15 hockey.

xlviii. There will be no differences in frequency of very low level MPS glove-to-head impacts between M15 minor hockey and AAA U15 hockey.

xlix. There will be no differences in frequency of low level MPS glove-to-head impacts between M15 minor hockey and AAA U15 hockey.

l. There will be no differences in frequency of medium level MPS glove-to-head impacts between M15 minor hockey and AAA U15 hockey.

li. There will be no differences in frequency of high level MPS glove-to-head impacts between M15 minor hockey and AAA U15 hockey.

lii. There will be no differences in frequency of very high level MPS glove-to-head impacts between M15 minor hockey and AAA U15 hockey.

liii. There will be no differences in frequency of very low level MPS punch impacts between M15 minor hockey and AAA U15 hockey.

liv. There will be no differences in frequency of low level MPS punch impacts between M15 minor hockey and AAA U15 hockey.

lv. There will be no differences in frequency of medium level MPS punch impacts between M15 minor hockey and AAA U15 hockey.

lvi. There will be no differences in frequency of high level MPS punch impacts between M15 minor hockey and AAA U15 hockey.

lvii. There will be no differences in frequency of very high level MPS punch impacts between M15 minor hockey and AAA U15 hockey.

Figure 18. Example of head-to-boards dynamic response.

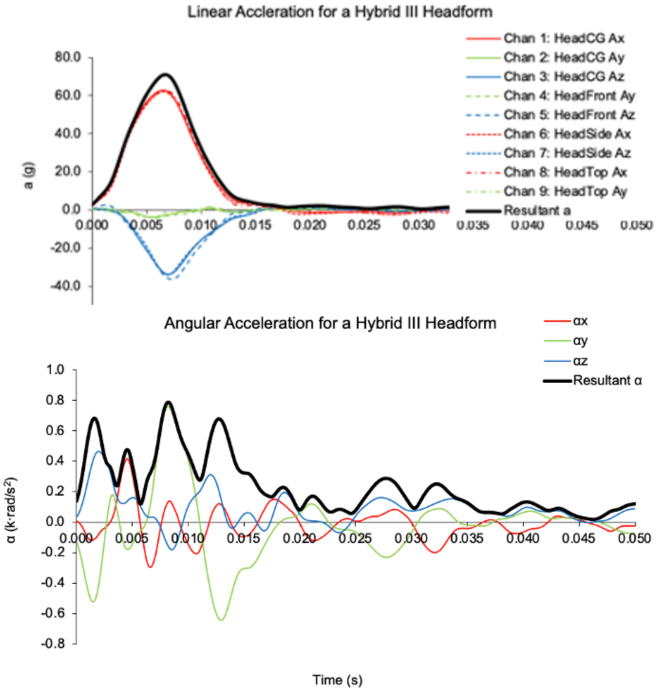
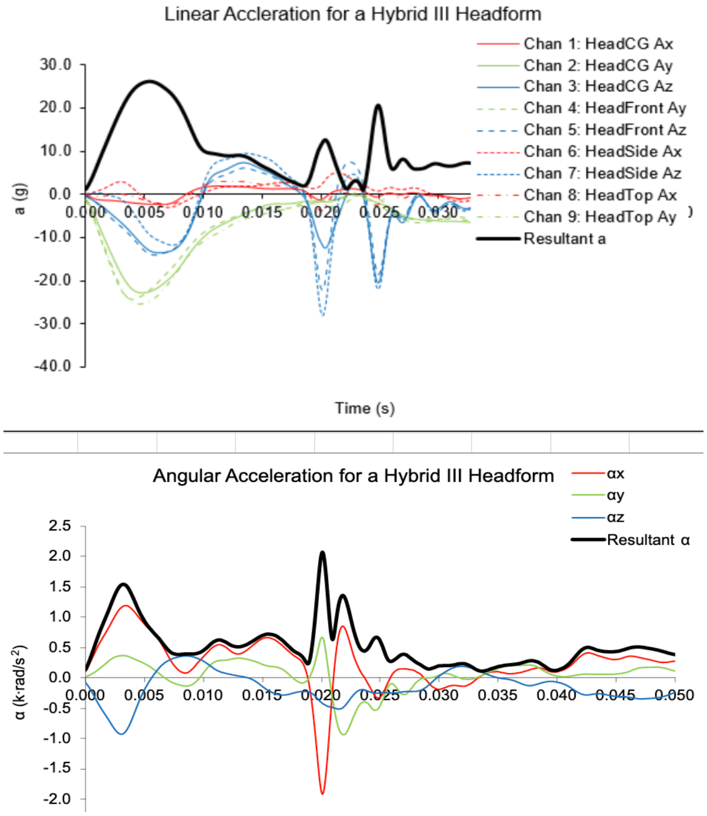


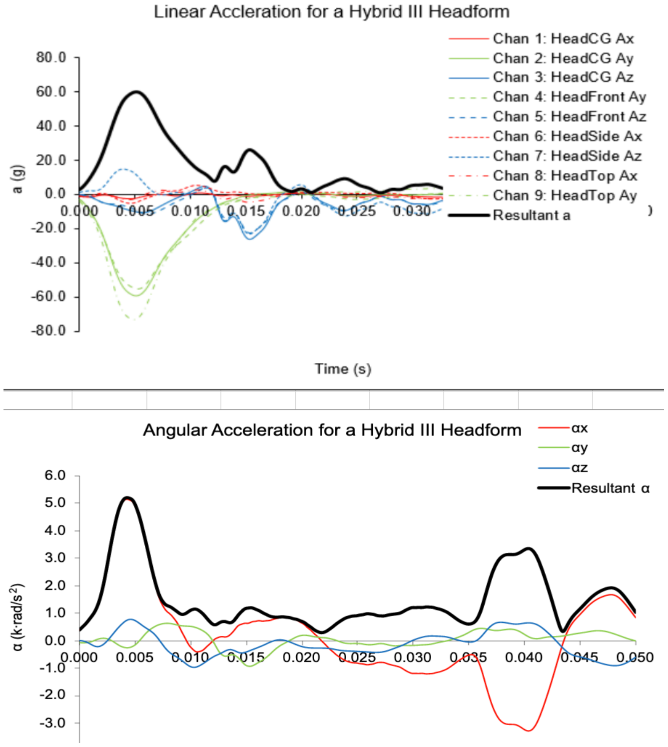
Figure 19. Example of head-to-glass dynamic response.



Linear Accleration for a Hybrid III Headform

Angular Acceleration for a Hybrid III Headform

Figure 20. Example of head-to-ice dynamic response.



Linear Accleration for a Hybrid III Headform

Angular Acceleration for a Hybrid III Headform

Figure 21. Example of shoulder-to-head dynamic response.

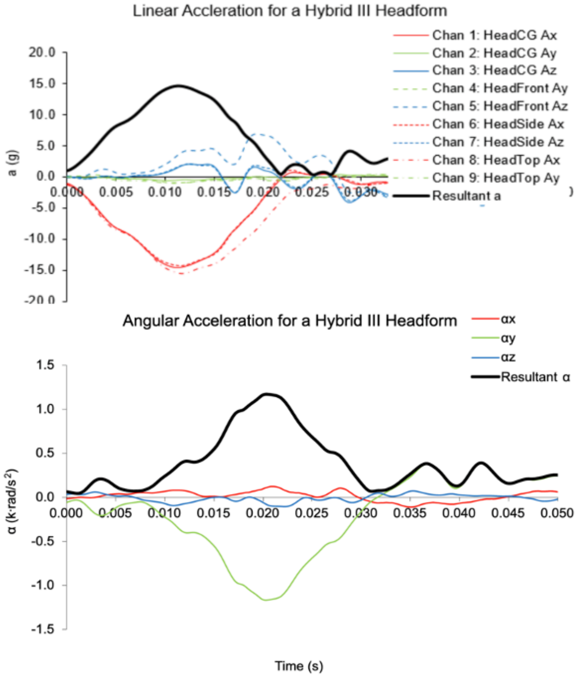


Figure 22. Example of head-to-head dynamic response.

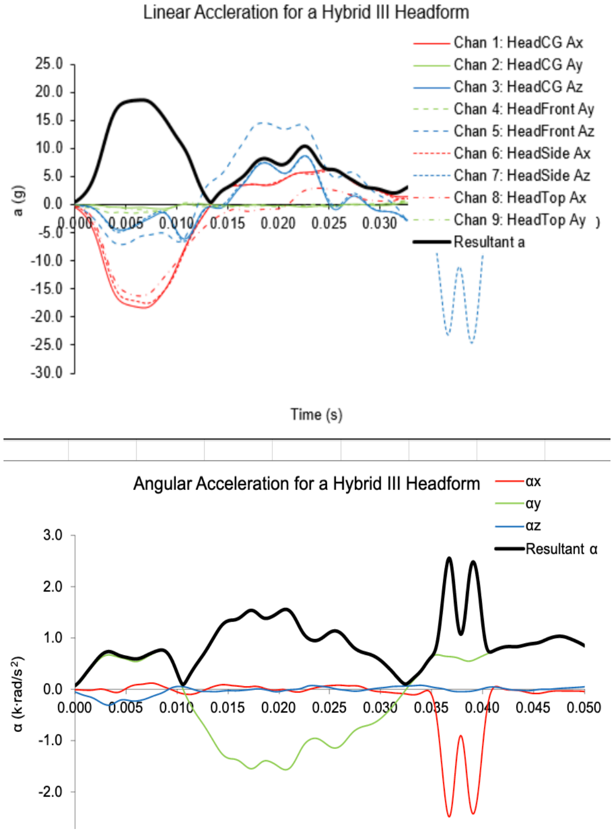


Figure 23. Example of head-to-boards dynamic response.

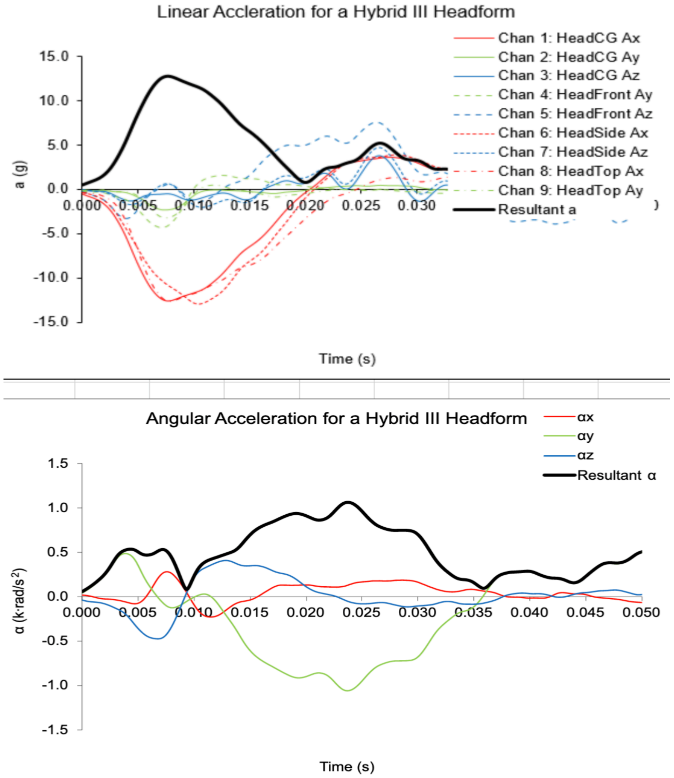


Figure 24. Example of punch dynamic response.

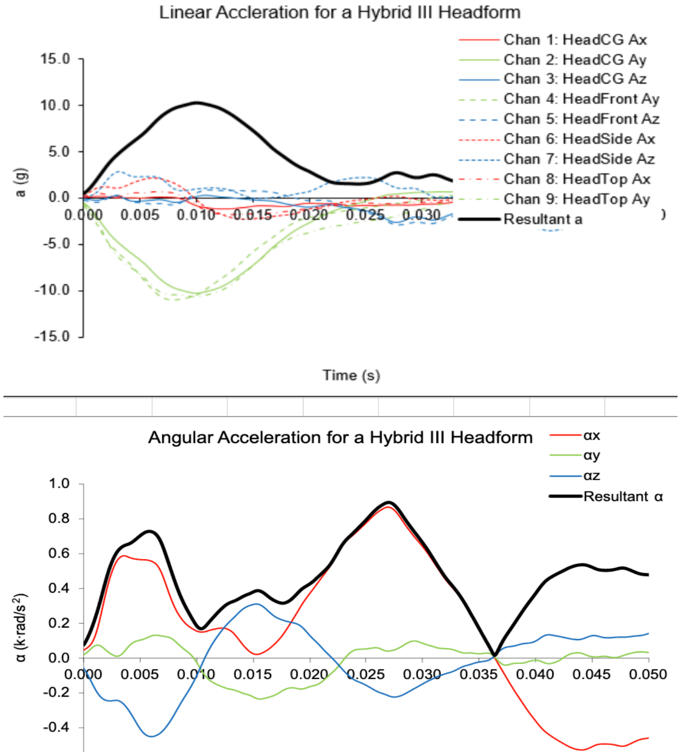


Figure 25. Example of glove-to-head dynamic response.