

**A COMPARISON OF A YOUTH AND A GENERAL ICE HOCKEY HELMET TEST
PROTOCOL**

JARETT CUTLER

Thesis submitted to the University of Ottawa
in partial Fulfillment of the requirements for the
Master of Science in Human Kinetics

School of Human Kinetics
Faculty of Health Sciences
University of Ottawa

© Jarett Cutler, Ottawa, Canada, 2022

Acknowledgements

I would like to begin by thanking my thesis supervisor, Dr. Thomas Blaine Hoshizaki, who has guided me throughout the completion of this thesis. Thank you for inviting me into your lab to complete a Master's degree, and offering me numerous opportunities to be a part of different research studies outside of my thesis. Your undivided attention to details and guidance have helped me become a stronger student and person within and outside academia. Thank you for helping develop my idea into a Master's thesis that am proud to call my own. Thank you to my committee members, Dr. Patrick Bishop and Dr. Karen Taylor, for volunteering your time to read and provide feedback on my thesis. Your questions and ideas enhanced the quality of this thesis, which I will forever be thankful for. Thank you CCM for providing me with the helmets and youth shoulder pads used in this thesis.

Next, I would like to thank the senior researchers in and associated with the lab, Dr. Andrew Post and Dr. Clara Karton, who I had the opportunity to work with and receive assistance from. Thank you for guiding me, answering my questions, and leaving no stone unturned in this thesis. I would also like to thank all my colleagues with whom I have had the pleasure of working with at the Neurotrauma Impact Science Laboratory: Dr. Karen Taylor, Dr. Michael Robidoux, Thomas Hoshizaki, Jasmine Ferdousi, Kayla Larson, Klara Doelle, Luc Champoux, Amir Azadi, Parisa Dehghan, Amy Murphy, Stephanie Lowther, and Benjamin Krbavac. I have enjoyed working and learning from you.

Lastly, I would like to thank my family and friends for supporting me throughout this degree. To my parents Mike and Cindy, and my girlfriend Sarah, thank you for always supporting and encouraging me during my academic career. Thank you for being there through my most stressful days and always being voices of reason, I will always be grateful.

Abstract

Ice hockey helmet standards are employed to test ice hockey helmets to ensure that they mitigate the risk of traumatic brain injuries. These standards primarily reflect adult ice hockey players' anthropometrics and play styles; however, they may not address youth ice hockey players anthropometrics and play styles. This study created a youth helmet test protocol using head impact characteristics specific to the Learn to Play (5-8 years old) youth ice hockey age group environment. The youth helmet test protocol was compared to a general helmet test protocol with the head mass, shoulder mass, and impacting velocities modified to reflect real-world conditions. The dependent variables used in the study included peak resultant linear acceleration, peak resultant rotational velocity, peak resultant rotational acceleration, and maximal principal strain (MPS). Two-way ANOVA identified significant interactions between the test protocols and two helmets tested in this study. This was followed by ANOVA to test for significance across the levels of the independent variables followed by paired t-tests to identify significant differences between the test protocols for each dependent variable for the head to boards and shoulder to head condition ($p < 0.05$). The only significant difference identified between the test protocols for the head to ice condition was linear acceleration. The paired t-tests identified significant differences between the two helmets for all dependent variables for the head to ice and head to boards conditions ($p < 0.05$).

The results from this study revealed that youth are being exposed to similar amounts of brain trauma when compared to adults for the head to ice event. The head to ice condition is one of the most common types of impact events in the Learn to Play age group supporting the need to consider a youth specific ice hockey helmet standard test. This study demonstrated that the CCM

FL 500 provided better protection for youth ice hockey players, and helmet companies could employ similar technologies to better protect youth from the risk of brain injuries.

Table of Contents

ACKNOWLEDGEMENTS	II
ABSTRACT	III
CHAPTER 1: INTRODUCTION	1
1.1 PROBLEM STATEMENT	1
1.2 PURPOSE	4
1.3 RESEARCH	4
1.4 LIMITATIONS.....	4
1.4.1 <i>Shoulder to head Impacts</i>	4
1.4.2 <i>Hybrid III Headforms</i>	5
1.4.3 <i>Unbiased Neckform</i>	5
1.4.4 <i>University College Dublin Brain Trauma Model (UCDBTM)</i>	5
1.4.5 <i>Head Impact Datasets</i>	6
1.5 DELIMITATIONS	6
1.5.1 <i>Shoulder to Head Impacts</i>	6
1.5.1.1 Youth Shoulder to Head Impacts	6
1.5.1.2 Adult Shoulder to Head Impacts	6
1.5.2 <i>Hybrid III Headforms</i>	7
1.5.3 <i>Hybrid III Neckform</i>	7
1.5.4 <i>UCDBTM</i>	7
1.5.5 <i>Head Impact Datasets</i>	8
CHAPTER 2: LITERATURE REVIEW	8
2.1 ICE HOCKEY HELMET TEST STANDARDS AND TEST PROTOCOLS	8
2.1.1 <i>Ice Hockey Helmet Test Standards</i>	8
2.1.2 <i>Ice Hockey Helmet Test Protocols</i>	8
2.2 HELMET DESIGN	9
2.2.1 <i>CCM FL 500</i>	11
2.2.2 <i>CCM Tacks 710</i>	11
2.3 DYNAMIC HEAD RESPONSES.....	12
2.3.1 <i>Peak linear acceleration</i>	12
2.3.2 <i>Peak Rotational velocity</i>	12
2.3.3 <i>Peak rotational acceleration</i>	13
2.4 BRAIN TISSUE STRAIN	13
2.4.1 <i>Maximum principal strain (MPS)</i>	14
2.5 YOUTH AND ADULT ICE HOCKEY	14
2.5.1 <i>Anatomical and Physiological Differences and Brain Trauma</i>	14
2.5.1.1 Head Mass and Brain Volume.....	15
2.5.1.2 Brain Density.....	16
2.5.1.3 Anthropometrics.....	17
2.5.1.4 Brain injury risk and incidence	17
2.5.2 <i>Play Style</i>	18
2.5.3 <i>Impact Characteristics</i>	18
2.6 HELMET TEST METHODS AND EQUIPMENT	20
2.7 SUMMARY.....	21
CHAPTER 3: METHODOLOGY	23
3.1 YOUTH HELMET TEST PROTOCOL MODIFICATIONS	23
3.2 TEST APPARATUS	24
3.2.1 <i>Monorail Drop Rig</i>	24
3.2.2 <i>Pendulum Drop</i>	25
3.2.3 <i>Hybrid III Headform</i>	26
3.2.4 <i>Ice Hockey Helmets</i>	27
3.3 FINITE ELEMENT MODELING	28

3.3.1	<i>University College Dublin Brain Trauma Model</i>	28
3.3.2	<i>Maximum Principal Strain</i>	29
CHAPTER 4: RESEARCH DESIGN		29
4.1	INDEPENDENT VARIABLES (HELMET TYPE, HELMET TEST PROTOCOL)	29
4.2	DEPENDENT VARIABLES	31
4.3	NULL HYPOTHESES.....	32
4.4	STATISTICAL ANALYSIS.....	36
CHAPTER 5: RESULTS		37
5.1	MEAN DYNAMIC HEAD RESPONSE AND MPS HELMET TEST PROTOCOL COMPARISON (ANOVA AND T-TESTS) 37	
5.2	MEAN DYNAMIC HEAD RESPONSES AND MPS HELMET COMPARISON (ANOVA AND T-TESTS).....	46
5.2.1	<i>Youth Helmet Test Protocol</i>	46
5.2.2	<i>General Helmet Test Protocol</i>	54
CHAPTER 6: DISCUSSION		63
6.1	<i>Youth Helmet Test Protocol and General Helmet Test Protocol</i>	63
6.1.1	HEAD TO ICE	63
6.1.2	<i>Head to Boards</i>	64
6.1.3	<i>Shoulder to Head</i>	65
6.2	HELMET COMPARISON WITHIN EACH TEST PROTOCOL	65
6.2.3	<i>Overall Helmet and Standard Modifications</i>	66
CHAPTER 7: CONCLUSION		67
REFERENCES		68
APPENDIX A		79
APPENDIX B		79
APPENDIX C		80
APPENDIX D		81
APPENDIX E		82
APPENDIX F		82

List of Tables

Table 1. Comparison of the overall mean (± 1 standard deviation) dynamic head responses and brain tissue deformation values between the youth and general helmet test protocols for head to ice, head to boards, and shoulder to head impacts (n=4). Two-way ANOVAs tested for interactions between helmet test protocols ($\alpha = 0.05$). Comparisons were made using paired t-tests ($\alpha = 0.05$).

Table 2. Comparison of the overall mean (± 1 standard deviation) dynamic head responses and brain tissue deformation between the youth and general helmet test protocols for the head to ice condition with the locations expanded. Comparisons were made using paired t-tests ($\alpha = 0.05$).

Table 3. Comparison of the overall mean (± 1 standard deviation) dynamic head responses and brain tissue deformation between the youth and general helmet test protocols for the head to boards condition with the locations expanded. Comparisons were made using paired t-tests ($\alpha = 0.05$).

Table 4. Comparison of the overall mean (± 1 standard deviation) dynamic head responses and brain tissue deformation between the youth and general helmet test protocols for the shoulder to head condition with the locations expanded. Comparisons were made using paired t-tests ($\alpha = 0.05$).

Table 5. Comparison of the overall average (± 1 standard deviation) dynamic head responses and brain tissue deformation values between the CCM FL 500 and CCM Tacks 710 in the youth helmet test protocol for head to ice, head to boards, and shoulder to head impacts (n=4). Two-way ANOVAs tested for interactions between helmet test protocols ($\alpha = 0.05$). Comparisons were made using paired t-tests ($\alpha = 0.05$).

Table 6. Comparison of the overall average (± 1 standard deviation) dynamic head responses and brain tissue deformation between the CCM FL 500 and CCM Tacks 710 in the youth helmet test protocol for head to ice with the locations expanded. Comparisons were made using paired t-tests ($\alpha = 0.05$).

Table 7. Comparison of the overall average (± 1 standard deviation) dynamic head responses and brain tissue deformation between the CCM FL 500 and CCM Tacks 710 in the youth helmet test protocol for head to boards with the locations expanded. Comparisons were made using Paired T-tests ($\alpha = 0.05$).

Table 8. Comparison of the overall average (± 1 standard deviation) dynamic head responses and brain tissue deformation between the CCM FL 500 and CCM Tacks 710 in the youth helmet test protocol for shoulder to head with the locations expanded. Comparisons were made using paired t-tests ($\alpha = 0.05$).

Table 9. Comparison of the overall average (± 1 standard deviation) dynamic head responses and brain tissue deformation values between the CCM FL 500 and CCM Tacks 710 in the general helmet test protocol for head to ice, head to boards, and shoulder to head impacts (n=4). Two-way ANOVAs tested for interactions between helmet test protocols ($\alpha = 0.05$). Comparisons were made using paired t-tests ($\alpha = 0.05$).

Table 10. Comparison of the overall average (± 1 standard deviation) dynamic head responses and brain tissue deformation between the CCM FL 500 and CCM Tacks 710 in the general helmet test protocol for head to ice with the locations expanded. Comparisons were made using paired t-tests ($\alpha = 0.05$).

Table 11. Comparison of the overall average (± 1 standard deviation) dynamic head responses and brain tissue deformation between the CCM FL 500 and CCM Tacks 710 in the general helmet test protocol for head to boards with the locations expanded. Comparisons were made using paired t-tests ($\alpha = 0.05$).

Table 12. Comparison of the overall average (± 1 standard deviation) dynamic head responses and brain tissue deformation between the CCM FL 500 and CCM Tacks 710 in the general helmet test protocol for shoulder to head with the locations expanded. Comparisons were made using Paired T-tests ($\alpha = 0.05$).

Table 13. Current ice hockey helmet standard summary of test equipment, impact parameters, and pass/fail criteria (ASTM F1045-16; CSA Z262.1-15; ISO 10256-2:2016).

Table 14. Physiological and anatomical differences between youth and adults which play a role in head injury (Bishop, Kendall, Post, & Hoshizaki, 2014; Fryar, Gu, Ogden, & Flegal, 2016; Koncan, 2018; Maxwell, 2012; Ommaya, 1995).

Table 15. Mechanical properties for UCDBTM V2.0. (Table retrieved from (Trotta, Clark, McGoldrick, Gilchrist, & Annaidh, 2020)).

Table 16. Youth (top) and general (bottom) helmet test protocol breakdown with 5th percentile hybrid III headform. Each event type was run 3 times per velocity and impact location. (de Grau et al., 2020; Karton et al., 2021; Meehan, Hoshizaki, Bishop, & Robertson, 2019; Post, Dawson, Hoshizaki, Gilchrist, & Cusimano, 2020; Robidoux et al., 2020).

Table 17. Helmet characteristic differences.

Table 18. 2x2 research design. This thesis resulted in 144 head impacts.

List of Figures

Figure 1. Monorail drop rig set up equipped with the 45° steel anvil.

Figure 2. Pendulum drop rig set up.

Figure 3. The Hybrid III 5th percentile headform (left) and the Hybrid III 50th percentile headform (right).

Figure 4. The CCM FL 500 size S/M (top) and the CCM Tacks 710 size S (bottom).

Figure 5. Comparison of the overall mean peak resultant linear acceleration (A), rotational velocity (B), rotational acceleration (C), and MPS (D) between the youth and general helmet test protocols for head to ice condition. Error bars denote ± 1 standard deviation. Significant differences are denoted by an asterisk (*).

Figure 6. Comparison of the overall mean peak resultant linear acceleration (A), rotational velocity (B), rotational acceleration (C), and MPS (D) between the youth and general helmet test protocols for head to boards condition. Error bars denote ± 1 standard deviation. Significant differences are denoted by an asterisk (*).

Figure 7. Comparison of the overall mean peak resultant linear acceleration (A), rotational velocity (B), rotational acceleration (C), and MPS (D) between the youth and general helmet test protocols for shoulder to head condition. Error bars denote ± 1 standard deviation. Significant differences are denoted by an asterisk (*).

Figure 8. Comparison of the overall mean peak resultant linear acceleration (A), rotational velocity (B), rotational acceleration (C), and MPS (D) for the CCM FL 500 and CCM Tacks 710 helmets during the head to ice condition in the youth helmet test protocol. Error bars denote ± 1 standard deviation. Significant differences are denoted by an asterisk (*).

Figure 9. Comparison of the overall mean peak resultant linear acceleration (A), rotational velocity (B), rotational acceleration (C), and MPS (D) for the CCM FL 500 and CCM Tacks 710 helmets during the head to boards condition in the youth helmet test protocol. Error bars denote ± 1 standard deviation. Significant differences are denoted by an asterisk (*).

Figure 10. Comparison of the overall mean peak resultant linear acceleration (A), rotational velocity (B), rotational acceleration (C), and MPS (D) for the CCM FL 500 and CCM Tacks 710 helmets during the shoulder to head condition in the youth helmet test protocol. Error bars denote ± 1 standard deviation. Significant differences are denoted by an asterisk (*).

Figure 11. Comparison of the overall mean peak resultant linear acceleration (A), rotational velocity (B), rotational acceleration (C), and MPS (D) for the CCM FL 500 and CCM Tacks 710 helmets during the head to ice condition in the general helmet test protocol. Error bars denote ± 1 standard deviation. Significant differences are denoted by an asterisk (*).

Figure 12. Comparison of the overall mean peak resultant linear acceleration (A), rotational velocity (B), rotational acceleration (C), and MPS (D) for the CCM FL 500 and CCM Tacks 710 helmets during the head to boards condition in the general helmet test protocol. Error bars denote ± 1 standard deviation. Significant differences are denoted by an asterisk (*).

Figure 13. Comparison of the overall mean peak resultant linear acceleration (A), rotational velocity (B), rotational acceleration (C), and MPS (D) for the CCM FL 500 and CCM Tacks 710 helmets during the shoulder to head condition in the general helmet test protocol. Error bars denote ± 1 standard deviation. Significant differences are denoted by an asterisk (*).

Figure 14. Development of white matter within the brain in 5-6 year old's, adolescence, and early adulthood (Figure taken from (Maxwell, 2012)).

Chapter 1: Introduction

1.1 Problem Statement

Certified ice hockey helmets are an important piece of safety equipment, used at all levels of ice hockey to protect against traumatic brain injuries, such as skull fractures, hematomas, comas, and death (ASTM F1045-16; Bishop, Kendall, Post, & Hoshizaki, 2014; CSA Z262.1-15; ISO 10256-2:2016; Meehan, Hoshizaki, Bishop, & Robertson, 2019). Even though youth ice hockey players (under 18 years old) experience head impacts with different impact characteristics, they use the same helmets as adult (over 18 years old) ice hockey players (Karton et al., 2021; Robidoux et al., 2020). Ice hockey helmets are designed for all ages and are certified using the same helmet test protocol (Hoshizaki, 2017; Post et al., 2016). As a result, helmets for Learn to Play age group (5-8 years old) are scaled-down versions of ice hockey helmets and are designed to manage impacts based on head injury risks associated with adult ice hockey games (Hoshizaki, 2017; Post et al., 2016). Ice hockey helmets are designed for adult ice hockey players, and then helmet manufacturers develop smaller sizes to fit a youth's head (ASTM F1045-16; CSA Z262.1-15; Hoshizaki, 2017; ISO 10256-2:2016; Post et al., 2016). There are standard tests for ice hockey helmet certification (ASTM F1045-16; CSA Z262.1-15: ISO 10256-2:2016), but to date no youth helmet certification test protocol has been developed. Youth ice hockey player's (5-8 years old) head injury profiles are different when compared to adult ice hockey player's head injury profiles (Bishop, Kendall, Post, & Hoshizaki, 2014; Koncan, 2018; Post et al., 2016). Youth experience more head impacts (84 in 53 games) when compared to adult ice hockey players (79 in 540 games) in head to ice, head to boards and shoulder to head events (Hutchison, Comper, Meeuwisse, & Echemendia, 2015b; Kontos et al., 2016; Robidoux et al., 2020; Wennberg & Tator, 2008). Learn to Play players also have different mechanisms of injury than adults which is due to Learn to Play players having less skill when skating, balancing,

and orienting themselves on the ice; whereas, adult ice hockey players have more developed skills and employ intentional contact with their opponents (Hutchison, 2011; Karton et al., 2021; Robidoux et al., 2020). In the Learn to Play age group (5–8-year old's) a reported 5% of players sustained a concussion, whereas professional ice hockey as high as 8.8% of players are reported to have sustained a concussion (Donaldson, Asbridge, & Cusimano, 2013; Doorly & Gilchrist, 2006; Post et al., 2019; Robidoux et al., 2020). However, in both levels of ice hockey concussions are underreported, so the actual number of concussions in either age group is unknown (Cusimano et al., 2017; Donaldson et al., 2013; Goldschmied & Espindola, 2013; McCrea, Hammeke, Olsen, Leo, & Guskiewicz, 2004; Robidoux et al., 2020; Williamson & Goodman, 2006). Consequently, ice hockey helmet designs may not be appropriate for protecting against the unique impact characteristics in Learn to Play ice hockey (Post et al., 2016). This research employed youth head impact parameters to measure the performance of two certified ice hockey helmets.

Ice hockey helmet standards primarily use peak resultant linear acceleration as the dependent variable representing the ability of a helmet to mitigate brain injuries (ASTM F1045-16; Bishop, Kendall, Post, & Hoshizaki, 2014; CSA Z262.1-15; Hoshizaki, 2017; ISO 10256-2:2016; Karton et al., 2021; Post et al., 2016). Several adult ice hockey helmet test protocols have been developed, but there has not been a helmet or helmet test protocol designed specific to youth (Meehan et al., 2019; Post et al., 2020; Post, Oeur, Hoshizaki, & Gilchrist, 2013; Rowson, Rowson, & Duma, 2015). Differences in the skull, the mass of the brain and the bulk modulus of the brain contribute to differences between youth and adults in susceptibility to brain injury (Bishop et al., 2014). Youth are exposed to head impact event types with lower masses, impact velocities with different impact angles, and frequencies compared to adult ice hockey players,

(ASTM F1045-16; Bishop, Kendall, Post, & Hoshizaki, 2014; CSA Z262.1-15; Hoshizaki, 2017; ISO 10256-2:2016; Karton et al., 2021; Post et al., 2016).

Meehan and colleagues (2019) developed three test methods to represent the impact characteristics for the most common head impacts in adult ice hockey (head to boards, head to shoulder, and head to ice). They measured the peak rotational velocity, peak rotational acceleration, and maximal principal strain. These variables provided measures of the brain trauma representing adult ice hockey (Meehan et al., 2019; Post et al., 2020; Post et al., 2013; Rowson et al., 2015). However, it is unknown if certified ice hockey helmets are effective under youth impact conditions.

The present study employed a modified version of Meehan and colleague's (2019) helmet test protocol to compare to a novel youth specific helmet test protocol (5-8 years old). The most common head impact event types (head to ice, head to boards, and head to shoulder) in Learn to Play ice hockey were included in the test. The hybrid III 5th percentile headform (3.73 kg) was used to represent youth between 5-8 years of age (Pion et al., 2015; Post et al., 2016). The shoulder to head test was modified to use a pendulum drop test to reduce the shoulder mass to 3.61 kg in order to represent the shoulder mass of young hockey players (Fryar, Gu, Ogden, & Flegal, 2016; Karton, Hoshizaki, & Gilchrist, 2014; Karton et al., 2021; Rousseau & Hoshizaki, 2015). The impact velocities reflected youth head impacts obtained using video capture. The helmets in this study were chosen based on design differences including offset, overall mass, geometry, material characteristics, construction, and the different STAR hockey helmet ratings (Rowson et al., 2015). The CCM FL 500 was expected to perform differently than the CCM Tacks 710 because of the FL 500's distinct construction and material characteristics. The FL 500 presents with a larger offset, multi density Vinyl Nitrile (VN) foams throughout the helmet with

softer foams against the skull, and the D30 smart material placed at the rear and side locations (CCM Hockey, 2022). The CCM Tacks 710 is a conventional helmet with similar construction and material characteristics to many other helmets presenting with a smaller offset, a fluid pod technology (R.E.D. system), and the D30 smart material is placed at nine different locations surrounding the head (CCM Hockey, 2022). This research was designed to employ head impact characteristics specific to Learn to Play ice hockey and to compare the protective capacity of two existing certified helmets.

1.2 Purpose

The purpose of this research was to compare a youth specific helmet test protocol (5-8 years old) to an adult specific helmet test protocol and to compare two CSA certified ice hockey helmets using the two test protocols.

1.3 Research

- 1) To compare a general helmet test protocol to a youth specific helmet test protocol by evaluating peak resultant linear acceleration, peak resultant rotational velocity, peak resultant rotational acceleration, and maximum principal strain (MPS) values.
- 2) To compare the CCM FL-500 and the CCM Tacks 710 ice hockey helmets using both the youth and general helmet test protocols to obtain peak resultant linear acceleration, peak resultant rotational velocity, peak resultant rotational acceleration, and MPS.

1.4 Limitations

1.4.1 Shoulder to head Impacts

The compliance for shoulder to head impacts in this study was based on adult parameters and was not scaled down due to the absence of youth specific impact compliance values. The pendulum drop cannot achieve a velocity higher than 6.0 m/s, so the highest velocity of 9.0 m/s

of an adult shoulder to head impact cannot be achieved using a pendulum. The linear impactor could not be used in this study because the mass of the impacting arm was too high to represent a youth.

1.4.2 Hybrid III Headforms

The hybrid III headform design includes a steel interior with a vinyl skin. This design exists so the headform can sustain multiple high energy impacts without damage. However, these material characteristics are not biofidelic and do not fully represent the human head. The difference in mass between the 50th percentile Hybrid III headform and the 5th percentile Hybrid III headform is 82%, yet literature suggest the difference for youth between 5-8 years old is 95%; however, this option was the closest headform size (Bishop et al., 2014; Koncan, 2018). Although the headforms are not fully biofidelic, the hybrid III 5th percentile is a reasonable representation of the youth head and the hybrid III 50th percentile is a reasonable representation of the adult head in biomechanical impact testing.

1.4.3 Unbiased Neckform

The University of Ottawa developed an unbiased neckform to respond similarly in all degrees of freedom (Walsh, Kendall, Post, Meehan, & Hoshizaki, 2018).

1.4.4 University College Dublin Brain Trauma Model (UCDBTM)

FE models are surrogates and do not fully capture the characteristics of the youth brain as it is based on adult characteristics and do not reflect age specific geometry and material properties of brain tissues such as mass, volume, and density (Koncan, 2018). University College Dublin Brain Trauma Model Version 2.0 (UCDBTM V2.0) does not fully represent all the loading characteristics the brain experiences in the Learn to Play youth ice hockey age group. Although, this model is based on cadaver testing, evaluating *in vivo* brain tissue response is not feasible

(Trotta et al., 2020). The assumption has been made that the strain outputs from this model represent the human brain.

1.4.5 Head Impact Datasets

The youth ice hockey head impact dataset contained inbound velocities for confirmed head impacts to the ice (n=32), to the boards (n=16), and the shoulder (n=36). The video recording for this dataset only shows the impacts from one angle, which limits the accuracy of velocity measurements. The suspected head contacts were not used in this study so the reported number of head impacts reported in this study should be considered conservative.

1.5 Delimitations

1.5.1 Shoulder to Head Impacts

The pendulum was used for the youth and adult ice hockey player shoulder to head impacts due to the inability to adjust the mass of the linear impactor and to remove the bias of comparing the pendulum drop and the linear impactor.

1.5.1.1 Youth Shoulder to Head Impacts

Adult shoulder compliance values for shoulder to head impacts were used for both youth and adult tests in this study because in the Learn to Play ice hockey level there are currently no youth shoulder compliance values available.

1.5.1.2 Adult Shoulder to Head Impacts

In the general test protocol, the velocity of 6.0 m/s was used instead of 9.0 m/s because 6.0 m/s is representative of concussion in the professional ice hockey (Meehan et al., 2019; Post et al., 2019).

1.5.2 Hybrid III Headforms

For the Learn to Play youth age group the closest head mass that could be achieved using the hybrid III headform was the hybrid III 5th percentile headform.

1.5.3 Hybrid III Neckform

The hybrid III neckforms were not used in this study because they are biased and designed for non-impacts in the sagittal planes such as car accidents.

1.5.4 UCDBTM

The UCDBTM V2.0 material characteristics were derived using cadavers, pigs, and dogs. The geometry was developed from magnetic resonance images of live human brains. The UCDBTM V2.0 also allows the scalp to have sliding properties. It has refined hexahedral elements to improve the mechanical and material properties of the brain (Horgan & Gilchrist, 2003; Trotta et al., 2020). All finite element (FE) models are a surrogate of the brain, so they present with limitations. The FE model was reduced to 95% of its original size to reflect the brain size of youth between 5-8 years old (Horgan & Gilchrist, 2003; Koncan, 2018; Lenroot & Giedd, 2006; Reiss, Abrams, Singer, Ross, & Denckla, 1996; Trotta et al., 2020). However, it is understood that the model does not accurately represent all brain characteristics such as volume, mass, and density at this age as these variables are not controlled separately when scaling down the model (Horgan & Gilchrist, 2003; Koncan, 2018; Trotta et al., 2020). Additionally, the model does not accurately represent all material characteristics such as young's modulus, skull stiffness, bulk modulus, and shear modulus at this age as these variables are not controlled separately when scaling down the model (Horgan & Gilchrist, 2003; Koncan, 2018; Trotta et al., 2020). UCDBTM versions 1 and 2 have been used to reconstruct multiple head impacts in the Neurotrauma Impact Science Laboratory at the University of Ottawa.

1.5.5 Head Impact Datasets

Although the single camera angle is a limitation as some impacts are not captured within the cameras view. The number of confirmed impacts provided a conservative representation of head impacts that are experienced in Learn to Play ice hockey.

Chapter 2: Literature Review

2.1 Ice Hockey Helmet Test Standards and Test Protocols

2.1.1 Ice Hockey Helmet Test Standards

Current ice hockey helmet standards and testing methods are primarily designed to decrease the risk of traumatic brain injury (TBI) by testing high energy head to ice impacts to a rigid anvil and employing peak resultant linear acceleration as a criterion measure (ASTM F1045-16; CSA Z262.1-15; ISO 10256-2:2016). A helmeted CEN EN 960 magnesium headform is rigidly attached to a monorail drop rig and impacted at 4.5 m/s. The impact anvil is a 25mm 60 ± 5 Share A MEP (ASTM F1045-16; CSA Z262.1-15; ISO 10256-2:2016). The standards incorporate headforms with masses between 3.1 to 5.6 kg to account for differences in youth and adult ice hockey player head sizes and the pass/fail criteria of 275g for hockey helmets of all sizes (ASTM F1045-16; Bishop, Kendall, Post, & Hoshizaki, 2014; CSA Z262.1-15: ISO 10256-2:2016). However, the current standards are limited in that the test only represents a head to ice injury event (Bishop et al., 2014; Meehan et al., 2019). Other testing methods have been developed including dependent variables more reflective of brain trauma (Meehan et al., 2019; Post, 2013; Post et al., 2019; Rowson et al., 2015).

2.1.2 Ice Hockey Helmet Test Protocols

The helmet test protocol developed by Post and colleagues (2013) employed adult head impacts in ice hockey and uses an MEP linear impactor at 4.5 m/s at different impact angles and

locations. The helmet test protocol developed by Rowson and colleagues (2015) employed a pendulum impacting system with a low compliant impactor at different impact energies, angles, and locations. Post and colleagues (2020) employed a monorail drop rig with a flat, low compliant MEP anvil for head to ice impact, and the linear impactor with a high compliant impactor for shoulder to head and elbow to head impacts. Recently, a testing method on concussive events from the NHL was investigated (Meehan et al., 2019). The helmet test protocol by Meehan and colleagues (2019) employed a monorail drop rig with a 45-degree angled anvil for head to board impacts, a flat, MEP anvil for head to ice impact, and the linear pneumatic ram with a high compliance impactor for head to shoulder impacts. In two of these studies, the relationship between both peak linear and rotational acceleration and MPS was reported (Meehan et al., 2019; Post et al., 2013). Rowson and colleagues (2015) reported a relationship between both peak linear and rotational acceleration with the risk of brain injury. The ice hockey helmet standards and test methods employed loading characteristics reflecting adult ice hockey head impact characteristics, and youth players experience different impact characteristics.

2.2 *Helmet Design*

Currently there are many different types of ice hockey helmets, with different geometries, materials, and technologies creating differences in performance. Researchers and manufacturers employ testing methods with dynamic head response and brain tissue deformation variables that best represent head trauma to determine differences that may exist between helmets (Champoux, 2021). However, only the STAR system ranks helmet performance based on their capacity to decrease the risk of a head injury (Rowson et al., 2015). This system was primarily designed for football helmets and was modified for ice hockey helmets with the equation using a linear

acceleration, α rotational acceleration, E exposure per season, L location of impact, θ angle of impact, and R the risk of concussion based on linear and rotational head accelerations (Rowson et al., 2015). Modification for hockey included exposure incorporating linear and rotational acceleration of hockey player, impact locations of hockey players (front, side, rear, and crown), and common impact angles of hockey players (Rowson et al., 2015).

$$R(a, \alpha) = \frac{1}{1 + e^{-(10.2 + 0.0433 * a + 0.000873 * \alpha - 0.00000920 * a \alpha)}}$$

$$\text{Hockey STAR} = \sum_{L=1}^4 \sum_{\theta=1}^3 E(L, \theta) * R(a, \alpha)$$

In the STAR rating system, a low value reflects a low risk of concussion and a high value reflects a high risk of concussion (Rowson et al., 2015).

Although the STAR system is the only ranking system, there are other test methods that can be used to evaluate helmet performance. The helmets were also chosen based on their differences in offsets, overall masses, geometries, material characteristics, and construction (Appendix E Table 17). When a helmet is placed on a person's head it becomes part of a spring-mass system when impacted. In a spring-mass system (hockey helmet headform system) the mechanism which controls the entire system is the softest spring (Bishop et al., 2014). Softer foam is an important material characteristic to be included in a youth helmet because a youth's brain tissue is stiffer than adult brain tissue, but a youth's skull at this age is much more flexible than an adult's skull (Bishop et al., 2014; Koncan, 2018). The FL 500 and Tacks 710 were chosen because the FL 500 presented with softer foam which may mean it can perform better than the Tacks 710.

2.2.1 CCM FL 500

The CCM FL 500 helmet consists of a relatively smooth outer shell, multi density vinyl nitrile (VN) foams and softer foams against the skull creating a larger offset, when compared to similar helmets. The soft foams in this helmet may provide better protection to youth (5-8 years old) by transferring a greater amount of the impact energy to the helmet (Bishop et al., 2014). The CCM FL 500 also contains the D30 smart material a soft and flexible two-layer technology designed to help distribute impact energies away from the head. This material is placed at the rear and side locations and the helmet received a score of 0.16 on the STAR rating system out performing all other helmets (CCM Hockey, 2022; "Hockey Helmet Ratings," 2022; Rowson et al., 2015). The offsets of this helmet are 27mm at the front, 22mm at the sides, and 36mm at the rear of the helmet (CCM Hockey, 2022; "Hockey Helmet Ratings," 2022; Rowson et al., 2015).

2.2.2 CCM Tacks 710

The CCM Tacks 710 features the R.E.D. system, which is a fluid pod technology designed to help displace energies from multiple directions (CCM Hockey, 2022). In this helmet the R.E.D. system is placed between the shell and the liner throughout the helmet (CCM Hockey, 2022). The D30 smart material is placed at nine different locations surrounding the head (CCM Hockey, 2022). The CCM Tacks 710 is a conventional helmet with similar construction and material characteristics to many other helmets and received a score of 1.32 on the STAR rating system making it an average performing helmet when compared to the other helmets on the market (CCM Hockey, 2022; "Hockey Helmet Ratings," 2022; Rowson et al., 2015). The offsets of this helmet are 25mm at the front, 25mm at the sides, and 32mm at the rear of the helmet (CCM Hockey, 2022; "Hockey Helmet Ratings," 2022; Rowson et al., 2015).

2.3 *Dynamic head responses*

2.3.1 *Peak linear acceleration*

Peak resultant linear acceleration is used by ice hockey helmet certification standards to represent the ability of the helmet to manage impacts (ASTM F1045-16; CSA Z262.1-15: ISO 10256-2:2016). The unit of measure of peak resultant linear acceleration is gravity, g ($1g = 9.81 \text{ m/s}^2$). In early research, linear acceleration was used to measure brain trauma in anesthetized dogs (Gurdjian, Webster, & Lissner, 1958). Data obtained from cadaver and animal head impact research was used to develop the Wayne State Tolerance Curve (WSTC). WSTC was developed to define a threshold for skull fracture using linear acceleration and duration of the event (Gurdjian, Roberts, & Thomas, 1966). The Gadd Severity Index (GSI) (Gadd, 1966) and the Head Injury Criterion (HIC) (Versace, 1971) were used to measure head injury severity and developed using similar linear acceleration time curves. Since these measures were developed, they have been widely used in automotive crash tests and sport-related helmet testing. Peak resultant linear acceleration was included in this thesis to provide a measure of the helmet material properties and overall effectiveness of the helmet (ASTM F1045-16; Bishop et al., 2014; CSA Z262.1-15: ISO 10256-2:2016).

2.3.2 *Peak Rotational velocity*

Peak rotational velocity is the change in rotational displacement through an axis over time and is used to analyze head impacts in adult helmet testing methods (Meehan et al., 2019; Post et al., 2013). Rotational velocity is a predictive measure of head injury risk that is related to the severity of shear strains (Holbourn, 1943) and has been correlated with Maximum Principal Strain (MPS) (Takhounts, Craig, Moorhouse, Mcfadden, & Hasija, 2013). Rotational velocity has also been used in head injury studies to distinguish between concussive and non-concussive

head impact events (McIntosh et al., 2014). Peak resultant rotational velocity was an important variable in this thesis because it correlates with MPS, and a youth brain is susceptible to injuries resulting from peak resultant rotational velocity (Holbourn, 1943; Takhounts et al., 2013).

2.3.3 Peak rotational acceleration

Peak rotational acceleration is the change in rotational velocity over time (radians/s²), and is correlated with concussive injuries (Holbourn, 1943). Due to the brain's low shear modulus (low modulus of rigidity) and high bulk modulus (high incompressibility), brain tissue is more susceptible to shear strains rather than to compression (Holbourn, 1943). This relationship has been reported in studies involving primates demonstrating the effects of rotational acceleration on brain tissue (Gennarelli, Thibault, & Ommaya, 1972). Rotational acceleration associates with concussive events more than linear acceleration (Gennarelli et al., 1972). Gennarelli and colleagues (1972) reported that all primates suffered a concussion after rotational acceleration, and only half of the primates sustained concussions following exposure to linear acceleration. Rotational acceleration also creates a higher risk of sustaining head injuries such as subdural hematomas and diffuse axonal injuries (Gennarelli et al., 1972; Kleiven, 2013). Finite element (FE) modelling also supports rotational acceleration as a more significant association with brain tissue strain than linear acceleration (Zhang, Yoganandan, Pintar, & Gennarelli, 2006). Rotational acceleration is used as a means of evaluating ice hockey helmet performance because of its relationship with concussive events (Meehan et al., 2019; Post et al., 2019). Peak resultant rotational acceleration was included in this thesis because the brain tissue is susceptible to shear forces (Gennarelli et al., 1972; Holbourn, 1943).

2.4 Brain Tissue Strain

2.4.1 Maximum principal strain (MPS)

Brain tissue strain resulting from a head impact is associated with concussive injuries (Gennarelli et al., 1972; Holbourn, 1943; Zhang, Yang, & King, 2001). Brain tissue strain is linked to rotational acceleration of the head (Gennarelli et al., 1972). Concussive events in youth report lower strain values when compared to adults, suggesting youth are more susceptible to concussive injuries (Koncan, 2018). MPS is an important variable because it considers both the kinematics of the head and material characteristics and geometry of the brain. A baseline of the original tissue length is established and how far the tissue has stretched during an impact provides a tissue strain value (Bain & Meaney, 2000; Hoshizaki, Post, Kendall, Karton, & Brien, 2013; Hoshizaki & Cournoyer, 2019; Zhang et al., 2004).

2.5 Youth and Adult Ice Hockey

2.5.1 Anatomical and Physiological Differences and Brain Trauma

Throughout physiological development during childhood, many significant head and brain changes occur (Figure 1) (Koncan, 2018). During the brain and skull's growth and development, the brain mass increases, the volume of the brain tissue increases, changes in density of brain tissue occur, the skull thickens and hardens, and sutures develop between different bones of the skull (Bishop et al., 2014; Koncan, 2018; Lenroot & Giedd, 2006; Ommaya, 1995; Reiss, Abrams, Singer, Ross, & Denckla, 1996). Following a head injury, brain development may be affected. The brain must repair neuronal damage to reconnect previous pathways while creating new neural pathways (Koncan, 2018; Post, Hoshizaki, Gilchrist, et al., 2017; Post, Hoshizaki, Zemek, et al., 2017). In adults, the brain's focus is on repairing and recovering from the damages which may result in shorter recovery times when compared to

youth (Choe et al., 2012; Gilchrist et al., 2011; Koncan, 2018; Lax et al., 2015; McClincy et al., 2006).

2.5.1.1 Head Mass and Brain Volume

Head mass increases through development with the bones that make up the skull increasing in thickness and sutures between the bones begin to develop and close (Bishop et al., 2014; Ommaya, 1995). The thickness of an adult's skull is approximately 10 millimetres, whereas a youth's skull is approximately 4 millimetres (Bishop et al., 2014; Ommaya, 1995). The sutures between the skull bones have not fully developed decreasing the stiffness and young's modulus of a youth skull when compared to adult skulls (Bishop et al., 2014; Ommaya, 1995). The differences in thickness and lack of sutures create a risk of skull fractures for youth 2.5 times greater than adults (Bishop et al., 2014; Ommaya, 1995). A youth's skull and brain are smaller than an adult's skull and brain, causing different characteristics to contribute to risk of injury (Bishop et al., 2014; Koncan, 2018; Ommaya, 1995). A youth's brain mass is 800g, whereas an adult brain is 1400g (Bishop et al., 2014). A youth's brain is smaller and more resilient to applied impact forces and less susceptible to lower levels of rotational forces than larger adult brains (Bishop et al., 2014; Ommaya, 1995). However, the larger bulk modulus of the youth brain means there is little resistance to shear modulus, creating a larger susceptibility to angular motion, which is a contributor to concussive injuries (Bishop et al., 2014). Additionally, because a youth's brain has a smaller mass, youth are exposed to 1.78 times more acceleration when the same amount of force is applied to the head (Gimbel & Hoshizaki, 2008). The youth's brain (5-8 years old) is 57.1% of the mass of the adult brain. However, the volume of a youth's brain is a much larger percentage compared to an adult brain (Bishop et al., 2014; Koncan, 2018). At approximately six years of age, the brain is 90-95% of its mature volume, suggesting

that the predicted acceleration to injure a youth would be 3.5-7.3% higher when compared to an adult (Bishop et al., 2014; Koncan, 2018; Lenroot & Giedd, 2006; Reiss et al., 1996).

2.5.1.2 Brain Density

As a youth's brain develops, unique density changes occur as the tissues mature and essential neural pathways are created (Bishop et al., 2014; Koncan, 2018; Lenroot & Giedd, 2006; Maxwell, 2012; Ommaya, 1995; Reiss et al., 1996). In early adulthood, the white matter increases, and the grey matter decreases, which is associated with myelination within the cerebral cortex (Figure 1) (Lenroot & Giedd, 2006; Reiss et al., 1996). A larger proportion of the youth brain is occupied by unmyelinated gray matter, which is less stiff and more susceptible to injury than white matter (Coats, Margulies, & Ji, 2007; Jin, Zhu, Mao, Shen, & Yang, 2013; Koncan, 2018). Grey matter has been reported to be 1.2-1.6 times less stiff than white matter, meaning there are structural differences between the two types of brain matter, which affects density and their response to an impact (Bayly, Clayton, & Genin, 2012; Chatelin, Vappou, Roth, Raul, & Willinger, 2012; Clayton, Genin, & Bayly, 2012). The differences in percentages between mass and volume of a youth's brain highlighted above leave 32.9-37.9% of the brain mass unaccounted for which may mean that brain tissue density accounts for the additional brain mass during development. This would suggest a youth's brain (5-8 years old) would be 62.1-67.1% as dense when compared to an adult brain and have a lower shear modulus compared to adults making youth brains more susceptible to injury (Choe, Babikian, Difiori, Hovda, & Giza, 2012; Gilchrist, Thomas, Xu, McGuire, & Coronado, 2011; Lax et al., 2015; McClincy, Lovell, Pardini, Collins, & Spore, 2006).

2.5.1.3 Anthropometrics

Youth between the ages of 5 and 8 years old are anthropometrically different than adults (Fryar, Gu, Ogden, & Flegal, 2016; Pion et al., 2015). Youth have lower mass, height, and relative size than adults, anthropometrically each body part is significantly smaller than their adult counterparts (Fryar et al., 2016; Pion et al., 2015). Despite these differences, ice hockey helmets for youth are scaled-down models of adult helmets. The average mass of an adult head is 4.54 kg, while a youth head (5-8 years old) is 3.73 kg (Pion et al., 2015; Post et al., 2016). In standard testing for ice hockey helmets, head mass is accommodated by size of the helmet, but other impact parameters such as compliance and event types are not (ASTM F1045-16; Bishop, Kendall, Post, & Hoshizaki, 2014; CSA Z262.1-15: ISO 10256-2:2016). In ice hockey, the average adult ice hockey shoulder impact occurs with an estimated mass of 13.1 kg, and youth (5-8 years old) shoulder impacts have an estimated mass of 3.61 kg (Fryar et al., 2016; Karton et al., 2021; Meehan et al., 2019; Post et al., 2019; Rousseau & Hoshizaki, 2015). There are published shoulder to head test methods for adult ice hockey players, but not one representing youth (5-8 years old) (Meehan et al., 2019). No ice hockey helmet test method currently accommodates the unique anthropometric differences between youth and adult ice hockey players. This study considered the anthropometric differences observed between youth and adult ice hockey players and account for the differences in a youth specific testing method.

2.5.1.4 Brain injury risk and incidence

Youth and adults play ice hockey differently, and as a result the risk and incidence of injury differ. In the Learn to Play youth ice hockey age group, 51 games were recorded and analyzed with 411 head impacts (Karton et al., 2021). In professional ice hockey, 540 games were recorded and analyzed with 125 head impacts (Post et al., 2019). This difference in the

number of head impact events suggests that youth are exposed to a substantially higher number of head impacts and are at a higher risk for concussions when compared to adults (Choe et al., 2012; Fryar et al., 2016; Gilchrist et al., 2011; Lax et al., 2015; McClincy et al., 2006; Pion et al., 2015). Gimbel and Hoshizaki (2008) reported that youth could be exposed to higher amounts of impact accelerations due to lower brain and head mass compared to adults. The difference in mass may outweigh the differences in velocity, creating a greater susceptibility to brain injuries (Table 16). Since youth brains have unique density characteristics, they may have a higher or similar susceptibility to injury as adults at lower impact velocities (Koncan, 2018; Post, Hoshizaki, Gilchrist, et al., 2017; Post, Hoshizaki, Zemek, et al., 2017).

2.5.2 Play Style

Youth ice hockey is played differently than adult ice hockey. These differences may, in part, be explained by player development. As players get older and develop skill, they develop better balance, strength, agility, coordination, spatial awareness, and positioning leading to fewer falls (Robidoux et al., 2020). Frequencies of event types change from head impacts with hard surfaces (ice, boards, glass) to head to body impacts (shoulder and elbow) as the players get older and develop skill (Robidoux et al., 2020). Players learn to protect themselves and prevent their head from hitting hard surfaces during a fall (Robidoux et al., 2020). Due to limited skill and shorter heights at the Learn to Play age group level, the impact velocities are typically lower than in older age groups (Robidoux et al., 2020). In older players, unintentional collisions decrease as skill levels increase (Robidoux et al., 2020).

2.5.3 Impact Characteristics

At all levels of youth ice hockey, there are approximately 6.74 head impacts per game (Robidoux et al., 2020). Within the Learn to Play age group, which includes U7 (under 7 years

old) and U9 (under 9 years old) hockey players, there is an average of 8 head impacts per game (Karton et al., 2021; Robidoux et al., 2020). In the Learn to Play age group, the most common head impact event types are head to ice, head to boards, and shoulder to head (Karton et al., 2021; Robidoux et al., 2020). The majority of these head impacts occurred at velocities below 4 m/s and occurred most frequently at the front, front boss, side, and rear locations (Karton et al., 2021). As players age, the head impact event types, velocities, and locations change. In U18 hockey, the event types change from predominantly head to ice and head to boards impacts to head to shoulder, head to elbow, and head to glass impacts (Karton et al., 2021). In older age groups, a higher number of impact velocities between 4.00 and 8.00+ m/s are reported with more impacts occurring at the front, front boss, and side locations (Karton et al., 2021). In the National Hockey League (NHL), 88% of concussions were the result of contact with an opponent (Hutchison, Comper, Meeuwisse, & Echemendia, 2015a). In Learn to Play ice hockey, 52% of head impacts resulted from body to body contacts across all levels (Robidoux et al., 2020).

Impact compliance is the hardness of the impacting surface; a hard surface such as the ice or boards have a low compliance, whereas a soft surface such as a shoulder pad has a high compliance (De Grau et al., 2020; Rousseau & Hoshizaki, 2015). Low compliant impacting surfaces increase the duration of the impact (De Grau et al., 2020; Rousseau & Hoshizaki, 2015). With high compliant impacts the magnitude of linear and rotational acceleration decrease, however the increased duration of the event combined with the viscoelastic properties of brain tissue may still result in damage to brain tissue (De Grau, Post, Hoshizaki, & Gilchrist, 2019; De Grau et al., 2020; Gilchrist, 2003; Gennarelli, 1983; Willinger, Ryan, McLean, & Kopp, 1994). In adult ice hockey, impact durations (time) for head to boards, head to ice, and shoulder to head impacts are categorized as low (5ms), medium (15ms), and high (25ms) as it pertains to

protective capacities of helmets (De Grau et al., 2020; Post, Dawson, Hoshizaki, Gilchrist, & Cusimano, 2020; Rousseau & Hoshizaki, 2015). Rousseau and Hoshizaki (2015) replicated elbow to head and shoulder to head impacts by having adult ice hockey players impact a headform. This was used to determine the striking shoulder mass (14.6 percent of body mass) and compliance of the shoulder and shoulder pad by replicating the linear and rotational acceleration loading curves (Rousseau & Hoshizaki, 2015). Rousseau and Hoshizaki (2015) reported that ice hockey helmets are less effective at reducing the impact energies transferred to the head during high compliance impacts due to the increased duration of the impact (shoulder to head). Ice hockey helmets were less effective at reducing the forces applied to the head under high compliant impact conditions (De Grau et al., 2020; Rousseau & Hoshizaki, 2015).

2.6 *Helmet test Methods and Equipment*

In Learn to Play ice hockey, the head impact event types are similar, but the mechanism of injury different when compared to adult ice hockey. At this age, the most common types of high energy head impacts include: shoulder to head (36), head to ice (32), head to boards (16) (Karton et al., 2021; Robidoux et al., 2020). The most common types of concussive head impacts in adult ice hockey include shoulder to head (42), head to boards/glass (7), and head to ice (4) (Meehan et al., 2019; Post et al., 2019). Youth between the ages of 5-8 years have higher frequencies of head impacts because they lack skills in skating, balancing, and orienting themselves on the ice (Robidoux et al., 2020). In adult ice hockey, players fall less and sustain a lower amount of head impacts from falling because they have developed better skills such as skating, balancing, orienting themselves on the ice, and making intentional contact with their opponents (Robidoux et al. 2020).

The impact characteristics for each event type are different compared to adult ice hockey as youth have an average head mass of 3.73 kg versus an average adult head mass of 4.54 kg (Karton et al., 2021; Meehan et al., 2019; Post et al., 2019). Shoulder impact mass was calculated for youth as approximately 3.61 kg, and for adults as approximately 13.1 kg (Fryar et al., 2016; Karton et al., 2021; Meehan et al., 2019; Post et al., 2019). For the Learn to Play age group there were different impact velocities and impact locations. In adult competitive ice hockey, body contact is permitted resulting in a higher incidence of shoulder to head impacts (Hutchison, 2011; Hutchison et al., 2015a; Post et al., 2019). Standards reflect general impact parameters for a head to ice impact, but do not account for other head impact events including shoulder to head impacts and head to board impacts. Meehan and colleagues (2019) described three testing methods that represent the most common types of head impacts in adult competitive hockey (shoulder to head, head to boards/glass, and head to ice). In youth, the head impact event types are the same, so Meehan and colleague's (2019) general helmet test protocol was modified to account for the difference observed in youth hockey.

2.7 *Summary*

Youth are different than adults anthropometrically and physiologically. Concerning head injury in ice hockey a youth helmet test protocol should consider important characteristics that are different between youth and adults such as head and brain mass, brain density, and the less developed skull (Bayly, Clayton, & Genin, 2012; Bishop et al., 2014; Chatelin et al., 2012; Clayton, Genin, & Bayly, 2012; Gimbel & Hoshizaki, 2008). Youth's lower head and brain mass exposes youth to 1.78 times the amount of acceleration during a head impact (Gimbel & Hoshizaki, 2008). Youth's higher brain density, higher bulk modulus, and lower shear modulus of the brain increases the risk the detrimental axonal damage from shear forces increasing the

risk of sustain a concussion (Choe et al., 2012; Gilchrist et al., 2011; McClincy et al., 2006). Youth's developing skulls have a lower stiffness and young's modulus expose youth to a higher probability of skull fracture than adults, and a lower compliance of the skull itself during a head impact increasing the risk to head injuries (Bishop et al., 2014). When creating a youth helmet test protocol these key differences between youth and adults should be considered. An ice hockey helmet test protocol that reflects the impact mass, impact velocities, and impact compliance of youth ice hockey players with independent variables and the dependent variables that reflect the youth ice hockey environment has not been investigated. The unique head trauma characteristics experienced by youth when compared to adult ice hockey players warrants the investigation of a youth specific helmet test protocol.

CHAPTER 3: Methodology

3.1 *Youth helmet test protocol modifications*

The helmet test protocol included impact locations (4), mass (2), velocity (3), and compliance obtained from the literature (Table 4). The youth helmet test protocol was compared to a modified general helmet test protocol developed by Meehan and colleagues (2019), which employs adult impact parameters. In the youth helmet test protocol, the Hybrid III 5th percentile headform (3.73 kg) was used. This headform has been chosen because it represents the head mass (3.73kg) of youth between the ages of 5-8 years old (Pion et al., 2015; Post et al., 2016). The Hybrid III 50th percentile headform (4.54 kg) was used for all impacts in the general helmet test protocol. The youth shoulder mass was 3.61 kg to reflect the impacting mass of youth shoulder to head impacts compared to 13.1 kg used in general testing (Fryar et al., 2016; Karton et al., 2021; Meehan et al., 2019; Post et al., 2019). The effective impact mass for the youth shoulder was calculated by multiplying the average 50th percentile body masses for youth males (5-8 years old) by the percentage of body mass during a shoulder check (14.6%) in ice hockey (Fryar et al., 2016; Rousseau & Hoshizaki, 2015). These values were calculated from values published in the literature. To replicate youth shoulder to head impacts, a pendulum system was used with an impact velocity of 3.7 m/s and a mass of 3.61 kg. A CCM Jet Speed youth size medium shoulder pad was attached to a pendulum to represent youth shoulder to head impacts. This shoulder pad consisted of a hard plastic outer shell with a thin, soft liner on the inside (CCM Hockey, 2022). To replicate the adult shoulder to head impacts, the pendulum system was used with a velocity of 6.0 m/s and a mass of 13.1 kg. The shoulder pad that the pendulum was equipped with for the adult impacts was the Bauer supreme 190 senior size large. This shoulder pad consists of a hard plastic outer shell with a thin, soft liner on the inside (Bauer Hockey,

2022). The average size of a shoulder pad based on an average height (6'1") of adult national hockey league players is size large (Wendorf, 2015).

The compliance of the shoulder to head impacts for youth was estimated from impact data used in the adult helmet test protocol because youth specific impact compliance values were not available. Shoulder to head impacts in youth ice hockey are usually incidental and occur at around 3.7 m/s during the highest velocity shoulder to head impacts. In adult competitive ice hockey, body contact is allowed, and shoulder to head impacts are both incidental and intentional and occur at around 9.0 m/s during the highest velocity shoulder to head impacts. In this thesis, the mass of the impact was adjusted, as velocity values in this research for shoulder to head impacts were based on concussive events in professional ice hockey. Therefore, the velocity of 6.0 m/s was employed as the representative impact resulting in concussions in adult ice hockey players (Meehan et al., 2019; Post et al., 2019). The linear impactor cannot be adjusted to represent the youth shoulder mass of 3.61kg, therefore the linear impactor could not be used to reconstruct youth shoulder impacts (Fryar et al., 2016; Rousseau & Hoshizaki, 2015). The youth helmet test protocol employed impact velocities reflective of real-world head impacts within each event (Table 4). The highest velocity sustained in each event type category was obtained from 53 Learn to Play youth hockey games from the NSERC database from NISL.

3.2 *Test Apparatus*

3.2.1 *Monorail Drop Rig*

The monorail drop rig is a guided impact system used in ASTM F1045-16, CSA Z262.1-15, and ISO 10256-2:2016 ice hockey helmet standards. The monorail is a 4.7m rail secured to a concrete wall and floor. The drop rig employs the Cadex Impact Acquisition Software, where the impact velocity is set. Once the impact velocity has been entered, a motor sets the drop carriage

and headform to the correct drop height. The carriage and headform is released, creating a low friction guided free fall and the helmeted headform impacts an anvil. The anvil can be equipped with multiple surfaces to replicate head impacts on multiple surfaces. This thesis employed the flat MEP anvil and the 45-degree steel anvil, as the flat MEP anvil has similar material characteristics to ice in ice hockey and the 45-degree steel anvil has similar material characteristics to the boards in ice hockey (ASTM F1045-16; CSA Z262.1-15; ISO 10256-2:2016; Meehan et al., 2019; Post et al., 2019). The flat anvil drop test was used to replicate head to ice impacts. the angled anvil (45-degree steel anvil) drop test was used to replicate a fall resulting in a head to boards impact.

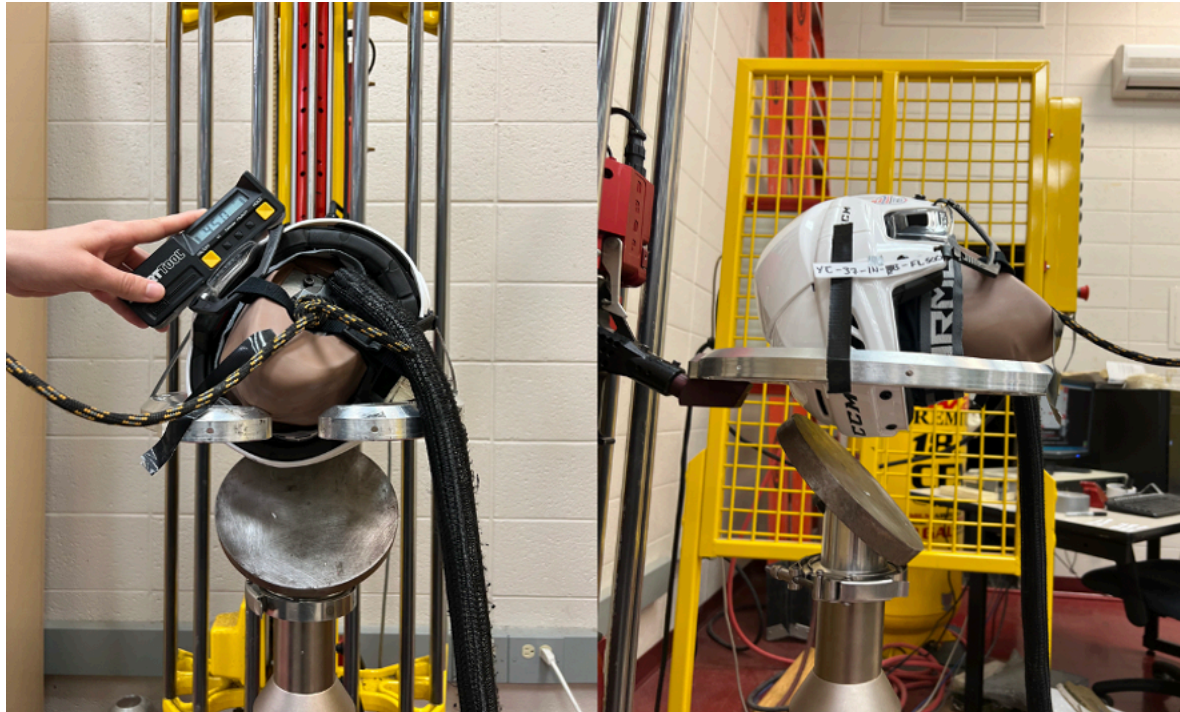


Figure 1. Monorail drop rig set up equipped with the 45° steel anvil.

3.2.2 Pendulum Drop

The pendulum system was composed of a hollow metal frame mass of 3.36 kg suspended with 3/32" aviation cable at 9.25 meters in length (Karton, Hoshizaki, & Gilchrist, 2014). The impact surface was composed of compliant striker caps equipped with certified youth shoulder

pads. The headform was attached to a sliding table with the unbiased neckform with 6 degrees of freedom (Karton, Hoshizaki, & Gilchrist, 2014; Post et al., 2016). The pendulum drop test is designed to be adjusted to represent the mass of both the adult and youth shoulders, so it was used to reconstruct shoulder impacts for both groups. The youth shoulder to head impacts occurred at the mass of 3.61 kg and a velocity of 3.7 m/s. The adult shoulder to head impacts were represented by a mass of 13.1 kg and a velocity of 6.0 m/s.



Figure 2. Pendulum drop rig set up.

3.2.3 Hybrid III Headform

The 5th percentile male Hybrid III headform with a mass of 3.73 kg was used for the youth helmet test protocol, and the 50th percentile male Hybrid III headform with a mass of 4.54 kg was employed for the general helmet test protocol (Meehan et al., 2019; Oeur, Gilchrist, & Hoshizaki, 2019; Pion et al., 2015; Post et al., 2016). The 5th percentile male headform represented Learn to Play ice hockey players as the size and geometry reflect youth between ages

6-11 (Oeur et al., 2019; Post et al., 2016). The 50th percentile male headform represented adult ice hockey players head size and geometry (Gurdjian, Lissner, Webster, Latimer, & Haddad, 1954; Oeur et al., 2019; Post et al., 2016). The Hybrid III headform was attached to an unbiased neckform (Post et al., 2016). The headform was equipped with nine Endevco 7264C-KTZ_2_300 accelerometers (Meggit, Irvine, USA) set up in the 3-2-2-2 array to measure linear and rotational accelerations (Horgan & Gilchrist, 2003; Post et al., 2016).



Figure 3. The Hybrid III 5th percentile headform (left) and the Hybrid III 50th percentile headform (right).

3.2.4 Ice Hockey Helmets

Two helmets were tested in this thesis: the CCM Tacks 710 and the CCM FL-500. The CCM Tacks 710 was chosen to represent the common construction, material characteristics, and average performance in the STAR rating system. The CCM Tacks 710 is a two-piece helmet with the R.E.D. system between the shell and liner made up of the D30 smart foam and a thin layer of I.Q. Shion comfort foam. The CCM FL 500 was chosen because of its unique construction, material characteristics, and high score in the STAR rating system. The CCM FL-500 is a two-piece helmet lined with multi density Vinyl Nitrile (VN) foams throughout the

helmet with D30 smart foam at the rear and side locations and a thin layer of I.Q. Shion comfort foam.



Figure 4. The CCM FL 500 size S/M (top) and the CCM Tacks 710 size S (bottom).

3.3 *Finite Element Modeling*

3.3.1 *University College Dublin Brain Trauma Model*

There are a number of finite element (FE) models to represent the adult brain (Horgan & Gilchrist, 2003), but few youth models. To replicate a youth's brain tissue properties, and geometry the UCDBTM V2.0 can be scaled to accommodate size differences between a youth and adult brain (Horgan & Gilchrist, 2003; Trotta et al., 2020). In this thesis, UCDBTM V2.0 was scaled to 95% to reflect the brain of players between 5-8 years old (Koncan, 2018; Lenroot

& Giedd, 2006; Reiss et al., 1996). UCDBTM V2.0 was designed based off UCDBTM V1.0 (Trotta et al., 2020). Several modifications were made in the creation of UCDBTM V2.0, such as defining the scalp to have sliding properties (Table 3) (Trotta et al., 2020). The mesh in UCDBTM V2.0 was also refined from 28 286 to 184 261 hexahedral elements to improve performance, and reduce element distortion (Trotta et al., 2020).

3.3.2 *Maximum Principal Strain*

To obtain maximum principal strain (MPS), an ABAQUS simulation software was used to calculate the magnitude of strain using the UCDBTM V2.0. When the simulations were complete, each head impact was individually analyzed. The peak maximum principal strain for the white and gray matter was selected and the highest value between each type of matter was used. For the MPS value to be included, the aspect ratio had to be below 3.00. If the ratio was above 3.00, the next highest peak was selected until an aspect ratio below 3.00 was achieved.

Chapter 4: Research Design

The research design of this thesis included 2 helmet types x 2 helmet test protocols (Table 6). 53 Learn to Play youth (5-8 years old) hockey games from the NISL database were analysed to obtain all confirmed head impacts logged for this age group. The three impact event categories with the highest incidents of head impacts (head to ice, head to boards, shoulder to head) were represented in this study. The testing method employed was a modified version of Meehan and colleagues (2019) helmet test protocol.

4.1 *Independent Variables (Helmet type, helmet test protocol)*

- 1) Helmet types (2)
 1. CCM Tacks 710 ice hockey helmet
 2. CCM FL-500 ice hockey helmet

2) Helmet Test Protocols (2) (Table 4)

1. Youth helmet test protocol (Learn to Play youth age group (LTP) (5-8 years old))

Head-to-boards (Headform: 5th Hybrid III)

- Mass: 3.73 kg
- Impact velocity: 3.7 m/s
- Impact Compliance: 45-degree metal anvil
- Impact location: Front, Front Boss, Side, and Rear.

Head-to-ice (Headform: 5th Hybrid III)

- Mass: 3.73 kg
- Impact velocity: 4.6 m/s
- Impact Compliance: flat MEP Anvil
- Impact location: Front, Side, Rear Boss, and Rear.

Head-to-shoulder (Headform: 5th Hybrid III)

- Mass: 3.61 kg
- Impact velocity: 4.1 m/s
- Impact Compliance: high compliance CCM Jet speed youth size
medium shoulder pad
- Impact location: Front, Front Boss Positive Azimuth, Side, and Rear
Boss Negative Azimuth.

2. General helmet test protocol (Meehan et al., 2019)

Head-to-boards (Headform: 50th Hybrid III)

- Mass: 4.54 kg
- Impact velocity: 6.0 m/s

- Impact Compliance: 45-degree metal anvil
- Impact location: Front, Front Boss, Side, and Rear.

Head-to-ice (Headform: 50th Hybrid III)

- Mass: 4.54kg
- Impact velocity: 5.0 m/s
- Impact Compliance: flat MEP Anvil
- Impact location: Front, Side, Rear Boss, and Rear.

Head-to-shoulder (Headform: 50th Hybrid III)

- Mass: 13.1kg
- Impact velocity: 6.0 m/s
- Impact Compliance: high compliance Bauer supreme 190 senior size large shoulder pad
- Impact location: Front, Front Boss Positive Azimuth, Side, and Rear Boss Negative Azimuth.

4.2 *Dependent Variables*

- Dynamic head response
 - Peak resultant linear acceleration (g)
 - Peak resultant rotational velocity (rad/s)
 - Peak resultant rotational acceleration (rad/s²)
- Brain tissue deformation
 - Maximum Principal Strain (MPS) UCDBTM V2.0 (Trotta et al., 2020)

4.3 *Null Hypotheses*

Comparison between youth and general helmet test protocol

1. There will be no significant difference between the youth helmet test protocol and the general helmet test protocol.
2. There will be no significant difference in peak resultant linear acceleration between the youth helmet test protocol and the general helmet test protocol for head to boards.
3. There will be no significant difference in peak resultant linear acceleration between the youth helmet test protocol and the general helmet test protocol for head to ice.
4. There will be no significant difference in peak resultant linear acceleration between the youth helmet test protocol and the general helmet test protocol for shoulder to head.
5. There will be no significant difference in peak resultant rotational velocity between the youth helmet test protocol and the general helmet test protocol for head to boards.
6. There will be no significant difference in peak resultant rotational velocity between the youth helmet test protocol and the general helmet test protocol for head to ice.
7. There will be no significant difference in peak resultant rotational velocity between the youth helmet test protocol and the general helmet test protocol for shoulder to head.
8. There will be no significant difference in peak resultant rotational acceleration between the youth helmet test protocol and the general helmet test protocol for head to boards.
9. There will be no significant difference in peak resultant rotational acceleration between the youth helmet test protocol and the general helmet test protocol for head to ice.
10. There will be no significant difference in peak resultant rotational acceleration between the youth helmet test protocol and the general helmet test protocol for shoulder to head.

11. There will be no significant difference in maximum principal strain between the youth helmet test protocol and the general helmet test protocol for head to boards.
12. There will be no significant difference in maximum principal strain between the youth helmet test protocol and the general helmet test protocol for head to ice.
13. There will be no significant difference in maximum principal strain between the youth helmet test protocol and the general helmet test protocol for shoulder to head.

Comparison between the youth and general helmet for the youth helmet test protocol

1. There will be no significant difference for the youth helmet test protocol between the two types of helmets.
2. There will be no significant difference in peak resultant linear acceleration for the youth helmet test protocol during head to boards impacts between the two types of helmets.
3. There will be no significant difference in peak resultant linear acceleration for the youth helmet test protocol during head to ice impacts between the two types of helmets.
4. There will be no significant difference in peak resultant linear acceleration for the youth helmet test protocol during head to shoulder impacts between the two types of helmets.
5. There will be no significant difference in peak resultant rotational velocity for the youth helmet test protocol during head to boards impacts between the two types of helmets.
6. There will be no significant difference in peak resultant rotational velocity for the youth helmet test protocol during head to ice impacts between the two types of helmets.
7. There will be no significant difference in peak resultant rotational velocity for the youth helmet test protocol during head to shoulder impacts between the two types of helmets.

8. There will be no significant difference in peak resultant rotational acceleration for the youth helmet test protocol during head to boards impacts between the two types of helmets.
9. There will be no significant difference in peak resultant rotational acceleration for the youth helmet test protocol during head to ice impacts between the two types of helmets.
10. There will be no significant difference in peak resultant rotational acceleration for the youth helmet test protocol during head to shoulder impacts between the two types of helmets.
11. There will be no significant difference in maximum principal strain for the youth helmet test protocol during head to boards impacts between the two types of helmets.
12. There will be no significant difference in maximum principal strain for the youth helmet test protocol during head to ice impacts between the two types of helmets.
13. There will be no significant difference in maximum principal strain for the youth helmet test protocol during head to shoulder impacts between the two types of helmets.

Comparison between the youth and general helmet for the general helmet test protocol

1. There will be no significant difference for the general helmet test protocol between the two types of helmets.
2. There will be no significant difference in peak resultant linear acceleration for the general helmet test protocol during head to boards impacts between the two types of helmets.
3. There will be no significant difference in peak resultant linear acceleration for the general helmet test protocol during head to ice impacts between the two types of helmets.

4. There will be no significant difference in peak resultant linear acceleration for the general helmet test protocol during head to shoulder impacts between the two types of helmets.
5. There will be no significant difference in peak resultant rotational velocity for the general helmet test protocol during head to boards impacts between the two types of helmets.
6. There will be no significant difference in peak resultant rotational velocity for the general helmet test protocol during head to ice impacts between the two types of helmets.
7. There will be no significant difference in peak resultant rotational velocity for the general helmet test protocol during head to shoulder impacts between the two types of helmets.
8. There will be no significant difference in peak resultant rotational acceleration for the general helmet test protocol during head to boards impacts between the two types of helmets.
9. There will be no significant difference in peak resultant rotational acceleration for the general helmet test protocol during head to ice impacts between the two types of helmets.
10. There will be no significant difference in peak resultant rotational acceleration for the general helmet test protocol during head to shoulder impacts between the two types of helmets.
11. There will be no significant difference in maximum principal strain for the general helmet test protocol during head to boards impacts between the two types of helmets.

12. There will be no significant difference in maximum principal strain for the general helmet test protocol during head to ice impacts between the two types of helmets.
13. There will be no significant difference in maximum principal strain for the general helmet test protocol during head to shoulder impacts between the two types of helmets.

4.4 *Statistical Analysis*

Prior to completing the statistical analysis, a two-way ANOVA was run for MPS to look for significance between the helmet test protocols and the helmet types. A two-way ANOVA was run followed by paired t-tests were run for each location within each event type for both the helmet test protocol comparison and the helmet comparisons within each helmet test protocol. If no significance was found the locations remained collapsed for the paired t-tests were conducted. If the paired t-test found significance with locations collapsed the locations were expanded and separate. Paired t-tests were conducted for each location to determine where the significance existed. The first paired t-tests were used to test for significant differences in MPS responses between the youth helmet test protocol and the general helmet test protocol within each impact event type. The second set of paired t-tests were used to test for significant differences in MPS responses between the CCM FL-500 and CCM Tacks 710 within each helmet test protocol. If significant differences were found, a secondary analysis was conducted which expands on the impact locations to determine where the significance exists. In this statistical analysis peak resultant linear acceleration, peak resultant rotational velocity, and peak resultant rotational acceleration were also tested for significance and for descriptive purposes only.

Chapter 5: Results

All comparisons were tested for significance using two-way ANOVAs for each dependent variable.

5.1 Mean Dynamic Head Response and MPS Helmet Test Protocol Comparison (ANOVA and T-tests)

Mean peak resultant linear acceleration, peak resultant rotational velocity, peak resultant rotational acceleration, and MPS were compared between the youth helmet test protocol and the general helmet test protocol in the head to ice, head to boards, and shoulder to head event types (Table 1).

Table 1. Comparison of the overall mean (± 1 standard deviation) dynamic head responses and brain tissue deformation values between the youth and general helmet test protocols for head to ice, head to boards, and shoulder to head impacts ($n=4$). Two-way ANOVAs tested for interactions between helmet test protocols ($\alpha = 0.05$). Comparisons were made using paired *t*-tests ($\alpha = 0.05$).

Event Types	Helmet Test Protocols	Dynamic Head Response			Brain Trauma Deformation
		Peak Res. Linear Acceleration (m/s^2)	Peak Res. Rotational Velocity (rads/s)	Peak Res. Rotational Acceleration ($rads/s^2$)	MPS (%)
Collapsed	Youth Helmet Test Protocol	72.37 (29.53)	24.29 (7.39)	4868.33 (2179.98)	0.38 (0.12)
	General Helmet Test Protocol	101.57 (20.83)	30.16 (10.38)	6443.13 (2598.95)	0.48 (0.07)
	p-value (ANOVA)	<0.001**	<0.001**	<0.001**	<0.001**
	p-value (paired T-test)	---	---	---	---
Head to Ice	Youth Helmet Test Protocol	111.54 (15.39)	22.34 (9.47)	5589.39 (3252.14)	0.52 (0.12)
	General Helmet Test Protocol	122.20 (21.30)	21.56 (9.46)	5208.99 (2619.35)	0.51 (0.04)
	p-value (ANOVA)	0.053	0.778	0.657	0.609
	p-value (paired T-test)	0.002**	0.426	0.211	0.628
Head to Boards	Youth Helmet Test Protocol	53.78 (5.13)	25.28 (6.04)	4507.81 (1280.63)	0.31 (0.03)

	General Helmet Test Protocol	91.26 (10.48)	34.45 (7.98)	7060.20 (2664.45)	0.47 (0.08)
	p-value (ANOVA)	<0.001**	<0.001**	<0.001**	<0.001**
	p-value (paired T-test)	---	---	---	---
	Youth Helmet Test Protocol	11.87 (1.70)	22.37 (6.84)	1308.06 (369.46)	0.13 (0.02)
Shoulder to Head	General Helmet Test Protocol	21.61 (5.25)	31.94 (5.16)	2042.00 (382.74)	0.25 (0.04)
	p-value (ANOVA)	<0.001**	<0.001**	<0.001**	<0.001**
	p-value (paired T-test)	---	---	---	---

Res.=Resultant; --- = interactions were found so collapsed T-test was not run; *=significant difference (p<0.05); **=significant difference (p<0.01).

The helmet test protocol comparison found that the youth helmet test protocol resulted in significantly lower values when compared to the general helmet test protocol for peak resultant linear acceleration (p<0.001), peak resultant rotational velocity (p<0.001), peak resultant rotational acceleration (p<0.001), and MPS (p<0.001) with the event types and locations collapsed (Figure 5). The helmet test protocol comparison found that the youth helmet test protocol resulted in significantly lower values when compared to the general helmet test protocol for peak resultant linear acceleration (p=0.002) in the head to ice condition in terms of the paired t-test with locations collapsed, so the locations were expanded to determine which locations were significant (Figure 5). The helmet test protocol comparison found that the youth helmet test protocol resulted in significantly lower values when compared to the helmet general test protocol for peak resultant linear acceleration (p<0.001), peak resultant rotational velocity (p<0.001), peak resultant rotational acceleration (p<0.001), and MPS (p<0.001) in the head to boards condition in terms of the two-way ANOVA with locations collapsed, so the locations were separated to determine which locations were significant (Figure 6). The helmet test protocol comparison found that the youth helmet test protocol resulted in significantly lower values when compared to the general helmet test protocol for peak resultant linear acceleration (p<0.001),

peak resultant rotational velocity ($p < 0.001$), peak resultant rotational acceleration ($p < 0.001$), and MPS ($p < 0.001$) in the shoulder to head condition in terms of the two-way ANOVA with locations collapsed, so the locations were expanded to determine which locations were significant (Figure 7).

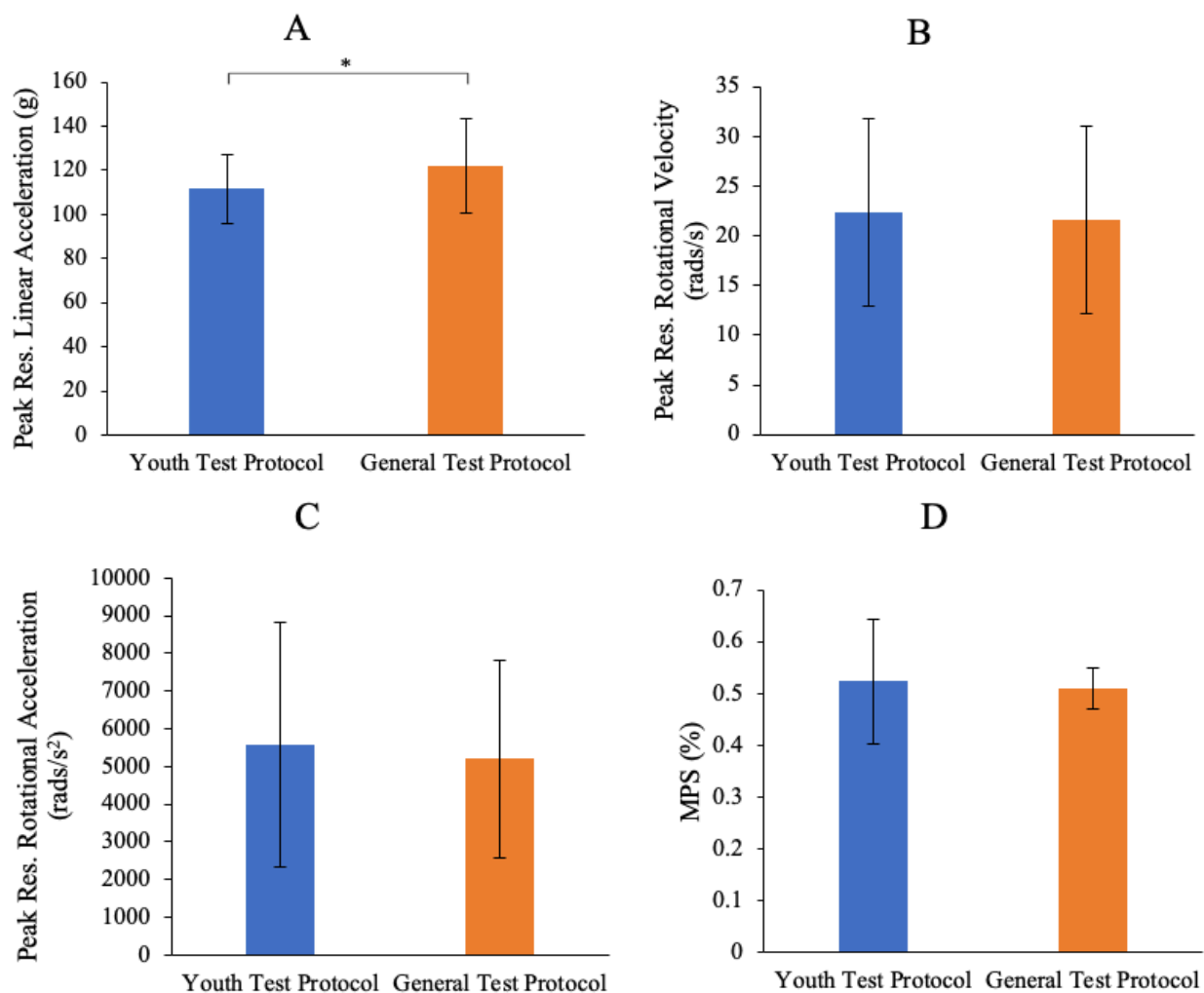


Figure 5. Comparison of the overall mean peak resultant linear acceleration (A), rotational velocity (B), rotational acceleration (C), and MPS (D) between the youth and general helmet test protocols for head to ice condition. Error bars denote ± 1 standard deviation. Significant differences are denoted by an asterisk (*).

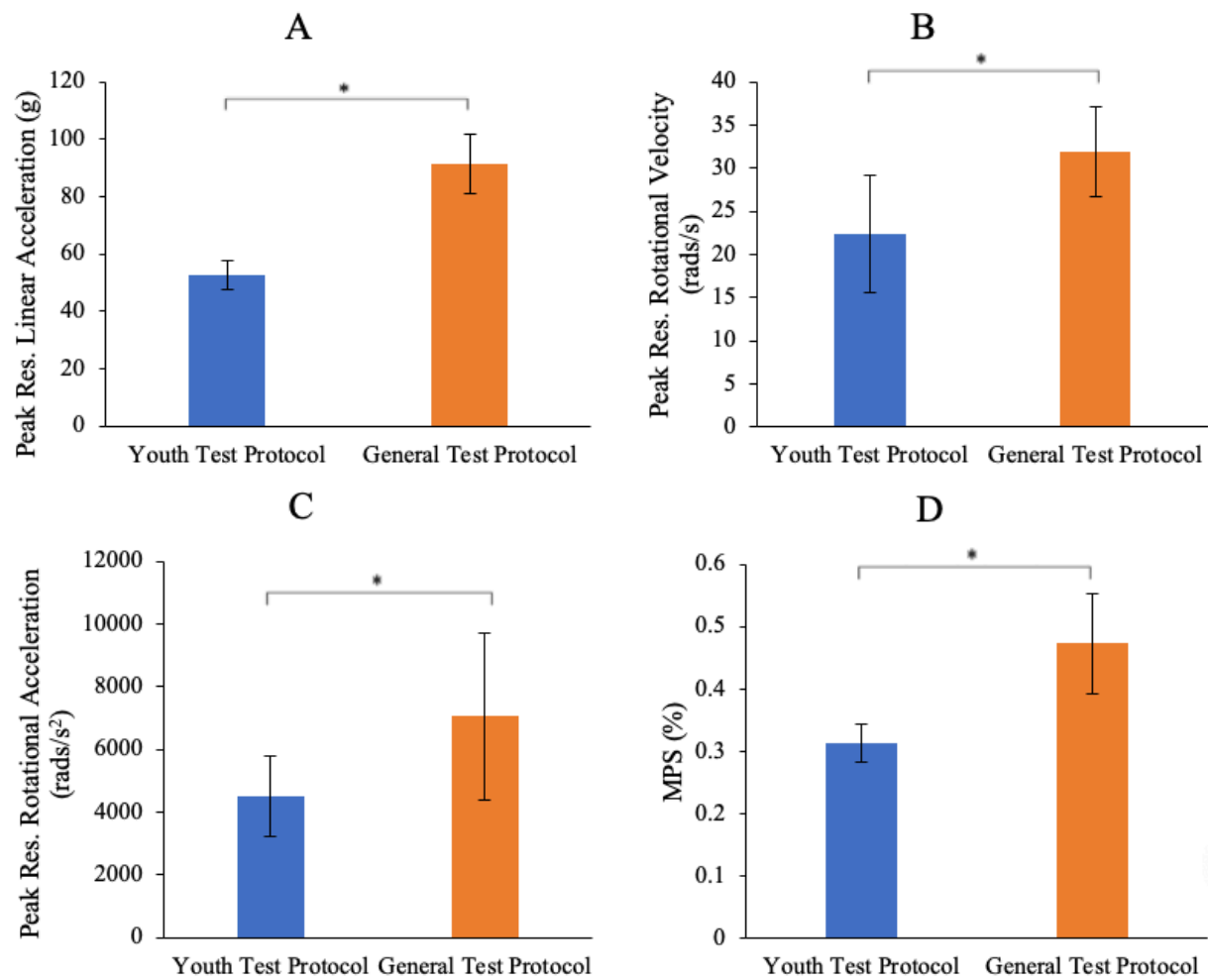


Figure 6. Comparison of the overall mean peak resultant linear acceleration (A), rotational velocity (B), rotational acceleration (C), and MPS (D) between the youth and general helmet test protocols for head to boards condition. Error bars denote ± 1 standard deviation. Significant differences are denoted by an asterisk (*).

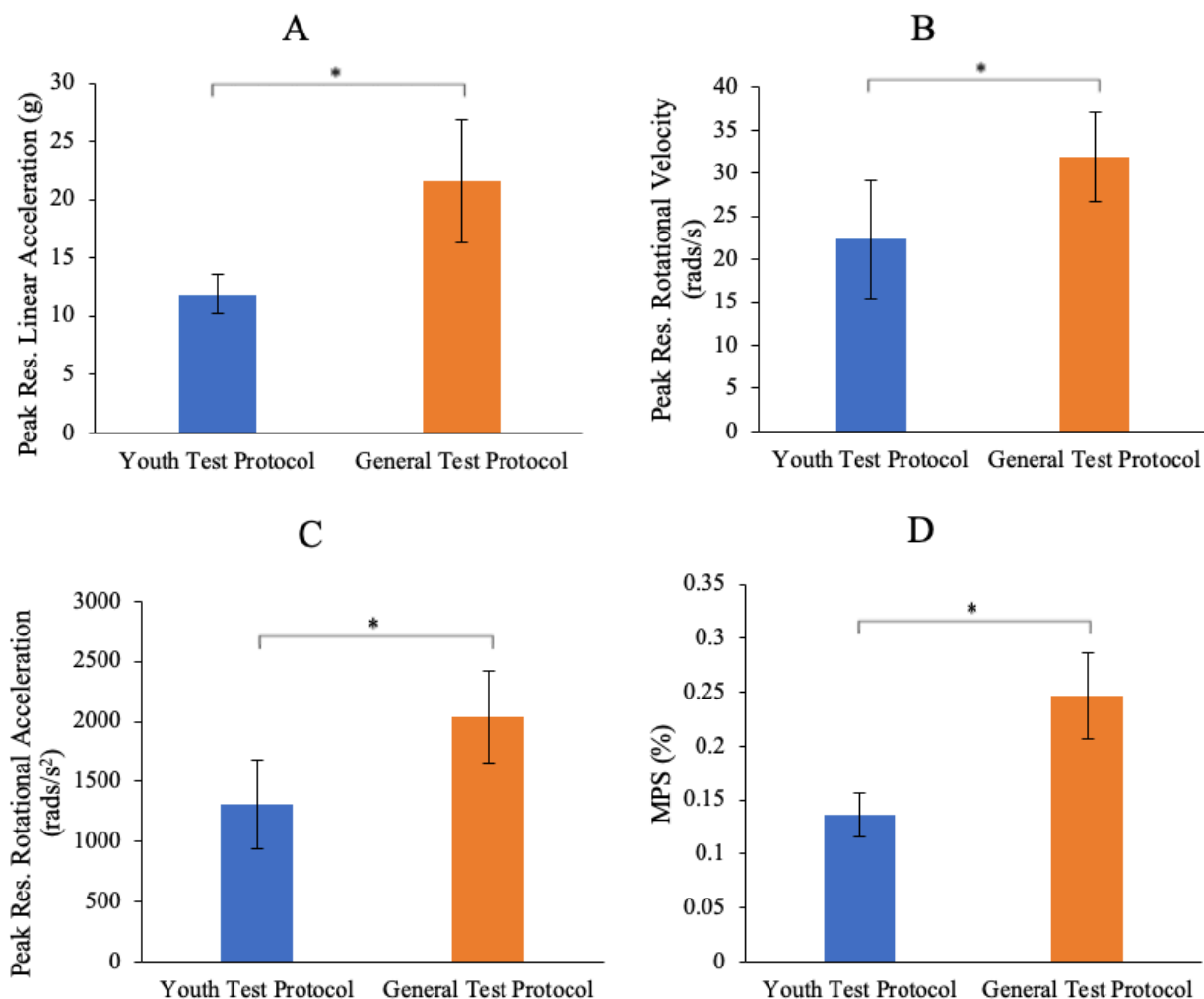


Figure 7. Comparison of the overall mean peak resultant linear acceleration (A), rotational velocity (B), rotational acceleration (C), and MPS (D) between the youth and general helmet test protocols for shoulder to head condition. Error bars denote ± 1 standard deviation. Significant differences are denoted by an asterisk (*).

The helmet test protocol comparison found that the youth helmet test protocol resulted in significantly lower values than the general helmet test protocol at the front location for peak resultant linear acceleration ($p=0.01$), peak resultant rotational velocity ($p<0.001$), peak resultant rotational acceleration ($p<0.001$), and MPS ($p=0.001$) in the head to ice condition (Table 2). The helmet test protocol comparison found that the youth helmet test protocol resulted in significantly lower values when compared to the general helmet test protocol at the side location

for peak resultant rotational velocity ($p < 0.001$), peak resultant rotational acceleration ($p < 0.001$), and MPS ($p < 0.001$) in the head to ice condition (Table 2). The helmet test protocol comparison found that the youth helmet test protocol resulted in significantly lower values when compared to the general helmet test protocol at the rear boss location for peak resultant rotational velocity ($p < 0.001$) and peak resultant rotational acceleration ($p = 0.043$) in the head to ice condition (Table 2). The helmet test protocol comparison found that the youth helmet test protocol resulted in significantly lower values when compared to the general helmet test protocol at the side location for MPS ($p = 0.017$) in the head to ice condition (Table 2).

Table 2. Comparison of the overall mean (± 1 standard deviation) dynamic head responses and brain tissue deformation between the youth and general helmet test protocols for the head to ice condition with the locations expanded. Comparisons were made using paired t-tests ($\alpha = 0.05$).

Head to Ice Impact Locations	Helmet Test Protocols	Dynamic Head Response			Brain Trauma Deformation	
		Peak Res. Linear Acceleration (m/s^2)	Peak Res. Rotational Velocity ($rads/s$)	Peak Res. Rotational Acceleration ($rads/s^2$)	MPS (%)	
Front	Youth Helmet Test Protocol	109.00 (4.50)	13.33 (0.66)	3056.83 (188.71)	0.41 (0.02)	
	General Helmet Test Protocol	134.20 (19.25)	9.93 (1.11)	2491.47 (208.81)	0.53 (0.03)	
	p-value	0.010*	<0.001**	<0.001**	0.001**	
	Side	Youth Helmet Test Protocol	127.30 (16.00)	34.97 (5.03)	10319.55 (2662.48)	0.71 (0.06)
		General Helmet Test Protocol	136.00 (15.65)	28.93 (4.09)	7972.17 (2150.29)	0.49 (0.02)
p-value		0.57	<0.001**	<0.001**	<0.001**	
Rear Boss		Youth Helmet Test Protocol	98.18 (9.32)	26.38 (2.53)	5590.40 (836.66)	0.47 (0.02)
		General Helmet Test Protocol	106.85 (19.70)	31.57 (1.78)	6648.88 (1523.79)	0.49 (0.02)
	p-value	0.290	<0.001**	0.043*	0.057	
	Rear	Youth Helmet Test Protocol	111.68 (14.37)	14.67 (1.18)	3390.78 (693.15)	0.51 (0.04)
		General Helmet Test Protocol	111.77 (16.39)	15.82 (1.85)	3723.47 (1188.01)	0.53 (0.05)

p-value	0.951	0.353	0.216	0.017*
---------	-------	-------	-------	--------

Res.=Resultant; *=significant difference (p<0.05); **=significant difference (p<0.01).

The helmet test protocol comparison found that the youth helmet test protocol had significantly lower values when compared to the general helmet test protocol at the front location for peak resultant linear acceleration (p<0.001), peak resultant rotational velocity (p=0.003), peak resultant rotational acceleration (p=0.004), and MPS (p<0.001) in the head to boards condition (Table 3). The helmet test protocol comparison found that the youth helmet test protocol resulted in significantly lower values when compared to the general helmet test protocol at the front boss location for peak resultant linear acceleration (p<0.001), peak resultant rotational velocity (p=0.007), peak resultant rotational acceleration (p=0.018), and MPS (p=0.006) in the head to boards condition (Table 3). The helmet test protocol comparison found that the youth helmet test protocol resulted in significantly lower values when compared to the general helmet test protocol at the side location for peak resultant linear acceleration (p<0.001), peak resultant rotational velocity (p<0.001), peak resultant rotational acceleration (p=0.012), and MPS (p=0.004) in the head to boards condition (Table 3). The helmet test protocol comparison revealed the youth helmet test protocol resulted in significantly lower values when compared to the general helmet test protocol at the front location for peak resultant linear acceleration (p<0.001), peak resultant rotational velocity (p<0.001), peak resultant rotational acceleration (p<0.001), and MPS (p<0.001) in the head to boards condition (Table 3).

Table 3. Comparison of the overall mean (± 1 standard deviation) dynamic head responses and brain tissue deformation between the youth and general helmet test protocols for the head to boards condition with the locations expanded. Comparisons were made using paired t-tests ($\alpha = 0.05$).

Head to Boards Impact Locations	Helmet Test Protocols	Dynamic Head Response			Brain Trauma Deformation
		Peak Res. Linear	Peak Res. Rotational	Peak Res. Rotational	MPS (%)

		Acceleration (m/s ²)	Velocity (rads/s)	Acceleration (rads/s ²)	
Front	Youth Helmet	55.35	22.58	3660.43	0.31
	Test Protocol	(2.43)	(1.93)	(322.39)	(0.01)
	General Helmet	96.90	27.87	5014.03	0.45
	Test Protocol	(6.06)	(4.08)	(683.30)	(0.04)
	p-value	<0.001**	0.003**	0.004**	<0.001**
Front Boss	Youth Helmet	47.80	27.02	4572.83	0.33
	Test Protocol	(2.98)	(4.44)	(1137.26)	(0.04)
	General Helmet	86.88	32.63	5925.00	0.49
	Test Protocol	(10.43)	(5.52)	(1860.50)	(0.12)
	p-value	<0.001**	0.007**	0.018*	0.006**
Side	Youth Helmet	51.73	32.80	6207.33	0.31
	Test Protocol	(3.02)	(2.92)	(847.34)	(0.01)
	General Helmet	89.78	45.13	10030.72	0.44
	Test Protocol	(7.16)	(5.77)	(3218.06)	(0.06)
	p-value	<0.001**	<0.001**	0.012*	0.004**
Rear	Youth Helmet	56.25	18.70	3590.63	0.30
	Test Protocol	(6.63)	(1.91)	(294.07)	(0.03)
	General Helmet	91.47	32.18	7271.03	0.52
	Test Protocol	(15.63)	(3.72)	(1076.94)	(0.040)
	p-value	<0.001**	<0.001**	<0.001**	<0.001**

Res.=Resultant; *=significant difference (p<0.05); **=significant difference (p<0.01).

The helmet test protocol comparison found that the youth helmet test protocol resulted in significantly lower values when compared to the general helmet test protocol at the front location for peak resultant linear acceleration (p<0.001), peak resultant rotational velocity (p<0.001), peak resultant rotational acceleration (p<0.001), and MPS (p=0.037) in the shoulder to head condition (Table 4). The helmet test protocol comparison found that the youth helmet test protocol resulted in significantly lower values when compared to the general helmet test protocol at the front boss positive azimuth location for peak resultant linear acceleration (p<0.001), peak resultant rotational velocity (p<0.001), peak resultant rotational acceleration (p<0.001), and MPS (p=0.023) in the shoulder to head condition (Table 4). The helmet test protocol comparison found that the helmet youth test protocol resulted in significantly lower values when compared to the general helmet test protocol at the side location for peak resultant linear acceleration

($p < 0.001$), peak resultant rotational velocity ($p < 0.001$), peak resultant rotational acceleration ($p < 0.001$), and MPS ($p < 0.001$) in the shoulder to head condition (Table 4). The helmet test protocol comparison found that the youth helmet test protocol resulted in significantly lower values when compared to the general helmet test protocol at the front location for peak resultant linear acceleration ($p < 0.001$), peak resultant rotational velocity ($p < 0.001$), peak resultant rotational acceleration ($p < 0.001$), and MPS ($p < 0.001$) in the shoulder to head condition (Table 4).

Table 4. Comparison of the overall mean (± 1 standard deviation) dynamic head responses and brain tissue deformation between the youth and general helmet test protocols for the shoulder to head condition with the locations expanded. Comparisons were made using paired *t*-tests ($\alpha = 0.05$).

Shoulder to Head Impact Locations	Helmet Test Protocols	Dynamic Head Response			Brain Trauma Deformation	
		Peak Res. Linear Acceleration (m/s^2)	Peak Res. Rotational Velocity (rads/s)	Peak Res. Rotational Acceleration ($rads/s^2$)	MPS (%)	
Front	Youth Helmet Test Protocol	9.97 (0.62)	12.5 (1.76)	767.99 (99.75)	0.10 (0.01)	
	General Helmet Test Protocol	24.63 (1.35)	24.95 (1.38)	1607.75 (71.21)	0.27 (0.01)	
	p-value	<0.001**	<0.001**	<0.001**	0.037*	
	Front Boss Positive Azimuth	Youth Helmet Test Protocol	13.18 (0.77)	22.77 (1.35)	1413.64 (165.29)	0.15 (0.02)
		General Helmet Test Protocol	23.52 (0.32)	32.75 (0.50)	1998.22 (54.15)	0.27 (0.01)
p-value		<0.001**	<0.001**	<0.001**	0.023*	
Side		Youth Helmet Test Protocol	13.62 (0.35)	23.17 (0.92)	1344.59 (90.85)	0.16 (0.004)
		General Helmet Test Protocol	25.22 (0.83)	32.27 (0.92)	1941.05 (28.42)	0.27 (0.01)
	p-value	<0.001**	<0.001**	<0.001**	<0.001**	
	Rear Boss Negative Azimuth	Youth Helmet Test Protocol	10.70 (0.75)	31.05 (1.06)	1706.02 (165.40)	0.14 (0.01)
		General Helmet Test Protocol	13.08 (2.51)	37.78 (4.38)	2621.00 (148.08)	0.18 (0.02)
p-value		<0.001**	<0.001**	<0.001**	<0.001**	

Res.=Resultant; *=significant difference ($p < 0.05$); **=significant difference ($p < 0.01$).

5.2 Mean Dynamic Head Responses and MPS Helmet Comparison (ANOVA and T-tests)

5.2.1 Youth Helmet Test Protocol

The CCM FL 500 and the CCM Tacks 710 were compared using the youth helmet test protocol for the head to ice, head to boards, and shoulder to head event types (Table 5). Mean peak resultant linear acceleration, peak resultant rotational velocity, peak resultant rotational acceleration, and MPS were the dependent variables.

Table 5. Comparison of the overall average (± 1 standard deviation) dynamic head responses and brain tissue deformation values between the CCM FL 500 and CCM Tacks 710 in the youth helmet test protocol for head to ice, head to boards, and shoulder to head impacts ($n=4$). Two-way ANOVAs tested for interactions between helmet test protocols ($\alpha = 0.05$). Comparisons were made using paired t -tests ($\alpha = 0.05$).

Event Types	Helmet Types	Dynamic Head Response			Brain Trauma Deformation
		Peak Res. Linear Acceleration (m/s^2)	Peak Res. Rotational Velocity (rads/s)	Peak Res. Rotational Acceleration ($rads/s^2$)	MPS (%)
Head to Ice	FL 500	102.69	20.72	4637.77	0.50
		(7.98)	(7.32)	(2150.51)	(0.10)
	Tacks 710	120.39	23.96	6541.01	0.55
		(16.15)	(11.32)	(3938.75)	(0.14)
	p-value (ANOVA)	0.003**	0.414	0.156	0.361
p-value (paired T-test)	---	0.023*	0.005**	0.012*	
Head to Boards	FL 500	50.55	23.77	4140.57	0.30
		(4.12)	(4.05)	(863.72)	(0.03)
	Tacks 710	55.02	26.77	4875.05	0.33
		(5.22)	(7.41)	(1545.59)	(0.03)
	p-value (ANOVA)	0.030*	0.229	0.165	0.026*
p-value (paired T-test)	---	0.040*	0.043*	---	
Shoulder to Head	FL 500	11.52	21.93	1280.02	0.13
		(1.74)	(7.36)	(401.99)	(0.03)
	Tacks 710	12.22	22.81	1336.09	0.14
		(1.66)	(6.57)	(349.44)	(0.02)
	p-value (ANOVA)	0.326	0.762	0.719	0.381
p-value (paired T-test)	0.010*	0.079	0.427	0.020*	

Res.=Resultant; --- = interactions were found so collapsed T-test was not run; *=significant difference ($p<0.05$); **=significant difference ($p<0.01$).

The results of the helmet comparison found that the CCM FL500 resulted in significantly lower values when compared to the CCM Tacks 710 for peak resultant linear acceleration ($p=0.003$) in the head to ice condition for the two-way ANOVA with locations collapsed, so the locations were expanded to determine which locations were significant (Figure 8). The results of the helmet comparison found that the CCM FL500 resulted in significantly lower values when compared to the CCM Tacks 710 for peak resultant rotational velocity ($p=0.023$), peak resultant rotational acceleration ($p=0.005$), and MPS ($p=0.012$) in the head to ice condition for the paired t-tests with locations collapsed, so the locations were expanded to determine which locations were significant (Figure 8). The results of the helmet comparison found that the CCM FL500 resulted in significantly lower values when compared to the CCM Tacks 710 for peak resultant linear acceleration ($p=0.03$), and MPS ($p=0.026$) in the head to boards condition for the two-way ANOVAs with locations collapsed, so the locations were expanded to determine which locations were significant (Figure 9). The results of the helmet comparison found that the CCM FL500 resulted in significantly lower values when compared to the CCM Tacks 710 for peak resultant rotational velocity ($p=0.04$) and peak resultant rotational acceleration ($p<0.043$) in the head to boards condition for the paired t-tests with locations collapsed, so the locations were expanded to determine which locations were significant (Figure 9). The results of the helmet comparison found that the CCM FL500 resulted in significantly lower values when compared to the CCM Tacks 710 for peak resultant linear acceleration ($p=0.01$), peak resultant rotational velocity ($p=0.079$), and MPS ($p=0.02$) in the shoulder to head condition for the paired t-tests with locations collapsed, so the locations were expanded to determine which locations were significant (Figure 10).

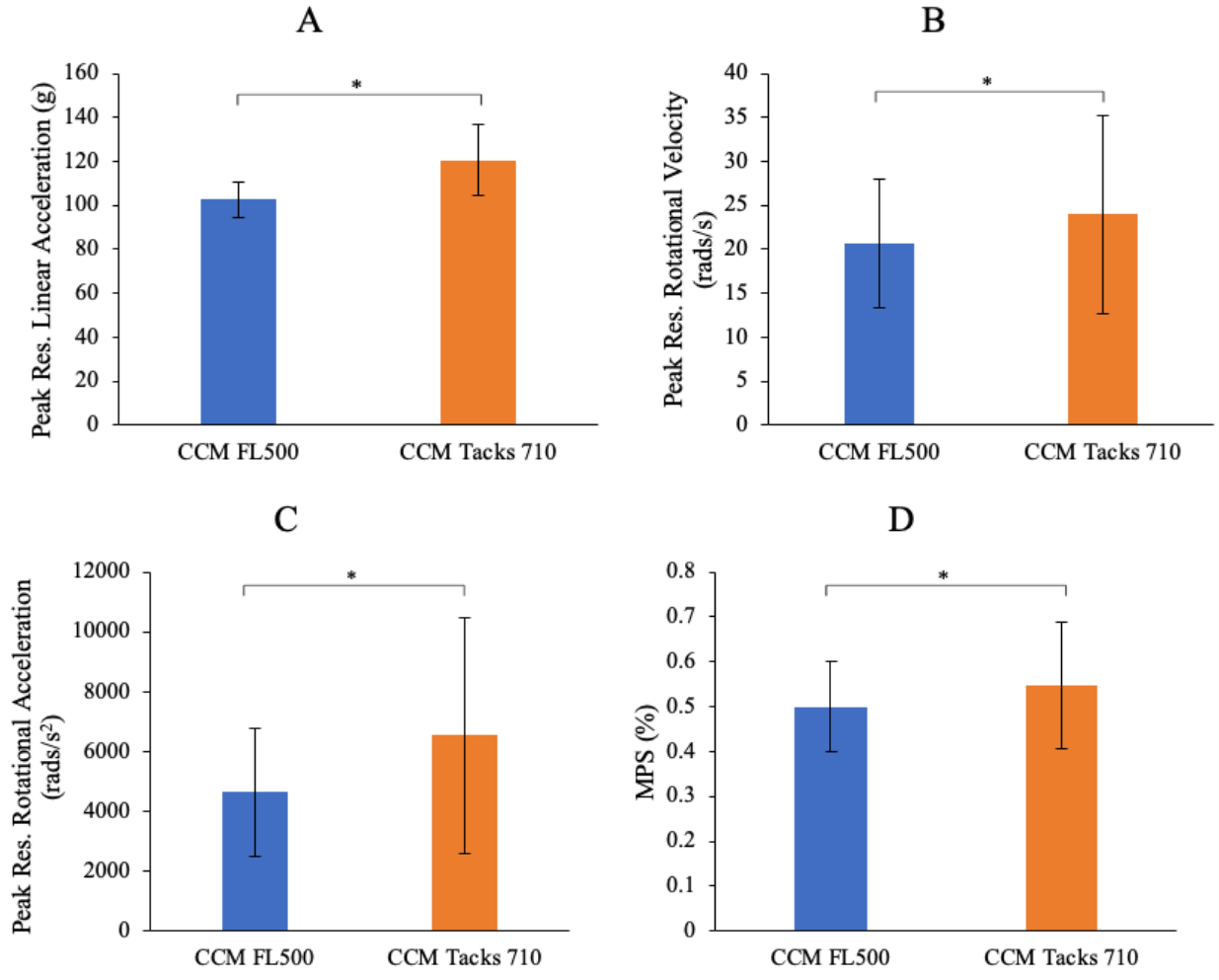


Figure 8. Comparison of the overall mean peak resultant linear acceleration (A), rotational velocity (B), rotational acceleration (C), for the CCM FL500 and CCM Tacks 710 helmets during the head to ice condition in the youth helmet test protocol. Error bars denote ± 1 standard deviation. Significant differences are denoted by an asterisk (*).

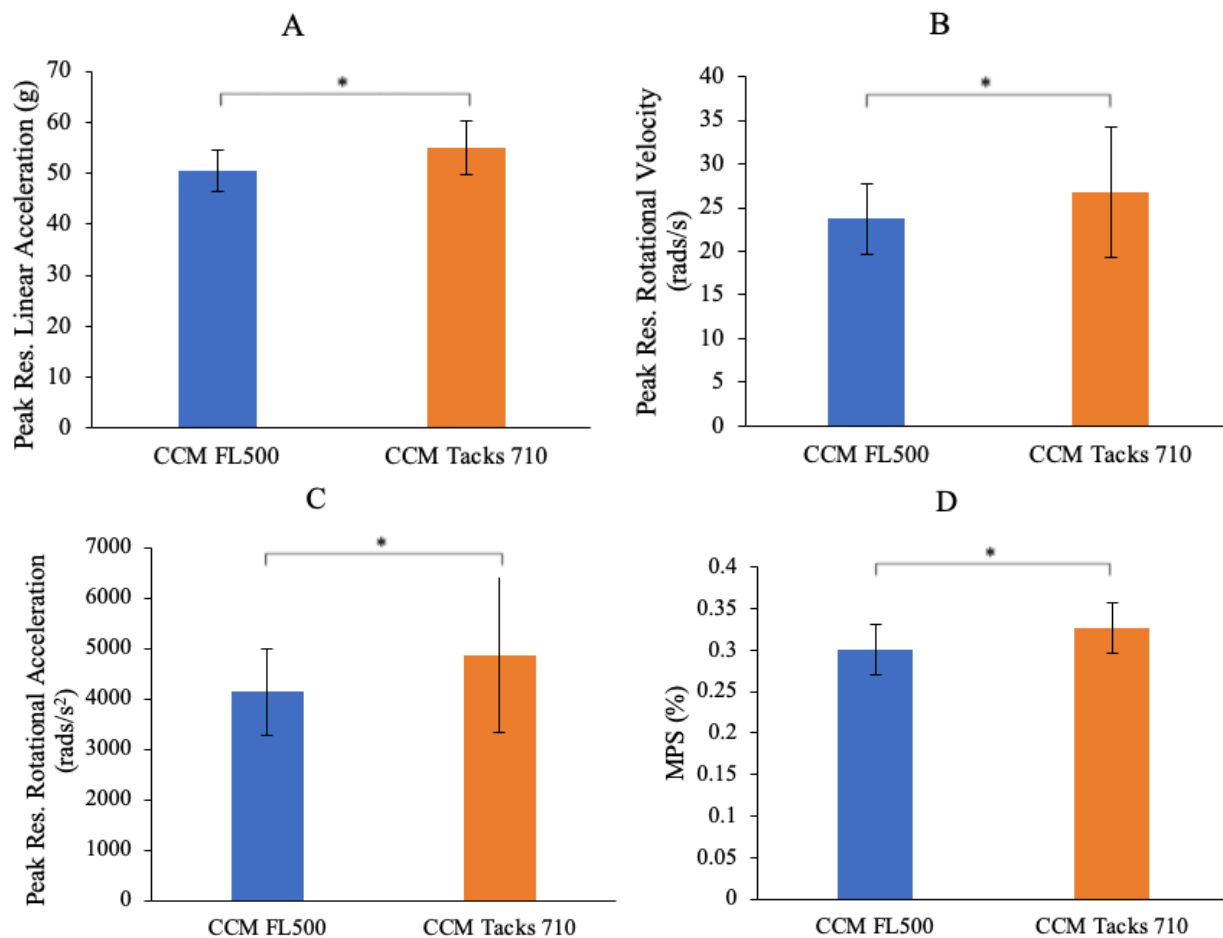


Figure 9. Comparison of the overall mean peak resultant linear acceleration (A), rotational velocity (B), rotational acceleration (C), and MPS (D) for the CCM FL 500 and CCM Tacks 710 helmets during the head to boards condition in the youth helmet test protocol. Error bars denote ± 1 standard deviation. Significant differences are denoted by an asterisk (*).

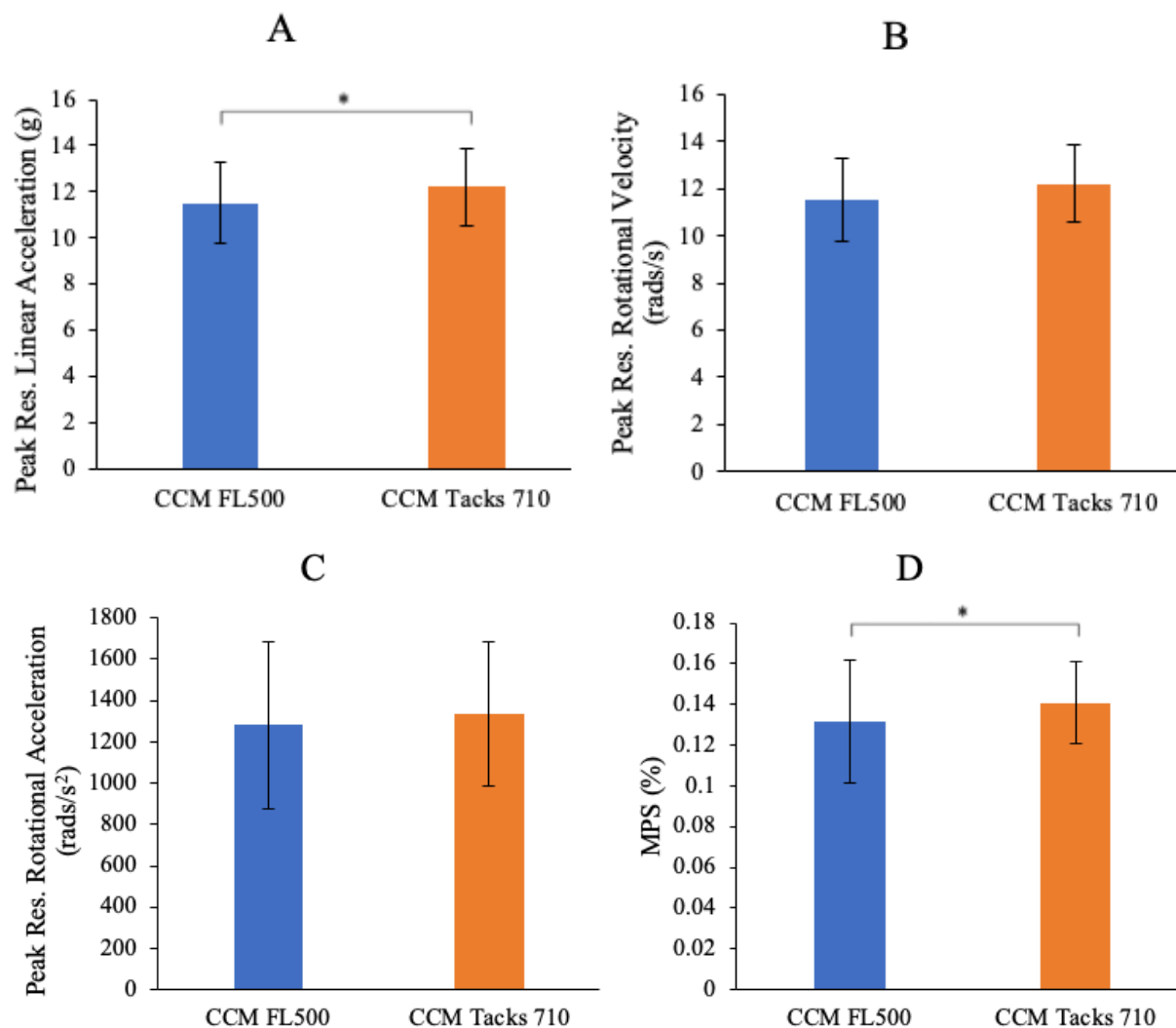


Figure 10. Comparison of the overall mean peak resultant linear acceleration (A), rotational velocity (B), rotational acceleration (C), and MPS (D) for the CCM FL 500 and CCM Tacks 710 helmets during the shoulder to head condition in the youth helmet test protocol. Error bars denote ± 1 standard deviation. Significant differences are denoted by an asterisk (*).

The results for helmet comparisons found that values for the CCM FL 500 were significantly lower than the CCM Tacks 710 in the youth helmet test protocol at the front location for peak resultant linear acceleration ($p=0.027$) and peak resultant rotational velocity ($p=0.005$) in the head to ice condition (Table 6). The results for helmet comparisons found that values for the CCM FL 500 were significantly lower than the CCM Tacks 710 in the youth helmet test protocol the side location for peak resultant linear acceleration ($p=0.009$), peak

resultant rotational velocity ($p=0.01$), peak resultant rotational acceleration ($p=0.002$), and MPS ($p=0.026$) in the head to ice condition (Table 6). The results for helmet comparisons found that values for the CCM FL 500 were significantly lower than the CCM Tacks 710 in the youth helmet test protocol at the rear boss location for peak resultant linear acceleration ($p<0.001$), peak resultant rotational velocity ($p<0.001$), peak resultant rotational acceleration ($p=0.012$), and MPS ($p=0.004$) in the head to ice condition (Table 6). The results for helmet comparisons found that values for the CCM FL 500 were significantly lower than the CCM Tacks 710 in the youth helmet test protocol at the rear location for peak resultant linear acceleration ($p=0.021$), peak resultant rotational acceleration ($p=0.048$), and MPS ($p=0.008$) in the head to ice condition (Table 6).

Table 6. Comparison of the overall average (± 1 standard deviation) dynamic head responses and brain tissue deformation between the CCM FL 500 and CCM Tacks 710 in the youth helmet test protocol for head to ice with the locations expanded. Comparisons were made using paired *t*-tests ($\alpha = 0.05$).

Head to Ice Impact Locations	Helmet Type	Dynamic Head Response			Brain Trauma Deformation
		Peak Res. Linear Acceleration (m/s^2)	Peak Res. Rotational Velocity ($rads/s$)	Peak Res. Rotational Acceleration ($rads/s^2$)	MPS (%)
Front	FL 500	105.13 (1.44)	12.93 (0.60)	2967.70 (85.96)	0.42 (0.01)
	Tacks 710	112.87 (1.90)	13.73 (0.50)	3145.97 (240.42)	0.41 (0.03)
	p-value	0.027*	0.005**	0.185	0.580
Side	FL 500	113.00 (4.33)	30.43 (0.83)	7897.53 (75.29)	0.65 (0.04)
	Tacks 710	141.60 (2.77)	39.50 (0.92)	12741.57 (343.33)	0.76 (0.01)
	p-value	0.009**	0.010*	0.002**	0.026*
Rear Boss	FL 500	93.40 (1.97)	24.17 (0.21)	4896.37 (181.57)	0.46 (0.01)
	Tacks 710	102.97 (12.04)	28.60 (1.13)	6284.43 (521.52)	0.47 (0.03)
	p-value	0.291	0.017*	0.041*	0.508
Rear	FL 500	99.23	15.33	2789.49	0.47

	(3.09)	(0.40)	(206.30)	(0.02)
Tacks 710	124.13	14.00	3992.07	0.54
	(6.45)	(1.41)	(271.88)	(0.01)
p-value	0.021*	0.245	0.048*	0.008**

Res.=Resultant; *=significant difference ($p<0.05$); **=significant difference ($p<0.01$).

The helmet comparisons found that the kinematic and strain values for the CCM FL 500 were significantly lower than the CCM Tacks 710 in the youth helmet test protocol at the front location for peak resultant linear acceleration ($p=0.049$) in the head to boards condition (Table 7). The helmet comparisons found that the kinematic and strain values for the CCM FL 500 were significantly lower than the CCM Tacks 710 in the youth helmet test protocol the front boss location for peak resultant rotational velocity ($p=0.009$), peak resultant rotational acceleration ($p=0.030$), and MPS ($p=0.039$) in the head to boards condition (Table 7). The helmet comparisons found that the kinematic and strain values for the CCM FL 500 were significantly lower than the CCM Tacks 710 in the youth helmet test protocol at the side location for peak resultant rotational velocity ($p=0.001$) and peak resultant rotational acceleration ($p=0.039$) in the head to boards condition (Table 7). The helmet comparisons found that the kinematic and strain values for the CCM FL 500 were significantly lower than the CCM Tacks 710 in the youth helmet test protocol at the rear location for peak resultant linear acceleration ($p=0.008$) in the head to boards condition (Table 7).

Table 7. Comparison of the overall average (± 1 standard deviation) dynamic head responses and brain tissue deformation between the CCM FL 500 and CCM Tacks 710 in the youth helmet test protocol for head to boards with the locations expanded. Comparisons were made using Paired T-tests ($\alpha = 0.05$).

Head to Boards Impact Locations	Helmet Type	Dynamic Head Response			Brain Trauma Deformation
		Peak Res. Linear Acceleration (m/s^2)	Peak Res. Rotational Velocity (rads/s)	Peak Res. Rotational Acceleration ($rads/s^2$)	MPS (%)
Front	FL 500	56.23 (2.11)	21.53 (0.12)	3834.63 (405.64)	0.30 (0.010)

	Tacks 710	54.47 (2.81)	23.63 (2.44)	3486.23 (65.21)	0.32 (0.000)
	p-value	0.049*	0.290	0.327	0.130
Front Boss	FL 500	46.03 (1.46)	23.10 (0.44)	3590.80 (255.30)	0.31 (0.03)
	Tacks 710	49.57 (3.28)	30.93 (1.77)	5554.87 (524.48)	0.35 (0.05)
	p-value	0.307	0.009**	0.030*	0.039*
	FL 500	49.63 (2.54)	30.17 (0.64)	5476.33 (430.00)	0.31 (0.02)
Side	Tacks 710	53.83 (1.76)	35.43 (0.35)	6938.33 (83.72)	0.31 (0.01)
	p-value	0.219	0.001**	0.039*	0.667
	FL 500	50.30 (0.26)	20.27 (1.33)	3660.50 (269.40)	0.28 (0.03)
Rear	Tacks 710	62.20 (1.87)	17.13 (0.06)	3520.76 (359.12)	0.33 (0.02)
	p-value	0.008**	0.052	0.240	0.107

Res.=Resultant; *=significant difference (p<0.05); **=significant difference (p<0.01).

The helmet comparisons found that the kinematic and strain values for the CCM FL 500 were significantly lower than the CCM Tacks 710 in the youth helmet test protocol at the front location for peak resultant rotational velocity (p=0.013) and peak resultant rotational acceleration (p=0.006) in the shoulder to head condition (Table 8). The helmet comparisons found that the kinematic and strain values for the CCM FL 500 were significantly lower than the CCM Tacks 710 in the youth helmet test protocol at the front boss positive azimuth location for peak resultant linear acceleration (p=0.002), peak resultant rotational velocity (p<0.001), and peak resultant rotational acceleration (p=0.012) in the shoulder to head condition (Table 8). The helmet comparisons found that the kinematic and strain values for the CCM FL 500 were significantly lower than the CCM Tacks 710 in the youth helmet test protocol at the side location for peak resultant rotational velocity (p=0.004) and peak resultant rotational acceleration (p=0.017) in the shoulder to head condition (Table 8). The helmet comparisons found that the kinematic and strain values for the CCM FL 500 were significantly lower than the CCM Tacks 710 in the youth

helmet test protocol at the rear boss negative azimuth location for peak resultant rotational velocity ($p=0.043$) in the shoulder to head condition (Table 8).

Table 8. Comparison of the overall average (± 1 standard deviation) dynamic head responses and brain tissue deformation between the CCM FL 500 and CCM Tacks 710 in the youth helmet test protocol for shoulder to head with the locations expanded. Comparisons were made using paired *t*-tests ($\alpha = 0.05$).

Shoulder to Head Impact Locations	Helmet Type	Dynamic Head Response			Brain Trauma Deformation
		Peak Res. Linear Acceleration (m/s ²)	Peak Res. Rotational Velocity (rads/s)	Peak Res. Rotational Acceleration (rads/s ²)	MPS (%)
Front	FL 500	9.8 (0.92)	11.70 (1.77)	750.93 (80.60)	0.10 (0.01)
	Tacks 710	10.13 (0.16)	22.73 (0.40)	1283.23 (27.22)	0.10 (0.01)
	p-value	0.590	0.013*	0.006**	0.184
Front Boss Positive Azimuth	FL 500	12.53 (0.35)	13.30 (1.64)	785.03 (132.31)	0.14 (0.02)
	Tacks 710	13.83 (0.31)	23.60 (1.25)	1405.94 (92.73)	0.15 (0.01)
	p-value	0.002**	<0.001**	0.012*	0.300
Side	FL 500	13.60 (0.20)	21.83 (0.21)	1268.11 (34.94)	0.16 (0.000)
	Tacks 710	13.63 (0.52)	31.47 (0.91)	1817.80 (162.42)	0.16 (0.01)
	p-value	0.874	0.004**	0.017*	0.423
Rear Boss Negative Azimuth	FL 500	10.13 (0.60)	23.70 (1.39)	1559.17 (59.52)	0.13 (0.01)
	Tacks 710	11.27 (0.29)	30.63 (1.22)	1594.23 (67.26)	0.14 (0.01)
	p-value	0.154	0.043*	0.667	0.225

Res.=Resultant*=significant difference ($p<0.05$); **=significant difference ($p<0.01$).

5.2.2 General Helmet Test Protocol

The CCM FL 500 and the CCM Tacks 710 were compared using the general helmet test protocol for the head to ice, head to boards, and shoulder to head event types (Table 9). Mean peak resultant linear acceleration, peak resultant rotational velocity, peak resultant rotational acceleration, and MPS were the dependent variables.

Table 9. Comparison of the overall average (± 1 standard deviation) dynamic head responses and brain tissue deformation values between the CCM FL 500 and CCM Tacks 710 in the general helmet test protocol for head to ice, head to boards, and shoulder to head impacts ($n=4$). Two-way ANOVAs tested for interactions between helmet test protocols ($\alpha = 0.05$). Comparisons were made using paired t -tests ($\alpha = 0.05$).

Event Types	Helmet Types	Dynamic Head Response			Brain Trauma Deformation
		Peak Res. Linear Acceleration (m/s^2)	Peak Res. Rotational Velocity (rads/s)	Peak Res. Rotational Acceleration ($rads/s^2$)	MPS (%)
Head to Ice	FL 500	107.10	19.77	4096.56	0.48
		(15.26)	(8.77)	(1707.58)	(0.03)
	Tacks 710	137.31	23.36	6321.43	0.54
		(14.76)	(10.16)	(2954.65)	(0.04)
	p-value (ANOVA)	<0.001**	0.364	0.034*	<0.001**
p-value (paired T-test)	---	<0.001**	---	---	
Head to Boards	FL 500	84.18	31.60	5761.71	0.44
		(9.23)	(5.72)	(1169.94)	(0.06)
	Tacks 710	98.33	37.31	8358.68	0.51
		(5.92)	(9.10)	(3129.94)	(0.07)
	p-value (ANOVA)	<0.001**	0.079	0.013*	0.014*
p-value (paired T-test)	---	0.004**	---	---	
Shoulder to Head	FL 500	20.76	31.32	2049.40	0.24
		(6.00)	(3.71)	(347.08)	(0.05)
	Tacks 710	22.46	32.56	2034.61	0.25
		(4.49)	(6.42)	(430.93)	(0.04)
	p-value (ANOVA)	0.438	0.568	0.927	0.602
p-value (paired T-test)	0.015*	0.283	0.714	0.168	

Res.=Resultant; --- = interactions were found so collapsed T-test was not run; *=significant difference ($p<0.05$); **=significant difference ($p<0.01$).

The helmet comparisons found that the kinematic and strain values for the CCM FL 500 were significantly lower than the CCM Tacks 710 in the general helmet test protocol for peak resultant linear acceleration ($p<0.001$), peak resultant rotational acceleration ($p=0.034$), and MPS ($p<0.001$) in the head to ice condition in terms of the two-way ANOVA with locations collapsed, so the locations were expanded to determine which locations were statistically significant (Figure 11). The helmet comparisons found that the kinematic and strain values for the CCM FL 500

were significantly lower than the CCM Tacks 710 in the general helmet test protocol for peak resultant rotational velocity ($p < 0.001$) in the head to ice condition in terms of the paired t-tests with locations collapsed, so the locations were expanded to determine which locations were significant (Figure 11). The helmet comparisons found that the kinematic and strain values for the CCM FL 500 were significantly lower than the CCM Tacks 710 in the general helmet test protocol for peak resultant linear acceleration ($p < 0.001$), peak resultant rotational acceleration ($p = 0.013$), and MPS ($p = 0.014$) in the head to boards condition in terms of the two-way ANOVAs with locations collapsed, so the locations were expanded to determine which locations were significant (Figure 12). The helmet comparisons found that the kinematic and strain values for the CCM FL 500 were significantly lower than the CCM Tacks 710 in the general helmet test protocol for peak resultant rotational velocity ($p < 0.004$) in the head to boards condition in terms of the paired t-tests with locations collapsed, so the locations were expanded to determine which locations were significant (Figure 12). The helmet comparisons found that the kinematic and strain values for the CCM FL 500 were significantly lower than the CCM Tacks 710 in the general helmet test protocol for peak resultant linear acceleration ($p = 0.015$) in the shoulder to head condition in terms of the paired t-tests with locations collapsed, so the locations were expanded to determine which locations were significant (Figure 13).

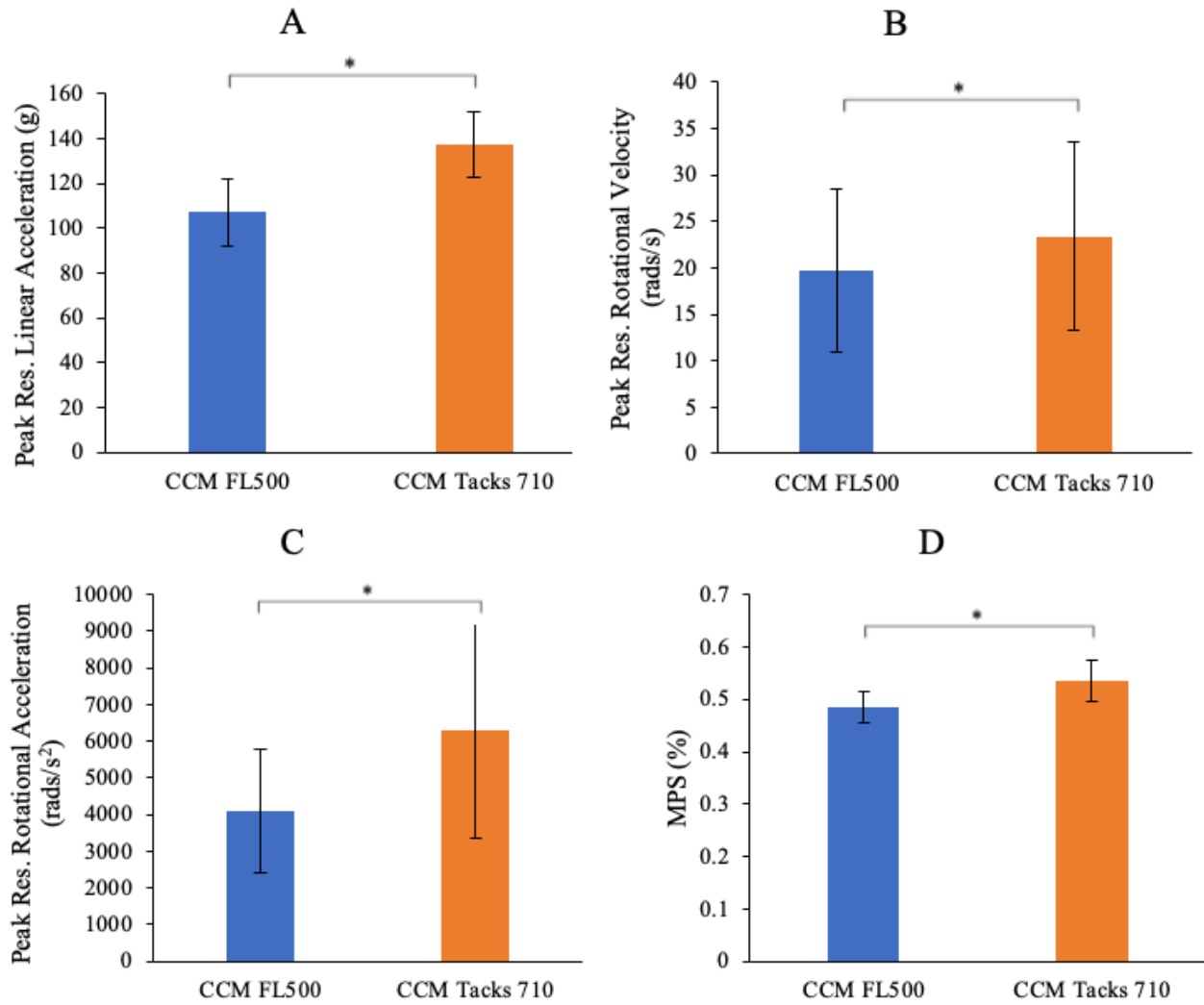


Figure 11. Comparison of the overall mean peak resultant linear acceleration (A), rotational velocity (B), rotational acceleration (C), and MPS (D) for the CCM FL 500 and CCM Tacks 710 helmets during the head to ice condition in the general helmet test protocol. Error bars denote ± 1 standard deviation. Significant differences are denoted by an asterisk (*).

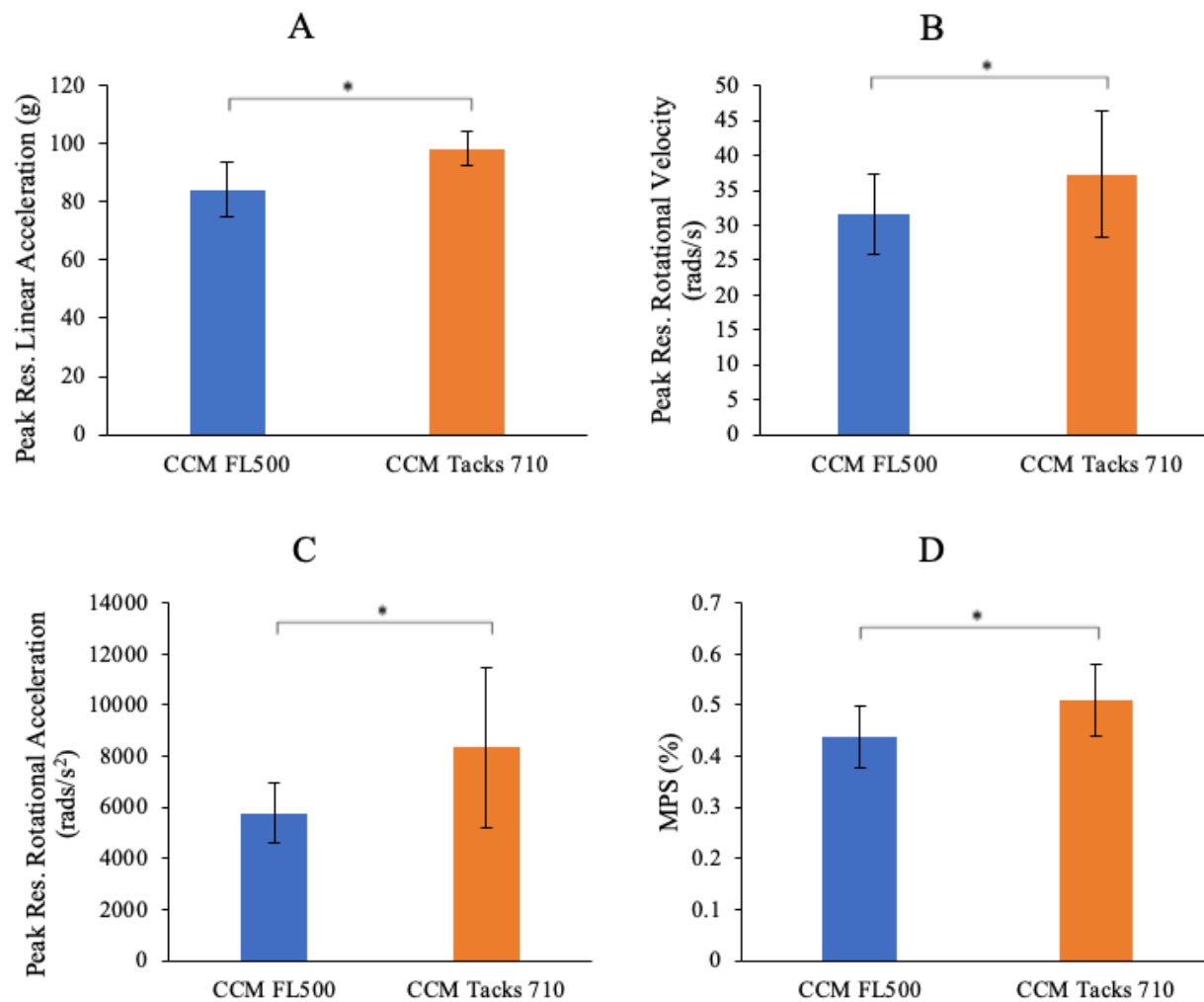


Figure 12. Comparison of the overall mean peak resultant linear acceleration (A), rotational velocity (B), rotational acceleration (C), and MPS (D) for the CCM FL 500 and CCM Tacks 710 helmets during the head to boards condition in the general helmet test protocol. Error bars denote ± 1 standard deviation. Significant differences are denoted by an asterisk (*).

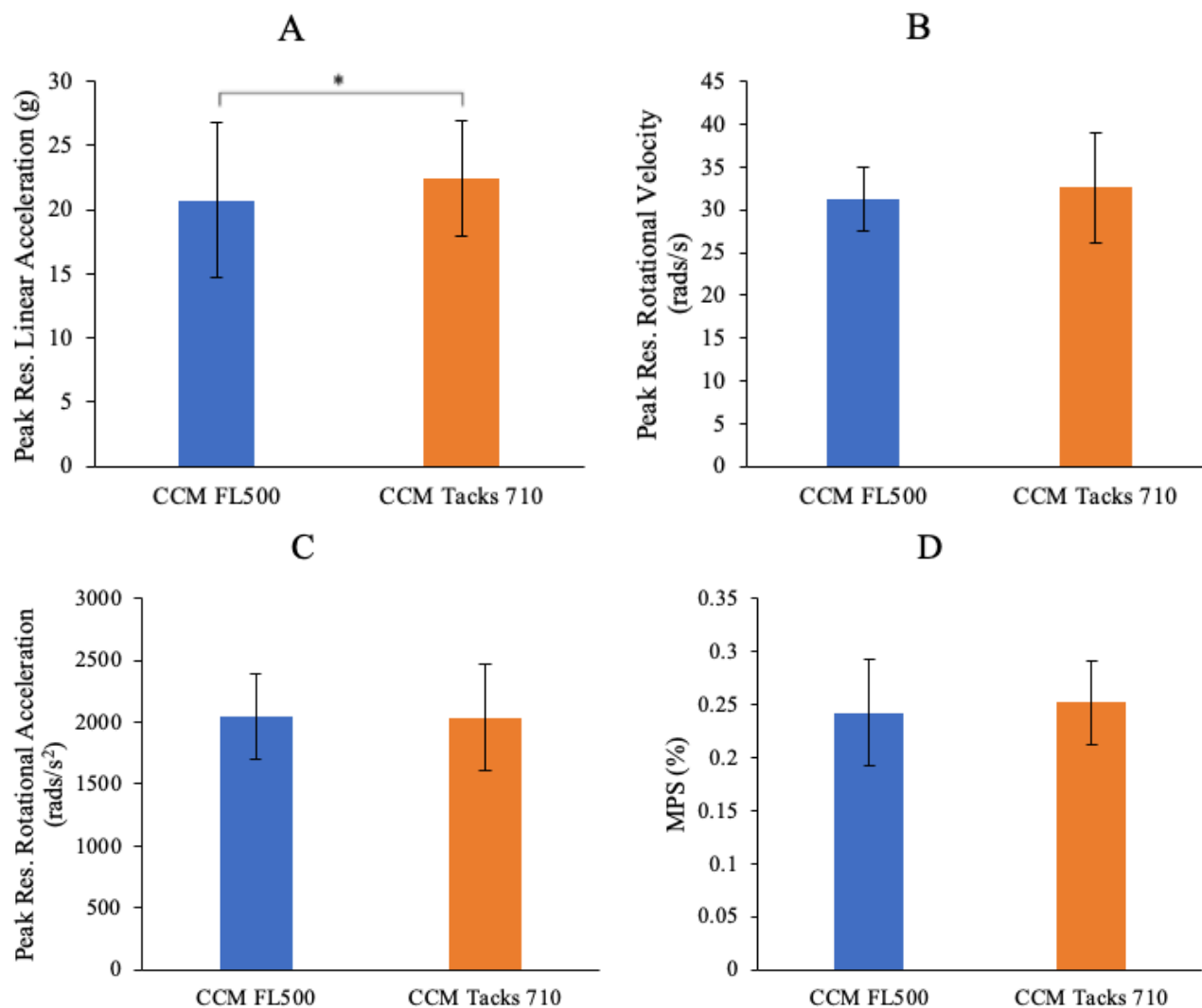


Figure 13. Comparison of the overall mean peak resultant linear acceleration (A), rotational velocity (B), rotational acceleration (C), and MPS (D) for the CCM FL 500 and CCM Tacks 710 helmets during the shoulder to head condition in the general helmet test protocol. Error bars denote ± 1 standard deviation. Significant differences are denoted by an asterisk (*).

The results of the helmet comparison found that the CCM FL 500 values were significantly lower than the CCM Tacks 710 in the general helmet test protocol at the front location for peak resultant linear acceleration ($p=0.006$) in the head to ice condition (Table 10). The results of the helmet comparison found that the CCM FL 500 were significantly lower than the CCM Tacks 710 in the general helmet test protocol, the side location for peak resultant rotational velocity ($p=0.034$) and peak resultant rotational acceleration ($p=0.032$) in the head to

ice condition (Table 10). The results of the helmet comparison found that the CCM FL 500 were significantly lower than the CCM Tacks 710 in the general helmet test protocol at the rear boss location for peak resultant linear acceleration ($p=0.035$), peak resultant rotational velocity ($p=0.021$), and peak resultant rotational acceleration ($p=0.008$) in the head to ice condition (Table 10). The results of the helmet comparison found that the CCM FL 500 were significantly lower than the CCM Tacks 710 in the general helmet test protocol at the rear location for peak resultant linear acceleration ($p=0.027$), peak resultant rotational velocity ($p=0.014$), peak resultant rotational acceleration ($p<0.001$), and MPS ($p=0.019$) in the head to ice condition (Table 10).

Table 10. Comparison of the overall average (± 1 standard deviation) dynamic head responses and brain tissue deformation between the CCM FL 500 and CCM Tacks 710 in the general helmet test protocol for head to ice with the locations expanded. Comparisons were made using paired *t*-tests ($\alpha = 0.05$).

Head to Ice Impact Locations	Helmet Type	Dynamic Head Response			Brain Trauma Deformation
		Peak Res. Linear Acceleration (m/s^2)	Peak Res. Rotational Velocity ($rads/s$)	Peak Res. Rotational Acceleration ($rads/s^2$)	MPS (%)
Front	FL 500	117.53 (4.14)	9.33 (0.35)	2384.87 (54.09)	0.51 (0.01)
	Tacks 710	150.87 (8.74)	10.53 (1.36)	2598.07 (268.31)	0.55 (0.03)
	p-value	0.006**	0.184	0.236	0.074
Side	FL 500	123.33 (8.23)	25.33 (1.42)	6072.80 (664.85)	0.45 (0.02)
	Tacks 710	148.67 (7.96)	32.53 (0.93)	9871.53 (542.69)	0.52 (0.04)
	p-value	0.081	0.034*	0.032*	0.094
Rear Boss	FL 500	90.07 (7.89)	30.20 (1.15)	5288.60 (156.83)	0.49 (0.02)
	Tacks 710	123.63 (7.92)	32.93 (1.00)	8009.17 (478.68)	0.50 (0.02)
	p-value	0.035*	0.021*	0.008**	0.754
Rear	FL 500	97.47 (0.75)	14.20 (0.26)	2639.97 (21.87)	0.49 (0.02)

Tacks	126.07	17.43	4806.97	0.57
710	(7.56)	(0.81)	(77.50)	(0.02)
p-value	0.027*	0.014*	<0.001**	0.019*

Res.=Resultant; *=significant difference ($p<0.05$); **=significant difference ($p<0.01$).

The results of the helmet comparison found that the CCM FL 500 values were significantly lower than the CCM Tacks 710 in the general helmet test protocol at the side location for peak resultant linear acceleration ($p=0.002$), peak resultant rotational velocity ($p<0.001$), and peak resultant rotational acceleration ($p=0.002$) in the head to boards condition (Table 11). The results of the helmet comparison found that the CCM FL 500 were significantly lower than the CCM Tacks 710 in the general helmet test protocol at the rear location for peak resultant linear acceleration ($p=0.005$) in the head to boards condition (Table 11).

Table 11. Comparison of the overall average (± 1 standard deviation) dynamic head responses and brain tissue deformation between the CCM FL 500 and CCM Tacks 710 in the general helmet test protocol for head to boards with the locations expanded. Comparisons were made using paired t-tests ($\alpha = 0.05$).

Head to Boards Impact Locations	Helmet Type	Dynamic Head Response			Brain Trauma Deformation
		Peak Res. Linear Acceleration (m/s^2)	Peak Res. Rotational Velocity ($rads/s$)	Peak Res. Rotational Acceleration ($rads/s^2$)	MPS (%)
Front	FL 500	96.93 (9.39)	25.30 (1.95)	4895.10 (822.59)	0.44 (0.06)
	Tacks 710	96.87 (1.96)	30.43 (4.26)	5132.97 (669.46)	0.46 (0.02)
	p-value	0.989	0.283	0.760	0.601
Front Boss	FL 500	78.57 (3.73)	29.33 (1.19)	4583.93 (172.44)	0.43 (0.10)
	Tacks 710	95.20 (7.09)	35.93 (6.48)	7266.07 (1796.82)	0.55 (0.13)
	p-value	0.082	0.195	0.124	0.080
Side	FL 500	83.33 (0.64)	39.87 (0.12)	7100.13 (233.14)	0.39 (0.01)
	Tacks 710	96.23 (1.72)	50.40 (0.000)	12961.30 (265.49)	0.48 (0.05)
	p-value	0.002**	<0.001**	0.002**	0.130
Rear	FL 500	77.90 (3.87)	31.90 (2.25)	6467.67 (354.33)	0.49 (0.04)

Tacks 710	105.03 (6.62)	32.47 (5.41)	8074.40 (915.28)	0.55 (0.01)
p-value	0.005**	0.790	0.73	0.101

Res.=Resultant; *=significant difference (p<0.05); **=significant difference (p<0.01).

The results of the helmet comparison found that the CCM FL 500 values were significantly lower than the CCM Tacks 710 in the general helmet test protocol at the front boss positive azimuth location for peak resultant rotational velocity (p=0.029), peak resultant rotational acceleration (p=0.011), and MPS (p=0.030) in the shoulder to head condition (Table 12). The results of the helmet comparison found that the CCM FL 500 values were significantly lower than the CCM Tacks 710 in the general helmet test protocol at the rear boss negative azimuth location for peak resultant linear acceleration (p=0.046) in the shoulder to head condition (Table 12).

Table 12. Comparison of the overall average (± 1 standard deviation) dynamic head responses and brain tissue deformation between the CCM FL 500 and CCM Tacks 710 in the general helmet test protocol for shoulder to head with the locations expanded. Comparisons were made using Paired T-tests ($\alpha = 0.05$).

Shoulder to Head Impact Locations	Helmet Type	Dynamic Head Response			Brain Trauma Deformation
		Peak Res. Linear Acceleration (m/s ²)	Peak Res. Rotational Velocity (rads/s)	Peak Res. Rotational Acceleration (rads/s ²)	MPS (%)
Front	FL 500	23.50 (0.80)	26.03 (0.68)	1654.53 (75.53)	0.27 (0.006)
	Tacks 710	25.77 (0.23)	23.87 (0.87)	1560.97 (20.18)	0.27 (0.006)
	p-value	0.060	0.137	0.100	0.184
Front Boss Positive Azimuth	FL 500	23.73 (0.32)	33.17 (0.12)	2045.30 (18.31)	0.28 (0.006)
	Tacks 710	23.30 (0.10)	32.33 (0.29)	1951.13 (18.57)	0.27 (0.006)
	p-value	0.145	0.029*	0.011*	0.030*
Side	FL 500	24.87 (1.01)	31.53 (0.42)	1946.50 (39.58)	0.25 (0.02)
	Tacks 710	25.57 (0.59)	33.00 (0.56)	1935.60 (19.05)	0.28 (0.006)
	p-value	0.109	0.747	0.063	0.081

Rear	FL 500	10.93 (1.32)	34.53 (3.53)	2551.27 (165.46)	0.17 (0.02)
Boss					
Negative	Tacks 710	15.23 (0.38)	41.03 (1.97)	2690.73 (113.37)	0.19 (0.00)
Azimuth	p-value	0.046*	0.081	0.360	0.184

Res.=Resultant; *=significant difference ($p<0.05$).

Chapter 6: Discussion

The youth helmet test protocol developed for this study was based on the three most severe event types that cause head injuries in the Learn to Play ice hockey age group (5-8 years old). This helmet test protocol was compared to a modified version of Meehan and colleagues (2019) helmet test protocol developed from real world head impact events for adult ice hockey players. Youth experienced head impacts at lower masses and velocities for all event types and locations, which was reflected in the test protocol used in this thesis (Appendix A, Table 16). This study also investigated the performance of two ice hockey helmets, the CCM FL500 and CCM Tacks 710, using dynamic head response and brain tissue deformation values. The following sections will discuss how the youth helmet test protocol developed for the study compared to the general helmet test protocol for each of the dependent variables and how the two helmets compared for each of the dependent variables.

6.1 Youth Helmet Test Protocol and General Helmet Test Protocol

6.1.1 Head to Ice

In the head to ice condition, the youth helmet test protocol produced significantly lower peak resultant linear acceleration values than the general helmet test protocol (Figure 5, Table 2). The youth helmet test protocol produced higher magnitudes of peak resultant rotational velocity, peak resultant rotational acceleration, and MPS compared to general helmet test protocol, however these differences were not significant. When it is considered that youth have lower

impacting velocities and lower masses the net result was, they had higher strain values during head to ice impacts. These results are important because there is evidence that youth may be more susceptible to sustaining a concussion than adults (Bishop et al., 2014; Gennarelli et al., 1972; Holbourn, 1943; Koncan, 2018; Lenroot & Giedd, 2006; Reiss et al., 1996 Takhounts et al., 2013; Zhang et al., 2001). Youth are exposed to similar amounts of brain trauma (52.5% strain) when compared to adults (51% strain) even though the impact velocities are lower, meaning that the mass of the headforms (3.73kg and 4.54kg) outweighed the differences in velocity (4.6m/s and 5.0m/s). In youth ice hockey, falling to the ice occurs more frequently (8 times) then in adult ice hockey. This supports the notion that a youth helmet test protocol that reflects this type of event is important in evaluating youth hockey helmets. The lower youth head mass resulted in higher brain strain values demonstrating that mass is an important variable to employ in a youth helmet test protocol to predict the risk of brain injury.

6.1.2 Head to Boards

In the head to boards condition, the youth helmet test protocol had significantly lower dynamic head response and brain tissue deformation values (Figure 6) for all locations (Table 3). Although there has not been a specific threshold developed for concussion in youth, exposure to lower amount of brain trauma could result pose a risk for concussion. Youth are at risk of sustaining a concussion when the predicted brain strain value is between 15-32% (Elkin & Morrison, 2007; Galbraith, Thibault, & Matteson, 1993; Karton, Hoshizaki, & Gilchrist, 2020; Kleiven, 2007; Margulies & Thibault, 1992; Singh, Sullivan, Deng, Mbye, & Hall, 2006). Consequently, youth sustained 31% brain strain on average and adults sustained 47% brain strain on average during the head to boards condition, meaning youth are at a high risk of sustaining a

concussion. The results of this research demonstrated that youth ice hockey players are being exposed to high amounts of brain trauma, including head impacts to the boards.

6.1.3 Shoulder to Head

In shoulder to head condition, the youth helmet test protocol had significantly lower dynamic head response and brain tissue deformation values (Figure 7) for all locations (Table 4). Although shoulder to head impacts have the highest frequencies in both age groups, the mechanism of injury is different. Youth tend to accidentally bump into each other resulting in a head contact, so the impact velocities are low. However, adults intentionally contact each other resulting in a shoulder to head impacts which are at much higher velocities than youth. During this event youth sustain a low amount of brain strain with an average strain value of 13.75%, which presents a lower risk for sustaining a concussion.

6.2 Helmet Comparison within each Test protocol

In this thesis, the CCM FL 500 significantly outperformed CCM Tacks 710 in both helmet test protocols for all dependent variables with locations collapsed. In the youth helmet test protocol, the CCM Tacks 710 produced similar results to the CCM FL 500 for peak resultant rotational velocity and acceleration and MPS at specific locations during the head to ice and boards impacts. In the general helmet test protocol, the CCM Tacks 710 produced similar results to the CCM FL 500 for peak resultant rotational acceleration during the shoulder to head impacts. The similar results obtained from both helmet test protocols demonstrated that the youth helmet test protocol can effectively distinguish the differences in performance between two certified ice hockey helmets under youth specific impact characteristics.

The CCM FL500 outperformed the CCM Tacks 710 because of its larger offset, rounder geometry, lack of protuberances, multi-density Vinyl Nitrile (VN) foams, and the D30 smart

material (Appendix E, Table 17). The larger offset and softer liner of the CCM FL 500 allowed the helmet liner to better manage the impact energies when compared to the CCM Tacks 710 (Bishop et al., 2014; Post, Gimbel, & Hoshizaki, 2012). The softer liner of the CCM FL 500 is important to include in a youth helmet design as the liner manages the impact energies without having to transfer as much energy to the head, which is one of the reasons why the FL 500 outperformed the CCM Tacks 710 (Bishop et al., 2014; Post, Gimbel, & Hoshizaki, 2012). The CCM FL 500 has a larger circumference compared to the CCM Tacks 710 making it more susceptible to creating higher rotational forces (Post et al., 2012). Interestingly, the larger circumference did not have a significant effect on all tests and impact locations, which may reflect the CCM FL 500's geometry. The rounded geometry and fewer protuberances on the CCM FL 500 allow it to deflect impacts decreasing rotational forces transferred to the head when compared to the CCM Tacks 710. This finding suggests that under specific conditions such as the youth ice hockey environment, a helmet with a larger offset and rounder geometry may be beneficial in providing better protection for youth ice hockey players. Although the results were not statistically significant, the CCM Tacks 710 outperformed the CCM FL 500 in peak resultant velocity and accelerations overall for the shoulder to head impacts in the general helmet test protocol, and the head to ice and boards impacts in the youth helmet test protocol.

6.2.3 Overall Helmet and Standard Modifications

The CCM FL 500 outperformed the CCM Tacks 710. The rotational velocity accelerations, and MPS values for both helmets were high enough to create a risk for concussion (15-32% strain) (Elkin & Morrison, 2007; Galbraith, Thibault, & Matteson, 1993; Karton, Hoshizaki, & Gilchrist, 2020; Kleiven, 2007; Margulies & Thibault, 1992; Singh, Sullivan, Deng, Mbye, & Hall, 2006). The results from this research provides helmet developers with a

youth specific helmet test protocol to help design a specific to youth helmet. Future research should investigate opportunities to use the youth specific test protocol to develop more effective youth helmets that to lower the risk of concussions for all ages.

Chapter 7: Conclusion

This study developed a youth ice hockey helmet test protocol using head impact characteristics specific to the Learn to Play (5-8 years old) youth ice hockey age group. It demonstrated that youth experience significantly lower trauma to the head to boards and shoulder to head condition. However, the strain values youth experienced for all event types are high (14-53% strain), putting youth at risk of brain trauma under all event types. Additionally, this research demonstrated that when creating a youth standard, it is crucial to understand the relationship between mass and impact velocity as it is associated with brain trauma. Although youth between 5-8 years old do not experience head impacts at higher velocities than adults, the difference in their mass compared to adults creates higher acceleration and a risk of sustaining brain trauma. It is important to continue to undertake research to support age and competition helmet test standards for youth hockey.

The helmet comparison supports the sensitivity of the youth helmet test protocol in distinguishing between the CCM FL 500 and CCM Tacks 710.

In the future, standards committees may want to consider a youth specific helmet test protocol to better reflect the differences in youth ice hockey play style, anatomical differences, and physiological differences.

References

- 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>
- Bayly, P. V., Clayton, E. H., & Genin, G. M. (2012). Quantitative Imaging Methods for the Development and Validation of Brain Biomechanics Models. <Http://Dx.Doi.Org.Proxy.Bib.Uottawa.ca/10.1146/Annurev-Bioeng-071811-150032>, 14, 369–396. <https://doi.org/10.1146/ANNUREV-BIOENG-071811-150032>
- Bishop, P. J., Kendall, M., Post, A., & Hoshizaki, T. B. (2014). Performance Criteria for a Child Specific Helmet. In A. Ashare & M. Ziejewski (Eds.), *Mechanism of Concussion in Sports* (pp. 1–12). Atlanta: West Conshohocken, PA : ASTM International.
- Champoux, L. (2021). *A comparison of three rotational ice hockey helmet test protocols*. University of Ottawa.
- Chatelin, S., Vappou, J., Roth, S., Raul, J. S., & Willinger, R. (2012). Towards child versus adult brain mechanical properties. *Journal of the Mechanical Behavior of Biomedical Materials*, 6, 166–173. <https://doi.org/10.1016/J.JMBBM.2011.09.013>
- Choe, M. C., Babikian, T., Difiori, J., Hovda, D. A., & Giza, C. C. (2012). A pediatric perspective on concussion pathophysiology. *Current Opinion in Pediatrics*, 24(6), 689–695. <https://doi.org/10.1097/MOP.0B013E32835A1A44>
- Clayton, E. H., Genin, G. M., & Bayly, P. V. (2012). Transmission, attenuation and reflection of shear waves in the human brain. *Journal of the Royal Society Interface*, 9(76), 2899. <https://doi.org/10.1098/RSIF.2012.0325>
- 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>
- De Grau, S., Post, A., Hoshizaki, T. B., & Gilchrist, M. D. (2019). Effects of surface compliance on the dynamic response and strains sustained by a player's helmeted head during ice hockey impacts. *Journal Sports Engineering and Technology*, 00(0), 1–9.
<https://doi.org/10.1177/1754337119871866>
- de Grau, S., Post, A., Meehan, A., Champoux, L., Hoshizaki, T. B., & Gilchrist, M. D. (2020). Protective capacity of ice hockey helmets at different levels of striking compliance. *Sports Engineering*, 23(1). <https://doi.org/10.1007/s12283-020-00325-y>
- Donaldson, L., Asbridge, M., & Cusimano, M. D. (2013). Bodychecking Rules and Concussion in Elite Hockey. *PLOS ONE*, 8(7).
- Doorly, M., & 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.
- Elkin, B. S., & Morrison, B. I. (2007). Region-Specific Tolerance Criteria for the Living Brain - ProQuest. *Stapp Car Crash Journal*, 51, 127–138. Retrieved from <https://www-proquest-com.proxy.bib.uottawa.ca/docview/223250254?pq-origsite=primo>
- Fryar, C. D., Gu, Q., Ogden, C. L., & Flegal, K. M. (2016). Anthropometric Reference Data for Children and Adults: United States, 2011-2014. *Vital and Health Statistics. Series 3, Analytical Studies*, (39), 1–46.
- 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>

Gennarelli, T. (1983). Head injury in man and experimental animals: clinical aspects. *Acta Neurochir Suppl*, 32, 1–13.

Gennarelli, T. A., Thibault, L. E., & Ommaya, A. K. (1972). Comparison of translational and rotational head motions in experimental cerebral concussion. *15th Stapp Car Crash Conference*, 797–803. New York: SAE.

Gilchrist, J., Thomas, K. E., Xu, L., McGuire, L. C., & Coronado, V. (2011). Nonfatal traumatic brain injuries related to sports and recreation activities among persons aged [less than or equal to] 19 years--United States, 2001-2009. *Morbidity and Mortality Weekly Report*, 60(39), 1337–1343. Retrieved from <https://go-gale-com.proxy.bib.uottawa.ca/ps/i.do?p=AONE&sw=w&issn=01492195&v=2.1&it=r&id=GALE%7CA278879291&sid=googleScholar&linkaccess=fulltext>

Gilchrist, M. D. (2003). Modelling and accident reconstruction of head impact Injuries. *Key Eng Mat*, 245, 417–430.

Gimbel, G., & Hoshizaki, T. (2008). Compressive properties of helmet materials subjected to dynamic impact loading of various energies. *European Journal of Sport Science*, 8(6), 341–349. <https://doi.org/10.1080/17461390802438763>

Goldschmied, N., & Espindola, S. (2013). I Went to a Fight the Other Night and a Hockey Game Broke Out: Is Professional Hockey Fighting Calculated or Impulsive? *Sports Health*, 5(5), 458–462.

Gurdjian, E. S. M. D. ., Lissner, H. R. ., Webster, J. E. M. D. ., Latimer, F. R. M. D. ., & Haddad, B. F. M. D. (1954). Studies on Experimental Concussion: Relation of Physiologic Effect to Time Duration of Intracranial Pressure Increase at Impact. *American Academy of*

- Neurology*, 4((9)), 674–681. Retrieved from <https://oce-ovid-com.proxy.bib.uottawa.ca/article/00006114-195409000-00004/HTML>
- Gurdjian, E. S., Roberts, V. L., & Thomas, L. M. (1966). TOLERANCE CURVES OF ACCELERATION AND INTRACRANIAL PRESSURE AND PROTECTIVE INDEX IN EXPERIMENTAL HEAD INJURY. *The Journal of Trauma: Injury, Infection & Critical Care*, 6(5), 600–604. Retrieved from <https://oce-ovid-com.proxy.bib.uottawa.ca/article/00005373-196609000-00005/HTML>
- Gurdjian, E. S., Webster, J. E., & Lissner, H. R. (1958). Mechanism of Scalp and Skull Injuries, Concussion, Contusion and Laceration. *Journal of Neurosurgery*, 15(2), 125–128. <https://doi.org/10.3171/JNS.1958.15.2.0125>
- Hockey Helmet Ratings. (2021). Retrieved December 21, 2021, from <https://www.helmet.beam.vt.edu/hockey-helmet-ratings.html>
- Holbourn, A. H. S. (1943). MECHANICS OF HEAD INJURIES. *The Lancet*, 242(6267), 438–441. [https://doi.org/10.1016/S0140-6736\(00\)87453-X](https://doi.org/10.1016/S0140-6736(00)87453-X)
- Horgan, T. J., & Gilchrist, M. D. (2003). Influence of FE model variability in predicting brain motion and intracranial pressure changes in head impact simulations. *International Journal of Crashworthiness*, 401–418. Retrieved from https://journals-scholarsportal-info.proxy.bib.uottawa.ca/pdf/13588265/v09i0004/401_iofmvipcihis.xml
- Hoshizaki B, Post A, Kendall M, Karton C, & Brien S. (2013). The Relationship between Head Impact Characteristics and Brain Trauma. *Journal of Neurology and Neurophysiology*, 5(181).
- Hoshizaki, T. B. (2017). Development and validation of a test protocol for hockey helmets to measure rotational velocity using angular velocity change. *Canadian Standards Association*

(CSA), 1–39.

Hoshizaki, T. B., & Cournoyer, J. (2019). *Establishing Test Parameters for American Youth Football Helmets Informed by Injury Surveillance*. (October).

Hutchison, M.G. (2011). *Concussions in the National Hockey League (NHL): The Video Analysis Project - ProQuest* (University of Toronto). Retrieved from <https://search-proquest-com.proxy.bib.uottawa.ca/docview/924638428/abstract/A8E747F32C3D413DPQ/1?accountid=14701>

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

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

Karton, C., Blaine Hoshizaki, T., & Gilchrist, M. D. (2020). A novel repetitive head impact exposure measurement tool differentiates player position in National Football League. *Scientific Reports*, *10*(1). <https://doi.org/10.1038/S41598-019-54874-9>

Karton, C. M., Hoshizaki, T. B., & Gilchrist, M. D. (2014a). The influence of impactor mass on the dynamic response of the Hybrid III headform and brain tissue deformation. *The Mechanism of Concussion in Sports*, 23–40. <https://doi.org/10.1520/STP155220120175>

Karton, C. M., Hoshizaki, T. B., & Gilchrist, M. D. (2014b). The influence of impactor mass on

the dynamic response of the Hybrid III headform and brain tissue deformation. In *American Society for Testing & Materials* (pp. 23–40).

<https://doi.org/https://doi.org/10.1520/STP155220120175>

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

Kleiven, S. (2013). Why most traumatic brain injuries are not caused by linear acceleration but skull fractures are. *Frontiers in Bioengineering and Biotechnology*, (1), 1–5.

<https://doi.org/https://doi.org/10.3389/fbioe.2013.00015>

Kleiven, Svein. (2007). Predictors for Traumatic Brain Injuries Evaluated through Accident Reconstructions - ProQuest. *Stapp Car Crash Journal*, 51, 81–114. Retrieved from <https://www.proquest.com/docview/223249836/abstract/75EFC4BD8C3B4461PQ/1?accountid=14701>

Koncan, D. (2018). *Finite Element Modelling of Sport Impacts-Brain Strains from Falls Resulting in Concussion in Young Children and Adults*. University of Ottawa, Ottawa.

Koncan, D., Gilchrist, M., Vassilyadi, M., & Hoshizaki, T. B. (2019). A three-dimensional finite element model of a 6-year-old child for simulating brain response from physical reconstructions of head impacts. *Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology*, 233(2), 277–291.

<https://doi.org/10.1177/1754337118822940>

Kontos, A. P., Elbin, R., Sufrinko, A., Dakan, S., Bookwalter, K., Price, A., ... Collins, M. W. (2016). Incidence of Concussion in Youth Ice Hockey Players. *PEDIATRICS*, 137(2), 20151633. <https://doi.org/10.1542/peds.2015-1633>

- Lenroot, R. K., & Giedd, J. N. (2006). Brain development in children and adolescents: Insights from anatomical magnetic resonance imaging. *Neuroscience & Biobehavioral Reviews*, 30(6), 718–729. <https://doi.org/10.1016/J.NEUBIOREV.2006.06.001>
- 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](https://doi.org/10.1016/0021-9290(92)90231-O)
- Maxwell, W. L. (2012). Traumatic brain injury in the neonate, child and adolescent human: An overview of pathology. *International Journal of Developmental Neuroscience*, 30(3), 167–183. <https://doi.org/10.1016/j.ijdevneu.2011.12.008>
- McClincy, M. P., Lovell, M. R., Pardini, J., Collins, M. W., & Spore, M. K. (2006). Recovery from sports concussion in high school and collegiate athletes. *Brain Injury*, 20(1), 33–39. <https://doi.org/10.1080/02699050500309817>
- McCrea, M., Hammeke, T., Olsen, G., Leo, P., & Guskiewicz, K. (2004). Unreported concussion in high school football players: implications for prevention. *Clinical Journal of Sports Medicine*, 14(1), 13–17.
- McIntosh, A. S., Patton, D. A., Fréchède, B., Pierré, P.-A., Ferry, E., & Barthels, T. (2014). The biomechanics of concussion in unhelmeted football players in Australia: a case–control study. *BMJ Open*, 4(5), e005078. <https://doi.org/10.1136/BMJOPEN-2014-005078>
- Meehan, A., Hoshizaki, S. T. B., Bishop, P., & Robertson, G. (2019). *Describing the relationship between three ice hockey helmet impact tests and reconstructions of concussive injuries in professional ice hockey Committee Members.*
- Oeur, R. A., Gilchrist, M. D., & Hoshizaki, T. B. (2019). Interaction of impact parameters for simulated falls in sport using three different sized Hybrid III headforms. *International*

Journal of Crashworthiness, 24(3), 326–335.

<https://doi.org/10.1080/13588265.2018.1441617>

Ommaya, A. K. (1995). Head Injury Mechanisms and the Concept of Preventive Management: A Review and Critical Synthesis. *Journal of Neurotrauma*, 12(4), 527–546.

Pion, J., Segers, V., Franssen, J., Debuyck, G., Deprez, D., Haerens, L., ... Lenoir, M. (2015). Generic anthropometric and performance characteristics among elite adolescent boys in nine different sports. *European Journal of Sport Science*, 15(5), 357–366.

<https://doi.org/10.1080/17461391.2014.944875>

Post, A., Gimbel, G., & Hoshizaki, T. B. (2012). The influence of headform circumference and mass on alpine ski helmet performance in laboratory tests. *ASTM Special Technical Publication*, 1553 STP(4), 261–268. <https://doi.org/10.1520/STP103978>

Post, Andrew. (2013). The influence of dynamic response characteristics on traumatic brain injury. *ProQuest Dissertations and Theses*, (May), 308. Retrieved from https://www.ruor.uottawa.ca/handle/10393/24333%0Ahttps://search.proquest.com/docview/1443485235?accountid=26642%0Ahttp://link.periodicos.capes.gov.br/sfxlcl41?url_ver=Z39.88-2004&rft_val_fmt=info:ofi/fmt:kev:mtx:dissertation&genre=dissertations+%26+theses

Post, Andrew, Dawson, L., Hoshizaki, T. B., Gilchrist, M. D., & Cusimano, M. D. (2020). Development of a test method for adult ice hockey helmet evaluation. *Computer Methods in Biomechanics and Biomedical Engineering*, 23(11), 690–702.

<https://doi.org/10.1080/10255842.2020.1758680>

Post, Andrew, De Grau, S., Ignacy, T., Meehan, A., Zemek, R., Hoshizaki, T. ., & Gilchrist, M. . (2016a). Comparison of Helmeted Head Impact in Youth and Adult Ice Hockey. *IRCOBI*

- Conference 2016*, 194–204. Retrieved from <http://www.ircobi.org/wordpress/downloads/irc16/pdf-files/30.pdf>
- Post, Andrew, De Grau, S., Ignacy, T., Meehan, A., Zemek, R., Hoshizaki, T. B., & Gilchrist, M. D. (2016b). *Comparison of Helmeted Head Impact in Youth and Adult Ice Hockey*. 194–204. IRCOBI Conference.
- Post, Andrew, Hoshizaki, T. B., Karton, C., Clark, J. M., Dawson, L., Cournoyer, J., ... 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, Andrew, 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>
- Reiss, A. L., Abrams, M. T., Singer, H. S., Ross, J. L., & Denckla, M. B. (1996). Brain development, gender and IQ in children: A volumetric imaging study. *Brain*, 119(5), 1763–1774. <https://doi.org/10.1093/BRAIN/119.5.1763>
- 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., & Hoshizaki, T. B. (2015). Defining the effective impact mass of elbow and shoulder strikes in ice hockey. *Sports Biomechanics*, 14(1), 57–67. <https://doi.org/10.1080/14763141.2015.1025236>

- Rowson, B., Rowson, S., & Duma, S. M. (2015). Hockey STAR: A Methodology for Assessing the Biomechanical Performance of Hockey Helmets. *Annals of Biomedical Engineering* 2015 43:10, 43(10), 2429–2443. <https://doi.org/10.1007/S10439-015-1278-7>
- 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, 1407–1418.
- Takhounts, E. G., Craig, M. J., Moorhouse, K., Mcfadden, J., & Hasija, V. (2013). Development of Brain Injury Criteria (BrIC). *Stapp Car Crash Journal*, 57, 243–266.
- 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>
- Wendorf, B. (2015, February 19). NHL Player Size From 1917-18 to 2014-15: A Brief Look | Hockey Graphs. Retrieved April 26, 2022, from <https://hockey-graphs.com/2015/02/19/nhl-player-size-from-1917-18-to-2014-15-a-brief-look/>
- Wennberg, R. A., & Tator, C. H. (2008). Concussion incidence and time lost from play in the NHL during the past ten years. *Canadian Journal of Neurological Sciences*, 35(5), 647–651. <https://doi.org/10.1017/S031716710000946X>
- Williamson, I. J. S., & Goodman, D. (2006). Converging evidence for the under-reporting of

concussions in youth ice hockey. *British Journal of Sports Medicine*, 40, 128–132.

Willinger, R., & Baumgartner, D. (2005). *NUMERICAL MODELING OF THE HUMAN HEAD UNDER IMPACT: NEW INJURY MECHANISMS AND TOLERANCE LIMITS*.

Willinger, R., Ryan, G., McLean, A., & Kopp, C. (1994). Mechanisms of brain injury related to mathematical modelling and epidemiological data. *Accid Anal Prev*, 26(6), 767–779.

Zhang, J., Yoganandan, N., Pintar, F. A., & Gennarelli, T. (2006). (PDF) Role of translational and rotational accelerations on brain strain in lateral head impact. *Biomedical Sciences Instrumentation*, 42, 501–506. Retrieved from https://www.researchgate.net/publication/6966612_Role_of_translational_and_rotational_accelerations_on_brain_strain_in_lateral_head_impact

Zhang, L., Yang, K. H., & King, A. I. (2001). Biomechanics of neurotrauma. *Neurological Research*, 23(2–3), 144–156. <https://doi.org/10.1179/016164101101198488>

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 A

Summary of current ice hockey helmet standards

Table 13. Current ice hockey helmet standard summary of test equipment, impact parameters, and pass/fail criteria (ASTM F1045-16; CSA Z262.1-15; ISO 10256-2:2016).

	CSA Z262.1-15	ASTM F1045-16	ISO 10256-2:2016
Equipment	Monorail CEN EN 960	Monorail CEN EN 960	Monorail CEN EN 960
Headform	Magnesium headform, uniaxial accelerometer	Magnesium headform, uniaxial accelerometer	Magnesium headform, uniaxial accelerometer
Velocity	4.5 m/s	4.5 m/s	4.5 m/s
Anvil	MEP Pad	MEP Pad	MEP Pad
Locations	Crown, Front, Front Boss, Side, Rear Boss, Rear	Crown, Front, Front Boss, Side, Rear Boss, Rear	Crown, Front, Front Boss, Side, Rear Boss, Rear
Pass/Fail Criteria	275g	275g	275g

Appendix B

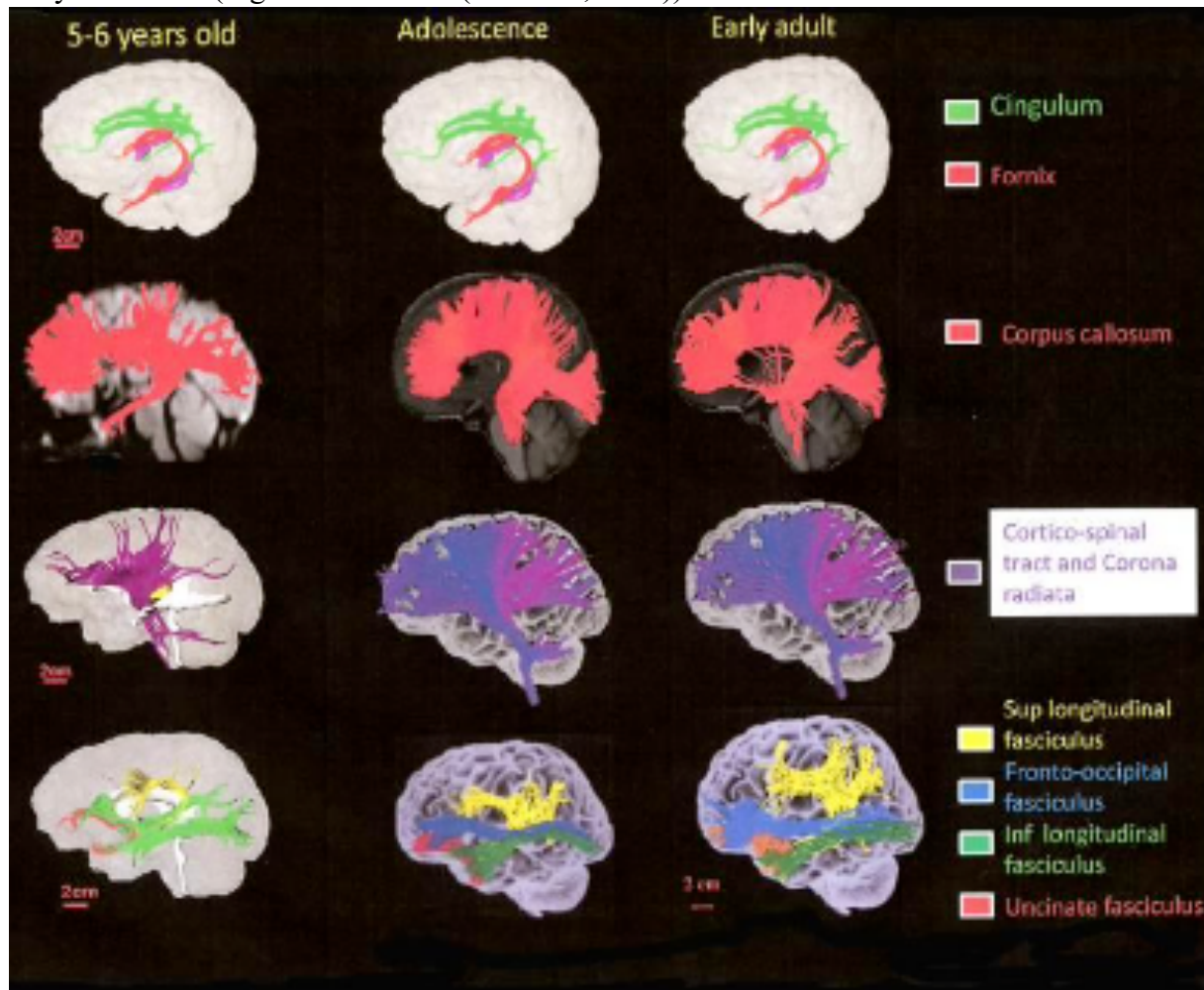
Summary of the anatomical and physiological differences between youth and adults.

Table 14. *Physiological and anatomical differences between youth and adults which play a role in head injury* (Bishop et al., 2014; Fryar et al., 2016; Koncan, 2018; Maxwell, 2012; Ommaya, 1995).

Physiological and Anatomical Differences	Youth	Adults
Height (50 th percentile)	122.8 cm (5-8 yoa)	177 cm
Total body mass (50 th percentile)	24.7 kg (5-8 yoa)	71 kg
Approximate Head mass	Based on Hybrid III headform 3.73kg	Based on Hybrid III headform 4.54kg
Head circumference (50 th percentile)	51.5 cm	56.0 cm
Brain size	90-95% full size by age 5-6 years old	Full size 100%
Brain mass	800 g	1400 g
Skull thickness	4 mm	10 mm
Skull sutures	undeveloped	developed
Bulk modulus of the brain	Larger	Smaller

White matter	Lower percentage	Higher percentage
Grey matter	3-11% is myelinated (4 yoa)	90-99% is myelinated (22 yoa)

Figure 14. Development of white matter within the brain in 5-6 year old's, adolescence, and early adulthood (Figure taken from (Maxwell, 2012)).



Appendix C

Summary of the mechanical properties of the University College Dublin Brain Trauma Model Version 2.0

Table 15. Mechanical properties for UCDBTM V2.0. (Table retrieved from (Trotta et al., 2020)).

Material	Young's Modulus (MPa)	Poisson's Ratio	Density (kg/m ³)
Scalp	Hyperelastic	~ 0.5	1133

Cerebellum	Visco-hyperelastic	~ 0.5	1060
Grey matter	Visco-hyperelastic	~ 0.5	1060
Brainstem	Visco-hyperelastic	~ 0.5	1060
Cortical bone	Linear elastic	0.22	2000
Trabecular bone	Linear elastic	0.24	1300
Pia	Linear elastic	0.45	1130
CSF	Linear elastic	~ 0.5	1000
Facial bone	Linear elastic	0.22	2100
Ventricles	Visco-hyperelastic	~ 0.5	1040
White matter	Viscoelastic	~ 0.5	1060
Dura, Falx, and tentorium	Hyperelastic	~ 0.5	1130

Appendix D

Summary of the differences between the youth test protocol and general helmet test protocol:

Table 16. Youth (top) and general (bottom) helmet test protocol breakdown with 5th percentile hybrid III headform. Each event type was run 3 times per velocity and impact location. (de Grau et al., 2020; Karton et al., 2021; Meehan et al., 2019; Post et al., 2020; Robidoux et al., 2020).

Event types	Impact system	Mass (kg)	Velocity (m/s)	Compliance	Locations
Youth Helmet Test Protocol					
Head to Ice	Monorail	3.73	4.6	Flat MEP anvil	Front (F), Side Positive Azimuth (SPA), Rear Boss (RB), rear (R)
Head to Boards	Monorail	3.73	3.7	45° steel anvil	Front Positive Azimuth (FPA), Front Boss Positive Azimuth (FBPA), Side (S), R
Head to Shoulder	Pendulum	3.61	4.1	Shoulder pad	FPA, Front Boss (FB), S, RB
General Helmet Test Protocol					
Head to Ice	Monorail	4.54	5.0	Flat MEP anvil	F, SPA, RB, R

Head to Boards	Monorail	4.54	6.0	45° steel anvil	FPA, FBPA, S, R
Head to Shoulder	Pendulum	13.1	6.0	Shoulder pad	FPA, FB, S, RB

Appendix E

Summary of the differences between the CCM FL 500 and the CCM Tacks 710 ice hockey helmets.

Table 17. Helmet characteristic differences.

	CCM FL 500	CCM Tacks 710
Offsets	Front = 27 mm Side = 22 mm Rear = 36 mm	Front = 25 mm Side = 25 mm Rear = 32 mm
Mass	646 g	554 g
Geometry	Round with small protuberances	Oval with large protuberances
Material Characteristics	Multi-density Vinyl nitrile foam liner, D30 Smart material	Vinyl nitrile foam liner, I.Q. Cushion, R.E.D. Technology, and D30 Smart material

Appendix F

Summary of the differences between the youth test protocol and general helmet test protocol.

Table 18. 2x2 research design. This thesis resulted in 144 head impacts.

		B1	B2
Head to Ice	A1	A1B1	A1B2
	A2	A2B1	A2B2
Head to Boards	A1	A1B1	A1B2
	A2	A2B1	A2B2
Shoulder to Head	A1	A1B1	A1B2
	A2	A2B1	A2B2

A1= Youth Helmet Test Protocol, A2= General Helmet Test Protocol, B1= FL 500, and B2= CCM Tacks 710.