Head Impacts in Hockey and Youth Football: Biomechanical Response and Helmet Padding Characteristics

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Abstract

The research presented herein is a combination of work done in two distinct subcategories of sport related head injury research. The body of work is aimed at increasing the understanding of head impact biomechanics across a broad spectrum of impact scenarios as well as the ability of helmets to affect head impact biomechanics over time. The first study utilizes in situ testing of controlled impacts of an instrumented head form to more fully characterize head accelerations resulting from impacts to the ice, board, and glass surfaces present in an ice hockey rink. The full characterization of head impacts across a spectrum of loading conditions and impact surfaces gives researchers insight into head impact tolerance and head protection capabilities and limitations in ice hockey. The second study details the development of a method to impact helmet pads for repeated loading studies based on published head impact exposure data. The third study uses this newly developed methodology to test the effects of a season of impacts on the energy absorbing properties of three different helmet padding technologies. The body of work is aimed at increasing understanding of head impact and concussion and the ability of existing helmet technologies to prevent these injuries with a goal of reducing the occurrence of injury.

Attribution

Several colleagues aided in the research behind the chapters presented in this thesis. A description of their contributions is included here.

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Chapter 1: Introduction

Opening Remarks

Head injury in sport is a problem currently at the forefront of societal awareness. Direct impacts to the head cause the acceleration of brain tissue leading to concussion, a complex physiological injury with symptoms including headaches, memory and concentration impairment, dizziness, blurred vision, and changes in sleep patterns and emotions. Although these short term symptoms of concussion typically resolve within a short time frame, the long term consequences of concussion and repeated head loading and injury are unknown. Characterization of head impact in sport and full understanding of the ability of a helmet to mitigate impact are important components of movements to reduce and prevent head injury in helmeted sports. Realistic studies of head and helmet loading require that unique and novel equipment and methods be developed. The research presented in this thesis utilizes innovative testing procedures and new equipment to build on the body of prior knowledge surrounding concussion and head impact in helmeted sports. The work is aimed at a better understanding of head impact and concussion and the ability of existing helmet technologies to prevent these injuries with a goal of reducing the occurrence of injury and preventing long term health consequences by arming athletes with information and equipment to keep them as safe as possible.

Head Impact in Ice Hockey

Ice hockey has an incidence rate of concussion second only to football. However, much less research has been conducted into hockey concussion than football concussions, despite the wide variety of surfaces to impact. Athlete impacts against the ice, board, and glass surfaces account for a majority of concussions in ice hockey. This study utilizes in situ testing of controlled impacts of an instrumented head form to more fully characterize head accelerations resulting from impacts to the ice, board, and glass surfaces present in an ice hockey rink. The full characterization of head impacts across a spectrum of loading conditions and impact surfaces gives researchers insight into head impact tolerance and head protection capabilities and limitations in ice hockey.

Helmet Loading in Youth Football

The second study details the development of a method to impact helmet pads for repeated loading studies based on published head impact exposure data. The third study uses this newly developed methodology to test the effects of a season of impacts on the energy absorbing properties of three different helmet padding technologies. The body of work is aimed at increasing understanding of head impact and concussion and the ability of existing helmet technologies to prevent these injuries with a goal of reducing the occurrence of injury.

Table 1. Research presented in this thesis.

Chapter	**Research Aim**
Chapter 2	Head Accelerations in Ice Hockey Impacts to the Ice, Board, and Glass Surfaces
Chapter 3	Methodology for Mapping Football Head Impact Exposure to Helmet Pads for Repeated Loading Testing
Chapter 4	Changes in Energy Management Properties of Football Helmet Pads with Repeated Loading

Chapter 2: Head Accelerations in Hockey Impacts to the Ice, Board, and Glass Surfaces

Abstract

Ice hockey has the second highest incidence rate of concussion of any organized sport. More than one third of collegiate men's concussions and over one half of collegiate women's concussions occur as a result of contact with the ice, board, or glass surfaces, rather than contact with another player or game equipment. The purpose of this study was to characterize the head accelerations resulting from controlled impacts to the different surfaces present in ice hockey rinks. An instrumented 50th percentile male Hybrid III head and neck were mounted on a pendulum arm and impacted to the ice, boards, and glass on a full scale collegiate ice hockey rink. A total of 25 tests were performed consisting of three target impact velocities and four impact locations. Peak linear acceleration values ranged from 49.8 g to 281.0 g. With the exception of the head to ice impacts, these magnitudes were found to be within reported ranges of moderate to high severity recorded impacts at the collegiate level. This study found that when controlling for impact velocity, impacts to the ice have significantly greater linear acceleration magnitudes than impacts to the boards or glass ($p = 0.05$). Only at the lowest impact velocity (4.7 ± 0.3 m/s) was a significant difference found between the magnitudes of linear accelerations resulting from impacts to the boards and impacts to the glass ($p = 0.03$). Impacts to the ice were found to produce greater rotational accelerations than impacts to the glass ($p = 0.05$). No significant differences were found between rotational acceleration magnitudes resulting from impacts to the boards versus impacts to the ice or glass. Additionally, when controlling for impact velocity, impacts to the ice had significantly shorter durations than impacts to either the boards or glass ($p = 0.05$). Impacts to the boards were found to produce significantly shorter impact durations than impacts to the glass only at the lowest impact velocity tested (p = 0.05). These data provide researchers with valuable insight into impact tolerance and head protection capabilities and limitations in ice hockey.

Keywords

Ice hockey, helmet, head impact, acceleration, impact surface

Introduction

Ice hockey has the second highest incidence rate of concussion of any organized sport.[20] Studies show that by high school, 60% of male ice hockey players have sustained a concussion, a much higher concussion rate than the 22% of all players estimated two decades ago.[16,35] Not only is the incidence of concussion in ice hockey higher than most other sports, concussion is also one of the most prevalent injuries among ice hockey players. Concussion is the most frequent game injury sustained among collegiate male and female and high school male ice hockey players.[1,13,20]

Previously, researchers have instrumented populations of ice hockey athletes to quantify impact magnitudes which provide some data regarding athlete exposure. Male and female collegiate ice hockey players have been instrumented using a custom version of the Head Impact Telemetry (HIT) System (Simbex, Lebanon, NH) for hockey helmets.[6,17] These systems use six single axis accelerometers to record head acceleration during impact with six degrees of freedom. From these studies, distributions of head acceleration magnitudes resulting from head impacts in ice hockey have been quantified. One study collected over 28,000 impacts during a two year period and reported the 95th percentile impact magnitudes for male and female collegiate ice hockey players as 67.2 ± 25.8 g and 66.4 ± 22.8 g respectively.[6] Similar studies of male high school ice hockey players using a triaxial accelerometer, Techmark IS100 (Lansing, MI), found peak linear accelerations resulting from impact as high as 125 g, and a mean impact magnitude of 35 ± 1.7 g.[28] Researchers have instrumented male youth ice hockey players ages 13-14 and found a mean impact magnitude between 22 and 23 g.[22,37] Additional studies of male youth ice hockey players have investigated the effects of different variables, including collision type, on head impact biomechanics.[21-25] These data provide valuable insight into the head impact exposure of several populations of ice hockey players, but do not address the high incidence of concussion in the sport.

Retrospective epidemiological studies using the National Collegiate Athletic Association Injury Surveillance System (NCAA ISS) have taken advantage of the careful reporting in this system to relate concussions with impact surface.[1,2] More than one-third of collegiate men's concussions occur as a result of contact with the ice, board, or glass surfaces, rather than contact with another player or game equipment.[2] Similarly, contact with the ice, board, or glass surfaces account for more than half of women's collegiate players' concussions.[1] Other studies have investigated differences in head impact biomechanics resulting from different helmet materials.[36,39] Unfortunately, there are no published data that completely link impact scenarios, biomechanics, and clinical outcome.

The purpose of this study is to characterize head accelerations resulting from controlled impacts to the different surfaces present in a full scale collegiate ice hockey rink. Full characterizations of head impacts across the full spectrum of loading conditions and impact surfaces in ice hockey can give researchers insight into impact tolerance and head protection capabilities and limitations in ice hockey.

Materials and Methods

A 50th percentile male Hybrid III headform and neck were used to study head impact response in ice hockey. Linear and rotational acceleration of the head were measured for impacts to the different surfaces in ice rinks. The Hybrid III head and neck were mounted on a pendulum arm and used to impact the ice, boards, and glass at three speeds and four locations on the head.

The Hybrid III headform was fitted with a large Easton Stealth S9 ice hockey helmet that meets the Hockey Equipment Certification Council (HECC) certification standards. The chin strap was adjusted to ensure a snug fit.[12] The same helmet was used for all tests to remove variability between different helmets. The helmet was visually inspected between tests for damage and adjusted to fit properly after each impact.

Because in situ testing on an ice hockey rink requires impacts to both vertical and horizontal surfaces, simple drop tests were not feasible. A portable, modular pendulum was designed with three pivot points to test each surface; ice, boards, and glass (**Figure 1**). The pendulum structure was constructed of 45x45 T-slotted aluminum framing (Bosch Rexroth, Charlotte, NC) (**Figure 1**). Two interchangeable pendulum arms were constructed of 51 mm square extruded aluminum tubing. An adaptor plate of aluminum was constructed to attach the Hybrid III neck to the end of the pendulum arms. The pendulum arm used to impact the front, back, and sides of the headform (Arm A) measured 1.32 m in length and the pendulum arm used to impact the top of the headform (Arm B) measured 1.51 m in length. The assembly of the adaptor plate, neck, headform, and Arm A weighed approximately 9.3 kg. The assembly of Arm B weighed approximately 9.8 kg. The pendulum arm assemblies could be attached to one of three pivot points mounted at 0.38 m, 2.11 m and 3.33 m above the ice surface to impact the ice, boards, or glass surface, respectively. The center of gravity of the Hybrid III headform was located a distance of 1.51 m from the pivot point when mounted to Arm A and 1.54 m from the pivot point when mounted to Arm B. The headform impacted the boards at a height of 0.62 m and the glass at a height of 1.84 m above the ice surface.

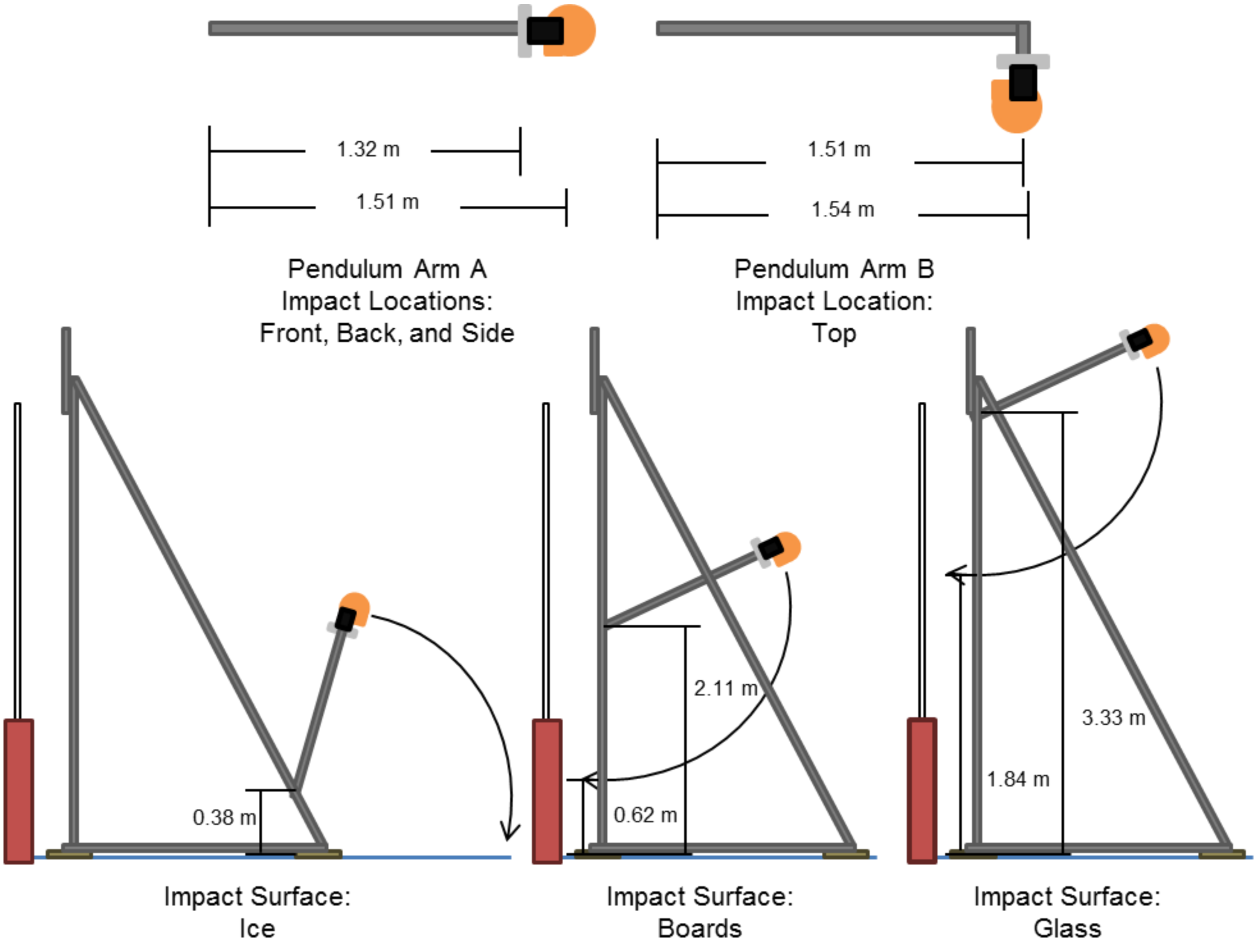

Figure 1. Pendulum schematic showing interchangeable pendulum arms, three pivot points, and corresponding impact surfaces.

For ice surface impacts, the pendulum arm was allowed to fall freely from the vertical, corresponding to a drop height of 1.83 m and a target impact velocity of 6 m/s. For the vertical impact surfaces, boards and glass, three starting angles were defined for each pivot point (71^0, 102^0, and 152^0) (**Figure 2**). Each starting angle corresponded to a specific height above the impact location on the boards or glass (1.03 m, 1.83 m, and 2.87 m), and therefore defined a target peak impact velocity according to Equation 1 (4.5 m/s, 6.0 m/s, and 7.5 m/s). The velocities of the vertical surface impacts were selected based on professional male ice hockey skating speeds.[26,38,48]

$$v = \sqrt{2gh} \qquad \text{(Equation 1)}$$

Figure 2. Pendulum set up on ice, in starting position for a frontal impact to the glass at a target velocity of 4.5 m/s. Photo by author.

To ensure rigid coupling of the structure to the ice surface, five wooden platforms were frozen to the ice surface 12 hours before testing began. The platform freezing was carried out according to standard practice at the rink. On the day of testing, the pendulum was constructed in place and secured to the wooden platforms. The pendulum was thereby held in place without drilling into the ice surface or damaging the subfloor beneath the ice.

A total of 25 tests were performed (**Table 2**). Three impact tests were performed to ice surface. The headform was tested against the surface in each of three locations (front, back, and side) at one target impact velocity (6 m/s). Eleven impact tests were performed each to the boards and to the glass in order to represent the loading conditions found in the epidemiological studies.[1,2] The headform was tested against both surfaces in each of four locations (front, back, side, and top) at three target impact velocities (4.5 m/s, 6 m/s, and 7.5 m/s) with the exception of the 7.5 m/s impacts to the top of the head. These impacts were deemed unrealistic and had the potential to damage the boards and glass due to the compressive stiffness of the Hybrid III neck.

Table 2. Test matrix of head impacts to collegiate ice hockey rink surfaces

Impact Surface	Target Impact Velocity		
	4.5 m/s	6 m/s	7.5 m/s
Ice	-	Front	-
	-	Back	-
	-	Side	-
Boards	Front	Front	Front
	Back	Back	Back
	Side	Side	Side
	Top	Top	-
Glass	Front	Front	Front
	Back	Back	Back
	Side	Side	Side
	Top	Top	-

The headform was instrumented with 9 single axis accelerometers (7264–2000B, Endevco, San Juan Capistrano, CA) positioned in a 3-2-2-2 array to provide linear acceleration along the x, y, and z axes and rotational acceleration about the x, y, and z axes. Acceleration data were collected at 20,000 Hz for each trial using TDAS Pro data acquisition system. High speed video (Phantom V9, Vision Research, Wayne, NJ) was recorded for each test at a frame rate of 1000 Hz. Video analysis was performed to confirm impact velocities.

A custom MATLAB script was used to filter the data according to the SAE J211 standard using Channel Frequency Class (CFC) 1000 and to find impact durations and resultant linear accelerations. To find resultant rotational accelerations, the data were filtered using CFC 180 to minimize the substantial effects of spurious noise on rotational acceleration calculations.[3,29,34] Peak linear and rotational accelerations were found from the resultant accelerations. Statistical comparisons were conducted to determine the significance of the observed differences. Because normality of the distribution of impacts was not assumed, one tailed Wilcoxon signed-rank tests were used to determine if impact magnitude and duration were significantly different between impact surfaces. A threshold value of $p \leq 0.05$ was used to determine statistical significance for all tests.

Results

Linear acceleration traces for all impacts to the ice, boards, and glass at all velocities are shown in **Figure 3** – **Figure 5**. Similar resultant acceleration curve shapes were observed for impacts between the same surface and helmet location across all impact velocities.

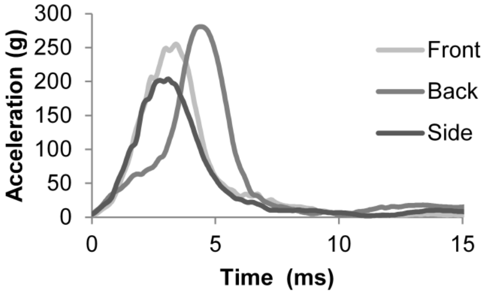

Figure 3. Linear acceleration as a function of time filtered at CFC 1000 for all impacts to the ice, shown for all impact locations tested. Pulses are aligned in time at the time of initial contact with the impact surface.

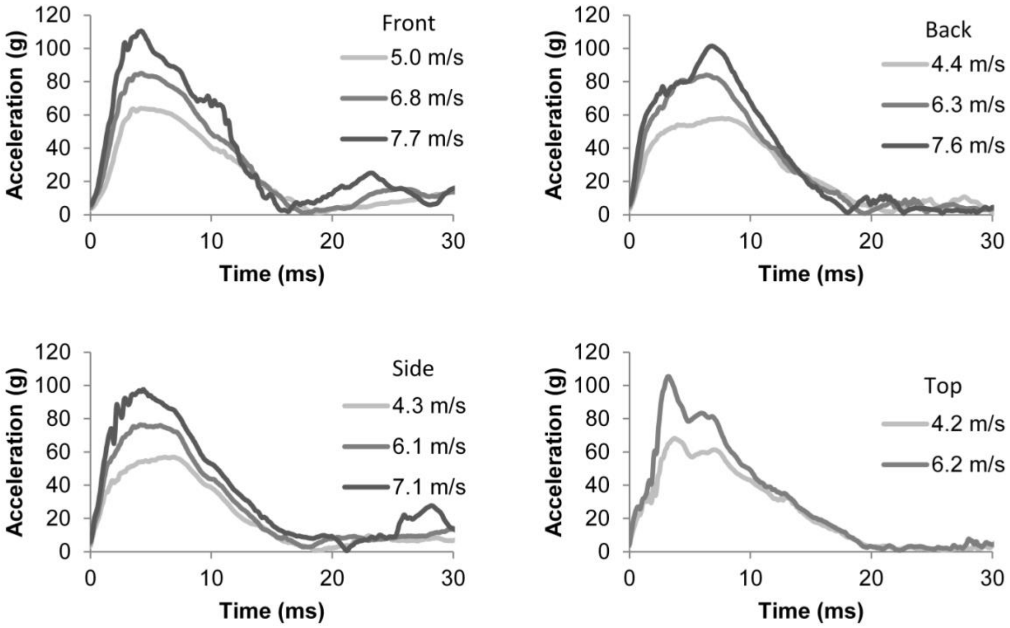

Figure 4. Linear acceleration as a function of time filtered at CFC 1000 for all impacts to the boards, stratified by location and shown for all impact velocities tested. Pulses are aligned in time at the time of initial contact with the impact surface.

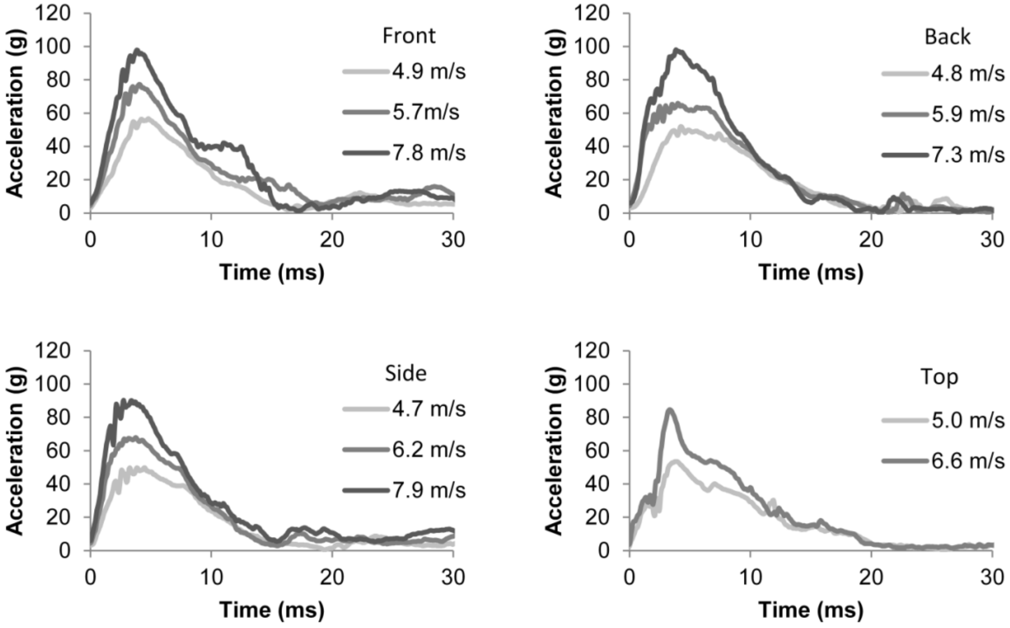

Figure 5. Linear acceleration as a function of time filtered at CFC 1000 for all impacts to the glass, stratified by location and shown for all impact velocities tested. Pulses are aligned in time at the time of initial contact with the impact surface.

Rotational acceleration traces for all impacts to the ice, boards, and glass at all velocities are shown in **Figure 6** – **Figure 8**.

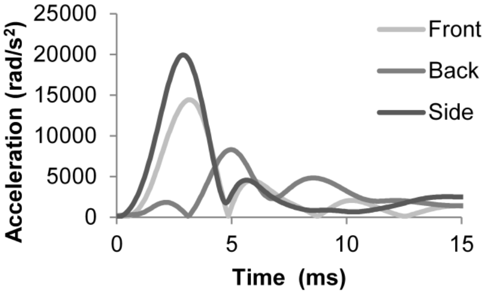

Figure 6. Rotational acceleration as a function of time filtered at CFC 180 for all impacts to the ice, shown for all impact locations tested. Pulses are aligned in time at the time of initial contact with the impact surface.

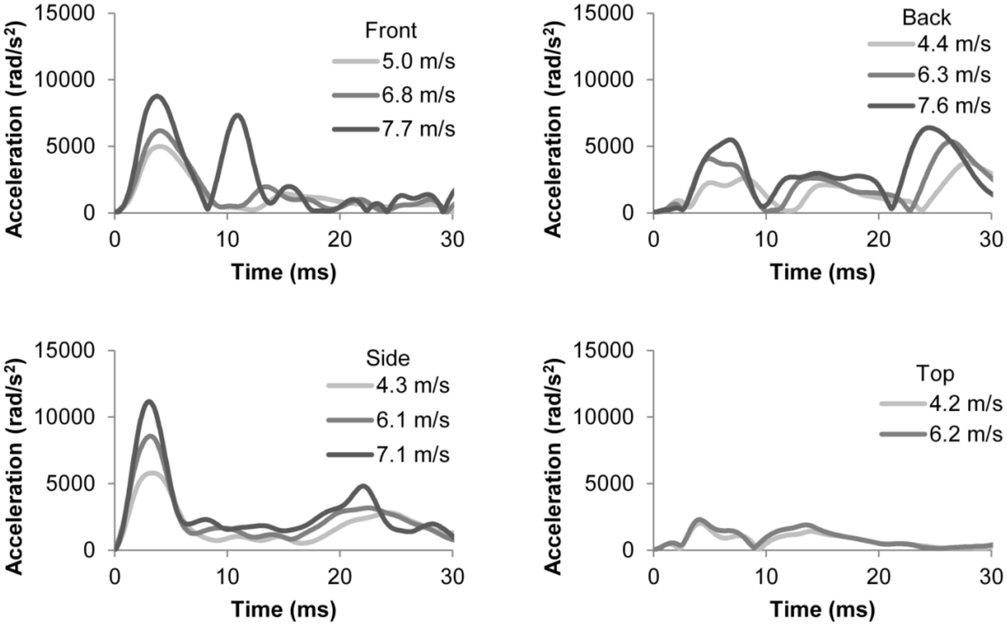

Figure 7. Rotational acceleration as a function of time filtered at CFC 180 for all impacts to the boards, stratified by location and shown for all impact velocities tested. Pulses are aligned in time at the time of initial contact with the impact surface.

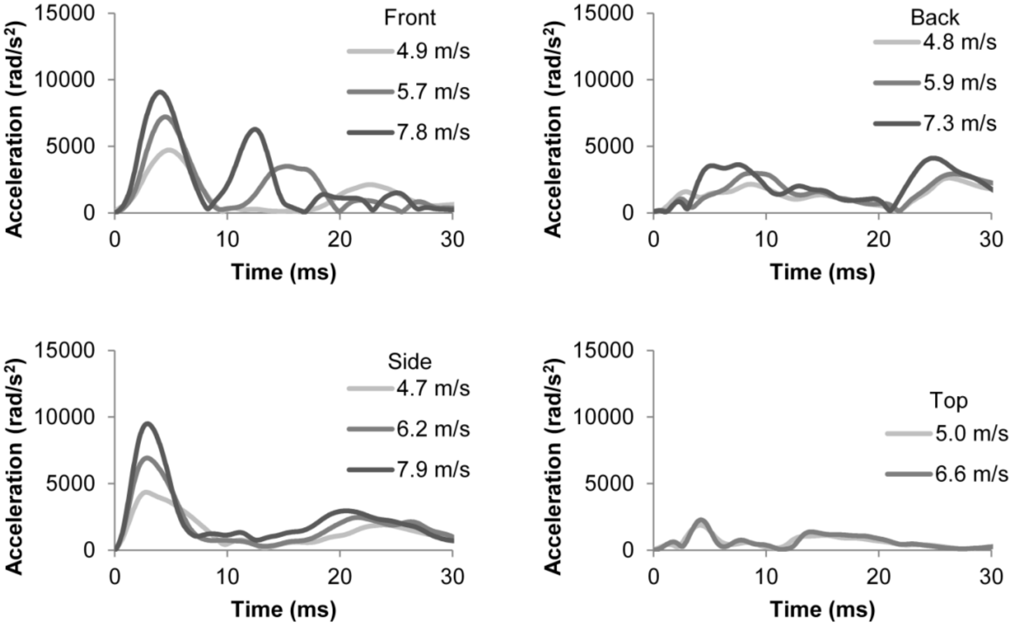

Figure 8. Rotational acceleration as a function of time filtered at CFC 180 for all impacts to the glass, stratified by location and shown for all impact velocities tested. Pulses are aligned in time at the time of initial contact with the impact surface.

Impact duration, measured impact velocity, and peak linear and rotational accelerations of the headform for each trial are given in **Table 3**. For all tests, peak linear acceleration magnitudes ranged from 49.8 g to 281.0 g. Peak rotational acceleration magnitudes ranged from 1873 rad/s^2 to 19934 rad/s^2. Impact durations ranged from 10.0 ms to 23.6 ms.

Table 3. Characteristics of head impacts to ice hockey rink surfaces.

Impact Surface	Target Impact Velocity (m/s)	Impact Location	Peak Linear Acceleration (g's)	Peak Rotational Acceleration (rad/s^2)	Measured Impact Velocity (m/s)	Impact Duration (ms)
Ice	6	Front	255.1	14426	6.1	10.4
		Back	281.0	8289	6.2	10.0
		Side	203.9	19934	6.1	12.2
Boards	4.5	Front	63.9	4990	5.0	18.7
		Back	58.0	3782	4.4	21.1
		Side	56.9	5797	4.3	19.2
		Top	68.3	2017	4.2	20.9
	6	Front	85.0	6166	6.8	18.0
		Back	84.0	5362	6.3	19.6
		Side	76.4	8567	6.1	18.6
		Top	105.4	2295	6.2	19.8
	7.5	Front	110.5	8763	7.7	18.2
		Back	101.4	6396	7.6	18.2
		Side	97.6	11160	7.1	18.8
Glass	4.5	Front	56.6	4722	4.9	23.6
		Back	52.1	2621	4.8	21.5
		Side	49.8	4349	4.7	21.5
		Top	53.5	1873	5.0	21.2
	6	Front	77.3	7210	5.7	18.9
		Back	66.0	2984	5.9	20.8
		Side	67.9	6916	6.2	14.9
		Top	84.6	2272	6.6	21.2
	7.5	Front	97.9	9070	7.8	17.4
		Back	98.1	4114	7.3	19.2
		Side	90.3	9495	7.9	21.0

The magnitudes of linear head acceleration resulting from impacts to the ice surface were found to be significantly greater than the magnitudes of linear head acceleration resulting from impacts to the boards or impacts to the glass, despite similar peak impact velocities for all trials (6.2 ± 0.3 m/s) ($p = 0.05$ and $p = 0.05$, respectively). Only at the lowest impact velocity (4.7 ± 0.3 m/s) was a significant difference was found between the magnitudes of linear accelerations resulting from impacts to the boards and impacts to the glass ($p = 0.01$). No significant differences were found between the magnitudes of linear acceleration resulting from impacts to the boards and impacts to the glass at the medium (6.2 ± 0.4 m/s) and high (7.6 ± 0.3 m/s) impact velocities (p = 0.1 and p = 0.2 respectively).

Impacts to the ice were found to produce greater rotational accelerations than impacts to the glass (p = 0.05). No significant differences were found between rotational acceleration magnitudes resulting from impacts to the ice and boards (p = 0.10). No significant difference was found between the magnitude of rotational acceleration resulting from impacts to the boards and glass at the average impact velocities of 4.7 ± 0.3 m/s, 6.2 ± 0.4 m/s, and 7.6 ± 0.3 m/s (p = 0.24, p = 0.44, and p = 0.5 respectively).

Impacts to the ice were found to have significantly shorter durations than impacts to the boards and impacts to the glass at similar impact velocities (6.2 ± 0.3 m/s) (p = 0.05 and p = 0.05, respectively). Only at the lowest impact velocity (4.7 ± 0.3 m/s) were impacts to the boards found to have a significantly shorter duration than impacts to the glass (p = 0.01). At the average impact velocities of 6.2 ± 0.4 m/s and 7.6 ± 0.3 m/s, impacts to the boards were not found to have significantly different durations than impacts to the glass (p = 0.34 and p = 0.30, respectively).

Discussion

This study found that impacts to the ice produced acceleration magnitudes of double to nearly triple the largest linear accelerations resulting from impacts to the boards or glass. The boards and glass of the ice rink offer a more compliant striking surface that absorbs more impact energy than the rigid ice surface and underlying concrete.

There was little significant difference between the peak accelerations produced by impacts to the boards and glass. The only observable difference between the magnitudes of impacts to the boards and impacts to the glass occurred at the lowest target impact velocity, 4.5 m/s, indicating that when comparing impacts to the boards and glass, impact velocity dictates peak acceleration more so than does impact surface. Impacts to the boards and glass produce very similar head impact responses because of the similar energy absorbing properties of the two surfaces.

Impact surface was found to have a significant effect on impact duration. Impacts to the ice were found to have significantly shorter durations than impacts to either the boards or glass. Impacts to the boards were found not to differ significantly in duration from impacts to the glass. These two surfaces are both designed to be more energy absorbent than the ice surface, resulting in the observed longer impact durations.

The risk of injury associated with each of the impact conditions was calculated according to the combined probability of concussion formula developed by Rowson and Duma using data collected over a decade from instrumented collegiate football players (**Figure 9**).[9,14,15,18,40-44,47] The impacts to the ice surface were found to produce head impact responses most associated with risk of injury, well beyond the threshold of concussion. However, unlike the impacts to the boards and glass, the peak linear accelerations recorded for impacts to the ice were found to be well beyond the reported ranges of average to high severity recorded impacts at the collegiate level.[6,17] Impacts of the head to the ice occurring at impact velocities of 6 m/s, like the ones tested in this study, represent severe and infrequent impact scenarios. An ice hockey player is unlikely to hit their head on the ice surface at an impact velocity of 6 m/s and this testing condition represents a worst case scenario. The impacts to both the boards and glass are more representative of typical impacts, both injurious and non-injurious, and were found to produce head impact responses correlated to injury risks ranging from less than 1% to greater than 99%, with increasing risk of concussion at increasing head impact velocities.

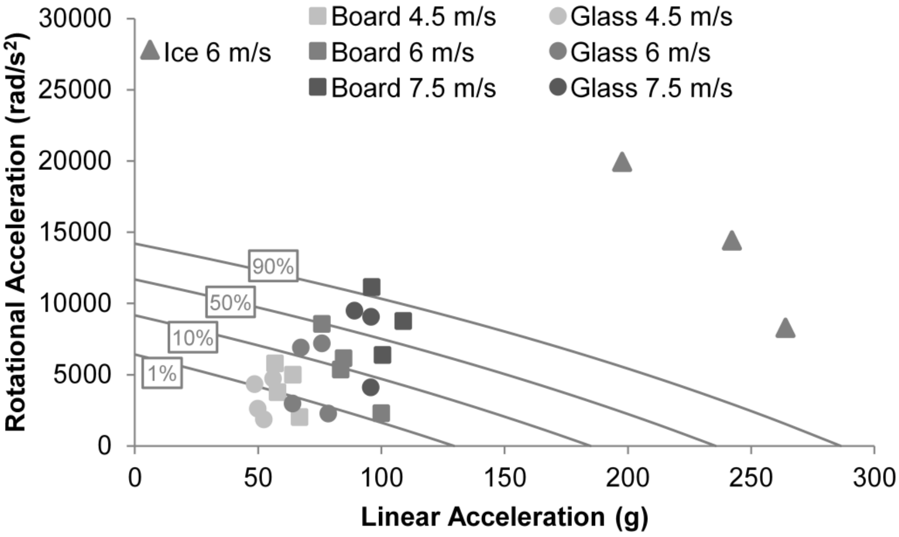

Figure 9. Combined probability of concussion for impacts to the ice, boards, and glass at target impact velocities of 4.5 m/s, 6 m/s, and 7.5 m/s.

Although this study is valuable in that it is the first attempt to quantify differences in head impact to response to different impact surfaces in ice hockey, it is subject to limitations. First, only one test of each set of impact conditions was conducted, which is typical of dummy testing.

Second, only one ice hockey helmet was used during testing. Different helmet models will likely modulate head accelerations differently than the helmet used. The Easton Stealth S9 helmet model was chosen because it was worn by athletes in studies using the HIT system to quantify the distribution of head acceleration magnitudes resulting from head impacts in ice hockey. No damage to the helmet was observed after any of the tests.

Third, the pendulum arm does not accurately model the human body. The pendulum arms do have some mass that could affect the response of the headform to impact. However, because it is unclear what an appropriate effective mass of the human body would be in ice hockey specific head impact scenarios, the use of the pendulum arm was reasonable. The pendulum testing structure was valuable in that it allowed for impact testing against vertical surfaces in situ that were not possible with a drop tower.

Lastly, the repeatability of the impact velocity was greatly reduced by a loss of energy to reverberation in the pendulum system. While there was variability in the head impact velocity at each of the target impact velocity levels, the purpose of this study was not to produce repeatable impact velocities. The impact velocities produced by each drop height of the pendulum were useful in separating the impacts into categories of impact severity. A more stable pendulum with higher repeatability could not be designed to be portable and could not have been assembled and dissembled on ice at a functional ice hockey rink. The pendulum used in this study is a useful tool and provides a range of impact accelerations for the study of head impact biomechanics.

This study utilized published collegiate ice hockey player head impact data to develop an in situ testing mechanism of realistic ice hockey impact scenarios. The effects of impact surface on head impact biomechanics resulting from these impacts was characterized and correlated to injury risk. Studies mirroring those of collegiate football players used by Rowson and Duma to develop their risk function have been conducted on youth football players for multiple seasons and could be used in conjunction with youth ice hockey head impact data to develop similar experiments and risk functions for youth ice hockey athletes, another at-risk population.[10,12,19,30]

In conclusion, head impact response is significantly different for impacts to the different surfaces contained with an ice hockey rink. The results of this study provide insight into the development of further studies and new hockey helmet and rink designs. Further tests of head impacts to the ice surface at a range of impact velocities must be conducted as part of the effort to fully characterize the head impact biomechanics of ice hockey head impacts. Future studies should quantify differences in head impact response as a result of impacts to different locations on the headform and include comparisons with similar head impact response data for player to player collisions.

Chapter 3: Methodology for Mapping Football Head Impact Exposure to Helmet Pads for Repeated Loading Testing

Abstract

Football helmets have a lifespan of 10 years; however, no work has investigated how helmet padding properties change over time with use. The purpose of this study is to develop a methodology to control repeated pad loading and quantify changes in energy management. Head impact exposure data for 7-8 year old football players were used to find an average impact magnitude. NOCSAE-style drop tests were performed using an instrumented headform fitted with the same style helmet (Helmet A) used to collect population data to determine the compression depth and rate of the helmet padding during an average impact. Drops from the same height were then conducted for two other helmet types (Helmet B and Helmet C). For the average impact of ~15 g, the compression depth and rate of the pads from Helmet A were found to be 9.8 mm and 0.72 m/s respectively. The compression depths and rates for Helmets B and C were found to be 6.1 mm and 0.71 m/s and 10.7 mm and 0.69 m/s respectively. These parameters were utilized by a material testing system program to impact helmet padding. Repeated helmet pad loading can be tested using a material testing system for populations with known head impact exposure. The energy absorbing characteristics of the padding can be used to develop new safety regulations regarding the lifetime of helmets, affording better protection to athletes.

Keywords

Concussion, youth, sports, helmet, head impact exposure, acceleration

Introduction

Concussion is an inherent risk of contact sports with potential for long term consequences.[4,5,11] Although the lasting effects of concussion are not fully characterized, efforts to limit head impact exposure, particularly among youth players, have gained traction in recent years.[8,10,12,50] The three main ways to limit head impact exposure in any sport, including football, are by creating and enforcing protective rules, maintaining safety conscious coaching styles, and by designing and selecting the equipment best able to reduce the risk of injury. Efforts by engineers to reduce head impact exposure have focused on improving equipment and quantifying the ability of helmets to reduce head acceleration as a result of impact.[7,15,19,45,46] However, no research has been conducted investigating how helmet padding properties change over time with use. To better understand the effects of repeated impact to helmet pads, long term controlled studies of helmet pad loading must be conducted.

The National Operating Committee on Standards for Athletic Equipment (NOCSAE) is responsible for certifying that newly manufactured helmets meet a defined level of safety prior to being sold. Football helmets that pass the NOCSAE standard endure impacts to the front, side, front boss, back boss, back, top, and a final random location of the helmet at impact velocities between 3.46 m/s and 5.46 m/s while limiting the peak severity index (SI) of each impact to less than 1200.[30,32] Helmets that meet this standard are embossed with the NOCSAE certified logo or given a NOCSAE sticker to indicate to consumers that the helmet is certified.[30,32] This method, while effective in promoting the use of safer helmets on the field, neglects to address changes that occur to the ability of a helmet to absorb energy over time.

The NOCSAE does recommend that football helmets undergo periodic reconditioning and recertification when they are in use for multiple seasons.[31,33] The National Athletic Equipment Reconditioning Association (NAERA) is a group of 21 athletic equipment reconditioners certified by the NOCSAE. The NAERA is responsible for implementing the NOCSAE approved program for helmet reconditioning and recertification. In the recertification process, a sample of the helmets returned by a football organization is retested according to the original standard to ensure the continuing ability of the helmets to reduce impact magnitude for the wearer.[31,33] Similar to the original certification process, helmets that pass the recertification are given a sticker denoting the year in which they were most recently recertified. There is currently no NOCSAE standard in place that regulates the time elapsed between helmet recertifications. There are no published data to support the policy of the NOCSAE not to recertify helmets that have been used for more than 10 seasons.[27]

The Virginia-Tech Helmet Ratings system tests and rates the ability of new football helmets to reduce the risk of concussion.[45] This STAR system provides consumers with even more data regarding helmet safety than the simple pass/fail NOCSAE standard. Published STAR ratings for different helmets are valuable and influence decisions regarding helmet selection. However, the STAR method, like the NOCSAE certification process, does not address the potential changes in the energy absorbing characteristics of different helmet paddings over the course of time with repeated loading.

The purpose of this study is to develop a method to control repeated pad loading that can be used for the quantification of changes in energy management of helmet pads over time with repeated impacts. Head impact exposure data from a population of 7-8 year old youth football players will be used to guide NOCSAE style drop tests of three different helmet types (Helmets A, B, and C). The acceleration data from the drop tests will guide the development of parameters to program a material testing system to deliver controlled, repeatable impacts to a helmet pad. A known history of impact magnitudes and pad energy dissipation for different types of helmet padding will provide data valuable in determining how a helmet's ability to reduce head acceleration changes over time with repeated loading.

Methods

Previously published data collected from football players between the ages of 7 and 8 years were used to model head impact exposure. This study used both the Head Impact Telemetry (HIT) system and a custom, 6 degree of freedom accelerometer array system in parallel to instrument 19 athletes over the course of two seasons. From these head impact exposure data, the distribution of head acceleration magnitudes for this population was quantified.[50] The back of the helmet was selected as the location to be tested because it is the second most frequently impacted location on the helmet. Although players sustained more impacts to the front of the head, the front was not chosen as the location to be tested due to the differences in the padding used in the front of the helmets. The linear acceleration experienced by the head during the average impact was reported to be 15 g.[50] Drop tests to the back of the helmet were performed using a NOCSAE style drop tower and headform equipped with the same helmet style used during the collection of the impact exposure data. The drops were performed to the bare metal anvil of the drop tower. The NOCSAE large headform was instrumented with a triaxial accelerometer to measure linear head acceleration. The linear acceleration of the average magnitude impact was replicated by a 0.11 m drop. The headform was fitted with Helmet B and Helmet C and the 0.11 m drop was repeated.

The acceleration data for each of the drops were sampled at 20,000 Hz and were filtered in accordance with the SAE J211 standard using a Butterworth 4-pole phaseless lowpass filter with a cutoff frequency of 1650 Hz using a custom MATLAB code. Acceleration traces in the x, y, and z directions were integrated to determine the component velocities of the headform (v_k) (Equation 2) which in turn were used to calculate the resultant velocity of the headform (v_h) (Equation 3).

$$v_k = \int_0^{t_f} a_k(t)\, dt \qquad \text{(Equation 2)}$$

$$v_h = \sqrt{{v_x}^2 + {v_y}^2 + {v_z}^2} \qquad \text{(Equation 3)}$$

The resultant velocity of the headform was integrated to calculate the resultant displacement of the headform (d_h) as a function of time (Equation 4).

$$d_h = \int_0^{t_f} v_h(t)\, dt \qquad \text{(Equation 4)}$$

The rate of compression of the helmet padding was calculated by dividing the peak displacement of the headform by the time at which peak displacement of the headform occurred (Equation 5).

$$Mean\ Compression\ Rate = \frac{d_{h_{Peak}}}{t_{Peak}} \qquad \text{(Equation 5)}$$

The displacement of the headform during the impact is equal to the compression depth of the pads. The displacement rate over the duration of the impact is equal to the compression rate. Displacement and displacement rate are parameters that could be used to program the MTS machine.

The metrics given **Table 4** correspond to parameters that were used to control a high rate servo-hydraulic material testing system (MTS) (MTS Systems Corporation, MTS-810, Eden Prairie, MN). Using the displacement control configuration, the MTS was programmed to extend to the peak displacement in the time of impact duration for each helmet type. Because of the level of accuracy required in the pad displacement and the slight delay in the response of the MTS to commands, the programs were altered iteratively to ensure the compression rate and peak displacement of each pad type were conserved. These programs were saved to be called by the machine at any point.

Table 4. Impact parameters measured from a 0.11 m drop test for 3 helmet varieties. Displacement and compression refer to the displacement of the headform with respect to the helmet shell and compression of the padding between the headform and helmet shell.

	Impact Duration (ms)	Peak Displacement (mm)	Mean Compression Rate (m/s)
Helmet Model A	13.6	9.8	0.72
Helmet Model B	8.6	6.1	0.71
Helmet Model C	15.5	10.7	0.69

Tests were performed using custom designed curved adaptors to support and impact helmet padding (**Figure 10**). The adaptors were designed with a 0.13 m radius of curvature to mimic the environment between the inner helmet shell and head occupied by the helmet padding.

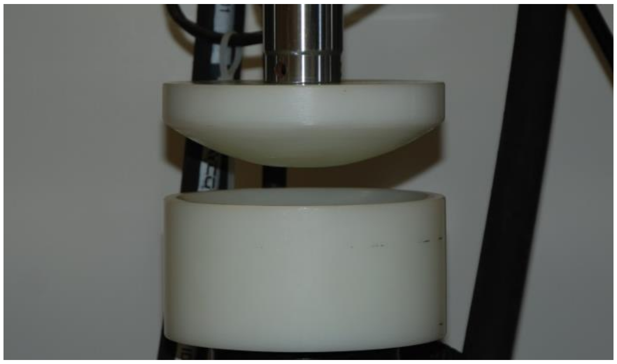

Figure 10. Custom adaptors designed to support and impact helmet padding.

Results

The measured, programmed, and targeted displacements are presented as functions of time for each of the three pad types tested in **Figure 11**. For each pad type tested, the MTS was programmed to pause at the targeted compression depth. This pause accounted for time delay in response of the machine and permitted the MTS to reach the full compression depth before beginning the upstroke of the cycle, as seen in the measured displacements for each pad type.

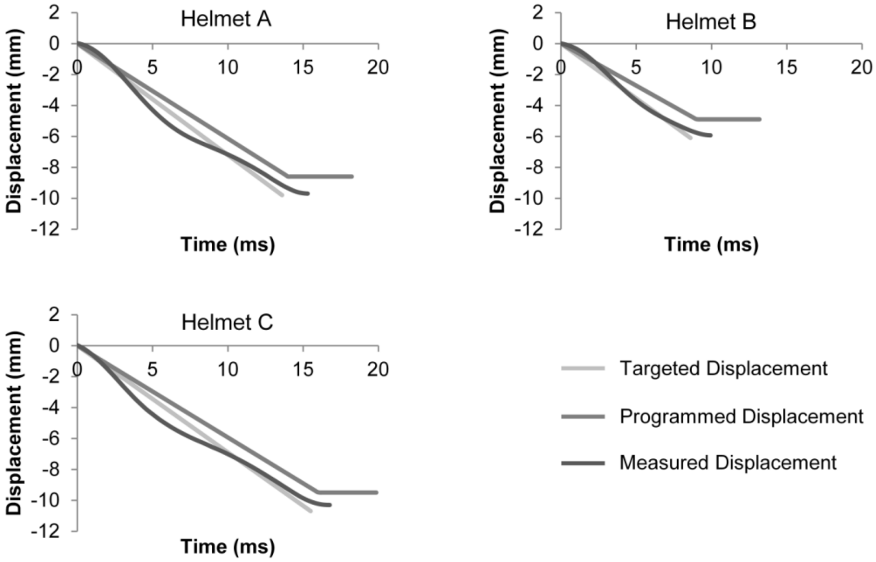

Figure 11. Targeted, programmed, and measured displacement of the pads from Helmets A, B, and C

The measured impact duration and peak displacement of the tested MTS impacts are presented in **Table 5**, as well as the calculated mean compression rates for each of the impacts to the three helmet pad types.

Table 5. Loading metrics measured from MTS impact tests of helmet pads. Displacement and compression rate refer to the displacement of the impactor and compression rate of the helmet pad respectively.

	Impact Duration (ms)	Peak Displacement (mm)	Mean Compression Rate (m/s)
Helmet Model A	15.3	9.7	0.63
Helmet Model B	9.9	5.9	0.60
Helmet Model C	16.8	10.3	0.62

Discussion

The pad from Helmet A was compressed to 99% of the targeted displacement at 88% of the targeted compression rate. Pads from Helmets B and C were compressed to 97% and 96% of the targeted displacements at compression rates of 85% and 90% of the targeted rates respectively. These results demonstrate that although there are time delays in the response of the MTS, drop test derived parameters can be used to command a MTS to deliver controlled impacts of a desired compression depth and rate to helmet padding with a high level of accuracy. The commands can be saved into a program that can be called and reused by the machine at any time to test the effects of repeated loading scenarios on helmet pad energy absorbing properties.

One major assumption that was made in developing this methodology was that any displacement of the headform during impact is a result of helmet pad compression. To reduce the effects of any other sources of displacement, the drop tests were performed to the bare metal anvil of the NOCSAE drop tower rather than the Modular Elastomeric Programmer (MEP) pad typically used for drop testing. The MEP pad was not used in order to eliminate any displacement of the headform as a result of MEP pad compression, rather than helmet pad compression. This method is limited in that it does not take into account any interactions between the anvil and helmet shell that could contribute to the displacement of the headform in addition to the displacement of the headform due to helmet pad compression.

While this method was useful in replicating average magnitude impacts for a youth population, this population experiences relatively low magnitude impacts compared to athletes of all ages and skill levels. Future work should repeat the process using higher magnitude impacts of different populations in order to expand the applicability of the method. Though the MTS used in this study is designed to perform at high displacement rates, it may be unable to replicate compression rates of higher severity impacts as accurately as the impact magnitudes tested in this study. Fortunately, increased understanding of the changes in helmet padding properties has a greater potential to positively affect the safety of youth football players rather than elite or professional players because of the large number of exposed athletes as well as the limited funds available for equipment replacement at this level.[12,49]

Conclusion

In conclusion, this study determined that using population head impact exposure data in combination with NOCSAE style drop tests and a high energy MTS machine to cause controlled impacts to helmet pads is feasible. These data can in turn be used to make decisions regarding relative performance of different helmet pad types over time. Characterization of changes in helmet pad performance over time can lead to developments of better technologies and equipment regulations for football and other helmeted sports and improvements in athlete safety.

Chapter 4: Changes in Energy Management Properties of Football Helmet Pads with Repeated Loading

Abstract

Concussion is an inherent risk of all sports, and has particularly high incidence rates in collision sports like football. Various helmet manufacturers have developed unique padding technologies designed to reduce the risk of concussion. To better understand the effects of repeated impact to helmet pads, long term controlled studies of helmet pad loading must be conducted. The purpose of this study is to quantify changes in energy management of helmet pads over time with repeated impacts by controlling repeated pad loading replicating a season's worth of helmet impacts. Peak force and head impact exposure data from a population of 7-8 year old youth football players was used to develop parameters to control a high energy MTS to deliver controlled impacts to pads from three youth helmet models. Each pad was impacted 153 times over the course of the replicated season for a total of 918 impacts. Force and impactor displacement data were collected for each impact and used to calculate the energy absorbed by each pad during each impact. Simple linear regressions were used to identify trends in energy absorbed by each pad type as a function of impact number. No significant relationship was found between energy absorbed and impact number for pads from Helmets A, B, or C (R^2 = 0.005, R^2 = 0.007, and R^2 = 0.04 respectively). These data demonstrate that the impacts accrued to the back of the helmet over the course of one season of play at the youth level do not induce changes in the energy management properties of the three pad types tested.

Keywords

Concussion, youth, sports, helmet, impact exposure, acceleration

Introduction

Concussion is an inherent risk of all sports, and has particularly high incidence rates in collision sports like football.[1,2,6] Although the lasting effects of concussion are not fully characterized, movements to limit head impact exposure, particularly among youth players, have gained traction in recent years in an effort to reduce potential negative long term consequences to health and cognition.[4,5,7,17] The three pronged effort to reduce head impact exposure in any sport includes creating and enforcing protective rules, maintaining safety conscious coaching styles, and designing and selecting the equipment best able to reduce the risk of injury. Engineers have focused efforts to reduce head impact exposure on improving equipment and quantifying the ability of helmets to reduce head acceleration as a result of impact.[3,8,9,15,16] Football helmet manufacturers have developed various unique padding technologies designed to reduce the risk of concussion. Unfortunately, no research has been conducted investigating how helmet padding properties change with use over time. To better understand the effects of repeated impact to helmet pads, long term controlled studies of helmet pad loading must be conducted.

The National Operating Committee on Standards for Athletic Equipment (NOCSAE) is responsible for certifying that all newly manufactured football helmets meet a defined level of safety prior to being sold. To pass the NOCSAE standard, football helmets must limit the peak severity index (SI) of impacts to the front, side, front boss, back boss, back, top, and a final random location of the helmet at impact velocities between 3.46 m/s and 5.46 m/s to less than 1200.[11,13] Helmets that meet this standard are embossed with the NOCSAE certified logo or given a NOCSAE sticker to indicate to consumers that the helmet is certified.[11,13] Although this method is effective in promoting the use of safer helmets on the field, NOCSAE certification procedures fail to address changes that occur to the ability of a helmet to absorb energy over time.

The National Athletic Equipment Reconditioning Association (NAERA) is a group of 21 athletic equipment reconditioners certified to implement the NOCSAE recommended program for helmet reconditioning and recertification.[12,14] In the recertification process, a sample of the helmets voluntarily returned by a football organization is tested according to the original standard to ensure the continuing ability of the helmets to reduce impact magnitude experienced by the wearer.[12,14] Similar to the original certification process, helmets that pass the recertification are given a sticker denoting the year in which they were most recently recertified. No NOCSAE standard currently regulates the time elapsed between helmet recertifications and no published data exist to support the policy of the NOCSAE not to recertify helmets that have been used for more than 10 seasons.[10]

The Virginia-Tech Helmet Ratings System tests and rates the ability of newly manufactured football helmets to reduce the risk of concussion in adult athletes using the Summation of Tests for the Analysis of Risks (STAR) system.[15] This STAR system provides consumers with more data regarding helmet safety than the simple pass/fail NOCSAE standard. Published STAR ratings for different helmets are valuable and influence decisions regarding helmet selection. However, the STAR method, like the NOCSAE certification process, does not address the potential changes in the energy absorbing characteristics of different helmet paddings over the course of time with repeated loading. Additionally, the STAR system was developed using collegiate head impact exposure data, and may not be valid for the youth helmets.

The purpose of this study is to control repeated pad loading replicating a season's worth of helmet impacts to quantify changes in energy dissipation of helmet pads over time with use. Peak force and head impact exposure data from a population of 7-8 year old youth football players will be used to guide NOCSAE style drop tests of three different helmet types (Helmets A, B, and C).[17] The acceleration data from the drop tests will guide the development of parameters to program a material testing system to deliver controlled, repeatable impacts to a helmet pad. Head impact exposure data from the same pediatric population of football players will be used to construct a realistic repeated loading scenario for helmet pads equivalent to a season's worth of impacts to the back of the head.[17] A known history of impact magnitudes and pad energy dissipation for different types of helmet padding will provide valuable data regarding a helmet's ability to reduce head acceleration changes over time with repeated loading that could affect regulations pertaining to helmet lifetimes and recertification.

Materials and Methods

Three commonly used youth helmet models designed by three different manufacturers using unique padding technologies were selected for repeated loading testing. Helmet A uses foam pads encased in plastic bladders that can be inflated to improve helmet fit. The padding from Helmet B is a molded thermoplastic composed of a thin layer in contact with the head and a thin layer in contact with the inside of the helmet shell connected by an arrangement of hollow tubular channels. Helmet C pads are hollow air-filled cylinders of rubber and plastic intended to absorb shock during impact.

Previously published data collected from football players between the ages of 7 and 8 years were used to model head impact exposure.[17] This study used both the Head Impact Telemetry (HIT) system and a custom, 6 degree of freedom accelerometer array system in parallel to instrument 19 athletes over the course of two seasons.[17] From these head impact exposure data, the distribution of head acceleration magnitudes for this population was quantified. The back of the helmet was selected as the location to be tested because it is the second most frequently impacted location on the helmet. Although players sustained more impacts to the front of the head, the front was not chosen as the location to be tested due to the different types of padding used in the front of the helmets. The linear acceleration experienced by the head during the average impact was reported to be 15 g.[17] Drop tests to the back of the helmet were performed using a NOCSAE style drop tower and headform equipped with the same helmet style used during the collection of the impact exposure data. The drops were performed to the bare metal anvil of the drop tower. The NOCSAE large headform was instrumented with a triaxial accelerometer to measure linear head acceleration. The linear acceleration of the average magnitude impact was replicated by a 0.11 m drop. The headform was fitted with Helmets A, B, and C and the 0.11 m drop was repeated, conserving the impact energy delivered to each helmet type.

The acceleration data for each of the drops were sampled at 20,000 Hz and were filtered in accordance with the SAE J211 standard using a Butterworth 4-pole phaseless lowpass filter with a cutoff frequency of 1650 Hz using a custom MATLAB code. Acceleration traces in the x, y, and z directions were integrated to determine the component velocities of the headform (v_k) (Equation 6) which in turn were used to calculate the resultant velocity of the headform (v_h) (Equation 7).

$$v_k = \int_0^{t_f} a_k(t)\, dt \qquad \text{(Equation 6)}$$

$$v_h = \sqrt{{v_x}^2 + {v_y}^2 + {v_z}^2} \qquad \text{(Equation 7)}$$

The resultant velocity of the headform was integrated to calculate the resultant displacement of the headform (d_h) as a function of time (Equation 8).

$$d_h = \int_0^{t_f} v_h(t)\,dt \qquad \text{(Equation 8)}$$

The rate of compression of the helmet padding was calculated by dividing the peak displacement of the headform by the time at which peak displacement of the headform occurred (Equation 9).

$$Mean\ Compression\ Rate = \frac{d_{h_{Peak}}}{t_{Peak}} \qquad \text{(Equation 9)}$$

The displacement of the headform during the impact is equal to the compression depth of the pads. The displacement rate over the duration of the impact is equal to the compression rate. Impact duration, peak displacement of the pads, and the average compression rate of the pad during impact were calculated for each of the drop tested helmet types (**Table 6**).

Table 6. Impact parameters measured from a 0.11 m drop test for 3 helmet varieties. Displacement and compression refer to the displacement of the headform with respect to the helmet shell and compression of the padding between the headform and helmet shell.

	Impact Duration (ms)	Peak Displacement (mm)	Mean Compression Rate (m/s)
Helmet Model A	13.6	9.8	0.72
Helmet Model B	8.6	6.1	0.71
Helmet Model C	15.5	10.7	0.69

Using the displacement control configuration, a high rate servo-hydraulic material testing system (MTS) (MTS Systems Corporation, MTS-810, Eden Prairie, MN) was programmed to extend to the peak displacement in the time of impact duration for each helmet type. Because of the level of accuracy required in the pad displacement and the slight delay in the response of the MTS to commands, the programs were altered iteratively to ensure the compression rate and peak displacement of each pad type were conserved. These programs were saved to be called by the machine in the repeated loading test series.

The MTS was used with a custom adaptor interface to impact helmet padding samples. Tests were performed using custom designed curved adaptors to support and impact helmet padding (**Figure 12**). The adaptors were designed with a 0.13 m radius of curvature to mimic the environment between the inner helmet shell and head occupied by the helmet padding. For each pad sample, zero displacement was set at the level of impactor contact with the pad sample, defined by a measured force of 2 N. For each impact, displacement is referenced from the contact defined zero.

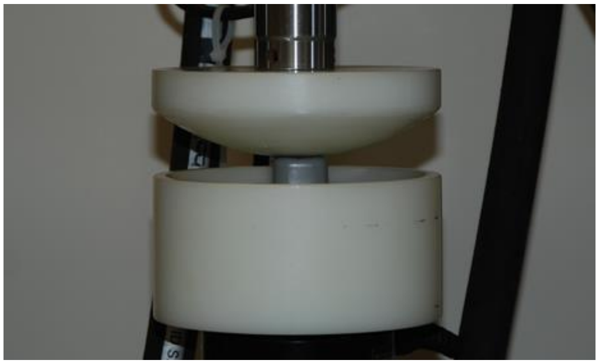

Figure 12. Custom adaptors designed to support and impact helmet padding. Photo by author.

Previously published data was used to determine modeled season length, as well as the total numbers of practices per season, games per season, impacts per practice and game, and session length. Two pad samples of each of the three different helmet brands were impacted 153 times over the course of nine weeks for a total of 918 impacts. Each week of testing, two practice modeled sessions and one game modeled session were completed, for a total of 27 sessions. Sessions within the same modeled week were conducted 48 hours apart. The first practice session of a week was started 96 hours after beginning the previous week's game session. Practice sessions consisted of 5 impacts at 15 minute intervals for each pad and game sessions consisted of 7 impacts at 13 minute intervals for each pad.

For each impact, programmed displacement, measured displacement, and force data were collected at approximately 6000 Hz, based on the capabilities of the MTS. A second custom MATLAB code was used to filter the data to 1,650 Hz, find the peak force and displacement, and to calculate the energy absorbed by the pad for each impact. Simple linear regressions were used to identify trends in energy absorbed by each pad type as a function of impact number.

Results

The impact duration and peak displacement of the tested MTS impacts are presented in **Table 7** as well as the calculated mean compression rates for each of the impacts to the three helmet pad types. Peak force and energy absorbed by each padding sample for all impacts during repeated loading testing are shown in **Figure 13** and **Figure 14**.

Table 7. Loading metrics measured from MTS impact tests of helmet pads. Displacement and compression rate refer to the displacement of the impactor and compression rate of the helmet pad respectively.

	Impact Duration (ms)	Peak Displacement (mm)	Mean Compression Rate (m/s)
Helmet A	14.9 ± 1.0	9.6 ± 0.09	0.64
Helmet B	9.3 ± 0.67	5.7 ± 0.8	0.61
Helmet C	16.6 ± 0. 49	10.4 ± 0.06	0.63

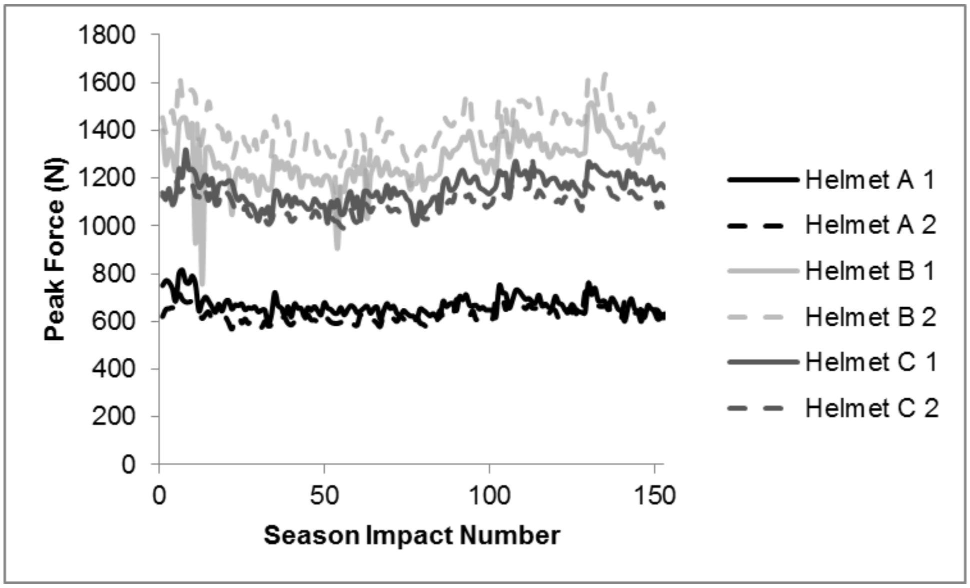

Figure 13. Peak force delivered to each padding sample for each impact during repeated loading

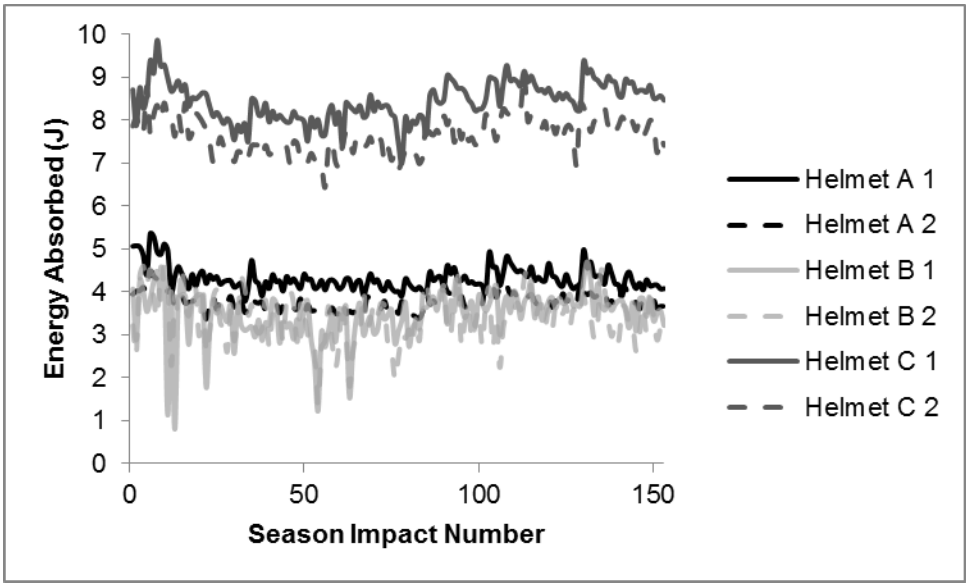

Figure 14. Energy dissipated by each padding sample for each impact during repeated loading

The peak force experienced during impact by padding from Helmet A ranged from 563 N to 816 N. The peak forces experienced during impact by paddings from Helmet B and C ranged from 756 N to 1633 N and 993 N to 1319 N, respectively. The energy absorbed by the padding from Helmet A during each impact ranged from 3.37 J to 5.36 J. The energy absorbed by the paddings from Helmets B and C during each impact ranged from 0.80 J to 4.71 J and 6.44 J to 9.87 J, respectively.

Energy dissipation was found not to depend on impact number for any of the three pad types tested ($R^2 = 0.005$, $R^2 = 0.007$, and $R^2 = 0.04$, respectively) (**Figure 15 - Figure 17**).

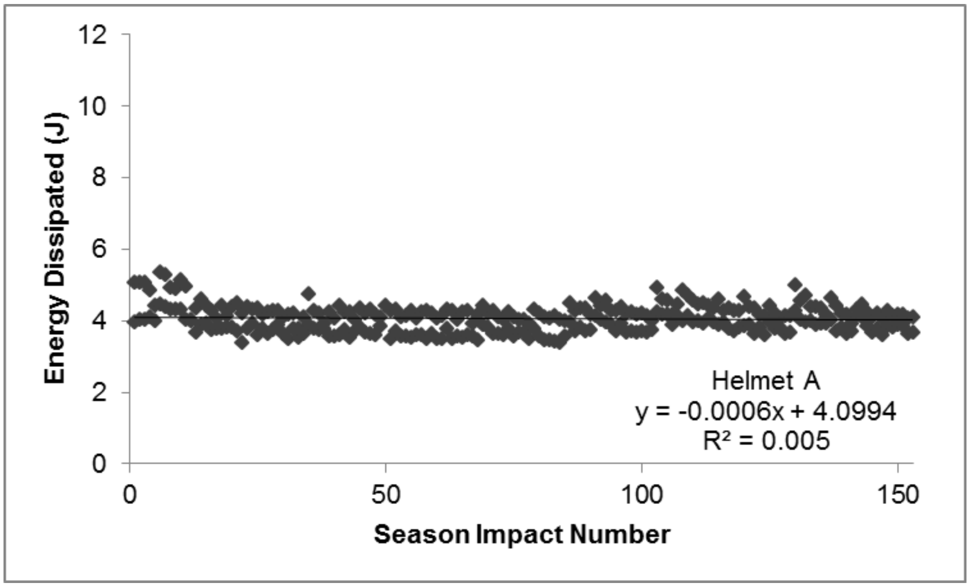

Figure 15. Energy dissipated by padding samples from Helmet A for each impact tested and linear regression with R^2 value of 0.005.

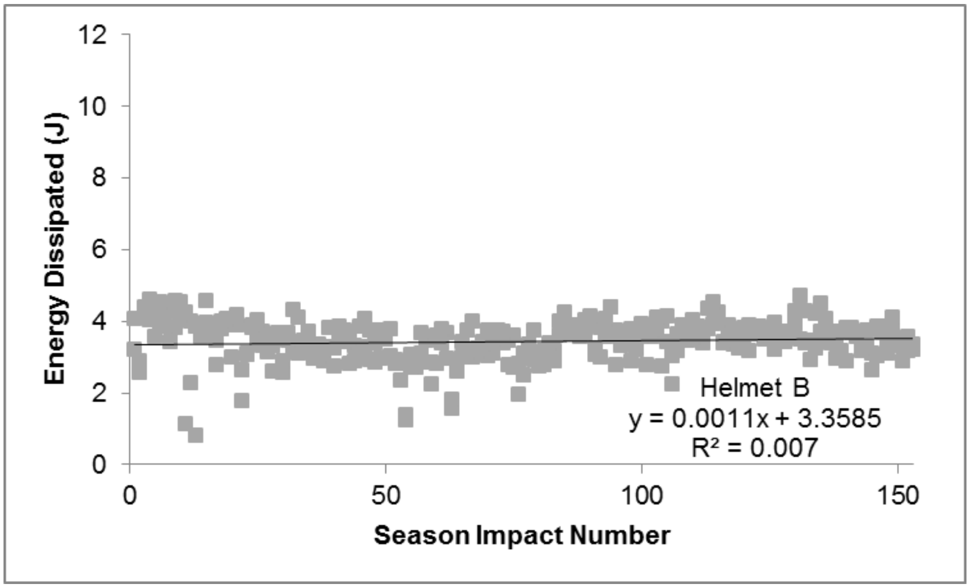

Figure 16. Energy dissipated by padding samples from Helmet B for each impact tested and linear regression with R^2 value of 0.007.

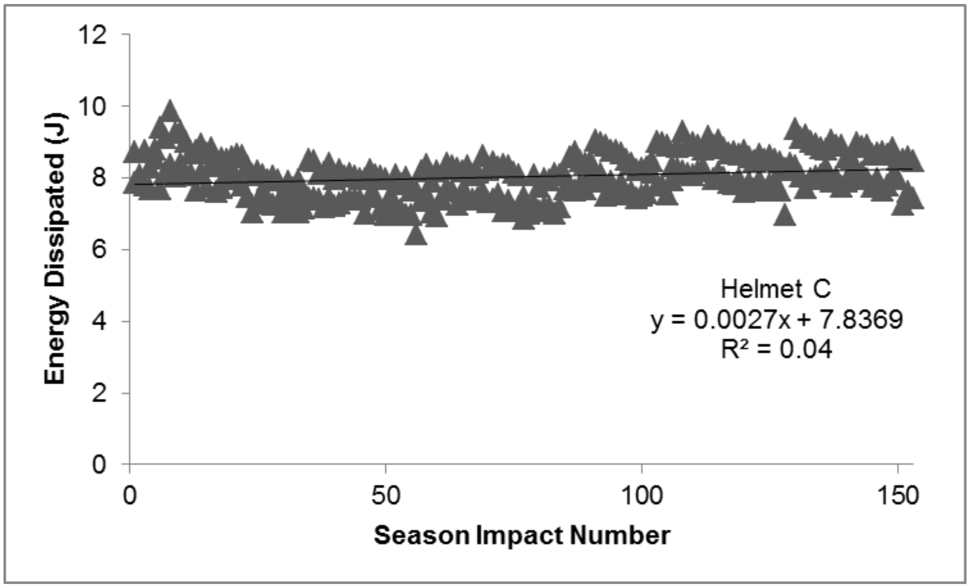

Figure 17. Energy dissipated by padding samples from Helmet C for each impact tested and linear regression with R^2 value of 0.04.

Discussion

This study found that the impacts accrued to the back of the helmet during the course of one season of play at the youth level do not induce changes in the energy management properties of the three helmet pad types tested.

While this study is valuable in that it is the first to detail the energy absorbing response of helmet padding to known loading histories as a function of the number of impacts, it is subject to some limitations. First, this study replicated repeated loading equivalent to play at the youth level. Helmet pads are likely to respond differently to different loading histories, especially those experienced by elite players. The youth population was selected for study because youth athletes playing in municipal leagues are more likely to use older equipment than elite players at the professional and collegiate levels. Therefore, the effects of repeated loading on helmet performance are most directly applicable to this population.

Second, the repeated loading tested in this study was equivalent to only one season of play. Although in many cases helmets are used for only one or two seasons between recertifications, further studies investigating changes in energy absorbing properties of helmet pads over the course of a helmet lifetime (≤ 10 years) would provide additional valuable information.

Lastly, only two samples of each pad type were tested in order to increase the number of types of pads that could be studied. Although each pad type responded consistently, further studies should utilize larger sample sizes of the helmet pads of interest.

Conclusion

In conclusion, a material testing system was used to deliver controlled impacts to helmet paddings equivalent to one season of play at the youth level. This repeated loading was found not to affect the energy management properties of the three helmet pad types tested. The results of this study provide insight into the range of helmet padding performance at the youth level. Future studies should quantify the changes in energy dissipation of a greater number and variety of helmet pad types over a longer period of time and repeated loading. A thorough understanding of the differing responses of various helmet padding types has the potential to influence the creation of standards for helmet recertification and helmet lifetime.

Chapter 5: Closing Remarks

Research Summary

The research presented in this thesis investigates the biomechanics of the helmeted head during impacts in ice hockey as well as changes in the performance of football helmets as a result of repeated loading. New testing equipment and methodologies were developed to collect data about these phenomena. Each of the three studies added to a prior body of knowledge and removed limitations from previous work. The measurement of head acceleration during impact to the different surfaces present in ice hockey provided a previously unavailable source of information linking impact scenario and head biomechanics. The method developed to control repeated pad loading was used to quantify the energy absorbance of helmet padding over the course of time with repeated loading and has the potential to influence future helmet ratings, as lifetime helmet performance becomes easier to evaluate. Increased data regarding the biomechanics of head impact and the performance of helmets will lead to greater understanding of human head injury, in sports and other injury modes.

Publication Outline

The research contained in this thesis is intended to be presented in various journals and conference proceedings. **Table 8** displays the publication destinations for each thesis chapter. All chapters are in their publication form.

Table 8. Publication plan for research presented in this thesis.

Chapter	**Title**	**Potential Journal/(*Conference*)**
2	Head accelerations in ice hockey impacts to the ice, board, and glass surfaces	Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology
3	Methodology for mapping head impact exposure to helmet pads for repeated loading testing	*(Biomedical Sciences Instrumentation §)*
4	Changes in football helmet pad energy management with repeated loading	Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology
§ Presented		

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