Head Impact Biomechanics and Helmet Performance in Youth Football

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Abstract

The research presented in this thesis aims to improve the knowledge of head impact biomechanics in youth football players by analyzing head impact exposure of youth football players and the performance of youth football helmets. The results of the studies presented provide a foundation for researchers, football leagues, and helmet manufactures to implement changes and modifications that aim to reduce concussion risk in youth athletes. The first study presented in this thesis aims to quantify the head impact exposure of 7 to 8 year old football players and determine the cause of variation in player exposure. To conduct this study, 19 players were instrumented with helmet mounted accelerometers that measured real-time acceleration data on the field. This data was analyzed to determine the magnitude, frequency, and location of each impact sustained by players in the 2011 and 2012 football season. From these data, it was determined that the average 7 to 8 year old player experienced 161 impacts per season, 60% of which were in practice and 40% were in games. The median impact for 7 to 8 year old players was 16 g and 686 rad/s^2. The magnitude of the 95th percentile impact was 38 g and 2052 rad/s^2. A total of 125 impacts above 40 g were recorded, 67% of which occurred in practices and 33% occurred in games. It was determined that returning players experienced significantly more impacts per season than first time players and practices had significantly higher magnitude impacts than games. These data can be used to further develop practice modifications that aim to reduce total impacts and high magnitude impacts experienced by youth football players. The second study presented in this thesis aims to quantify differences in youth football helmet performance before and after a football season. Currently, the only requirement regarding helmet recertification and reconditioning states that no helmet older than 10 years will be recertified or reconditioned. Quantitative data is needed to either support or refute this guideline and provide data describing how often youth football helmets should be recertified and reconditioned. To conduct this study, 6 youth Riddell Revolution football helmets, 3 that were new and 3 that had been used for one season, were tested on a drop tower from various heights and impact locations before and after the 2013 football season. It was determined that there was no significant difference in helmet performance before and after a season for new helmets or helmets that had been used for one season. In addition, there was no significant correlation between the frequency of impacts, the 95th percentile impact magnitude, or the product of the frequency and 95th percentile impact magnitude with the change in helmet performance. Future studies should be conducted that analyze the performance of youth football helmets over the course of multiple seasons.

Attribution

Several colleagues participated in the experimental design, data collection, and data analysis presented in this thesis. A description of their contributions is included here.

Chapter 2:

Ray W. Daniel, MS (Center for Injury Biomechanics, School of Biomedical Engineering and Sciences) is currently a graduate student at Virginia Tech. Mr. Daniel is a co-author of this chapter and aided in collection of data from the youth 2011 football season.

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Table of Contents

List of Figures

List of Tables

Chapter 1: Introduction

Opening Remarks

Each year an estimated 1.6 to 3.8 million sports related concussions occur in the United States and, due to its popularity, football accounts for the largest number of these injuries.[1,2] A concussion is defined as a complex pathophysiologic event that is caused by traumatic biomechanical forces and generally presents with one or more of the following symptoms: headache, nausea, loss of consciousness, amnesia, irritability, slowed reaction time, and insomnia.[3] Recent research analyzing the causes of chronic traumatic encephalopathy, a neurodegenerative disease, shows that repetitive mild head trauma may be associated with long term consequences on the brain.[4,5] Of the 5 million athletes who participate in organized football each year, there are approximately 3.5 million youth players, 1.3 million high school players, 100,000 college players, and 2,000 NFL players.[6-8] Athletes in the pediatric population may be more susceptible to damage from head trauma due to a lack of full development in neural tissue and neck musculature.[9,10] Over the last decade significant research has been conducted to study the biomechanics of concussions in order to understand how to reduce the number of head injuries that occur on the field. This research, however, has focused almost exclusively on adult athletes who make up a minority of the 5 million athletes participating in organized football each year.[11-25]

To quantify head acceleration during concussive impacts in NFL athletes, Pellman et al. reconstructed head impacts on the field in the laboratory using a Hybrid III crash test dummy.[20] In this study, non-concussive impacts and impacts that resulted in clinical diagnosis of concussions were identified on video footage and analyzed. Video footage was used to determine the direction, location, and speed of each impact. These parameters were reconstructed using a Hybrid III crash test dummy and the resultant head accelerations were measured. A total of 31 events were reconstructed in the laboratory, 25 of which were concussive impacts.[20] With these data, injury risk curves predicting concussion risk as a function of various injury metrics such as linear acceleration, rotational acceleration, Severity Index, and the Head Injury Criterion were developed.[20,26] While these data provide insight into the biomechanics of concussions, the use of a mechanical surrogate to predict a human response is major a limitation of the study.

In order to quantify the human response to head impacts, college football athletes have been instrumented over the past 10 years with accelerometers to directly measure head acceleration on the field.[15] Thus, researchers are able to analyze the human physiological response to injurious forces in an ethical manner. From these studies, over 1.5 million head impact events have been collected resulting in the development of injury risk curves that describe the probability of concussion as a function of linear acceleration, rotational acceleration, and their combined effect.[15,27-29] In addition, these data have been used to develop an adult helmet rating system to better predict the ability of a helmet to reduce the risk for head injury on the field.[21] Recently, head impacts at the youth level have been studied by Daniel et al. who instrumented 7 youth football players between the ages of 7 and 8 years with helmet accelerometers to quantify head impact exposure of youth players for the first time.[6] These studies have resulted in practice structure modifications that aim to reduce head injuries in football.[30]

The previous studies described have made progressive strides towards reducing the number of head injuries in football. However, more data needs to be collected on larger sample sizes at the youth level to adequately describe concussion mechanics in the pediatric population. The research presented in this thesis aims to better understand how to reduce the number of head impacts and injuries sustained by youth football players.

Research Aims

To understand the mechanism and causes of concussion in youth athletes, head impact exposure must be quantified. Thus, the first study presented in this thesis aims to quantify the magnitude, frequency, and location of all impacts sustained by 7 to 8 year old youth players over a season (**Table 1**). These data can eventually be used to implement further rule modifications that aim to reduce head impacts, develop youth specific injury risk curves for concussions, and develop a youth helmet rating system. In addition to rating a helmet's ability to reduce the risk for concussion it is important to consider how the properties of a helmet changes from season to season. Therefore, the second study presented in this thesis aims to quantify differences in a youth helmet's ability to reduce the risk for head injuries before and after a season of use (**Table 1**).

Table 1. Research presented in this thesis.

Chapter	**Research Aim**
Chapter 2	Head Impact Exposure in Youth Football: Elementary School Ages 7 to 8 Years and the Effect of Returning Players
Chapter 3	Effect of a Season of Use on Youth Football Helmet Performance

Chapter 2: Head Impact Exposure in Youth Football: Elementary School Ages 7 to 8 Years and the Effect of Returning Players

Abstract

Objective: To provide further data describing the head impact exposure of 7 to 8 year old football players.

Design: Head impact data were collected from 19 players over the course of two seasons using helmet-mounted accelerometer arrays.

Setting: Data were collected from two youth football teams in Blacksburg, VA spanning two seasons.

Participants: A total of 19 youth football players ages 7 to 8 years.

Interventions: None. Independent variables were the type of session (practice or game) and the player's experience.

Main Outcome Measures: Head impact frequency, acceleration magnitude, and location of impact for games, practices, and the season as a whole were measured.

Results: The average instrumented player sustained 9 ± 6 impacts per practice, 11 ± 11 impacts per game, and 161 ± 111 impacts per season. The average instrumented player had a median impact of 16 ± 2 g and 686 ± 169 rad/s^2 and a 95th percentile impact of 38 ± 13 g and 2052 ± 664 rad/s^2 throughout a season. Impacts of 40 g or greater tended to occur more frequently in practices than in games, and practices had a significantly higher 95th percentile impact magnitude than games ($p = 0.023$). Returning players had significantly more impacts than first time players ($p = 0.007$).

Conclusions: These data are a further step toward developing effective strategies to reduce the incidence of concussion in youth football and have applications toward youth-specific football helmet designs.

Keywords: Concussion, Brain injury, Biomechanics, Pediatric, Acceleration, Helmet

Introduction

In the United States, 500,000 children between the ages of 8 and 19 years old visited emergency departments seeking treatment for concussions between the years of 2001 and 2005.[31,32] Of these injuries, approximately 50 to 60% occurred during organized sporting events.[33] Due to its popularity and physical nature, football accounts for 50% of all sports related concussions in organized team sports.[31] To date, the primary focus of biomechanics research on concussions in football has been on professional, collegiate, and high school level players.[11-25] However, of the 5 million athletes participating in organized football in the United States each year, 3.5 million are between the ages of 6 and 13 years old (**Figure 1**).[6-8] Athletes in this age group may be more susceptible to damage from head trauma due to a lack of full development in neural tissue and neck musculature.[9,10] Thus, it is important to understand the exposure and tolerance to head impact at this level of play.

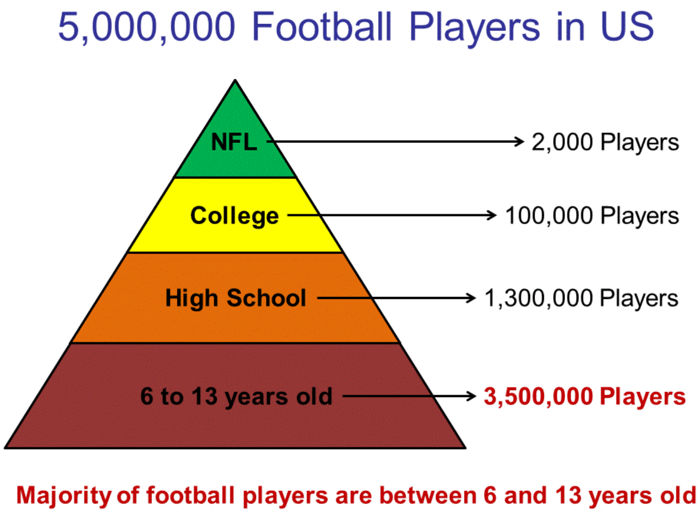

Figure 1. Of the 5 million football athletes in the United States, 3.5 million are between the ages of 6 and 13 years old.

To make educated decisions toward reducing the incidence of concussion in football, head impact exposure must be quantified in terms of impact frequency, acceleration magnitude, and location. Helmet-mounted accelerometer arrays have previously been used to collect over 1.5 million head impacts to quantify head impact exposure in players at the collegiate (19 to 23 years), high school (14 to 18 years) and youth level (7 to 8 years).[15] From these studies, it has been shown that the number of impacts per season and the magnitude of impacts both increase with player age.[6,11,21] Differences observed in each level of play suggest the need to study the head impact exposure at all age levels. However, limited data have been collected at the youth level and further work to quantify head impact exposure is needed.

These studies have resulted in concussion risk prevention initiatives at the collegiate level, such as: policies limiting contact during practice in certain conferences, the availability of medical personnel on the sideline who are trained in concussion treatment and recognition, and the development of an adult football helmet rating system.[12,13,21,34]

Unfortunately, many of these policies are not easily translatable to the youth level due to limited resources and a lack of youth-specific research. Of late, the safety of youth football has seen a sharp increase in attention as recent research suggests a link between repetitive head trauma and long term damage in adults.[4] Policies and awareness programs are currently being tested to try to eliminate unnecessary impacts that cause concussions. After a study found that the majority of high magnitude impacts occurred during practices rather than games in 7 and 8 year old football players, Pop Warner Football implemented a set of regulations limiting the amount of contact that can occur and the types of drills allowed in practices.[6] This regulation allows for contact in a maximum of 1/3 of the practice session and eliminates head-on blocking and tackling drills in which players line up 3 or more yards apart. The ability of these or similar regulations to reduce impact frequency and acceleration magnitude has yet to be determined.

The objective of this study is to provide further data describing head impact exposure at the youth level. It is hypothesized that differences in session type and player experience will affect the measured impact exposure of individual players. Understanding the head impact exposure in youth football has applications towards the development of laboratory testing protocols for youth football helmets, as it is imperative that the loading conditions and testing environment are representative of real-world impact events.[35-37] Furthermore, these data are a further step toward developing effective strategies to reduce the incidence of concussion in youth football.

Materials and Methods

A youth football team consisting of children ranging in age from 6 to 8 years participated in this study approved by the Virginia Tech Institutional Review Board over the course of two seasons. Each player gave assent and their parental guardians provided written informed consent. Head impact exposure was measured using accelerometer arrays installed into the helmets of 19 players. Instrumented players had an average age of 7.8 ± 0.4 years and an average body mass of 32.5 ± 8.1 kg. Each player was provided with a Riddell Revolution or Riddell Speed helmet that was fit to manufacturer specification. Helmets were instrumented with one of two accelerometer arrays that were used in parallel: the commercially available Head Impact Telemetry (HIT) System (Simbex, Lebanon, New Hampshire) or a custom 6 degree of freedom (6DOF) head acceleration measurement device.[14,38,39]

A total of 7 players were instrumented with the HIT System which consists of six accelerometers mounted on an elastic base to ensure that the head acceleration is measured rather than helmet shell vibrations (**Figure 2**).[40] During play, any time an accelerometer measured an acceleration greater than 14.4 g, data acquisition was triggered. Once collected, the data were transmitted wirelessly to a sideline computer where resultant linear head acceleration at the center of gravity of the head was computed and peak rotational acceleration was estimated.[28,41] The HIT System has previously been validated and is widely used to study concussions in athletes.[15,42]

A total of 12 players were instrumented with the 6DOF head acceleration measurement device that consists of 12 accelerometers mounted in the crown of the player's helmet that are oriented tangentially to the head (**Figure 2**).[38] Data are collected from the accelerometers and relayed to a sideline computer in the same manner as the HIT System. The novel sensor arrangement allows for linear and rotational acceleration about each axis of the head to be computed.[38,43] A detailed description of the 6DOF measurement device has previously been reported.[38]

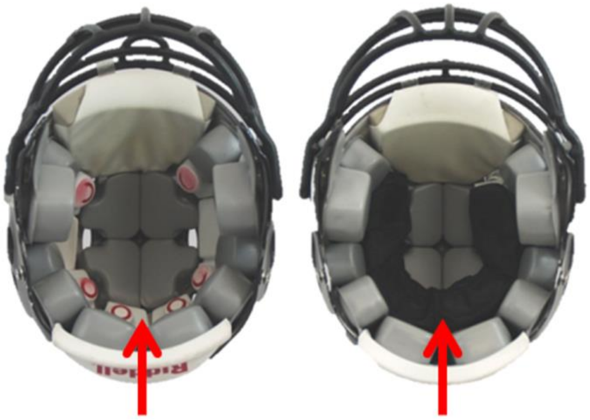

Figure 2. The HIT System (left) and the 6DOF measurement device (right) were installed between the existing padding in youth football helmets and used to measure head accelerations in each player.

Impacts were confirmed with video footage to remove any impacts collected while the player was not wearing their helmet. Head impact exposure is presented in terms of an empirical cumulative density function (CDF). The frequency of impact, the median impact, and the 95th percentile impact were determined for practices, games, and the total season. In addition, the impact distribution was analyzed by impact location. To compare differences between returning players and first time players and between players in different seasons, Kruskal-Wallis one-way analysis of variance tests were used. To compare differences between practices and games, Wilcoxon paired-sample tests were used. Statistical significance was determined using a threshold of $p < 0.05$ for both tests.

To identify and diagnose a concussion during this study, the following protocol was used. Coaches, parents, and players were informed of concussion symptoms at the start of the season. All parties were urged to seek a physician if a player exhibited or reported any symptoms of a concussion. A Virginia Tech sports medicine physician agreed to see players who did not see or use a primary care physician but had a suspected concussion. Concussions were only recorded if they were formally diagnosed by a physician.

Results

A total of 3059 impacts were collected from the 19 instrumented players throughout the 2011 and 2012 seasons. Practices accounted for 60% of the recorded impacts and games accounted for the remaining 40% of impacts. Linear and rotational acceleration empirical CDFs were computed for the 19 instrumented players (**Figure 3**). The distributions of linear and rotational acceleration were right-skewed with a large number of low magnitude impacts. Linear acceleration ranged from 10 g to 111 g with a median value of 16 g and a 95th percentile value of 37 g. Rotational acceleration ranged from 3 rad/s^2 to 7694 rad/s^2 with a median value of 621 rad/s^2 and a 95th percentile value of 2016 rad/s^2.

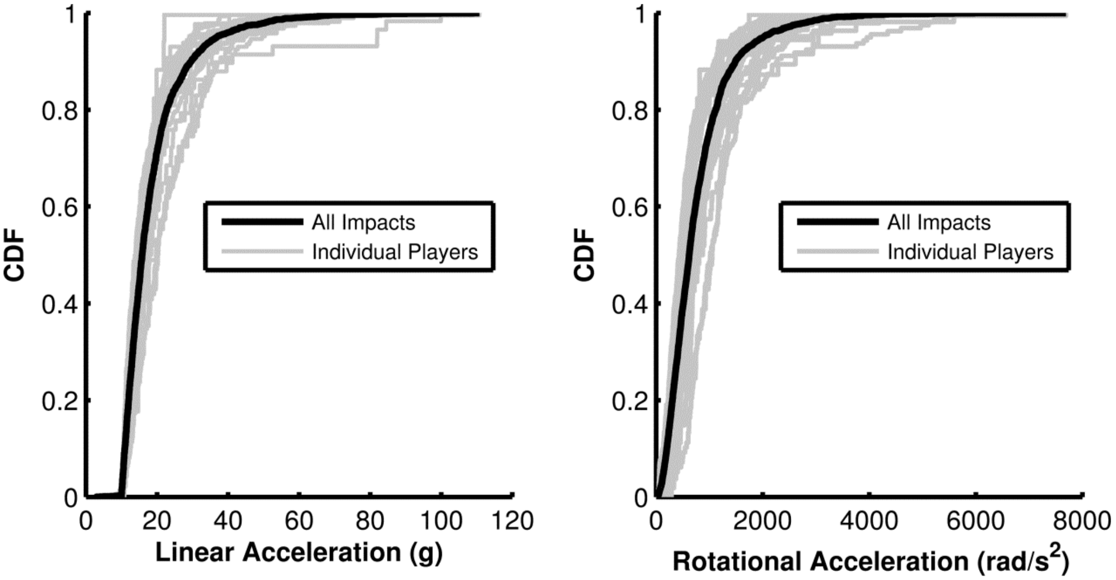

Figure 3. Empirical cumulative density functions for both linear and rotational acceleration are right skewed and heavily weighted towards low magnitude impacts.

The average instrumented player participated in 16 ± 6 sessions, including 10 ± 4 practices and 6 ± 2 games (**Table 2**). Each season, the average instrumented player experienced 161 ± 111 impacts, 96 ± 65 of which occurred in practices and 65 ± 54 occurred in games. For the entire season, the median impact was 16 ± 2 g and 686 ± 169 rad/s2 and the 95th percentile impact experienced was 38 ± 13 g and 2052 ± 664 rad/s2. During practices, the median impact experienced was 17 ± 2 g and 677 ± 164 rad/s2 and the 95th percentile impact experienced was 39 ± 13 g and 1988 ± 575 rad/s2. During games, the median impact experienced was 17 ± 3 g and 651 ± 236 rad/s2 and the 95th percentile impact experienced was 32 ± 9 g and 1848 ± 948 rad/s^2.

Table 2. Descriptive statistics on head impact exposure are listed for each player. Players denoted as "F" are first time players and players denoted as "R" are returning players. Players 1 and 2 are repeated because they participated in both seasons of data collection.

			Practices							Games							Total Season						
				Number of Impacts		Linear Acceleration (g)		Rotational Acceleration (rad/s^2)			Number of Impacts		Linear Acceleration (g)		Rotational Acceleration (rad/s^2)			Number of Impacts		Linear Acceleration (g)		Rotational Acceleration (rad/s^2)	
Player	Age	Year	Sessions	Total	Per Session	50%	95%	50%	95%	Sessions	Total	Per Session	50%	95%	50%	95%	Sessions	Total	Per Session	50%	95%	50%	95%
$1a_F$	7	2011	7	50	7	16	49	751	2327	6	60	10	16	35	678	1412	13	110	8	16	42	694	1834
$1b_R$	8	2012	13	97	7	19	43	950	2381	8	89	11	21	54	1158	3088	21	186	9	20	49	1017	2535
$2a_F$	7	2011	5	26	5	16	41	572	1685	5	34	7	16	30	716	1589	10	60	6	16	36	635	1718
$2b_R$	8	2012	8	205	26	15	29	410	1395	5	169	34	15	29	437	1418	13	374	29	15	29	431	1415
3_R	8	2011	9	68	8	15	49	773	2486	5	90	18	13	33	743	4207	14	158	11	14	38	762	3966
4_R	8	2011	18	120	7	15	37	628	1740	5	28	6	13	37	516	1633	23	148	6	15	37	596	1755
5_R	8	2011	10	56	6	15	82	601	2256	2	2	1	18	23	429	624	12	58	5	15	82	601	2211
6_R	8	2011	13	102	8	15	41	750	2169	6	58	10	15	27	633	2770	19	160	8	15	30	729	2324
7_F	8	2011	4	19	5	20	35	770	3217	4	35	9	16	42	901	2187	8	54	7	18	42	842	2579
8_F	8	2012	4	14	4	18	21	517	1376	1	3	3	18	21	185	616	5	17	3	18	22	510	1291
9_R	8	2012	15	99	7	15	30	731	2238	8	41	5	18	30	905	3126	23	140	6	15	30	784	2459
10_F	8	2012	14	125	9	16	33	473	1158	8	69	9	14	25	537	2093	22	194	9	15	31	485	1654
11_R	8	2012	7	141	20	17	36	449	1509	4	182	46	16	32	439	1420	11	323	29	17	33	445	1448
12_R	8	2012	17	244	14	15	34	602	1498	8	122	15	16	28	501	1154	25	366	15	15	34	576	1444
13_R	8	2012	15	185	12	16	32	730	1550	8	92	12	17	31	712	1513	23	277	12	16	31	726	1549
14_F	7	2012	10	31	3	17	45	771	3170	6	16	3	23	36	648	1256	16	47	3	20	36	750	3018
15_F	8	2012	9	36	4	15	30	732	1835	5	7	1	13	21	414	1023	14	43	3	15	29	692	1621
16_R	8	2012	10	127	13	17	32	603	1668	7	119	17	19	50	854	2717	17	246	14	17	45	699	2092
17_R	8	2012	10	86	9	20	43	1053	2108	5	12	2	20	22	960	1267	15	98	7	20	42	1053	2075
AVG	7.8	-	10	96	9	17	39	677	1988	6	65	11	17	32	651	1848	16	161	10	16	38	686	2052
SD	0.4	-	4	65	6	2	13	164	575	2	54	11	3	9	236	948	6	111	8	2	13	169	664

A total of 125 impacts collected were associated with peak linear accelerations of 40 g or greater. Of those impacts, 67% occurred during practices while the remaining 33% occurred during games. A total of 11 impacts collected were associated with peak linear accelerations of 80 g or greater. Of those impacts, 73% occurred during practices while the remaining 27% occurred during games. The average instrumented player experienced 6.6 ± 6.1 head impacts greater than 40 g, 1.6 ± 2 head impacts greater than 60 g, and 0.6 ± 1.3 impacts greater than 80 g each in a given season.

Returning players had a significantly higher impact frequency than first time players ($p = 0.007$). The average instrumented returning player experienced 15 ± 13 impacts per game, 11 ± 6 impacts per practice, and 211 ± 104 impacts per season; while the average instrumented first time player experienced 6 ± 3 impacts per game, 5 ± 2 impacts per practice, and 75 ± 59 impacts per season. There was no significant difference in the median ($p = 0.422$) or 95th percentile ($p = 0.398$) head accelerations between first time and returning players (**Figure 4**).

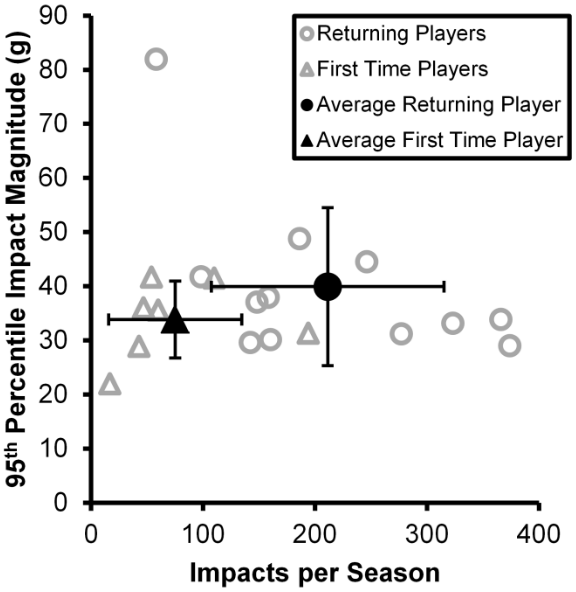

Figure 4. Instrumented returning players experienced a significantly higher number of impacts during the season compared to first time players ($p = 0.007$). However, no significant difference in the 95th percentile impact was observed ($p = 0.398$).

The 95th percentile impact was significantly higher in practices than in games ($p = 0.023$) (**Figure 5**). No significant differences were observed between the frequency of impacts ($p = 0.240$) or the median impact ($p > 0.500$) in games and practices. Instrumented players in the 2012 season had a lower 95th percentile impact in practices than players in the 2011 season ($p = 0.031$). No significant differences were observed between the frequency and median impact of players in the 2011 and 2012 for practices, games, or season.

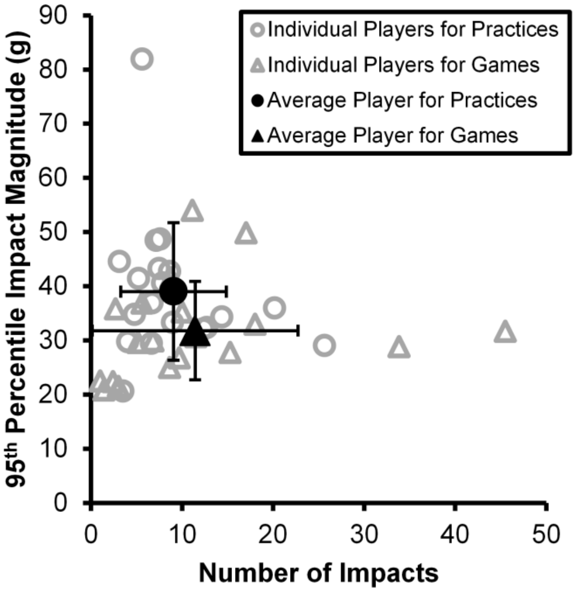

Figure 5. The 95th percentile impact experienced in practices was significantly larger than the 95th percentile impact experienced in games ($p = 0.023$). No significant differences in the frequency of impacts between games and practices were observed ($p = 0.240$).

Impacts to the front of the helmet were the most common, accounting for 42% of the total impacts. Impacts to the back, side and top of the helmet accounted for 24%, 23%, and 11%, respectively. Impacts to the top of the helmet resulted in the greatest magnitude of linear acceleration, while impacts to the front of the helmet resulted in the greatest magnitude of rotational acceleration. No diagnosed concussions were sustained by instrumented players during the 2011 or 2012 season.

Discussion

The results of this study provide a further understanding of the head impact exposure of 7 to 8 year old football players. The average instrumented player experienced 161 ± 111 impacts in a season with 60% of those head impacts occurring in practice. The higher frequency of impacts in practice is primarily due to the fact that, on average, each player participated in twice as many practices as games. Normalizing for the number of sessions, the average instrumented player experienced 11 ± 11 impacts per game and 9 ±

6 impacts per practice. Although regulations recently implemented by the Pop Warner will not directly affect the frequency or magnitude of impacts occurring in games, they offer value in reducing the frequency and magnitude of impacts sustained during impact drills in practice.

Between the 19 measured instrumented players-years, 125 head impacts over 40 g and 11 head impacts over 80 g were recorded. These data demonstrate that players as young as 7 and 8 years old experience head impacts similar in magnitude to severe impacts seen at the high school and collegiate level.[17,21,34,44] The high severity impacts measured in this study occurred more frequently during practices, while high severity impacts occur more frequently in games at high levels of play.[11-13] While no diagnosed concussions were reported during the two seasons used for data collection, it is possible that concussions went undetected due to underreporting.

Variation in head impact exposure can be attributed to differences in player experience, player position, and amount of playing time. Because it is the earliest level at which players are allowed full contact, players who have been tackling for one year or longer may be less hesitant to engage with other players on the field. In this study, 7 players were first time players and the remaining 12 players were returning players resulting in variation in impact frequency between players. At the collegiate level, position differences have been shown to affect head impact frequency, location, and magnitude.[9] These trends may not be as prevalent at the youth level due to the high frequency of position changes throughout a season. During practices instrumented players in this study generally split into two groups, linemen and skills players, with each group participating in different drills. The contact differences in these drills likely contributed to the observed variation in impact frequencies during practices. Similarly, an uneven distribution of playing time also contributed to variation in impact frequency. These characteristics are likely common to most teams at this level of play and are not thought to be unique to the team instrumented for this study.

Furthermore, variation in the frequency of high magnitude impacts was observed. Players who were less cautious on the field tended to be more prone to high magnitude impacts than other players, resulting in large variation in the 95th percentile impact magnitude and the number of impacts each player sustained over 40 g, 60 g, and 80 g. Returning players experienced significantly more impacts than first time players. Moreover, players experienced high magnitude impacts significantly more frequently in practices compared to games. In order to minimize the frequency of high magnitude impacts, practice modifications can be further developed and implemented.

The impacts collected in this study were analyzed by helmet impact location. The majority of head impacts were to the front of the player's helmet which is consistent with data seen at the high school and collegiate level. Impacts to the side of the helmet, however, occur more frequently than they do at the high school and collegiate level. Players between the ages of 6 and 8 years old age have proportionally larger heads and weaker necks than adult players. In addition, helmets used in youth football are similar in size, mass, and material to adult helmets. These characteristics may result in young players impacting the side of their helmets when falling to the ground more frequently than adult players.

Exposure data collected from football players aged 7 to 8 years old were compared to those of high school and collegiate players. Players that are 7 to 8 years old experience a median and 95th percentile impact of 16 g and 38 g, respectively. High school players experience a median and 95th percentile impact of 21 g and 56 g, respectively. Collegiate players experience a median and 95th percentile impact of 18 g and 63 g, respectively. These results were not surprising because the size and speed of players at the youth level are lower than those of high school and collegiate players. Similarly, players that are 7 to 8 years old experience 161 impacts per season compared to 565 impacts per season experienced by high school players and 1000 impacts per season experienced by collegiate players.[21,44,45] This result was also not surprising because youth football practices and games are fewer in number than high school and collegiate practices and games.

This study has several limitations. First, a sample size of 19 players was used to report the impact exposure of 7 to 8 year olds. This is a small sample size compared to other studies investigating head impact exposure in high school (95 players) and college (>300 players) football.[11,13,28] Second, since the participants in this study were between the ages of 7 and 8 years old, the results are specific to this age group. Youth football encompasses players ranging in age from 6 to 13 years old, and head impact exposure likely varies by age. Third, the HIT System and 6DOF measurement device are associated with some measurement error. On average, the HIT System overestimates the linear acceleration by 1% and rotational acceleration by 6%.[28,38,42] While there may be greater error associated with individual data points, these errors are minimized when working with the overall data distribution.

Conclusion

In conclusion, this study provides data further describing the impact exposure in youth football and provides insight to the differences in head impact exposure between games and practices, and between returning and first time players. This study demonstrated that some head impacts at this level are similar in magnitude to high severity impacts at the high school and collegiate level. High magnitude impacts were more frequently associated with participation in practices. Returning players experienced significantly more impacts than first time players. The data presented in this study will serve as a foundation for making scientifically based recommendations on practice modifications and youth-specific helmet design and standards.

Chapter 3: Effect of a Season of Play on the Performance of Youth Football Helmets

Abstract

Each year there are an estimated 1.6 to 3.8 million sports-related concussions that occur in the United States with football having the highest injury rate among team sports. Of the 5 million athletes who participate in organized football leagues in the United States, 3.5 million are between the ages of 6 and 13 years. Because helmets are used season to season, they must be periodically reconditioned and recertified to ensure they remain in compliance with the NOCSAE standard. Currently, there is no requirement by NOCSAE or NAERA dictating how often helmets should be reconditioned or recertified. The objective of this study is to quantify differences in Riddell Revolution youth football helmet performance over the course of a season by testing helmets in the laboratory on a drop tower before and after the 2013 football season. It was determined that there was no significant effect of time on helmet performance in helmets tested before and after a season ($p = 0.629$). In addition, it was determined that there was no significant correlation between the change in performance and the number of impacts ($p = 0.390$), the magnitude of the 95th percentile impact ($p = 0.500$), or the product of the number of impacts and 95th percentile impact ($p = 0.367$). Future studies should be conducted that aim to quantify changes in helmet performance over multiple seasons to provide evidence to develop scientifically based regulations and guidelines for youth football helmet use.

Introduction

Each year over 5 million athletes participate in organized football leagues in the United States. Of these athletes, 3.5 million are between the ages of 6 and 13 years.[6-8] To equip these players, football helmet manufactures market youth helmets for players between the ages of 6 and 13 years and adult helmets for players 14 years and older. In certain models, such as Riddell Revolution helmets, youth and adult helmets are almost identical in that they have the same dimensions and padding technology.[6] In most cases, youth players rent helmets and other pads from their league. Helmets are recycled from season to season and are reconditioned and recertified on a schedule determined by each individual league. Currently, no studies have been conducted that quantify a helmet's performance from season to season. If a helmet's performance is determined to diminish with repeated use, football players wearing these helmets will have an increased risk for concussion. There are an estimated 1.6 to 3.8 million sports-related concussions that occur in the United States annually with football having the highest injury rate among team sports.[1,2] To better understand how to reduce the number of concussions in youth football, further studies should be conducted to analyze the properties of youth football helmets from season to season.

All newly manufactured helmet models are tested against a standard set by the National Operating Committee on Standards for Athletic Equipment (NOCSAE). This standard involves testing helmets on a drop tower from various heights resulting in impact velocities ranging from 3.46 m/s to 5.46 m/s.[46,47] Impacts to the front, front boss, rear, rear boss, side, and top of the helmet are tested. To become NOCSAE certified, the Severity Index calculated from each impact must not exceed 1200. Each helmet that passes certification receives a sticker indicating that it meets NOCSAE standards and the year it was initially certified.[46,47] Because helmets are used season to season, they must be periodically reconditioned and recertified to remain in compliance with the NOCSAE standard. The National Athletic Equipment Reconditioning Association (NAERA) is an organization of 21 athletic equipment reconditioners and manufacturers who have been licensed by NOCSAE to conduct helmet reconditioning and recertification. The reconditioning process consists of inspecting, cleaning, sanitizing, repairing, and restoring the helmet back to its original standard.[48] The recertification process involves testing a representative sample of the helmets sent in for reconditioning using the same NOCSAE drop test used for original certification. Helmets receive a sticker indicating the initial year of certification and the year of recertification.[48]

Currently, there is no requirement by NOCSAE or NAERA dictating how often helmets should be reconditioned and recertified. NOCSAE recommends that each league make their own reconditioning schedule based on the types of helmets, the age of players, and the amount of impacts sustained.[46,47] Beginning in 2012, NAERA no longer recertifies any helmet that was in use for more than 10 seasons.[48] These guidelines, however, are not based on scientific studies that test the longevity of football helmets. To accurately determine the minimum time between reconditioning and recertification cycles and the working lifespan of a helmet, helmets should be tested season to season.

The objective of this study is to quantify differences in Riddell Revolution youth football helmet performance before and after a season. New helmets and helmets that have been used for one season were tested before and after a season of use by 9 to 12 year old football players to quantify differences in their performance. These data and future studies will allow researchers to provide recommendations on how frequently youth football helmets should be reconditioned and recertified and define the working lifespan of youth football helmets.

Materials and Methods

To test the effect of a season of use on a helmet's performance, 6 youth Riddell Revolution football helmets were tested before and after the 2013 football season in this study that was approved by the Virginia Tech Institutional Review Board. Players wearing helmets analyzed in this study had an average age of 10.0 years and an average mass of 48.0 kg. Of the 6 helmets tested, 3 were new helmets and 3 were helmets that have been used for one season by 7 to 8 year old football players. Riddell Revolution helmets were tested in large and medium sizes to provide a sample that accurately represents the sizes of helmets used by 9 to 12 year old players.

Helmets were tested in the laboratory before the 2013 football season. During the season, players between the ages of 9 and 12 years wore the helmets on the field and were instrumented with the Head Impact Telemetry (HIT) System to quantify head impact exposure. Helmets were retested in the laboratory after the 2013 season. Analysis was conducted to quantify differences in performance and correlate various exposure metrics to changes in performance.

Helmets were placed on a NOCSAE headform instrumented with accelerometers and were tested on a drop tower with impacts to various locations (front, rear, side, and top) and energies (dropped from 12, 24, 36, 48, and 60 inches) for a total of 20 tests per helmet to quantify helmet performance in the laboratory before and after the season (**Figure 6**). Two drop tests were conducted for every drop location and height. The average value of these two replicated measurements was the value used for analysis. Locations and drop heights were chosen to assess linear acceleration due to the full range of clinically significant impact magnitudes that are seen on the youth football field.[6,49-51]

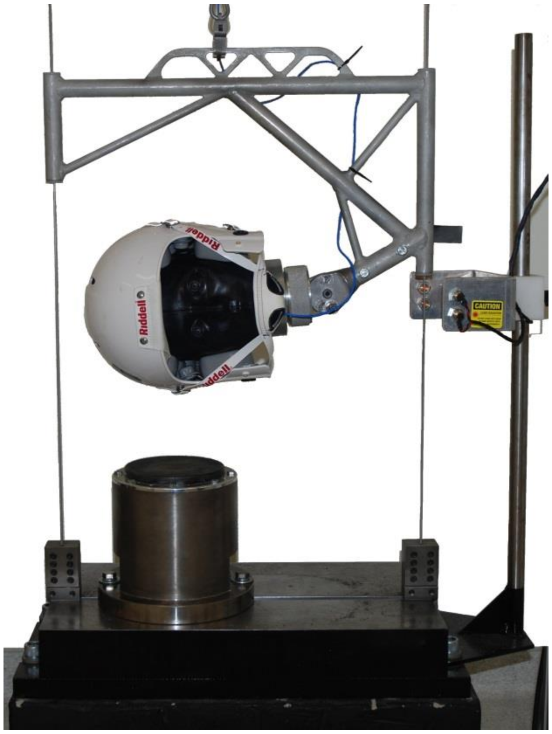

Figure 6. A NOCSAE style drop tower was used to quantify the performance of each helmet.

In addition to quantifying helmet performance in the laboratory before and after the season, all helmets used in this study were instrumented with the Head Impact Telemetry System (HIT System) to quantify impact exposure experienced on the field. The HIT System consists of 6 accelerometers mounted normal to the skull in the crown of the helmet (**Figure 7**). Once any accelerometer measured an impact with an acceleration of 14.4 g or higher, 8 ms of pre-trigger data and 32 ms of post-trigger data were wirelessly transmitted to a sideline computer where the impact was analyzed. Only impacts that were greater than 10 g were deemed clinically significant and included in the study. It has been reported that non-impact events, such as running or jumping, are associated with peak accelerations of 10 g.[13,52] Thus, any impacts that were less than 10 g were removed from the data set. The HIT System recorded the acceleration, location, and time of each impact sustained by a player wearing the helmet. These data were used to quantify the impact exposure for each helmet during the season. The HIT System has been widely validated and used as a tool to quantify head impact exposure in youth, high school, and college football players.[6,11-25,49] Currently, the HIT System is limited in that it can only be installed in Riddell helmets. Thus, this study was constrained to only test Riddell Revolution helmets.

Figure 7. The HIT System wirelessly transmits impact data collected from 6 accelerometers to a sideline computer where the data are analyzed.

To analyze factors affecting helmet performance, a three-factor repeated measure ANOVA was used. A repeated measure ANOVA was chosen because each helmet was repeatedly measured in each impact condition. A three-factor test was chosen to assess the effect of three different independent variables on helmet performance: time, impact location, and drop height. Additionally, a multiple linear regression was used to determine if a significant correlation existed between the average paired difference of linear acceleration for each helmet and the impact frequency, the 95th percentile impact magnitude, or the product of these exposure metrics. Statistical significance was determined using a threshold of $p < 0.05$ for all tests.

Results

Peak linear acceleration was measured for each helmet at each drop height and location before and after the 2013 season. The average paired difference of the linear acceleration measured in all drop tests for all helmets before and after each season can be seen in (**Table 3**). Helmets 1A-1C had never been used prior to the 2013 football season and helmets 2A-2C had been used for one season prior to the 2013 football season by 7 to 8 year old football players. Helmets with a positive average paired difference in linear acceleration exhibited a reduction in performance while helmets with a negative average paired difference in linear acceleration exhibited an improvement in performance. Of the 6 helmets tested, 4 helmets decreased in performance over the season while 2 helmets improved.

Table 3. The average paired difference before and after the season varied slightly from helmet to helmet.

Helmet	Average Paired Difference (g)
1A	0.446
1B	0.004
1C	-1.099
2A	0.037
2B	-1.071
2C	1.162

Helmet performance in each drop test conducted was analyzed using a three-factor repeated measure ANOVA. It was determined that neither time ($p = 0.629$) nor impact location ($p = 0.186$) had a significant effect on measured linear acceleration. As expected, the drop height had a significant effect on measured linear acceleration ($p < 0.01$). In addition to the independent effect of each factor on helmet performance, significant interactions were found between time and location ($p = 0.003$), height and location ($p < 0.01$), and time and height and location ($p < 0.01$).

The head impact exposure of each player wearing a helmet analyzed in this study was quantified. The average player experienced 387 impacts per season with values ranging from 94-626 impacts. The average 95th percentile impact magnitude was 45 g with values ranging from 36 – 58 g. Players sustained 40% of impacts to the front of their helmets, 28% to the rear, 22% to the top, 5.5% to the right and 4.5% to the left (**Figure 8**). These values are similar to values previously determined by studies quantifying the head impact exposure of similar age athletes.[6,49,51]

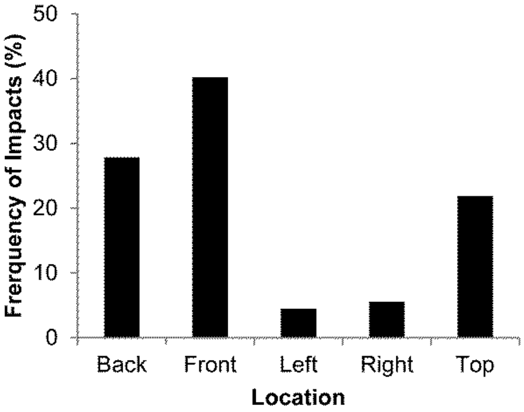

Figure 8. The front received the highest percent of impacts while the right and left sides of the helmet received the lowest number of impacts.

Using exposure values for each helmet, the number of impacts experienced by each helmet was compared to the average paired difference in linear acceleration measured in all drop tests for each helmet. A multiple regression analysis determined that no significant linear correlation existed between the average paired difference in helmet performance and the number of impacts (p = 0.390), the 95th percentile impact (p = 0.500), or the product of the number of impacts and the 95th percentile impact (p = 0.367) (**Figure 9**).

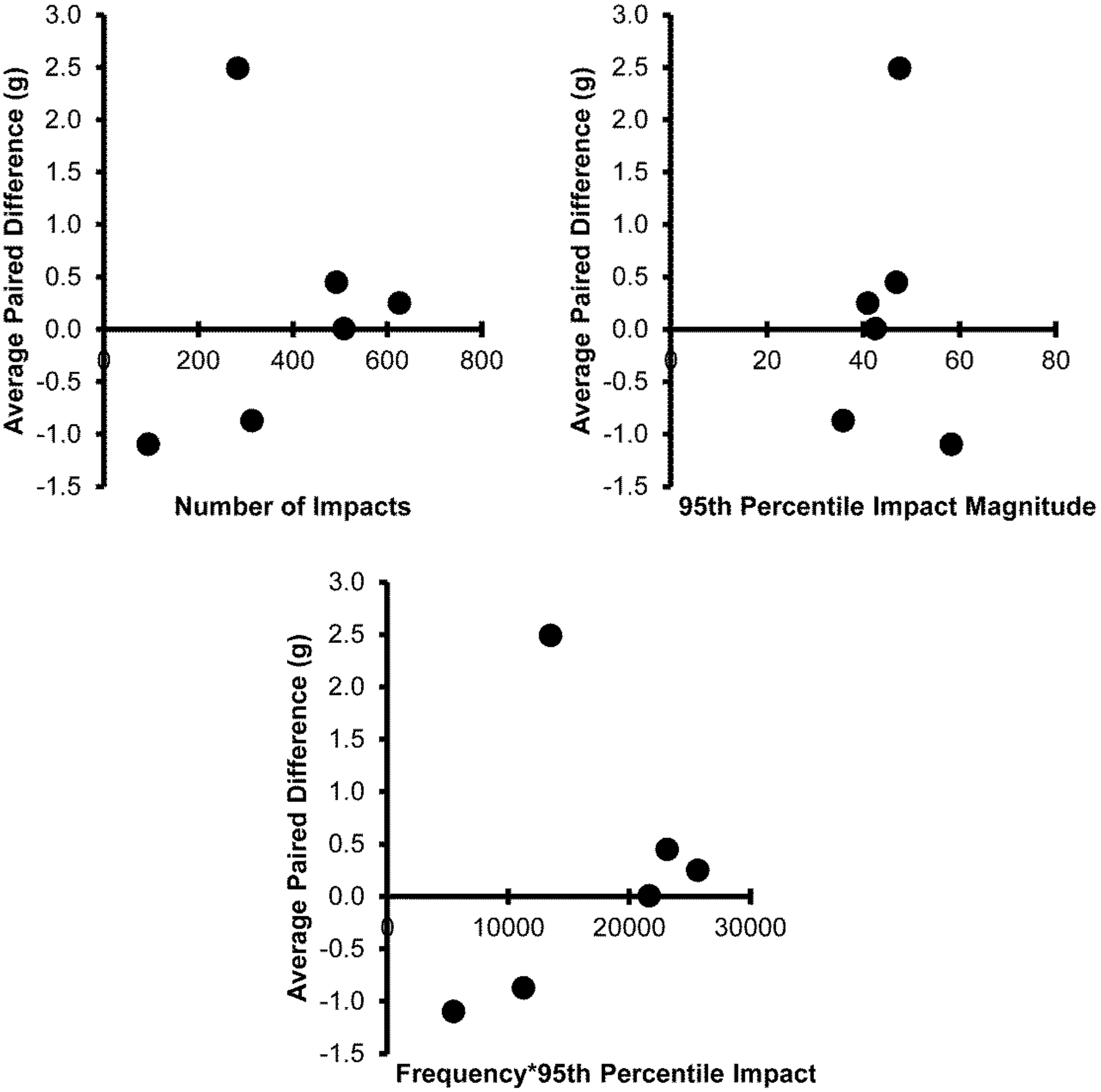

Figure 9. No significant correlation between the number of impacts experienced by the helmet (top left), the magnitude of the 95th percentile impact (top right), or the product of number of impacts and the 95th percentile impact magnitude (bottom) and the average paired difference in linear acceleration for each helmet was found.

Discussion

From this study it was determined that there is no significant change over the course of a season in new youth Riddell Revolution football helmets or youth Riddell Revolution helmets that have been used for one season. Thus, no significant helmet pad degradation or protective break-in effect was found in youth football helmets early in their lifespan. While this finding was expected, it is an important step toward quantifying the working lifespan of a youth football helmet. Changes in a helmet’s performance over the course of multiple seasons are still unclear. Helmet testing should be conducted over multiple seasons to provide football helmet recertification regulators with scientific evidence to support or refute a 10 year lifespan limit on helmets and provide guidelines dictating how often to recertify and recondition youth football helmets.

No significant effect of time or impact location on linear acceleration was found in the helmets tested in this study. Significant interactions between time and location, height and location, and time and height and location indicate that the helmets tested respond differently over time and at each drop height depending on the location analyzed. Follow up t-tests were conducted to determine how the behavior of the helmet varied by location. From this analysis it was concluded that 4 of the 20 drop tests conducted resulted in significant changes in performance over the season: improvement in the front 24 inch drop, reduction in performance in the rear 12 inch drop, top 24 inch drop, and top 36 inch drop. These drop tests, however, resulted in mean paired differences of 4 g or less and were not deemed clinically significant.

No significant correlation between helmet performance and impact exposure was found in this study. However, to conduct this analysis a small sample size of Revolution helmets was tested. To accurately assess the effect of helmet exposure on helmet performance, a more controlled study looking at helmets with the same usage history and a larger sample size should be conducted.

While this study is valuable in that it provides a first look at how helmet performance changes over a season, it is subject to several limitations. First, a small number of helmets were used in this study. This study was constrained to 6 helmets due to a limited number of helmets that were known to only have been used for one season and helmets that had not been used before. Second, the number and magnitude of impacts sustained by the helmets that were previously used for one season prior to this study is unknown. However, these helmets were used by 7 to 8 year old players so no significant effect was expected. Third, the HIT System is associated with a linear acceleration error of 1 ± 16%. [28,38,42] This error, however, cancels out when analyzing impact distributions.

Conclusion

In conclusion, Riddell Revolution youth helmet performance was found not to vary between the beginning of a season and the end of a season for helmets that are new or one year old. The results of this study provide a foundation for regulations and guidelines dictating the lifespan of helmets and how often helmets should be recertified and reconditioned. Future studies that aim to quantify changes in helmet performance over multiple seasons should be conducted that provide evidence to develop scientifically based regulations and guidelines for youth football helmet use.

Chapter 4: Closing Remarks

Research Summary

The research presented in this thesis seeks to quantify the head impact exposure of 7 to 8 year old football players and understand how the performance of youth football helmets changes over the course of a season. In the past, significant research has been conducted focused on concussion biomechanics in sports.[6,12-15,21,27-29,34-40,49,53-73] With recent studies linking a neurodegenerative brain disease to mild repetitive head trauma, understanding head impact exposure and biomechanics at the youth level has become increasingly important. This research provides football leagues with data describing the types of impacts sustained by 7 to 8 year old players on the field and the session type that caused them. With these data, modifications to practices that aim to reduce the number of impacts and the impact severity that players experience throughout a football season can be implemented. In addition to league modifications, concussion prevention can be approached by means of protective equipment improvement. In this thesis, it has been shown that the performance of youth football helmets used by 9 to 12 year old players does not change over the course of one season early in a helmet's lifespan. However, further research analyzing the change in performance over multiple seasons still needs to be conducted. This research provides a foundation for the development of novel methods to test youth specific football helmets, design of youth specific helmets, and the development of youth specific concussion risk curves.

Publication Outline

The research presented in this study has been or will be published in various journals and presented at various conferences. The publication and presentation plan for this research is presented in **Table 4**.

Table 4. Publication plan for research conducted.

Chapter	Title	Journal/(Conference)
2	Head Impact Exposure in Youth Football: Elementary School Ages 7 to 8 Years and the Effect of Returning Players	Clinical Journal of Sports Medicine† (Biomedical Engineering Society 2013 Annual Meeting)§
3	Effect of a Season of Play on the Performance of Youth Football Helmets	Undecided
NA	Head Impact Biomechanics of 9 to 11 Year Old Football Players in the 2013 Football Season*	(Rocky Mountain Bioengineering Symposium 2014)§
† Accepted, § Presented, * Not presented in thesis		

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