Head Acceleration Measurements in Helmet-Helmet Impacts and the Youth Population

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Abstract

The research presented herein is an analysis of acceleration measurements of the head during helmet-helmet impacts, where a player's helmet impacts another player's helmet, and with a youth population in football. This research is aimed at advancing current understanding of impact biomechanics for two specialized groups. The first study is an observational analysis focusing on helmet-helmet impacts, and the difference in effective mass and head acceleration measurements between the striking player and the struck player. The study involved working with football players outfitted with a sensor integrated into their helmets containing a 6 accelerometer array, capable of measuring linear accelerations and estimating angular accelerations. To evaluate helmet-helmet impacts, video analysis of past NCAA football competitions between Virginia Tech and University of North Carolina (UNC) were utilized to identify these impacts between instrumented players. A force balance was then carried out for the observed impacts and their respective acceleration measurements to compute the effective mass of the players. It was determined that the total mass recruited by the striking player was 28% to 77% more than that of the struck player. The second study focused on documenting the head impact biomechanics of a youth population. To accomplish this objective, unique accelerometer arrays, capable of measuring linear and angular accelerations, were integrated into existing youth football helmets for 7 players on a local team. Acceleration data were collected for every practice and game during the 2011 season to amass a total of 748 impacts. No instrumented player sustained a concussion during the 2011 season. Results of the study indicated impacts of greater magnitudes were more likely to occur in practices, and can be minimized by augmenting practice activities.

Attribution

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

Chapter 2: Investigation of Effective Mass Differences for Helmet to Helmet Impacts in Football: Role of the Neck and Implications on Injury

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Chapter 3: Head Impact Exposure in Youth Football

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Chapter 1: Introduction

Opening Remarks

Throughout the years, the topic of concussions and the effect that they have on the human brain have been increasingly scrutinized by media, political, and academic personnel. And, this increased awareness may be rightfully deserved, as concussions have been linked to severe neurocognitive impairment late in life. However, studying concussions and the effects on the human brain require testing of subjects with higher critical thinking skills. Thus, post-mortem human subjects and animal models are not completely accurate models for testing and receiving accurate results for the effects of a concussion. On the other hand, football players regularly impact their heads as a result from participation in the sport and often receive concussive-like impacts, in terms of magnitude. Therefore, football players are ideal candidates for studying the effects of concussion due to their exposure. As they are human volunteers, their difference in anatomical geometry with the average male is non-existent compared to those of animal subjects. Also, many of the indications of a concussion are verbally conveyed by the patient, such as dizziness, confusion, or headaches, making diagnosis difficult with other types of testing subjects. The research presented in this thesis utilizes unique methods to collect biomechanical data regarding specialized groups. The main function of this research is to better understand these injuries, and provide data that will benefit the enhancement of protective equipment and regulations of the game.

Research Objectives

To investigate the risk of concussion associated with specialized subgroups of impacts in football, understanding the underlying principles of a concussion is first necessary. A concussion is a form of mild traumatic brain injury (mTBI), and can be caused by a direct impact to the head or any other region of the body resulting in a force transmitted to the brain. There are many symptoms of a concussion, which may or may not be experienced. Among these symptoms, headaches, dizziness, confusion, nausea, and lack of motor coordination are some of the more prominent (Kushner, 1998). Although the aforementioned symptoms may be apparent immediately after the onset of a concussion, several other symptoms may arise over the course of time. These symptoms include, but are not limited to, a memory deficit, a decline in attention-span and movement speed, and possible chronic traumatic encephalopathy (Cantu, 2007).

Each year in the United States, approximately 300,000 athletes sustain concussions while playing contact sports, with football having the largest occurrence (Thurman, 1998). As the awareness for the potential harm of a concussion has increased, regulations for the game of football in the National Football League (NFL) have been augmented to "take the head out of the game." These types of rules attempt to discourage players from specific impacts, including helmet-helmet impacts. The first study presented in this thesis investigates the biomechanics behind these types of impacts. This research also attempts to draw correlations between the effective mass of a player during an impact and whether he is the striking player or the stuck player.

Much focus has been placed on high school, collegiate, and professional athletes in the past, overlooking the youth population despite the dramatically lager size. The second study in this thesis focuses on documenting the head impact exposure in youth football. These biomechanical data will influence enhancements in protective equipment, as well as regulations at the youth level to make the game safer. Also, these data may serve as validation for computational models of the pediatric anatomy, resulting in an improved understanding of the developmental differences. The goal of this work is to provide the information necessary to help make the aforementioned improvements possible.

Chapter 2: Investigation of Effective Mass Differences for Helmet to Helmet Impacts in Football: Role of the Neck and Implications on Injury

Abstract

Among the many types of impacts involved in the sport of football, impacts involving one players helmet directly impacting another players helmet, helmet-helmet impacts, have been judged as more severe. This judgment has led to the augmentation and implementation of several rules in football. The objective of this study was to investigate the differences in effective mass and head acceleration between players involved in helmet-helmet impacts. This was done through video analysis and force balancing. After identifying and analyzing several impacts between players, it was found that the total mass recruited by the striking player was 28% to 77% more than that of the struck player. This difference in recruited effective mass can be attributed to the neck muscles of the striking player tensing and creating a better coupling with the body of the striking player. As previous work has suggested, a stronger neck may result in a greater coupling with the torso that likely lowers the risk of concussion.

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Introduction

Of the 1.6 to 3.8 million sports-related traumatic brain injuries that occur each year in the US, participation in football yields the greatest incidence.[19] The high incidence rate of concussions in football provides a unique opportunity to collect biomechanical data from humans to characterize mild traumatic brain injuries (mTBI). However, collecting human head acceleration data is not a new method. There have been several studies in the past that have had football players wear headbands instrumented with accelerometers to measure head acceleration during football games.[15-17, 21, 24-33] The earliest studies laid the groundwork for future research and provided a proof of concept, but ran into limitations as far as measuring head accelerations and the number of instrumented players.

One study recreated concussive impacts in an attempt to quantify head accelerations experienced by football players.[25] The National Football League utilized game video to reconstruct injurious game impacts using Hybrid III dummies. Although the analysis was exceptionally well done, due to the selection of only injurious impacts, the dataset was biased. Since then, there have been several studies that have quantified head accelerations by instrumenting helmets worn by college football players.[15-17, 24-33] In one of these studies, conducted by Duma et al, a six accelerometer sensor was integrated into football helmets. These sensors recorded the resultant linear head acceleration for every impact that a player experienced, which produced a large and unbiased dataset. Over 27,000 head impacts were recorded over 4 seasons, with 4 of the impacts being concussive.

The 6 accelerometer sensor used by Duma et al. (2005) is part of the Head Impact Telemetry System (HITS), developed by Simbex, LLC (Lebanon, NH). The sensor consists of 6 orthogonally mounted single-axis accelerometers positioned normally to the head. The HITS sensor also includes an integrated radio board that communicates wirelessly with a computer stationed on the sideline. In order to measure head acceleration as opposed to helmet acceleration, all 6 accelerometers are spring mounted so that they stay in contact with the head at all times (Figure 1). Validation of the HITS sensor was completed by impacting a helmeted Hybrid III head and then comparing the acceleration measurements of both the Hybrid III head's center of gravity and the helmet shell with that of the HITS sensor.[12] Manoogian et al. found that the HITS sensor was in strong agreement with the acceleration measurements of the Hybrid III head.

Figure 1. The 6 spring-mounted accelerometer sensor records resultant accelerations for every impact that a player experiences (Photo by Steven Rowson, 2010, Used with permission.)

Any impact that generates a peak acceleration measurement above 10 g triggers the data collection for the sensor. For every impact, the data is transmitted from the sensor to the sideline computer, which processes and displays data in real-time. Data are collected for

40 ms, with 12 ms of pre-trigger data and 28 ms of post-trigger data. In order to determine impact magnitude and direction, the sensor utilizes a unique algorithm developed by Crisco et al. The developed algorithm also allows the calculation of resultant linear accelerations throughout time.

Recent research has suggested that long-term neurocognitive effects may be associated with a history of concussions.[4, 13, 22-23] Studies investigating the biomechanics of concussion in football agree that helmet to helmet impacts pose an increased risk of concussion. The objective of this study is to investigate the differences in effective mass and head acceleration between striking and struck players for helmet to helmet impacts, which have implications on the effect of neck strength. An increased understanding of the mechanical characteristics associated with helmet to helmet impacts in football can provide valuable insight applicable to future improvements in injury prevention techniques.

Materials and Methods

In order to better assess the kinetics of such head impacts, select players from the Virginia Tech (VT) football team have been instrumented with the HITS sensor in their helmets. The individual 6 accelerometer configuration in each player's helmet communicates wirelessly to a computer system, stationed on the sideline for every game and practice for real-time data collection (Figure 2). Data collected from these accelerometers is used to characterize impacts experienced by the players, and cross-referenced with video analysis to identify the specific impact. The University of North

Carolina (UNC) has also instrumented select players on their respective football team in order to characterize impact kinetics.

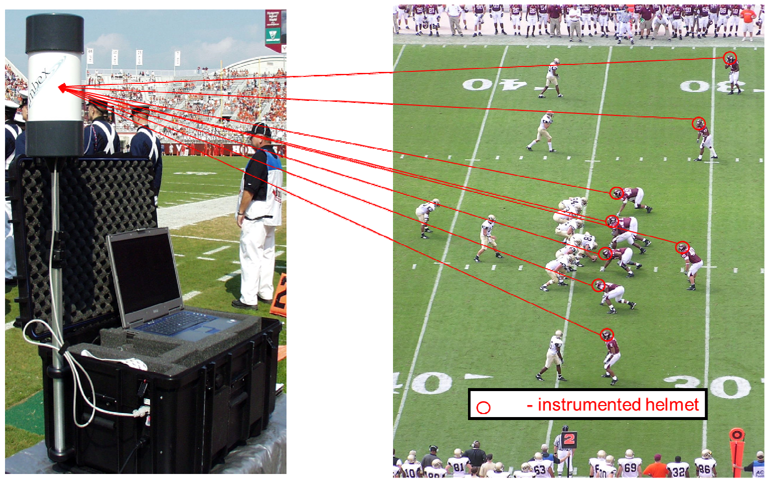

Figure 2. The HIT computer stationed on the sideline for real-time data collection during a VT football game (Photo by Steven Rowson, 2010, Used with permission.)

By utilizing game footage of recorded NCAA collegiate football competitions between the two teams, helmet-helmet impacts were identified and approximate times were noted. The times were noted by noting the kickoff of the game and factoring in the amount time since kickoff on the video. The player numbers of the individuals involved in the helmet-helmet impact were also noted. Once the approximate time of the impact was noted, as well as the players involved in the impact, the HITS data was analyzed to confirm the impact by taking note of the impact time. Thus, by utilizing the HITS data from both teams, the helmet to helmet impacts between the instrumented players can be singled out and the correlating HITS data can be recorded. The linear head acceleration values for each player, noted by the individual HITS sensors from the respective teams, were used in a force balancing equation. Through this equation the effective mass of each player was calculated and compared. For each helmet to helmet impact, the relationship between effective mass and head acceleration was analyzed, knowing that each helmet experienced equal and opposite force. In this analysis, effective mass is defined as the combined mass of the head and the mass of the neck and torso recruited by the musculature of the neck. The exact amount of mass of the torso recruited by the neck is often dependent on if the neck is tense or not, i.e. a strong or weak coupling between the head and the torso via the neck musculature. Variances between the effective masses of striking and struck players were expressed as percent differences.

Results

Due to this being an observational study, a limited number of helmet-helmet impacts were able to be identified between instrumented players. Thus, only two helmet-helmet impacts between instrumented players on opposing teams were able to be verified via video analysis over the course of four years. After identifying and analyzing the helmet-helmet impacts between VT and UNC players through biomechanical and video analysis, a force balance was completed for each impact ($m_{r1}a_1 = m_{r2}a_2$) (Table 1). Where, m_{r1} and m_{r2} refer to the total mass recruited for each player involved in the impact, and a_1 and a_2 refer to the linear acceleration of each player. For the impacts analyzed, the total mass recruited by the striking player was 28% to 77% more than that of the struck player.

	Impact Time	Resultant Linear Acceleration (g)	Estimated Resultant Rotational Acceleration (rad/sec^2)
VT player	16:20.36.230	60.2	5209.6
UNC player	16:20.36.240	77.4	4544.5

Table 1. Example HITS data for matched impacts between players.

Discussion

While this study provides insight into the differences in effective mass between players, there are limitations that must be acknowledged. The main limitation of this study is that the sample size of impacts between instrumented players is very low. The reason for the low number of samples stems from only some of the players were instrumented on either team. Therefore, having helmet-helmet impacts between instrumented players is rare. Also, due to rules put into place regarding flagrant impacts, helmet-helmet impacts are discouraged among the players. Due to this small sample size, current analysis of this study has yielded a large range in the ratio of the total mass recruited by the striking player over that of the struck player. A larger pool of data would allow a more detailed estimate of the ratio of total mass recruited between striking player and struck player to be identified. Another limitation of the study is the assumption of equal and opposite forces, both in magnitude and impact location. This assumption is based on assuming that a helmet has the same ability to modulate energy generated from an impact regardless of impact location or direction. Studying how a helmet specifically modulates energy for a generalized location would be a good addition to the study as acceleration values can be modified accordingly. Future analyses will also provide new insight to the effect of the musculature of the neck.

The results also suggest that the striking player has a greater amount of total recruited mass than that of the struck player. This can be attributed to the fact that the striking player may be tense, expecting the impact. By tensing the neck, the striking player may recruit a greater amount of mass from the torso, with a better coupling of the head and torso, via the neck musculature. Whereas, with the struck player, it is possible that there is less mass recruited due to the impact being unexpected. By not expecting the impact, the struck player is assumed to be less tense and have less of a coupling between the head and the torso, thus recruiting less mass than that of the striking player.

In summary, this study investigated the role of the neck in total mass recruitment with relation to head accelerations experienced by players. In this preliminary analysis, differences in mass recruited during head impact were shown to vary up to 77%. It is important to understand the effect of the neck during head impacts due to implications on injury, as previous work has suggested that a stronger neck may result in a greater coupling with the torso that likely lowers risk of concussion. The methods presented in this study use head acceleration data from football players matched with video as a first step to quantifying effective mass during head impact.

Chapter 3: Head Impact Exposure in Youth Football

Abstract

The head impact exposure for athletes involved in football at the college and high school levels has been well documented; however, the head impact exposure of the youth population involved with football has yet to be investigated. The objective of this study was to investigate the head impact exposure in youth football. Impacts were monitored using a custom 12 accelerometer array equipped inside the helmets of 7 players aged 7-8 years old during each game and practice for an entire season. A total of 748 impacts were collected from the 7 participating players during the season, with an average of 107 impacts per player. Linear accelerations ranged from 10 g to 100 g, and the rotational accelerations ranged from 52 rad/s^2 to 7694 rad/s^2. The majority of the high level impacts occurred during practices, with 29 of the 38 impacts above 40 g occurring in practices. Although less frequent, youth football can produce high head accelerations such as the concussion-causing impacts measured in adults. In order to minimize these more severe head impacts, youth football practices should be modified to eliminate high impact drills that do not replicate the game situations.

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Introduction

Sports related concussions have received increased public awareness, with many states considering or implementing laws directing the response to suspected brain injury. This is a result of new research suggesting possible links to long-term consequences from repetitive concussions.[13, 22, 23] Emergency department visits for concussions increased 62% between 2001 and 2009, and researchers estimate that between 1.6 and 3.8 million sports related concussions occur each year in the United States.[5, 19] Of all sports, football accounts for the highest incidence of concussion, and therefore receives the most attention.[34] One of the leading thoughts to minimize the incidence of concussion in football is to limit players' exposure to head impacts.[9] Strategies to reduce a player's exposure to head impact include teaching proper tackling techniques and modifying the rules of the game.

To make educated decisions towards reducing the incidence of concussion in football, head impacts in football have been extensively studied over the past decade.[3, 8, 10-12, 15, 16, 21, 24, 27, 31] The National Football League (NFL) was the first to investigate this problem in detail by reconstructing concussive impacts through analysis of game film using instrumented crash test dummies.[24-27] While this work was of high quality, it was limited by a dataset that did not account for the full exposure to head impacts that players experienced.[30, 31] Since then, new technology, the Head Impact Telemetry (HIT) System (Simbex, Lebanon, NH), has allowed for the direct instrumentation of headgear in sports.[7, 14, 18, 28] The HIT System consists of a series of accelerometers that fit inside football helmets, and records a player's biomechanical head response to every head impact they receive. Since Virginia Tech first instrumented college football players with the HIT System in 2003, over 1.5 million head impacts have been collected and analyzed across participating institutions.[12] This has allowed head impact exposure and injury risk to be investigated at the high school and college level.[2-4, 8, 10, 11, 15, 16, 20, 29-31, 33] Based on this research, some colleges have made educated recommendations about contact in practices in an effort to reduce the head impact exposure of players. Furthermore, this research has led to design guidelines for improved adult football helmets.[31]

There are approximately 5 million athletes participating in organized football in the United States; with 2000 NFL players, 100,000 college players, 1.3 million high school players, and 3.5 million youth players.[17, 27] Previous research has investigated head impacts in high school football, college football, and the NFL; however, this population only accounts for 30% of football players. To date, no work has been performed investigating head impact exposure in youth football, which accounts for 70% of all football players. Investigating head impact exposure at the youth level would allow researchers to understand when head impacts occur most frequently and which activities cause the most severe impacts. With this increased understanding, educated decisions can be made to effectively minimize head impact exposure in youth football.

The objective of this study was to investigate the head impact exposure in youth football. This was accomplished by instrumenting the helmets of a youth football team with head acceleration measurement devices similar to the HIT System. Youth head impact data are reported and compared to that of the high school and college levels of play. These data are the first step towards educated decisions about changes to youth football, and have applications towards youth-specific football helmet designs.

Materials and Methods

A youth football team consisting of children ranging in age from 6 to 9 years old participated in this study approved by the Virginia Tech Institutional Review Board. Each player gave assent and their parental guardians provided written informed permission. This study investigated head impact exposure in youth football by instrumenting the helmets of youth football players with a custom six degree of freedom (6DOF) head acceleration measurement device.[29, 30] Of the 26 players on the youth team, the helmets of 7 players were instrumented with the 6DOF measurement device. The 7 players had an average body mass 31.7 kg ± 6.44 kg and were all 7 or 8 years old. The players were chosen due to anticipation of high participation in practices and games, as well as playing both offense and defense. Furthermore, these players wore youth medium or youth large sized Riddell Revolution (Elyria, OH) helmets that were compatible with the 6DOF measurement device.

The 6DOF measurement device consists of 12 accelerometers and is designed to integrate into Riddell Revolution football helmets (Figure 3). While the 6DOF measurement device was originally designed for adult Revolution football helmets, the device is compatible with youth helmets due to the same sizing conventions and identical padding geometries between adult and youth Revolution helmets. Instrumented helmets were worn by youth football players during each game and practice they participated in. Each time an instrumented helmet was impacted and an accelerometer exceeded a specified threshold, data acquisition was automatically triggered. A total of 40 ms of data from each accelerometer were recorded, including 8 ms of pre-trigger data. Once data acquisition was complete, data were wirelessly transmitted to a computer on the sideline. Acceleration data were then processed to compute linear and rotational head acceleration using a novel algorithm.[6, 29] While a brief overview of the 6DOF measurement device is presented here, a detailed technical description has previously been reported.[29]

Figure 3. The helmets of youth football players were instrumented with the 6DOF head acceleration measurement device. Each time an instrumented player experienced a head impact, data were collected and then wirelessly transmitted to a computer on the sideline (Photo by author, 2012).

Impact location for each head impact recorded was determined from the acceleration traces using methods that have been previously described.[14] All head impacts were generalized into 1 of 4 impact locations on the helmet: front, side, rear, and top. Overall acceleration distributions were analyzed by impact location. Overall accelerations distributions were also analyzed by session type, which was divided into practices and games. Head impact exposure is presented in terms of the frequency of impacts, median accelerations, and 95th percentile accelerations. Furthermore, empirical cumulative distribution functions (CDF) with 95th percentile confidence intervals were computed for linear and rotational acceleration. Results of this study are then compared to studies quantifying head impact exposure in high school and college football players.

Results

Both the linear and rotational acceleration distributions were right-skewed, and heavily weighted toward low magnitude impacts. Cumulative distribution functions for resultant linear and rotational accelerations with 95th percentile confidence intervals were determined (Figure 4). Linear accelerations ranged from 10 g to 100 g. The distribution of linear acceleration had an average value of 18 g, a median value of 15 g, and a 95th percentile value of 40 g. Rotational accelerations ranged from 52 rad/s^2 to 7694 rad/s^2. The distribution of rotational acceleration had an average value of 901 rad/s^2, a median value of 671 rad/s^2, and a 95th percentile value of 2347 rad/s^2.

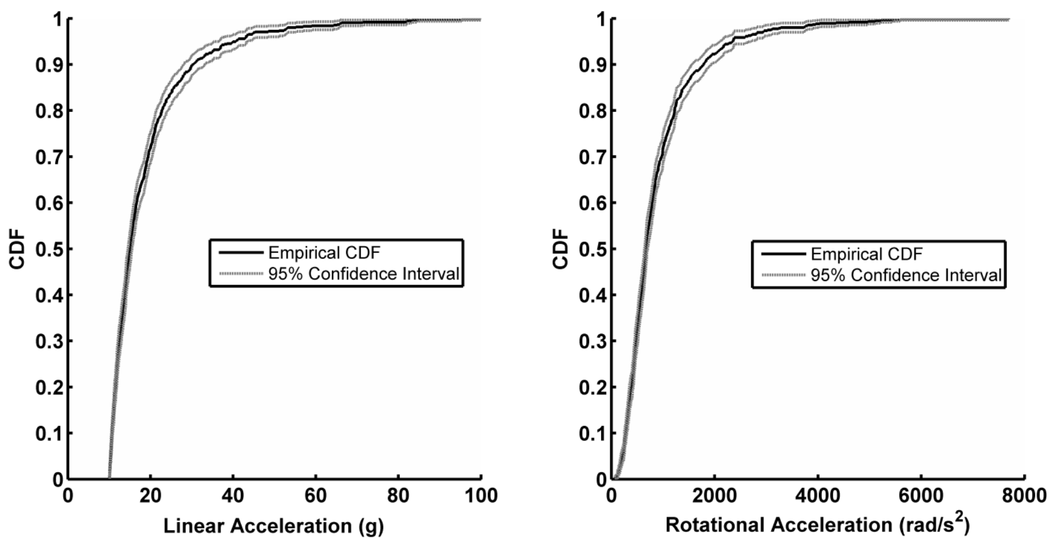

Figure 4. Cumulative distribution functions for linear and rotational accelerations show that the distribution of impacts were right skewed and heavily weighted toward low magnitude impacts.

The 6DOF data set also allows for the analysis of head acceleration data about each axis of the head. Distributions of each axis' peak linear acceleration for every recorded impact were then determined (Figure 5). The median linear head acceleration along the x-axis was 7 g. Along the y-axis, the median linear head acceleration was 6 g. And, the median head acceleration along the z-axis was 11 g. Large peak linear accelerations were most common along the z-axis, while lower peak linear accelerations were most common along the y-axis.

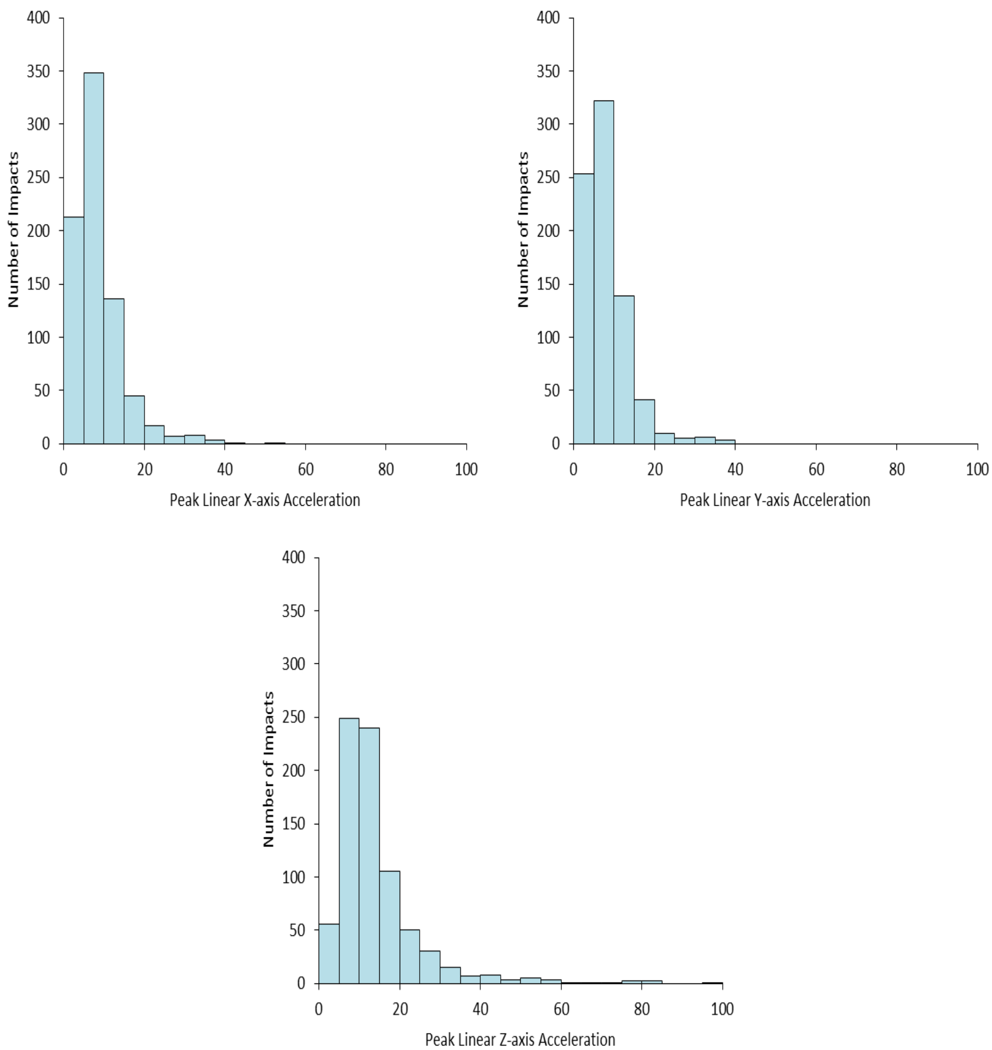

Figure 5. Distributions of peak linear acceleration values for all impacts with respect to axis.

Distributions of each axis' peak angular acceleration for every recorded impact were also determined (Figure 6). The median value for angular head acceleration about the x-axis was 266 rad/s^2. About the y-axis, the median value for angular head acceleration was 341 rad/s^2. And, the median value for angular head acceleration about the z-axis was 450 rad/s^2. Large peak angular accelerations were more common about the z-axis, while low peak angular accelerations were more common about the x-axis.

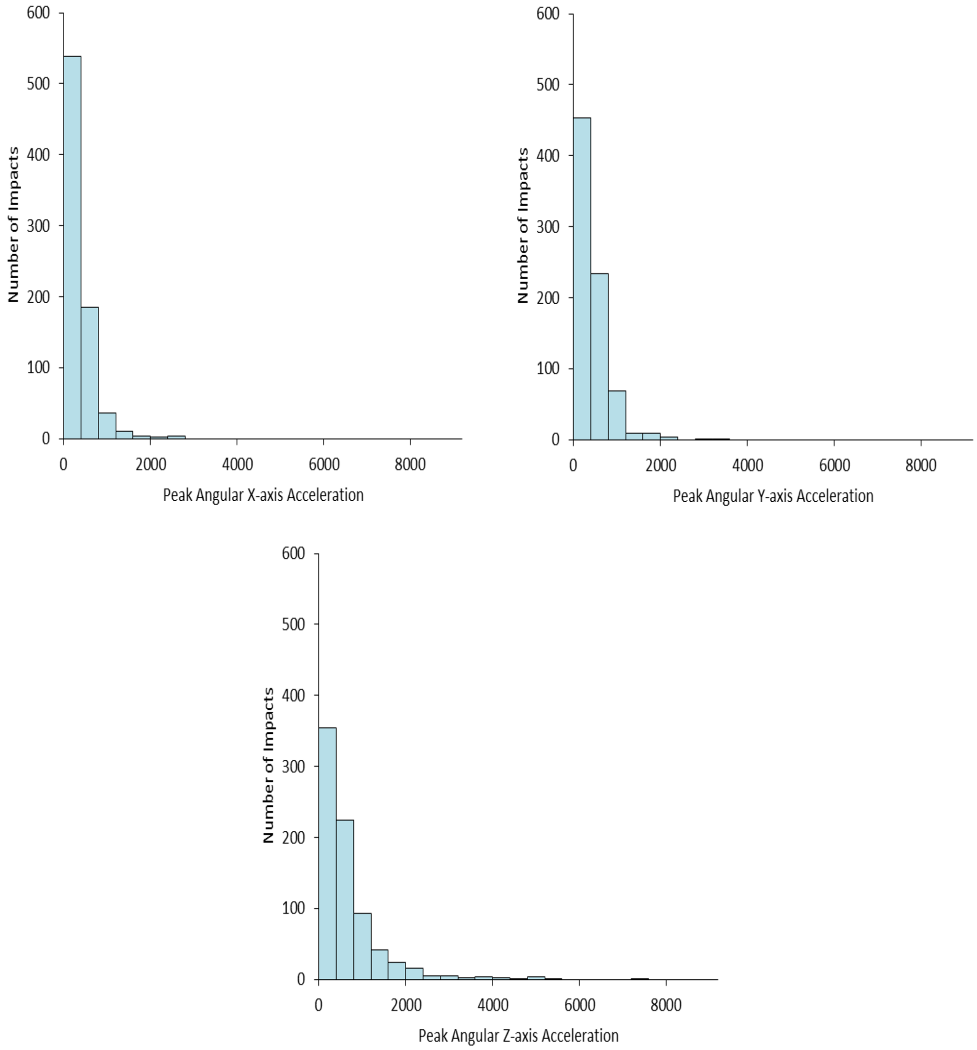

Figure 6. Distributions of peak angular acceleration values for all impacts with respect to axis.

A total of 748 impacts were recorded during practices and games for the 7 instrumented players during the youth football season. During games, 307 impacts (41% of total) were collected, while 441 impacts (59% of total) were collected during practices. The average instrumented player experienced at least one impact greater than 10 g in 14.1 sessions, consisting of 4.7 games and 9.4 practices. The average instrumented player experienced 107 head impacts, which included 44 impacts during games and 63 impacts during practices. Furthermore, the average player experienced 6.7 impacts per practice and 5.8 impacts per game. A total of 38 impacts above 40 g were collected, 29 of which occurred during practices. A total of 6 impacts were collected with linear accelerations above 80 g, with all 6 occurring in practices. No instrumented players sustained a concussion throughout the season.

Impacts to the sides of the helmet were most common, accounting for 36% of all impacts. The front of the helmet received approximately 31% of all the impacts. The top and rear of the helmet were impacted least frequently, accounting for 18% and 14% of all impacts, respectively. Impacts to the top of the helmet exhibited the greatest magnitudes of linear acceleration, while impacts to the sides of the helmet resulted in the greatest magnitudes of rotational acceleration (Table 2).

		Linear Acceleration (g)		**Rotational Acceleration (rad/s^2)**	
Impact Location	**Number of Impacts**	**Median (50%)**	**95%**	**Median (50%)**	**95%**
Front	235	14.4	27.6	670	1516
Side	272	14.2	24.7	747	2104
Rear	106	15.4	30.3	679	2057
Top	135	19.6	44.9	467	1483

Table 2. Comparison of head impact exposure across impact locations.

Discussion

This study reports, for the first time, the head impact biomechanics experienced with participation in youth football. From these data, how frequently and how severely 7 and 8 year old children impact their heads while playing in organized tackle football can be characterized. Interestingly, high magnitude impacts (>80 g) were experienced by the instrumented children during play. This level of severity is similar to some of the more severe impacts that college players experience, even though the youth players have less body mass and play at slower speeds.[31] These data serve as the basis of educated decisions related to rule changes and practice structure in youth football, as well as design criteria for youth-specific football helmets.

Of the 107 head impacts the average player sustained, 59% occurred during practices and 41% occurred during games. This was not solely attributed to the average player participating in more practices than games (9.4 practices to 4.7 games), as players experienced 15% more impacts per practice than per game. More notably, impacts of higher magnitude were associated with practices rather than games, where 76% of impacts greater than 40 g and 100% of impacts greater than 80 g occurred during practices. This contrasts trends exhibited in high school and college football, where more severe impacts are associated with games.[3, 8, 10, 34] Head impact exposure in youth football, particularly at higher severities, can be reduced through evaluating and restructuring practices. This can be achieved through teaching proper tackling techniques and minimizing drills that involve full contact; and instead, focusing on practicing fundamental skill sets needed in football at these young ages.

Head impact exposure in football has two components: frequency of impacts and magnitude of impacts. While this study is the first to report on head impact exposure in youth football, research quantifying head impact exposure in high school and college football has been ongoing for the last decade.[12] When comparing the frequency component of head impact exposure across level of play, the number of head impacts a player sustains each season rises with increasing level of play (Table 3). This is not unexpected, as the youth football season (in terms of the number of practices and games, as well as session length) is shorter than the high school football season, which is shorter than the college football season. When comparing the magnitude component of head impact exposure across level of play, the 95th percentile impact increases with level of play for both linear and rotational acceleration, which is indicative of how frequently high magnitude impacts are sustained by players (Table 3). This finding is also not surprising, as the size of the players and speed of play both increase with age. With that said, it is important to note that all levels of play experience high magnitude impacts (>80 g), but these impacts occur more frequently as the player gets older.

Level of Play	Impacts per Season	Linear Acceleration (g)		Rotational Acceleration (rad/s^2)	
		Median (50%)	95%	Median (50%)	95%
Youth (7-8 yrs)	107	15	40	672	2347
High School (14-18 yrs)	565	21	56	903	2527
College (19-23 yrs)	1000	18	63	981	2975

Table 3. Comparison of head impact exposure between youth, high school, and college football. These data were quantified from studies using similar methodologies to instrument youth, high school, and college football players.[1, 2, 31, 33]

The head impact data can be further analyzed by the distribution of helmet impact locations. The instrumented youth players impacted the side of their helmets most frequently. When compared to high school and college impact distributions, youth players experienced a substantially higher percentage of impacts to the side of the helmet and a substantially lower percentage of impacts to the rear of the helmet (Figure 7). This can likely be attributed to the differences in the style of play between the different age groups, as well as the youth players having a tendency to fall to the side while being tackled. Furthermore, the helmets that the youth players wear may influence some of these trends. Youth football helmets are very similar in size and mass to adult football helmets. With that said, the neck muscles of 7-8 year olds are undeveloped in comparison to high school and college football players. These two factors may result in a youth player being more susceptible to impacting his head on the ground while being tackled than a high school or college player.

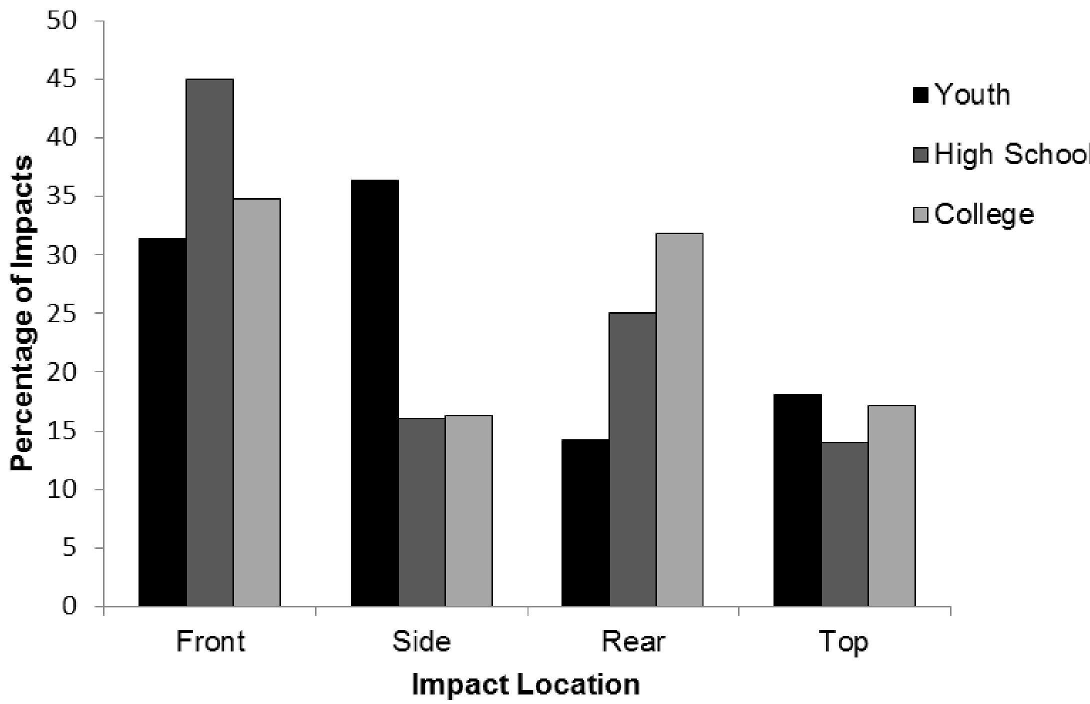

Figure 7. Comparison of helmet impact location distributions between youth, high school, and college football.

Moreover, these data have applications towards future youth helmet design. Currently, youth football helmets are remarkably similar to adult helmets in relation to size, mass, and design materials. In the past, researchers have used data collected from instrumented college football players to develop the STAR evaluation system that assesses a helmet's overall ability to reduce the probability of concussion.[29] This evaluation system is derived from quantified head impact exposure in college football. Head impact exposure measured on the field is related to laboratory tests that evaluate impact performance. The results of the laboratory tests are then disseminated to the public to provide information to consumers on relative helmet performance. Furthermore, the STAR evaluation system provides manufacturers with design guidelines to improve future helmet safety. Unfortunately, this system cannot be extrapolated to youth football helmets because the head impact exposure of youth football is different than that of college football. This study is an important step towards development of a helmet evaluation system for youth football, which would provide guidelines for designing youth-specific football helmets. While this study provides a first glimpse of head impact exposure in youth football, more data is currently needed across the age continuum (6 to 13 years old) of youth football.

This study has several limitations. First, it should be noted that a total of 7 youth football players were included in this study. This is a small sample size in comparison to some of the studies investigating head impact exposure in high school (95 players) and college (>300 players) football.[3, 29] Second, the instrumented players ranged in age from 7 to 8 years old. However, youth football encompasses players ranging in age from 6 to 13 years old. A larger sample size of players ranging from 6 to 13 years old is needed to completely define head impact exposure in youth football. Third, the 6DOF measurement device is associated with some measurement error. However, average acceleration measurement error is on the order of 1-3%.[29] While there may be greater error associated with individual data points, these errors are of little consequence when working with the overall data distributions.

In conclusion, this study is the first to report the head impact biomechanics associated with youth football. Valuable insight to the head impact exposure in youth football has been presented. While youth football players impact their heads less frequently than high school and college players, and have impact distributions more heavily weighted toward low magnitude impacts; high magnitude impacts still occur. Interestingly, the majority of these high magnitude impacts occur during practice. Restructuring youth football practices may be an effective method of reducing the head impact exposure in youth football. These data are the basis of educated decisions about future changes to youth football and have applications towards determining guidelines for youth-specific helmet design.

Chapter 4: Closing Remarks

Research Summary

The research presented in this thesis investigates the head biomechanics of two specialized groups during impacts in football. In the past, there has been much related research focusing on biomechanics.[34-174] By utilizing available video and innovative technologies, insightful data regarding human biomechanics was collected. Instrumented helmets on both sides of the competition allows for biomechanical comparison between striking players and struck players during game scenarios. The instrumentation of a youth population gives insight to the exact exposure conditions that youth players endure during football. By taking note of the specific impact scenarios that occur more often in the youth population, specific regulations or regiments can be augmented to better protect such a large population of football players. While these studies provide the beginning datasets for theses specialized groups, expanded datasets can be created in the future by utilizing the same methodologies.

Although there were no concussions noted in either study, the work presented herein provides the most comprehensive biomechanical analysis for two specialized and important groups involved with playing football to date. Furthermore, the expansion of head acceleration datasets to include concussive impacts would have applications beyond the football field. This is especially true for the youth study, where quantifying the human brain biomechanics as a result of impact will lead to a better understanding of pediatric brain injury and perhaps developmental differences in injury tolerance. In addition, this data may serve as validation for computational models. By applying these techniques to other sport scenarios in which concussive impacts occur, considerable progress can be made towards improving equipment safety, and augmenting rules and regulations to better protect the player from injury.

Publication Outline

The research presented in this thesis is intended to either be published in a peer-reviewed journal or presented at a professional conference. Table 4 presents the destination for each article.

Table 4. Publication plan for research presented in this thesis.

Chapter	Title	Journal/ (Conference)
2	Investigation of Effective Mass Differences for Helmet to Helmet Impacts in Football: Role of the Neck and Implications on Injury	(Biomedical Engineering Society 2011 Annual Meeting)§
3	Head Impact Exposure in Youth Football	Annals of Biomedical Engineering* (ASME Summer Bioengineering Conference)†
* Published, † Accepted, § Presented		

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