Head Impact Exposure in Youth Football: Evaluation of Practice Drills and Age and Weight Based Levels of Play

By

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ABSTRACT

The estimated number of sport-related mild traumatic brain injuries (mTBI) occurring each year in the United States is 1.6 to 3.8 million with football having one of the highest rates of injury. Considerable research has been done to better understand concussions as well as quantifying head impact exposure sustained by a football athlete, but efforts have been mainly focused on the high school and collegiate population. More research is needed to study head impact exposure in the youth population as it makes up the largest proportion of football athletes in the U.S. with approximately 3.5 million participants. A small number of studies have begun to examine head impact exposure in youth football and have shown that youth football players sustain head impacts approaching the magnitude of high school and collegiate players, but these studies have been limited in size, scope, and duration. Additionally, recent clinical evidence reveals that football players can develop cognitive deficits and neurodegeneration later in life, which has been associated with repetitive head trauma. With millions of youth athletes participating in contact sports more research is needed to quantify exposure to repetitive head impacts and identify methods for reducing head impact exposure to make youth sports safer.

The first part of this research studied head impact exposure among drills practiced by a single youth team to identify drills exposing youth athletes to high magnitude and/or high frequency of head impacts. The second part of this research focused on collecting and quantifying head impact exposure data of 9-13 year old football athletes participating on three age and weight based levels of play over four seasons and comparing exposure among the levels of play and session type.

Chapter I: Introduction & Background

Concussions and Brain Injury in Football

The estimated number of sport-related concussions occurring each year in the United States is 1.6 to 3.8 million with football having one of the highest rates of injuries [1, 2]. Concussions occur at all levels of play in football: youth, high school, college, and professional [3-5]. Concussions can range from being relatively mild to severe, and can result in symptoms such as headaches, dizziness and vertigo, difficulty concentrating, poor concentration, memory problems, depression, and irritability [6-8]. Symptoms can persist for days or weeks or even months [6, 7]. Concussion symptoms can affect an individual's ability to function in their daily life and participate in sports, activities, school, or work while they are recovering [6]. Youth football athletes are of particular concern because it's generally agreed upon that youth athletes take longer to recover after a concussion with studies reporting 90% of college athletes recovered within 7 days, but only 50% of high school athletes recovered within 7 days [7, 9, 10]. Additionally, youth football athletes make up the largest proportion of football athletes in the United States with approximately 3.5 million participants.

In addition to concern over the acute injury of concussion, concern has also been growing over the long-term side effects of repetitive head impacts [11-15]. Recent reports of former professional football players suffering from memory loss, dementia, and depression and case reports of chronic traumatic encephalopathy (CTE) have brought attention to possible long-term effects of head impacts, both concussive and subconcussive [13]. CTE can be a devastating disease with symptoms of this neurodegenerative disease including unsteady gait, mental confusion, dementia, slowed muscular response, hesitant speech, and tremors [16]. However, CTE can currently only be diagnosed with post-mortem biopsies of the brain [13, 16]. Although the study of CTE is on-going with more research needed to better understand the specific reasons for the development of this disease, a strong relationship between mild traumatic brain injury (mTBI) and chronic neurodegeneration has been established [16]. However, youth sports participation and long-term neurological deficits are still not well understood. A study by Stamm et al. investigated the relationship between age of first exposure to repeated head impacts through tackle football with later in life neurological deficits [17]. The study evaluated 42 former professional football player's cognitive ability using objective neuropsychological tests and demonstrated an association between involvement in tackle football prior to age 12 with cognitive impairment later in life [17]. However, Solomon et al. conducted a similar study with 45 former professional football players, but failed to find an association between participation in football prior to high school and later-life neurological deficits [18]. Further research quantifying the effects of exposure to repetitive head impacts in the youth population later in life as well as quantifying head impact exposure at the youth level and throughout a lifetime of participation in tackle football is needed to better understand the biomechanical risk factors for CTE from repetitive head impacts.

Several studies utilizing medical imaging have found measureable changes in the brain in football players using imaging metrics over the course of a single season which correlate to the amount of head impact exposure, even in cases without a clinically diagnosed concussion [14, 19-22]. In particular, Davenport et al. evaluated the relationship between head impact exposure of 24 high school football players with brain MRI changes from pre- to postseason and demonstrated significant relationships between biomechanical metrics of head impact exposure during a season of play and diffusion tensor imaging (DTI) measures. Additionally, Bazarian et al. evaluated cerebral white matter changes in 10 college football athletes and 5 non-athlete controls and the results demonstrated that exposure to repetitive head impacts in a single season of football, even without a clinically diagnosed concussion, resulted in changes to white matter in the brain and there was a lack of white matter recovery after 6 months of no-contact rest [14]. These studies show that, even without the acute injury of a concussion, exposure to repetitive subconcussive impacts can result in changes in the brain. Participation in sports, particularly at the youth level, can be beneficial for overall physical health and development [23]. Research is needed to better understand head impact exposure in youth football and improve methods for mitigating injury risk to make youth sports safer.

MEASURING HEAD IMPACT EXPOSURE IN FOOTBALL ATHLETES

The advent of head acceleration measurement devices has allowed researchers to measure head impacts during live play and better understand the relationship between head impact characteristics and concussion, but research efforts have been mainly focused on the high school and collegiate population [24-30]. More research needs to be done to study head impact exposure in the youth population because it makes up the largest proportion of football athletes in the United States with 3.5 million participants, while the high school, college, and professional levels have 1.3 million, 100,000, and 2000 athletes, respectively [24, 31]. Sport related concussion is a major public health concern with recent studies of youth, high school, and college football athletes showing concussion incident rates of (per 1000 athletic exposures [AEs]) 1.76, 0.60, and 0.61, respectively [1, 4, 32]. Epidemiological studies have provided insight into the number of concussions football athletes sustain in a season, but they do not capture the exposure to subconcussive impacts [28, 33]. The use of head acceleration measurement devices in youth football athletes can provide critical information about exposure to subconcussive impacts in the youth population and can contribute to our knowledge of lifetime exposure of football athletes. Additionally, biomechanical data of head impacts can inform youth organizations, coaches, and players on ways to reduce exposure and keep athletes safe.

Although youth head impact data at the youth level is limited, a small number of studies have begun to examine head impact exposure in youth football [3, 31, 34-36]. Daniel et al. was the first to publish youth football head impact exposure data [34]. This study instrumented seven 7-8 year old athletes for a single season and reported data on the frequency and magnitude of head impacts experienced by those athletes and found that high magnitude impacts, greater than 80 g, were occurring in practices, not games [34]. The results from the study by Daniel et al. were influential in Pop Warner's decision in 2012 to implement rules to limit the amount of time allowed for contact in practices (maximum of either 40 minutes total of each practice or 1/3 of total weekly practice time) and eliminate certain high speed tackling drills [34, 37]. Cobb et al. published another study of head impact exposure of fifty 9 – 12 year old football athletes on three teams and evaluated the effect of one team that implemented the aforementioned practice limitations and two teams that did not [31]. The athletes on the team with limitations on contact in practice experienced 37-46% fewer head impacts over the course of an entire season than those on the other two teams that did not implement limitations on contact [31]. It was also found that the 9-12 year old athletes experienced higher magnitude and higher number of impacts compared to the 7-8 year old athletes studied by Daniel et al. [31, 34]. A study by Young et al. evaluated the head impact exposure of nineteen 7-8 year old football athletes and reported that first-time football athletes experienced significantly less head impacts than athletes with previous years of football experience [36].

These early studies provided crucial insight into the head impact exposure of youth football athletes and influenced recent efforts to improve safety at the youth level of play, especially through rule changes and education. Heads Up Football is an educational program, which aims to inform coaches and leagues about concussion recognition and response, proper equipment fitting, proper tackling technique, and several other key factors in maintaining player safety. A study by Kerr et al. investigated the effect of the Heads Up Football program on head impact exposure and found that athletes on teams that implemented this educational program experienced significantly fewer head impacts than athletes on teams that did not implement the Head Up Football program [35]. These studies of head impact exposure in youth football have not only improved our understanding of subconcussive impacts experienced by youth athletes, but that rules, regulations, and education can reduce head impact exposure and make positive changes in improving safety of youth athletes. Nevertheless, studies at the youth level have been limited in size and duration, especially compared to studies at the high school and collegiate level [24, 26, 27, 29, 30, 33, 38]. More data are needed from larger population-based studies of youth football athletes spanning a larger age range over multiple years and there is also a need to better understand and mitigate high magnitude impacts.

CHAPTER SUMMARIES

Chapter II: Practice Drill Head Impact Exposure Measured from a Single Youth Football Team

The objective of this study was to evaluate frequency and magnitude of head impacts in practice drills within a single youth football team.

Chapter III: Head Impact Exposure in Youth Football: Comparison among Age and Weight Based Levels of Play

The objective of this study was to collect and quantify head impact exposure data of 9-13 year old football athletes participating on three age and weight based levels of play within a single youth football organization over four seasons. Specifically, this study evaluated head impact exposure among the age and weight based levels of play and session type.

Chapter V: Summary of Research

A brief overview of work presented in this thesis.

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Chapter II: Practice Drill Head Impact Exposure Measured from a Single Youth Football Team

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ABSTRACT

The purpose of this study was to evaluate frequency and magnitude of head impacts in practice drills within a youth football team. On-field head impact data were collected from 9 athletes (age = 11.1 ± 0.6 years, weight = 98.9 ± 9.1 lbs.) participating in an age and weight restricted youth football team for a season using the Head Impact Telemetry (HIT) System head acceleration measurement device. Video was recorded for all practices and games and video analysis was performed to verify head impacts and assign each impact to a specific drill. Drills were identified as: dummy/sled tackling, install, kickoff practice, Oklahoma, one-on-one, open field tackling, passing, position skill work, multi-player tackle, scrimmage, and tackling drill stations. Mixed effects linear models were fitted and Wald tests were used to assess differences in head accelerations, number of impacts, and concussion risk among drills. There were significant differences in mean linear ($p<0.0001$) and rotational ($p=0.003$) acceleration, number of impacts per player ($p<0.0001$), and risk of concussion ($p<0.0001$) among drills. Open field tackling drills had the highest median/95th percentile linear accelerations of 24.6g/95.7g and resulted in significantly higher mean head accelerations and higher risk of concussion compared to several other drills. The multi-player tackling drill resulted in the highest head impact frequency of 6.6 impacts per player in a drill session. Head impact exposure varies significantly in youth football practice drills with several drills exposing athletes to high magnitude or high frequency of head impacts. These data suggest study of practice drills is an important step in making evidence-based recommendations for modifying certain high intensity drills to reduce head impact exposure and injury risk.

1. INTRODUCTION

Approximately 5 million athletes play organized football in the United States; 2,000 NFL, 100,000 college, 1.3 million high school, and 3.5 million youth [1-3]. Despite making up the largest proportion of football athletes, youth football has seen declines in participation in recent years [4, 5]. Although several factors may be attributing to the decline in participation, concern over injuries, particularly concussion and the long-term side effects of repetitive head impacts, have been suggested as major reasons [6-9]. However, youth sports participation and long-term neurological deficits are still not well understood. A study by Stamm et al. demonstrated an association between involvement in tackle football prior to age 12 and cognitive impairment in former NFL players later in life, but a similar study by Solomon et al. failed to find an association between participation in football prior to high school and later-life neurological deficits [10, 11]. Further research is necessary to better understand the effect of exposure to repetitive head impacts. In particular, more head impact exposure data, specifically the magnitude, location, and kinematics of head impacts, are needed in the youth football population. Head impact exposure has been studied at the high school, collegiate, and professional levels, but studies at the youth level have been limited [12-15]. Although impact data from youth athletes are scarce, preliminary data suggest that youth football players sustain head impacts approaching the magnitude of high school and collegiate football players [1, 15, 16]. Additionally, a study of head impact exposure in youth football athletes aged 7-8 years showed that the majority of high level impacts (greater than 80g) occur during practice, as opposed to during games [1].

In an effort to reduce risk of concussion and overall head impact exposure, some football organizations have taken steps to implement rule changes that affect practice structure. For example, in 2012 Pop Warner limited the amount of contact allowed at each practice (1/3 of total weekly practice time or 40 minutes total at each practice) and eliminated full speed head-on blocking or tackling drills where athletes start more than 3 yards apart from each other [17]. Recently, Cobb et al. studied the effect of limiting contact in practices in youth football by comparing one team that adopted these practice limitations and two teams that did not [15]. Players participating on the team with contact limitations in practice had 37-46% fewer head impacts for the entire season than those on the other two teams that did not implement contact limitations [15]. Football organizations have also implemented educational programs such as the Heads Up Football program to train coaches on tackling technique, proper equipment fitting, and strategies to reduce player-to-player contact and concussions [18-20]. A study evaluating the effectiveness of the Heads Up Football program found that leagues implementing this program accumulated significantly fewer head impacts per practice compared to leagues that did not [18].

These studies have shown that head impact exposure can be directly controlled by the coaches, leagues, and organizations by adopting rules and regulations to limit contact or improve the quality of contact. However, it is yet to be determined how specific practice drills play a role in the magnitude and frequency of head impacts measured on the field. The objective of this study is to evaluate the frequency and magnitude of head impacts in practice drills within a single youth football team through biomechanical data collection and detailed video analysis. These data, along with future research, may inform coaches, leagues, and organizations on methods to restructure practice to limit head impact exposure and make rule changes to modify or eliminate drills for safer play.

2. METHODS

On-field head impact data from athletes participating in a local youth football team were collected during one season of play. The study protocol was approved by the Wake Forest School of Medicine Institutional Review Board and participant assent and parental written consent were properly acquired for participation in the study. The athletes enrolled in the study participate in a youth football league in which athletes range in age from 5-14 years and are placed on teams based on age and weight requirements set by the national governing organization. The athletes evaluated in this study participated in a team with athletes meeting the age and weight requirements of 10 years old or younger with a maximum weight of 124 lbs. or 11 years old with maximum weight of 104 lbs.

Head impact data were collected by instrumenting the helmets of youth football players with the Head Impact Telemetry (HIT) System head acceleration measurement device during all preseason, regular season, and play-off practices and games. Each study participant was issued a Riddell Speed helmet with the HIT System installed. The HIT System measures location and magnitude of head impacts with an encoder, which is an array of six spring-mounted single-axis accelerometers oriented normal to the surface of the head, a telemetry unit, data storage device, and battery pack. The encoder is designed to fit between the existing padding of a Riddell Speed helmet. The spring-mounted accelerometers allow the encoder to remain in contact with the head throughout the duration of a head impact, ensuring measurement of head acceleration, not helmet acceleration [21]. Each time an instrumented helmet receives an impact greater than 10g, data acquisition is initiated and a total of 40 ms of data with 8 ms of pre-trigger data are recorded at 1000 Hz. The data from the encoder are transmitted wirelessly via radio wave transmission to the sideline base unit. The data are then used to compute peak and resultant linear acceleration, estimated peak resultant rotational acceleration, location of impact, and other biomechanical indicators. The HIT System has been extensively described and has been found to reliably compute peak linear acceleration, peak rotational acceleration, and impact location [22, 23].

Video was recorded for all practices and games to verify head impacts recorded by the HIT System and to identify drills performed during practices. Post-season video analysis was performed to remove false impacts (e.g. dropped helmet) and to pair the video with the biomechanical data. For each drill, the name, start time, and end time was recorded such that each head impact was identified as belonging to a specific drill. Drill names and descriptions were provided by the coaches for the team at the beginning of the season and were classified as: dummy/sled tackling, install, kickoff practice, multi-player tackle, Oklahoma, one-on-one, open field tackling, passing drill, position skill work, scrimmage, and tackling drill stations (Table 1).

Table 1: Descriptions of each drill classification.

Drill	Description	Purpose
Dummy/Sled tackling	Players tackle a dummy or sled	Reinforce wrapping while tackling and improve form for blocking
Install	Full 11-on-11 intra-team scrimmage	Within-team practice of offense and defense game strategy in a game-like situation
Kickoff practice	Special teams install	Practice alignment and responsibilities for different kickoff scenarios
Multi-player tackle	One offensive player versus two or three defensive players	Improve blocking/tackling form and technique and encourage athletes to move their feet
Oklahoma	Two vs. two or three vs. three tackling drill	Simulate game speed while working to improve blocking, running, and tackling technique in a confined space
One-on-One	One vs. one tackling drill with the two athletes starting less than 3 yards apart	Improve one-on-one tackling form and technique
Open Field tackling	One vs. one tackling drill with the two athletes starting greater than 3 yards apart at an angle	Improve form and technique for tackling in full speed game-like situations
Passing drill	Athletes receive passes from coaches	Improving passing/catching skills and hand-eye coordination
Position skill work	Athletes separate into offense and defense groups to practice skill-set specific drills	Practice offensive or defensive specific skills and game strategy
Scrimmage	Inter-team scrimmage with another team	Practice of offense and defense game strategy in a game-like situation between adjacent age and weight classified teams
Tackling drill stations	Separate team into smaller groups and complete a series of tackling drills	Practice tackling drills in smaller groups with a higher coach to player ratio than whole team tackling drills

All verified head impacts collected over the season were used to quantify head impact exposure for all practice drills in terms of impact frequency, location, and mean, median, and 95th percentile head acceleration. Mixed effects linear models were fitted and Wald tests were used to assess differences among athletes and drills in the associated linear and rotational accelerations, the number of impacts, and the combined probability risk of concussion [24]. For inference, log-transformations were applied to the number of impacts and the combined probability risk of concussion due to their right skewed distribution. A Bonferroni correction was applied for all statistical tests to identify significant pairwise differences while controlling the overall alpha level to be 0.05. All statistical analyses were performed using SAS software version 9.4 for Windows (SAS Institute Inc., Cary, NC, USA).

3. RESULTS

A total of 3,761 head impacts were recorded from 9 individual athletes during 36 practices and 11 games. Practices accounted for 2,171 (57.7%) head impacts and games accounted for 1,590 (42.3%) head impacts. The median/95th percentile linear and rotational accelerations of all practice head impacts were 20.1/56.1g and 960.1/2335.9 rad/s2, respectively. The median/95th percentile linear and rotational accelerations for all game head impacts were 20.9/54.0g and 986.8/2430.5 rad/s2, respectively. All athletes were monitored by a certified athletic trainer for signs and symptoms of concussion and no head impacts measured in this study resulted in a clinically diagnosed concussion. The average ± standard deviation age and weight of the athletes on the team was 11.1 ± 0.6 years old and 98.9 ± 9.1 lbs., respectively. The distribution of the total number of head impacts experienced during a season among players was right skewed and ranged from 169 to 1003 head impacts, with a median value of 350. A summary of the athlete's total number of head impacts over the course of the season and their 95th percentile linear acceleration magnitude is shown in Figure 1.

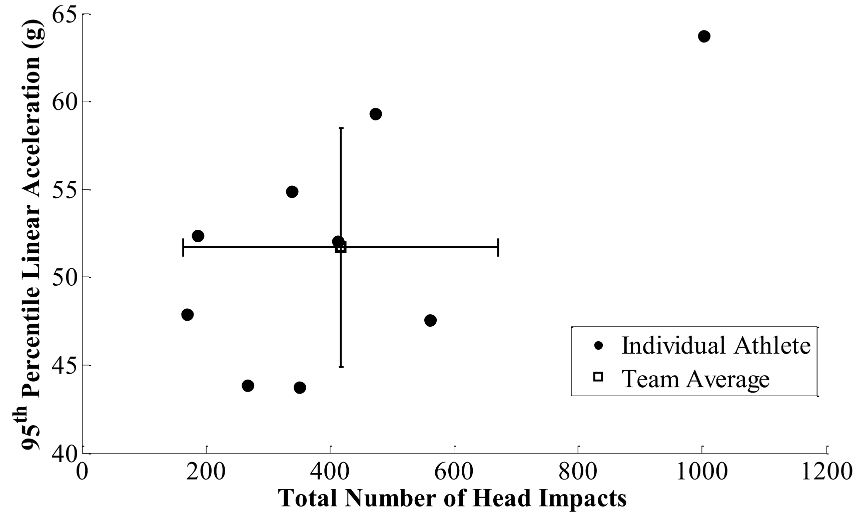

Figure 1: Athlete and team average 95th percentile linear acceleration vs. total number of impacts in season. Team average is shown with standard deviation error bars.

Table 2: Summary of impact frequency and impact magnitude for each practice drill. Mean number of impacts per player is computed per practice session. Mean number of impacts per player and mean risk of concussion are displayed with [95% confidence intervals]. Means in the same column that share the same subscripts differ at $p < 0.05$.

Drill	Number of Sessions	N (Total)	N (>60g)	N (>80g)	Mean Number of Impacts Per Player	Mean Risk of Concussion (%)	Linear Acceleration (g)		Rotational Acceleration (rad/s^2)	
							50th Percentile	95th Percentile	50th Percentile	95th Percentile
Dummy/Sled tackling	3	13	0	0	1.4 [0.8, 2.5]$_{a, b, c}$	0.012 [0.0083, 0.018]	18.0	48.7	905.5	1576.3
Install	33	1217	38	12	4.2 [3.7, 4.7]$_{a, d, e, f, g}$	0.010 [0.0010, 0.011]$_{a, c}$	19.7	51.7	953.2	2270.2
Kickoff practice	10	57	2	0	1.9 [1.4, 2.5]$_{d, h, i}$	0.010 [0.0088, 0.012]$_{d}$	18.7	51.0	833.1	2063.3
Multi-player tackle	3	164	3	0	6.6 [4.4, 9.8]$_{b, h, j, k, l, m}$	0.0097 [0.0084, 0.011]$_{b, e}$	21.4	44.1	1018.4	2279.7
Oklahoma	5	148	8	3	5.1 [3.6, 7.2]$_{c, i, n, o, p}$	0.011 [0.0097, 0.013]$_{f}$	22.9	61.6	1074.3	2958.0
One-on-One	7	109	7	3	2.7 [2.0, 3.6]$_{j, q}$	0.015 [0.013, 0.017]$_{a, b}$	22.6	64.8	894.6	2578.6
Open Field tackling	5	52	9	5	2.0 [1.4, 2.8]$_{e, k, n}$	0.018 [0.015, 0.021]$_{c, d, e, f, g, h, i}$	24.7	96.4	1326.4	3809.2
Passing drill	17	31	0	0	1.2 [0.9, 1.7]$_{f, l, o, q, r}$	0.0093 [0.0074, 0.012]$_{g}$	17.0	42.8	950.3	2342.8
Position skill work	12	156	10	4	2.3 [1.8, 2.9]$_{g, m, p}$	0.011 [0.010, 0.013]$_{h}$	19.5	69.0	902.6	2554.2
Scrimmage	2	89	2	1	3.4 [2.1, 5.6]$_{r}$	0.010 [0.0086, 0.013]$_{i}$	18.9	50.8	869.8	2197.6
Tackling drill stations	4	135	9	1	3.2 [2.0, 5.0]	0.012 [0.0098, 0.014]	21.2	63.3	1010.2	2524.5

As described earlier, the head impacts were classified into 11 drills: dummy/sled tackling, install, kickoff practice, multi-player tackle, Oklahoma, one-on-one, open field tackling, passing drill, position skill work, scrimmage, and tackling drill stations. The distribution of head impact magnitudes varied among practice drills and impact magnitude was not proportional to the frequency of head impacts for each drill (Figure 2). A summary of impact frequency and magnitude for each drill is shown in Table 2. Open field tackling drills had median/95th percentile linear accelerations of 24.6/96.4g, which was the highest magnitude of all drills practiced by the team. Install was the most common drill with 1,217 impacts and had a median/95th percentile linear acceleration of 19.7/51.7g. The drills with the lowest magnitude head impacts were dummy/sled tackling, passing drills, and multi-player tackle.

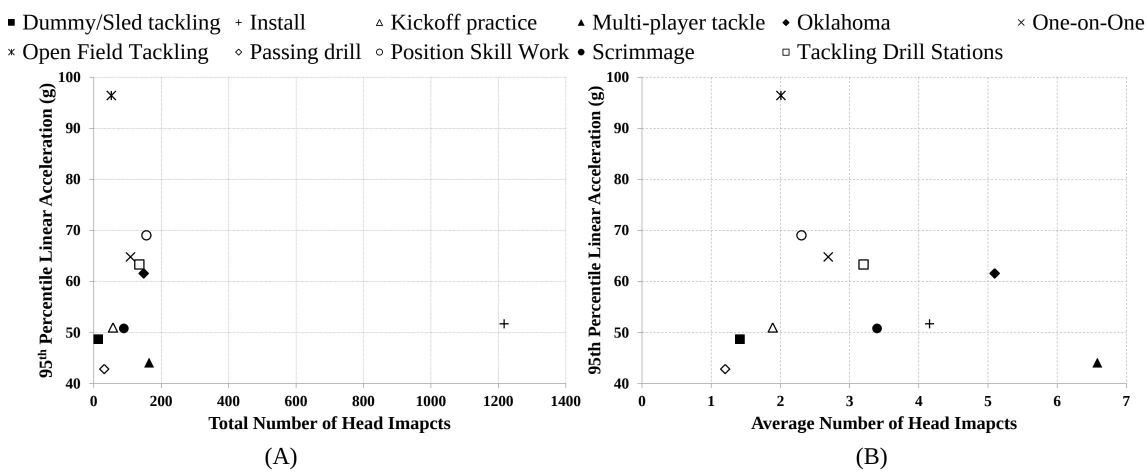

Figure 2: 95th percentile linear acceleration vs. (A) total number of head impacts in the season and (B) average number of impacts per player per drill session.

There were statistically significant differences in mean linear ($p<0.0001$) and rotational ($p=0.003$) acceleration measured among drills (Figure 3). Open field tackling had a significantly greater mean linear acceleration than install ($p<0.0001$), kickoff practice ($p=0.004$), multi-player tackle ($p=0.0002$), passing drill ($p=0.004$), position skill work (p=0.01), and scrimmage (p=0.02). One-on-one had a significantly greater mean linear acceleration than install (p=0.003) and multi-player tackle (p=0.02). Additionally, open field tackling had significantly greater mean rotational acceleration than install (p<0.0001), kickoff practice (p=0.0009), multi-player tackle (p=0.01), Oklahoma (p=0.02), passing drill (p=0.04), position skill work (p=0.002), and scrimmage (p=0.01).

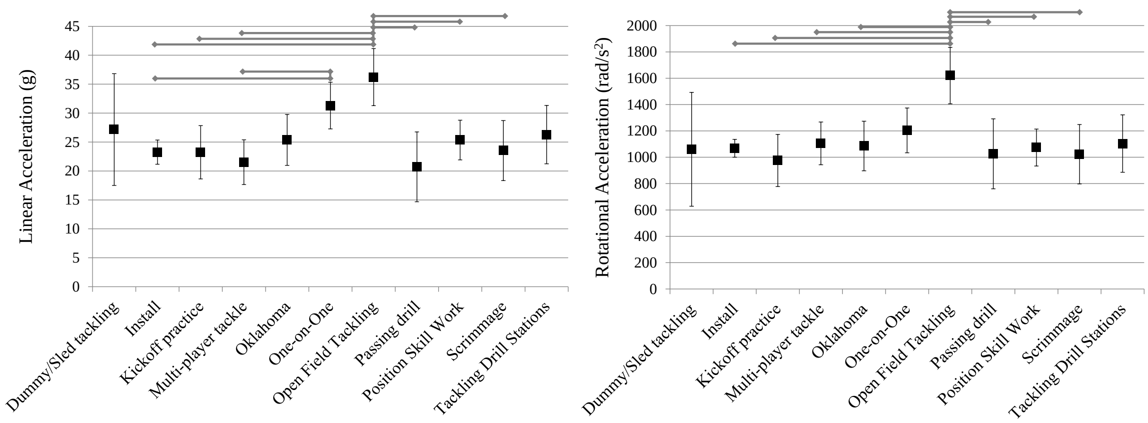

Figure 3: Mean and 95% confidence interval of (A) linear and (B) rotational acceleration for each drill. Lines connecting drills indicate significant differences in accelerations.

The mean number of impacts measured per athlete in a single practice session was evaluated for each drill (Table 2). The drill with the highest mean [95% confidence interval] number of impacts per athlete was multi-player tackle with 6.6 [4.4, 9.8] impacts, which was significantly greater than the mean number of impacts per athlete for dummy/sled tackling (p=0.002), kickoff practice (p=0.0002), one-on-one tackling (p=0.04), open field tackling (0.001), passing drill (p<0.0001), and position skill work (p=0.0004). Oklahoma had the second highest mean number of impacts per athlete with 5.1 [3.6, 7.2] impacts and had significantly greater number of impacts per athlete than dummy/sled tackling (p=0.02), kickoff practice (p=0.003), open field tackling (p=0.02), passing drill (p<0.0001), and position skill work (p=0.01). Install had significantly greater mean number of impacts per athlete than dummy/sled tackling (p=0.02), kickoff practice (p<0.0001), open field tackling (p=0.004), passing drill (p<0.0001), and position skill work (p=0.001). One-on-one and tackling drill stations had significantly greater mean number of impacts than passing drill (p=0.02 and p=0.04, respectively). The drill with the fewest mean number of head impacts per athlete was passing drill with 1.0 [-1.10, 3.03] impacts.

Given the non-linear relationship between impact magnitude and concussion risk, the linear and rotational magnitude of each impact were weighted by the risk computed from the combined probability risk function [24]. The mean risk of concussion for each drill is summarized in Table 2. The drill with the highest mean risk of concussion was open field tackling with a mean risk of 0.018% [0.015%, 0.021%], which was significantly greater than install (p<0.0001), kickoff practice (p=0.002), multi-player tackling (p<0.0001), passing drill (0.002), position skill work (p=0.007), and scrimmage (p=0.01). One-on-one had the second highest mean risk of concussion of 0.015% [0.013, 0.017], which was significantly greater than install (p=0.0008) and multi-player tackle (p=0.008). The drill with the lowest mean risk of concussion was passing drill with a mean risk of concussion of 0.0093% [0.0074%, 0.012%].

Lastly, the distributions of all head impacts and impacts with peak linear acceleration greater than or equal to 60g were evaluated by impact location and are shown in Figure 4. Impacts to the front of the helmet were most common for all drills, except dummy/sled tackling. While only considering impacts equal to or greater than 60g, impacts to the top of the helmet were most common in the Oklahoma, one-on-one, open field tackling, and position skill work drills (50%, 86%, 44%, and 50% respectively). Impacts to the front of the helmet were most common for impacts measured over 60g during install, multi-player tackle, and tackling drill stations (45%, 100%, and 67%, respectively). Note that there were no impacts over 60g for dummy/sled tackling and passing drill.

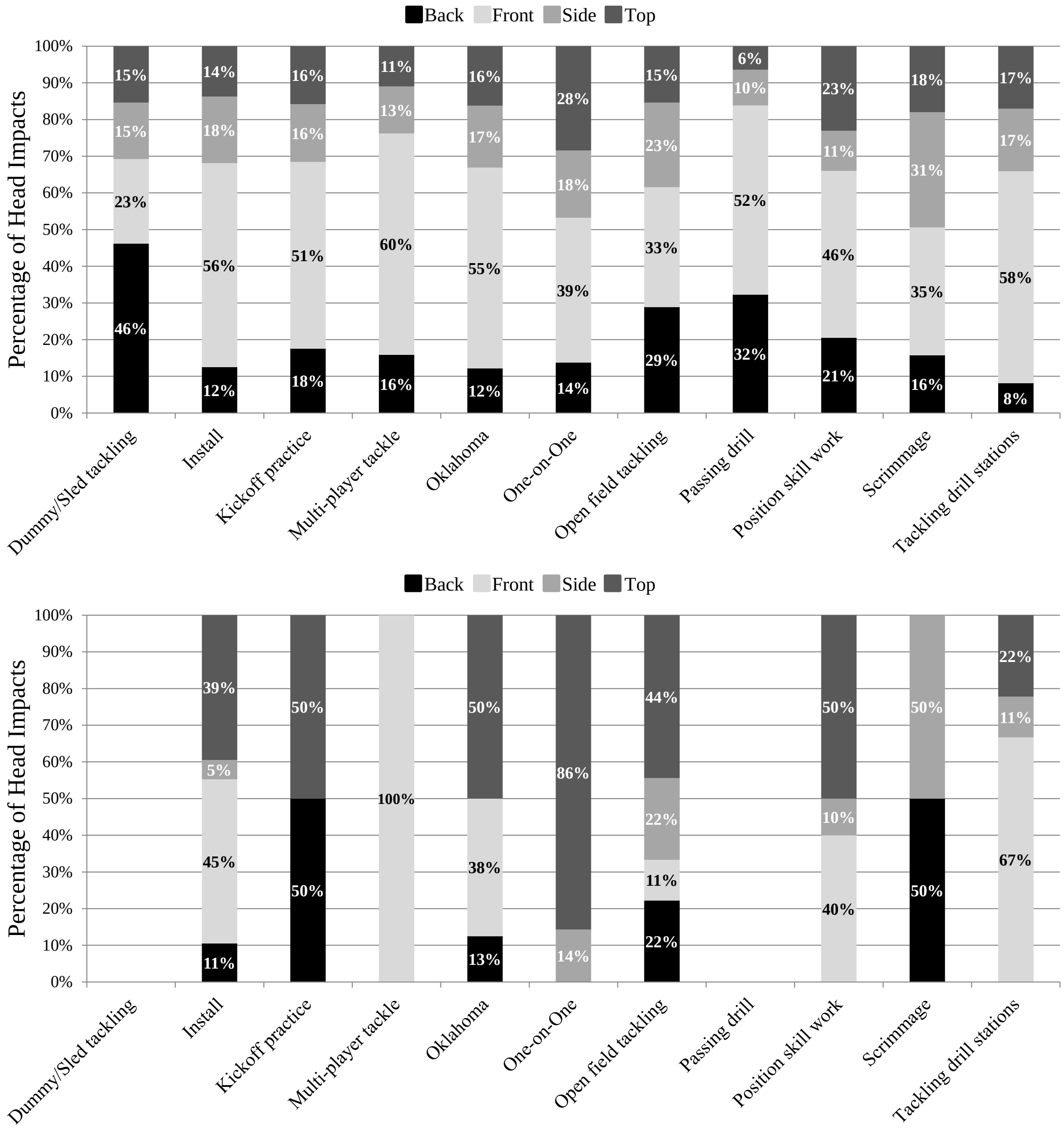

Figure 4: Percentage of head impacts by impact location for each drill for (top) all impacts and (bottom) impacts greater than or equal to 60 g. Refer to Table 2 for total number of impacts for each drill. No impacts equal to or greater than 60g were measured during dummy/sled tackling and passing drill.

4. DISCUSSION

Head impact data is limited at the youth football level compared to data available at the high school and college level, but youth studies have shown that head impact exposure in practice can be reduced by implementing rules, modifying practice structure, and educating coaches and leagues on methods to reduce concussion risk [1, 13, 15, 16, 18, 22, 25]. Quantifying head impact exposure in football practice drills is an important next step in an evidence-based approach to modifying rules and practice structure to reduce overall head impact exposure and head injury risk. This study presents a unique and innovative view into head impact exposure by evaluating specific football practice drills within a youth football team.

Open field tackling resulted in the highest median and 95th percentile linear and rotational acceleration (Table 2) with significantly greater mean linear and rotational acceleration as well as significantly greater risk of concussions compared to several of the drills practiced by the team. Despite only accounting for 2.4% of all practice head impacts, open field tackling drills accounted for 10.2% of practice head impacts greater than 60g and 17.2% of practice head impacts greater than 80g. Also, 17.3% and 9.6% of head impacts occurring in open field tackling were greater than 60g and 80g, respectively, which was the highest proportion of head impacts greater than 60g and 80g within any of the drills. It was not surprising that this drill had high head acceleration magnitudes given that this is a full-speed tackling drill with the athletes starting more than 3 yards apart from each other and tackling at an angle. Despite resulting in very high magnitude impacts, it was a relatively low frequency drill when compared to other drills. This drill only occurred in 5 practices with an average of 2.0 impacts per player, so it resulted in a relatively small contribution to the total number of impacts an athlete experienced in a single practice and to their total number of impacts in a season. As described in Table 1, the purpose of open field tackling type drills is to improve tackling technique and positioning in game-like situations, but this drill may expose athletes to high magnitude head impacts, which are often greater than those experienced in games and may not be an accurate simulation of game-like scenarios. These results suggest that open field tackling drills may be modified such that the athletes start at a shorter distance apart, however considerations may be made to remove this drill entirely from youth football practice structures.

The one-on-one tackling drill was similar to open field tackling as both were player versus player tackling drills, but the one-on-one drill had the athletes start less than 3 yards from each other and there was a greater focus on improving form and technique rather than simulating game-like speed. One-on-one tackling had the second highest mean linear and rotational accelerations. Although still a high impact magnitude drill, when compared to open field tackling, the closer starting position of athletes and lower speed of tackling may partially contribute to lower head impact magnitudes measured in one-on-one tackling. This drill had significantly higher mean number of impacts per athlete than the passing drill, but only contributed 5% of all practice impacts. Therefore, similar to open field tackling, one-on-one was a lower frequency, but high magnitude drill.

Another tackling drill was the Oklahoma drill, which accounted for 6.8% of all practice impacts, but 9% of practice impacts greater than 60g, and 10.3% of practice impacts greater than 80g. Unlike open field and one-on-one tackling drills, Oklahoma was a high frequency drill with the second highest number of impacts per athlete (Table 2). The high frequency of impacts per athlete in a practice session is partially due to this drill involving four to six athletes in each play, rather than just two, so each athlete participates in more iterations of this drill during a practice. Another high frequency drill was multi-player tackle, which had a mean number of impacts per player of 6.6, the highest of all drills evaluated in this study. However, this drill resulted in a distribution of relatively low magnitude impacts, especially compared to the other contact drills. Multi-player tackle had the second lowest 95th percentile linear acceleration of 44.1g, with only the passing drill having a lower 95th percentile linear acceleration. Additionally, multi-player tackle accounted for 7.6% of all practice impacts, but only 3.4% of impacts greater than 60g, and 0% of impacts greater than 80g. Although multi-player tackle is still a tackling drill, it was more focused on blocking and encouraging the athletes to move their feet rather than tackling the opposing player to the ground. Also, 3 to 4 athletes participated in each iteration of this drill, so that each athlete participated in more iterations in a single practice compared to open field and one-on-one tackling drills. Additionally, each iteration of multi-player tackle consisted of longer player to player contact than other tackling drills, allowing for more frequent smaller magnitude impacts. This shift in focus and drill set up may be one of the reasons this drill generally had lower magnitudes of head impacts, but higher frequency when compared to other tackling drills.

The position skill work drill had the second highest 95th percentile linear acceleration, but because the team would separate into offensive and defensive skill groups, it is suspected that the defensive skill group was contributing a greater proportion of high magnitude impacts compared to the offensive skill group. The defensive skill group often did one-on-one and sled tackling drills, while the offensive skill group would focus more on passing drills. However, further analysis will be needed to understand if one skill group has greater head impact exposure than the other in this particular drill. The dummy/sled tackling drill resulted in few recorded impacts. The reason is two-fold: this drill was only practiced 3 times during the season and head impacts were solely due to either contact with the dummy/sled or the ground. With the exception of one 48.7g impact, the peak linear acceleration for head impacts during this drill ranged from 13.4g to 25.4g. The 48.7g impact occurred during sled tackling and was due to the athlete's head contacting the padded sled. Dummy/sled tackling was generally a low impact magnitude and frequency drill, but more data are needed to better understand exposure during this drill.

Install was the most commonly practiced drill, resulting in 56% of all practice impacts. Install was practiced at almost every session and resulted in an average of 4.2 impacts for each athlete. This resulted in the third highest number of impacts per player in a given practice, following multi-player tackle and Oklahoma. Although the distribution of head impact magnitudes was not as high as other tackling drills like one-on-one, it was comparable to those observed in games. Scrimmage was similar to the install drill in that both drills were full 11-on-11 practice with the purpose of practicing offensive and defensive strategy in a game-like scenario, however, scrimmage was between adjacent age and weight based teams, not just within the team participating in this study. Although the current team only did the scrimmage drill with each adjacent (i.e. above and below) age and weight level once, each on separate practice days, the distributions of linear and angular acceleration head impact magnitudes were comparable to those in the within-team install drill (Table 2). Nevertheless, more data are needed to determine if scrimmaging adjacent age and weight classified teams during practice has significantly different head impact exposure than within-team scrimmage. Variables such as amount of contact allowed by the coaches during between-team scrimmages and the differences in age and weight between the teams may affect head impact exposure and injury risk.

Lastly, head impact data were evaluated in terms of helmet impact location. The most common impact location for each drill, except dummy/sled tackling, was to the front of the helmet. A distribution with the highest number of head impacts occurring to the front of the helmet is similar to other studies of youth football athletes [1, 15, 26]. However, the proportion of head impacts to the different impact locations changed when only evaluating impacts greater than 60g. For open field tackling, Oklahoma, one-on-one, and position skill work, impacts greater than 60g commonly resulted in impacts to the top of the helmet, which could be indicative of improper tackling technique with athletes leading with their head instead of leading with their shoulder and keeping their head up. However, it should be noted that other studies of head impact exposure of youth football athletes report the top of the helmet as having a distribution of the highest magnitude impacts [1, 15, 26]. More in-depth video analysis of tackling technique and head impact surface (e.g. helmet, player, or ground) is needed to better understand how tackling technique can be improved to lower head impact exposure. Unlike other drills practiced by this team, dummy/sled tackling had the majority (46%) of head impacts occurring to the back of the helmet, which is partially due to the technique used during dummy tackling. The athletes would typically run up to the dummy, wrap their arms around it, and often roll onto their backs after making the tackle. Of note for the tackling drill stations, the most common impact location for impacts greater than 60g was to the front of the helmet, rather than the top of the helmet. Due to the higher ratio of coaches to number of athletes in this drill, the coaches may have been able to better correct improper tackling technique, however further analysis of coach corrective behavior is needed to fully understand how coach interaction in a lower player to coach ratio setting might influence head impact exposure compared to whole team practice.

The nine youth athletes participating in this study demonstrated variations in head impact exposure with some athletes having greater head impact exposure compared to other athletes on the team. Specifically, one athlete had 1003 head impacts and a 95th percentile linear acceleration of 63.7g, which were both the highest compared to all other athletes on the team. Some possible reasons for this athlete's increased head impact exposure include increased involvement and intensity in practices and games. Also, the majority of this athlete's head impacts (53.1%) occurred in games rather than practices, which differs from the relative proportions of game and practice impacts for the team as a whole. This athlete's increased involvement in games and individual intensity could be contributing factors to his increased head impact exposure relative to other athletes on the team. A sensitivity analysis removing individual athletes, including this athlete with higher head impact exposure, attenuated the strength of some relationships presented here; however, the general trends and overall conclusions of the study remain unchanged.

A few limitations should be noted about this study. First, this study only sampled 9 athletes from one youth football team. This sample size is small compared to some other studies at the high school and collegiate level [16, 27]. Second, the results of this study are a limited snapshot of this youth population, as youth football leagues accommodate athletes ranging in age from 5-15 years old. However, this study of head impact exposure in youth football practice drills is ongoing and future work will be conducted to evaluate head impact exposure in specific practice drills for multiple seasons and between age and weight based teams at the youth level. Third, the results of this study are a limited representation of the youth population as a whole as it is focused to a single youth football organization. For each drill described in this study the exact set up and technique that is being taught will be coach, league, and organization dependent, therefore athletes on different teams may experience different head impact exposure while practicing similar drills. Other organizations may also have some variation in head impact exposure due to league-specific or organization-specific regulations for practices and games. This work is part of a multi-site study and will be expanded upon to include several youth leagues within various national organizations (e.g., Pop Warner) and demographic/cultural backgrounds. Fourth, the HIT system used for biomechanical data collection has some measurement error, but the error in 5DOF acceleration measurements are within the range of acceptable error for other measurement devices and methods [23].

5. CONCLUSION

This study quantified head impact exposure of 11 youth football practice drills for a single age and weight restricted youth football team and found that head impact exposure varies significantly between drills. Open field tackling drills had the highest median and 95th percentile head accelerations of 24.6g and 95.7g, respectively, and resulted in a significantly higher distribution of head impact magnitudes compared to several other drills. The multi-player tackling drill resulted in a relatively low distribution of head impact magnitudes compared to other tackling drills, but resulted in the highest head impact frequency of 6.6 impacts per player in a drill session. For all practice impacts, the highest percentage of impacts (52.7%) occurred to the front of the helmet, but for impacts greater than 60g and 80g the highest percentage of impacts (42.1% and 51.7%, respectively) occurred to the top of the helmet. Further research is needed to fully understand the role of coach/athlete interaction, corrective behavior, and proper tackling technique on head impact exposure. Evaluating head impact exposure in youth football practice drills is an important step in informing coaches, leagues, and organizations on methods to restructure practice and implement rules and regulations to ultimately reduce head impact exposure and make sports safer for youth.

6. ACKNOWLEDGEMENT

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Chapter III: Head Impact Exposure in Youth Football: Comparison among Age and Weight Based Levels of Play

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ABSTRACT

Approximately 5 million athletes play organized football in the United States and youth athletes make up the largest proportion with 3.5 million participants. However investigations of head impact exposure in youth football has been limited. The objective of this study was to evaluate head impact exposure of athletes participating in age and weight based levels of play within a youth league. Head impact data was collected from youth football athletes using the Head Impact Telemetry (HIT) system over four seasons. The youth athletes in the participating league were assigned teams based on age and weight. The three levels of play studied were level A (n=39, age=10.8 ± 0.7), level B (n=48, age=11.9 ± 0.5), and level C (n=32, age=13.0 ± 0.5). Mixed effects linear models were fitted and Wald tests were used to assess differences in head accelerations and number of impacts among levels of play and session type. The median/95th percentile linear head acceleration for levels A, B, and C was 19.8/49.4g, 20.6/51.0g, and 22.0/57.9g, respectively. Level C had significantly greater mean linear acceleration than both level A (p=0.0048) and level B (p=0.0164). Within each level of play, the distribution of head impact magnitudes was greater in competitions than in practices and there was significantly greater number of impacts per player in competitions than in practices (A, p=0.0005; B, p=0.0019; and C, p<0.0001). However, for 92% of athletes that participated in this study, practices contributed to greater than 50% of total number of impacts measured in a season. The results from this study demonstrate a trend of increasing magnitude and frequency of head impacts with increasing level of play and these data may be used to inform helmet manufacturers, coaches, and youth football safety regulations to keep youth sports safe.

1. INTRODUCTION

The estimated number of sport-related concussions occurring each year in the United States is estimated to be between 1.6 to 3.8 million and football is among the sports with the highest injury rates [1-3]. Although the acute injury of concussion is a major concern, recent studies suggest that repetitive subconcussive head impacts, or those impacts which do not result in clinical signs and symptoms of a concussion, may be of increasing concern [4-6]. Recent case reports of chronic traumatic encephalopathy (CTE) and associated memory loss, dementia, and depression in former professional athletes participating in collision sports have brought attention to possible long-term consequences of head impacts in sports, both concussive and subconcussive [7-11]. Additionally, several studies utilizing medical imaging have found measureable changes in white matter integrity measured from diffusion tensor imaging over the course of a single season which correlates with the amount of head impact exposure, even in the absence of a clinically diagnosed concussion [6, 12-15]. Recent efforts are being made to evaluate the relationship between an athlete's lifetime exposure to repetitive head impacts and neurocognitive decline later in life, but more data are needed to better describe head impact exposure, particularly exposure to subconcussive impacts, within the youth level [8, 16, 17].

With the advent of head-impact sensing devices, researchers are able to collect on-field head impact data in real time by instrumenting athletes with helmet mounted accelerometer arrays. On-field head impact data has been collected from collegiate football players and to a lesser extent from high school players, to better understand head impact exposure [18-22]. With youth football athletes making up the largest proportion of football athletes in the United States with 3.5 million participants, more research is needed to characterize head impact exposure in the youth population [22, 23]. Daniel et al. was the first to characterize head impact exposure in youth football athletes, ages 7-8, and these athletes experienced an average of 107 impacts in a season with a 95th percentile linear acceleration of 40g and impacts greater than 80g were only seen in practices, not competitions [24]. This study was followed by Cobb et al. who evaluated head impact exposure in youth football athletes, ages 9-12, participating in three different teams. Cobb et al. reported an average of 240 impacts measured in a season with a 95th percentile linear acceleration of 43g [23]. Additionally, one of the three teams studied by Cobb et al. experienced 37-46% fewer impacts than the other two teams and the decrease in head impacts was reported as being attributed to rules implemented by that team to reduce contact in practice [23]. The results from the studies from Daniel et al. and Cobb et al. have shown that head impact exposure may increase at each level of play and that coaching style, league rules and regulations, and other potential variables may play a role in the head impact exposure measured in youth athletes. A small number of other studies have also evaluated head impact exposure at the youth level, but due to the limited size and duration of these studies there is a need to generate larger population-based studies of youth athletes spanning a larger age range over multiple years [25, 26].

Youth football leagues accommodate athletes ranging in age from 5 to 15 years old and due to the large variations in weight, growth, and development that occurs during this time, teams are often formed based on age and/or weight requirements [27, 28]. A better understanding of head impact exposure in sequentially increasing age and weight classified youth teams can provide insight into how head impact exposure changes as youth athletes move up the levels of play. The purpose of this study is to quantify head impact exposure of youth football athletes (9-13 years old) participating in three age and weight based levels of play within a single youth football organization for all practices and competitions over multiple seasons.

2. METHODS

This study collected on-field head impact data from athletes participating in a local youth football league over four years (2012-2015). The study protocol was approved by the Wake Forest School of Medicine Institutional Review Board and participant assent and parental written consent were properly acquired for participation in the study. Teams, or levels of play, are formed in this league based on age and weight requirements as shown in Table 1 and will be referred to as levels A, B, and C from here forward.

Table 1: Age and weight requirements for each level of play included in the study.

Level	Age Requirements	2012-2014 Season Max Weight* (lbs.)	2015 Season Max Weight* (lbs.)
A	10 and under 11 Older/Lighter	119 99	124 104
B	11 and under 12 Older/Lighter	134 114	139 119
C	12 and under 13 Older/Lighter	149 129	159 139

* Five pounds are allowed at pre-competition weigh-in for all equipment.

Head impact data were collected for all preseason, regular season, and play off practices and competitions by instrumenting the helmets of youth football players with the Head Impact Telemetry (HIT) System head acceleration measurement device. Video was recorded for all practices and competitions in order to verify head impacts measured by the HIT System and remove false impacts (e.g. dropped helmet) from the data set. Each participant in the study was given a Riddell Revolution Speed helmet with the HIT

System installed. The HIT System measures location and magnitude of head impacts with an encoder, which is an array of six spring-mounted single-axis accelerometers oriented normal to the surface of the head, a telemetry unit, data storage device, and battery pack. The encoder is designed to fit between the existing padding of the helmet. The spring-mounted accelerometers allow the encoder to remain in contact with the head throughout the duration of a head impact, ensuring measurement of head acceleration, not helmet acceleration [29]. In addition to the encoder, the HIT System includes a sideline base unit with a laptop computer connected to a radio receiver. Each time an instrumented helmet receives an impact greater than 10g, data acquisition is initiated and a total of 40 ms of data with 8 ms of pre-trigger data is recorded at 1000 Hz. The data from the encoder are transmitted wirelessly via radio wave transmission to the sideline base unit. The data are then used to compute peak resultant linear acceleration, estimated peak resultant rotational acceleration, location of impact, and other biomechanical indicators. All rotational acceleration data were processed as per Rowson et al [30]. The HIT System has been described in previous literature and has been found to reliably compute linear acceleration, peak rotational acceleration, and impact location [29, 31, 32].

Head impact exposure was quantified for all verified head impacts in terms of impact frequency, head acceleration, and head impact location. Total number of impacts in a season of play as well as number of impacts in each session (practice or competition) was computed. Head acceleration was described in terms of 50th, mean, and 95th percentile linear and rotational acceleration. Four general locations were used to describe impact locations on the helmet: front, top, back, and side [33].

Head impact data was evaluated between, and within, the three distinct levels of play and were evaluated on a season-basis as well as between competitions and practices. Mixed effects linear models were fitted to the data and Wald tests were used to assess differences among athletes, levels of play, and session type in the number of impacts and the associated linear and rotational accelerations. An overall alpha value of 0.05 was used for all statistical tests. All statistical analysis was performed using SAS software version 9.4 for Windows (SAS Institute Inc., Cary, NC, USA).

3. RESULTS

Head impact data were recorded from a total of 119 individual athlete seasons over four years with a total of 39, 48, and 32 athletes participating in levels of play A, B, and C, respectively. Head impact data were recorded for levels A and B for all four seasons. Head impact data was recorded for level C during three out of the four seasons. A total of 40,538 head impacts were recorded across all levels with level A, B, and C accounting for 12,890, 15,987, and 11,661 impacts, respectively. Head impact data are presented as single season summaries. The number of head impacts measured for a single athlete in a single season of play ranged from 26 to 1003 (Figure 1A). For all three levels, the peak resultant linear acceleration measured ranged from 10g to 179.8g. The distribution for linear acceleration was right skewed with a median of 20.8g, mean of 25.0g, and a 95th percentile of 52.4g. The range of peak resultant rotational acceleration was from 1.7 rad/s2 to 8,571.4 rad/s2 with a median of 975g rad/s2, a mean of 1,120.7 rad/s2, and a 95th percentile of 2,427 rad/s2.

Head impact exposure was evaluated by level of play and by session activity (Table 2). For level A, the mean [95% confidence interval] number of impacts per athlete measured in a single season was 331 [272, 389] and the 95th percentile was 568. For level B, the mean number of impacts was 333 [280, 386] and the 95th percentile was 675. For level C, the mean number of impacts was 364 [299, 429] and the 95th percentile was 763. There was a general trend of increasing total number of head impacts per athlete measured in a single season with increasing level of play, but there were a number of athletes that experienced the same or higher total number of head impacts over the course of the season than athletes at higher levels of play, as shown in Figure 1B. There was no statistical difference in the mean number of total impacts in a season between levels.

There is a trend of increasing impact magnitude with increasing level of play (Figure 2). Level A had a median and 95th percentile linear acceleration of 19.8g and 49.4g, respectively, and median and 95th percentile rotational acceleration of 957.7 rad/s2 and 2323.2 rad/s2, respectively. Level B's distribution fell in between Level A and Level C, with median and 95th percentile linear acceleration values of 20.6g and 51g, respectively, and median and 95th percentile rotational acceleration values of 979.7 rad/s2 and 2415.7 rad/s2, respectively. Level C had a median and 95th percentile linear acceleration of 22g and 57.9g, respectively, and median and 95th percentile rotational acceleration of 991.5 rad/s2 and 2544.1 rad/s2, respectively.

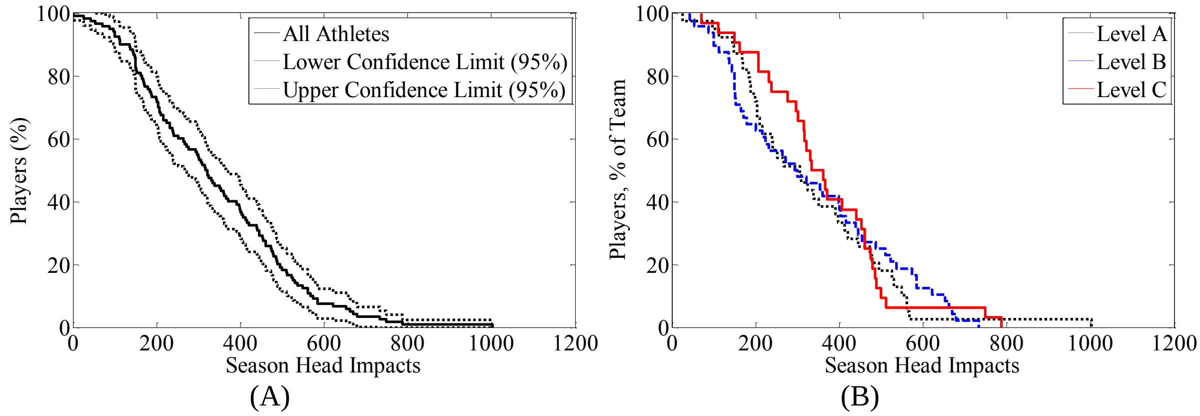
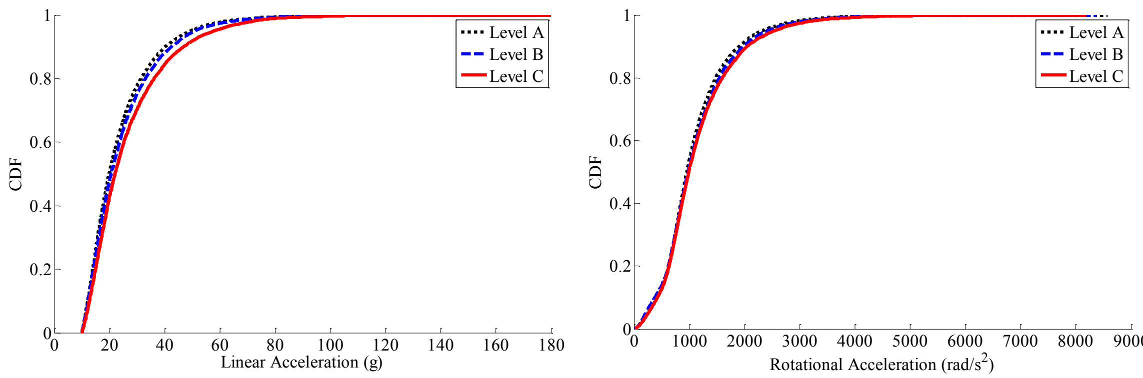


Figure 1: Distribution of the number of head impacts experienced in a season of play plotted as a cumulative histogram for (A) all athletes included in the study and for (B) all athletes by level of play.

Table 2: Summary of head impact magnitude and frequency for practice impacts, competition impacts, and all impacts for each level of play. Means are shown with [95% confidence intervals].

			LEVEL A	LEVEL B	LEVEL C
Practice	Number of Sessions in a Season (average ± standard deviation)		29.8 ± 5.3	30.3 ± 5.7	32.7 ± 3.1
	Mean Number of Impacts Per Player		10.2 [9.6, 10.8]	11.6 [11.1,12.1]	10.4 [9.8, 11.0]
	Linear Acceleration (g)	50th Percentile	19.6	20.6	21.5
		Mean	23.8 [23.0, 24.6]	24.2 [23.5, 24.9]	24.9 [24.0, 25.7]
		95th Percentile	48.9	50	55
	Rotational Acceleration (rad/s^2)	50th Percentile	951	973.5	970.9
		Mean	1093.5 [1050.9, 1136.1]	1092.5 [1055.4, 1129.6]	1069.1 [1023.25 1114.8]
		95th Percentile	2,305.20	2,351.90	2,393.10
Competition	Number of Sessions in a Season (average ± standard deviation)		10.0 ± 1.2	9.0 ± 0.0	10.3 ±1.2
	Mean Number of Impacts Per Player		12.0 [10.5,13.4]	13.4 [12.0, 14.7]	14.6 [12.9,16.2]
	Linear Acceleration (g)	50th Percentile	20.5	20.8	23.2
		Mean	24.0 [23.0, 25.0]	24.3 [23.4, 25.2]	27.4 [26.3, 28.4]
		95th Percentile	50.9	53.3	62.8
	Rotational Acceleration (rad/s^2)	50th Percentile	975.2	996.3	1052.4
		Mean	1108.8 [1055.2,1162.3]	1118.8 [1071.0, 1166.7]	1210.4 [1153.0, 1267.8]
		95th Percentile	2386.7	2600.5	2856.9
Season	Number of Sessions in a Season (average ± standard deviation)		39.8 ± 6.2	39.3 ± 5.7	43.0 ± 2.0
	Mean Number of Impacts Per Player		11.0 [10.4, 11.6]	11.8 [11.3, 12.3]	11.5 [10.9, 12.1]
	Linear Acceleration (g)	50th Percentile	19.8	20.6	22
		Mean	23.9 [23.1, 24.7]	24.3 [23.6, 24.9]	25.6 [24.8, 26.4]
		95th Percentile	49.4	51	57.9
	Rotational Acceleration (rad/s^2)	50th Percentile	957.7	979.7	991.5
		Mean	1099.0 [1057.1, 1141.0]	1105.1 [1068.3, 1141.9]	1114.6 [1069.3, 1159.8]
		95th Percentile	2323.2	2415.7	2544.2



(A) (B)

Figure 2: Cumulative distribution plots of (A) linear acceleration and (B) rotational acceleration for impacts collected over all seasons for each level of play.

Individual athlete and level of play averages of head impact magnitude and number of impacts for practice, competition, and all sessions are shown in Figure 3. Although general trends of increasing impact magnitude and frequency were seen with increasing level of play, there was also significant variability in impact magnitude and frequency between athletes ($p<0.0001$), both on the same and on different levels of play. Evaluating all impacts in a season of play, level C had significantly greater mean linear acceleration than both level A ($p=0.0048$) and level B ($p=0.0164$) while accounting for year of play in the mixed effects linear model, which captures variability in exposure from year to year. When the effect of year of play is removed from the model the significance between level C and levels A ($p<0.0001$) and B ($p<0.0001$) increased. There was no significant difference in mean rotational acceleration between the three levels. However, if year of play is removed from the model, level C has significantly greater mean rotational acceleration than level A ($p=0.0123$). There were no significant differences in linear or rotational acceleration magnitudes between levels A and B.

Head impact exposure was also evaluated by session type, both between levels and within levels of play (Table 2). There was a general trend of the distribution of linear and rotational accelerations increasing with level of play in practices with levels A, B, and C experiencing /95th percentile linear (and rotational) accelerations of 48.9g (2,305.2 rad/s2), 50.0g (2,351.9 rad/s2), and 55.0g (2,393.1 rad/s2), respectively. There was also a similar trend in distributions of linear and rotational accelerations in competitions with levels A, B, and C experiencing 95th percentile linear (and rotational) accelerations of 50.9g (2,386.7 rad/s2), 53.3g (2600.5 rad/s2), 62.8g (1052.4/2856.9 rad/s2), respectively. Within each age and weight level of play, the distributions of linear and rotational accelerations were of higher magnitudes in competitions than in practices.

Level C had significantly greater mean linear acceleration measured during competitions than levels A ($p<0.0001$) and B ($p<0.0001$). Additionally, level C had significantly greater mean rotational acceleration measured during competitions than levels A ($p<0.0167$) and B ($p<0.0196$). There were no significant differences in mean linear or rotational acceleration measured between levels during practices; however there was a trend of increasing mean linear acceleration with increasing level of play. When comparing mean linear and rotational acceleration measured during practices and competitions within each level, there was significantly greater mean linear accelerations in competitions compared to practices for both levels B ($p=0.0250$) and C ($p<0.0001$) and significantly greater mean rotational acceleration magnitudes in competitions compared to practices for both levels B ($p=0.0004$) and C ($p<0.0001$). There were no significant differences between acceleration measured during competitions and practices within level A, however there was a trend of higher magnitude impacts in competitions compared to practices.

The mean [95% confidence interval] number of impacts per player in a practice session for levels A, B, and C was 10.2 [9.6, 10.8], 11.6 [11.1, 12.1], and 10.4 [9.8, 11.0], respectively (Table 2). Level B had significantly greater mean number of impacts per player in practice than levels A (p=0.0019) and C (p=0.0059). The mean number of impacts per player in a competition session for level A, B, and C was 12.0 [10.5, 13.4], 13.4 [12.0, 14.7], and 14.6 [12.9, 16.2], respectively (Table 2). Level C had significantly greater mean number of impacts per player in competition than level A (p=0.0325). Within-level comparisons between mean number impacts per practice and per competition showed significantly greater impacts per player in competitions compared to practices for all levels (A, p=0.0005; B, p=0.0019; and C, p<0.0001).

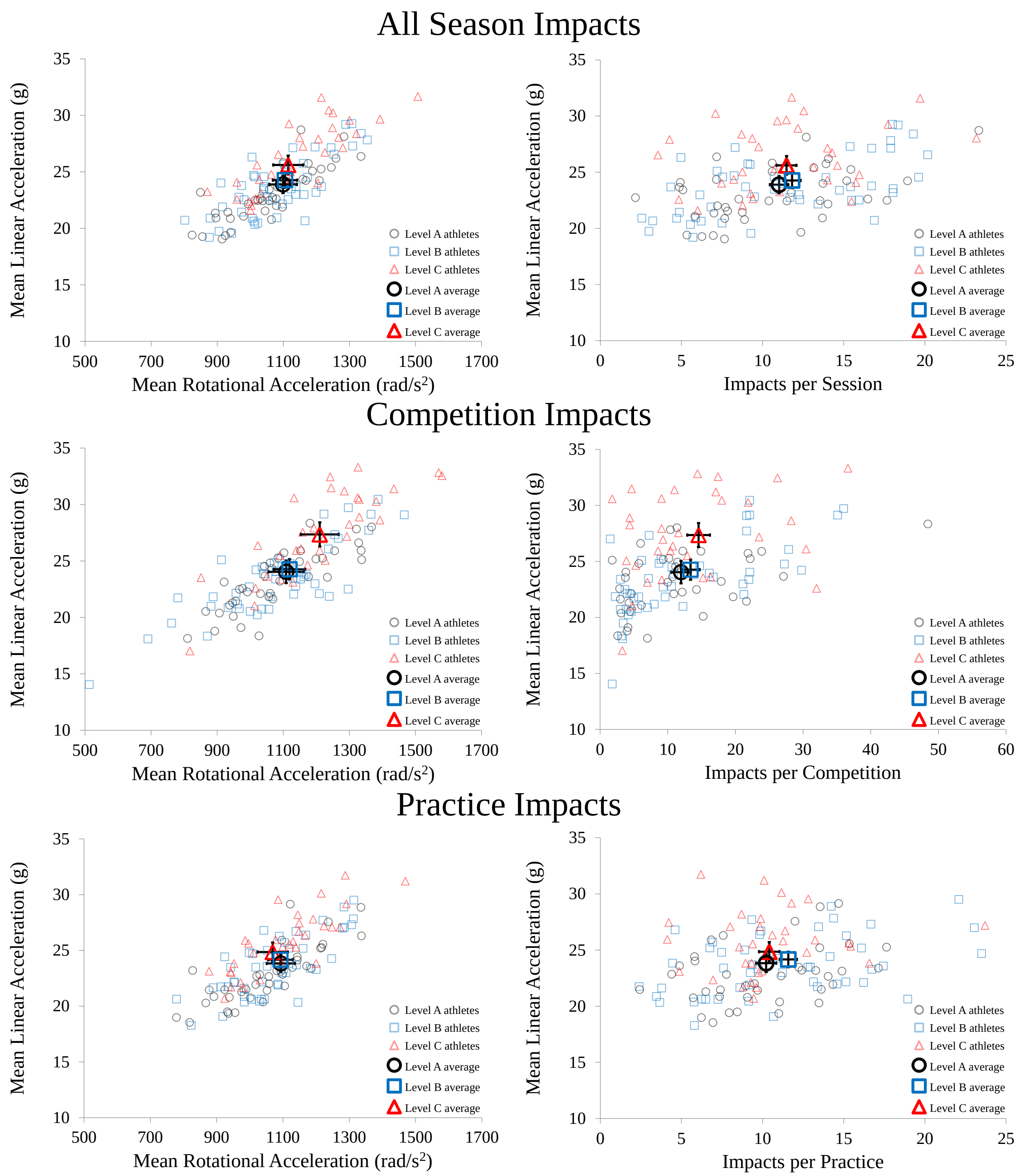


Figure 3: Mean linear acceleration vs. mean rotational acceleration and mean linear acceleration vs. mean number of impacts per session for all impacts, competition impacts, and practice impacts in a season of play. Individual athletes and level of play averages with 95% confidence interval error bars are displayed.

The distribution of high magnitude impacts differed between levels of play and between session types (Table 3). For all impacts recorded within levels A, B, and C only 31.7%, 28.7%, and 33.6% of impacts occurred in competitions, respectively. The highest percentage of high magnitude impacts (i.e. ≥60 g, ≥80 g, ≥100 g) for levels A and B occurred in practices. However, this trend was not evident for level C athletes with the highest percentage of high magnitude impacts occurring in competitions rather than practices. The percentage of impacts greater than or equal to 80 g and 100 g within level C were 54.9% and 61.1%, respectively.

Table 3: Percentage of impacts in practices or competitions for each level of play for all impacts, impacts greater than or equal to 60g, impacts greater than or equal to 80g, and impacts greater than or equal to 100g.

Level	All impacts		Impacts ≥ 60		Impacts ≥ 80		Impacts ≥ 100	
	Competition	Practice	Competition	Practice	Competition	Practice	Competition	Practice
A	31.71%	68.29%	32.99%	67.01%	29.11%	70.89%	26.32%	73.68%
B	28.71%	71.29%	35.41%	64.59%	35.64%	64.36%	38.24%	61.76%
C	33.62%	66.38%	46.35%	53.65%	54.92%	45.08%	61.11%	38.89%

The age, weight, and height information for the different levels of play is summarized in Table 4. Athletes were grouped into first and fourth age and weight quartiles and head impact exposure was compared between each level. Although statistically significant differences were not observed between the age or weight quartiles within each level, higher mean, 50th, and 95th percentile linear acceleration and total number of season impacts were seen in upper age quartiles for all levels of play Figure 4.

Table 4: Summary of age and weight of athletes participating in this study. *Complete age and weight information was collected for 105 athletes. **Height was collected for 69 athletes.

Level	Player Age (years)*			Player Weight (lbs.)*			Player Height (in.)**
	Mean ± StdDev	1st Quartile	4th Quartile	Mean ± StdDev	1st Quartile	4th Quartile	Mean ± StdDev
A	10.8 ± 0.7	9.7 – 10.3	11.5 – 11.9	97.5 ± 11.8	77.5 – 86.5	107.2 – 119.6	58.8 ± 2.4
B	11.9 ± 0.5	10.8 – 11.5	12.4 – 12.8	106.1 ± 13.8	72.8 – 96.5	114 – 137.6	60.0 ± 2.4
C	13.0 ± 0.5	12.0 – 12.6	13.5 – 13.9	126.5 ± 18.6	81.4 – 119.4	139.6 – 160.2	64.3 ± 2.8

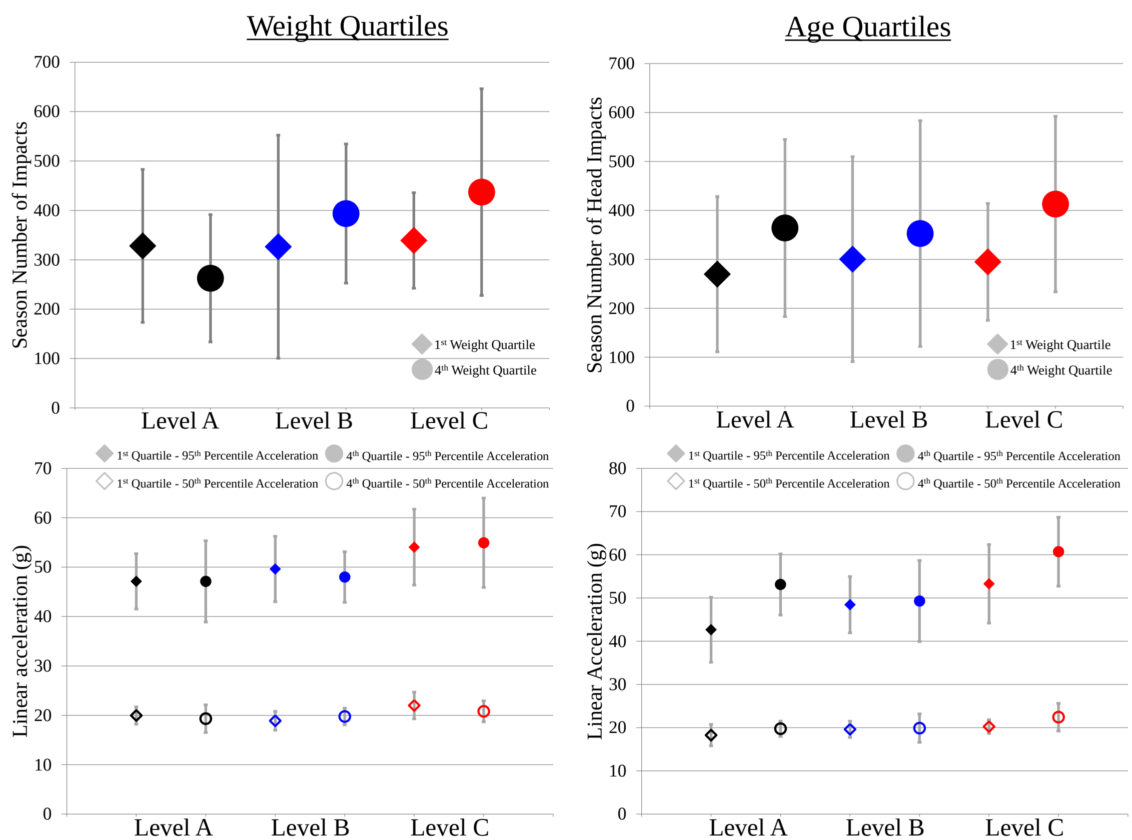


Figure 4: The average ± standard deviation (top) season number of impacts and (bottom) 50th and 95th percentile linear acceleration for the first and fourth quartile athletes based on (left) weight and (right) age quartiles for each level of play.

Lastly, we evaluated head impact exposure by impact location (Figure 5). The most common impact location for all three levels of play was the front of the helmet. The impact location with the highest peak linear acceleration for all three levels was the top of the helmet. The impact location with the lowest peak linear accelerations was to the side of the helmet. The impact location with the highest peak rotational acceleration was to the front of the helmet for levels A and B and the back of the helmet for level C.

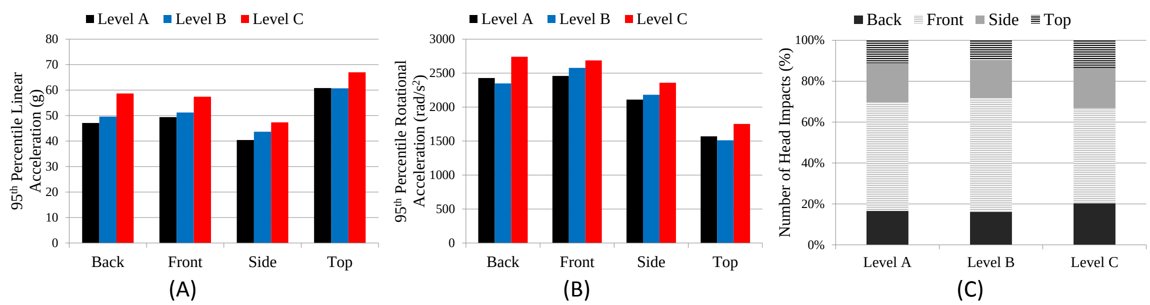


Figure 5: 95th percentile (A) linear and (B) rotational acceleration for each level by impact location on the helmet and (C) the percent number of head impacts occurring in the four different helmet locations for each level.

4. Discussion

This study reports the largest collection of biomechanical head impact data of youth football athletes to date. The collection of 40,538 head impacts from youth football athletes between the ages of 9-13 years old separated into sequentially increasing age and weight based levels of play provides insight into the overall head impact exposure of youth football athletes and how head impact exposure changes as they progress up the levels of play in youth football.

There was a general trend of increasing mean total number of head impacts measured in a season with increasing level of play; however the differences were not significant. This is partially due to individual athlete variability and the wide range in total number of head impacts individual athletes experienced in a season. Within level A 43.6% and 38.4% of athletes experienced more impacts in a season than the mean number of impacts experienced by athletes on levels B and C, respectively. Additionally, within level C 50.0% and 43.8% of athletes experienced fewer impacts than the mean number of impacts experienced by athletes on levels A and B, respectively. Many factors may have contributed to the large range in total number of head impacts measured between athletes including coaching styles, the types of practice drills, athlete intensity and involvement, and amount of time spent on contact in practice. Additionally, factors such as each team's success in playoffs could have increased the number of practices and competitions in a season and, consequently, the total number of head impacts. Even factors such as weather could have influenced the total number of head impacts if practices or competitions were cancelled.

Head acceleration data from this study showed a trend of increasing head accelerations with increasing level of play. Distributions of linear and rotational acceleration shifted towards higher magnitude head impacts with increasing level of play. Level C, which had the highest age and weight restrictions of all three levels of play, had significantly greater mean linear acceleration than both levels A and B. Although there were not significant differences of mean linear acceleration between levels A and B, there was a general trend of increasing head acceleration magnitude from level A, the youngest and lowest age and weight requirement, to level B. There were no significant differences in mean rotational acceleration magnitude between levels. However, there was still a general trend of increasing rotational acceleration magnitude with increasing level of play. For both mean linear and rotational acceleration, the level of significance between levels was attenuated when year of play was accounted for in the mixed linear model. The change in significance could be attributed to variability between years, which is expected given that coaching staff and athletes change from year to year.

Head impact exposure was also evaluated by session type. All three levels of play experienced higher magnitude impacts and higher number of impacts per session in competitions compared to practices, which was similar to findings of other studies of youth, high school, and college football athletes [22, 23, 34]. Evaluating only competition impacts, level C had significantly greater mean linear and rotational acceleration than levels A and B. However, when evaluating impacts collected in practice sessions, there were no significant differences in impact magnitude between any of the levels, but there was a general trend of increasing magnitude with increasing level of play. These data suggest that increased head impact magnitude with increasing levels of play was primarily driven by exposure to higher magnitude impacts during competitions, not practices. While evaluating impacts by session type within levels of play, levels B and C had significantly greater mean linear and rotational accelerations in competitions than in practices, and even though level A did not have significantly greater head accelerations in competitions, there was a general trend of higher magnitude impacts in competitions compared to practices. Additionally, the distribution of high magnitude impacts differed between session type and levels of play. The percentage of high magnitude impacts (i.e. ≥60 g, ≥80 g, ≥100g) occurring in competitions increased with increasing level of play; levels A, B, and C had 26.32%, 38.24%, and 61.11% of impacts of 100 g or greater, respectively, occur in competitions. However, within levels A and B, the highest percentage of impacts greater than 60 g, 80 g, and 100 g still occur in practices. These data suggest that more effort is needed to reduce exposure to high magnitude head impacts in practices, particularly at the lower levels of play, but with increasing level of play more effort may be needed to reduce high magnitude impacts in competitions.

The number of impacts per athlete increased with increasing level of play in competition sessions, but not in practice sessions. Level B, the mid-level of play evaluated in this study, had significantly greater number of impacts per player in a practice session than both levels A and C. Taking into account the fact that there were not significant differences in impact magnitude between levels within practice, these data further support that the differences seen in head impact exposure between levels of play were driven by head impact exposure during competitions rather than during practices. Additionally, the impact frequency per player in a competition session was significantly greater than the impact frequency per player in a practice session within each level. However, it is important to note that each level of play typically participated in 3 practices and 1 competition every week, so for 92% of athletes that participated in this study, practices contributed to greater than 50% of the total number of head impacts an athlete experiences in a season.

The athletes were placed on levels of play based on age and weight requirements (Table 1); however there was still a range in age and weights seen in each of the levels of play. This was partially due to the fact that the weight restrictions may result in younger athletes participating on teams with older athletes due to being on the higher end of their developmental weight percentile for their age [27]. There was also an older/lighter group within each level of play, which helped to accommodate kids that were in a low developmental weight percentile for their age [27, 28]. Comparing the number of impacts and impact magnitude between the bottom and top age and weight quartiles shows a trend of the upper age quartiles having a higher total number of head impacts and higher median and 95th percentile linear accelerations across all three levels of play. On the other hand, there was not a consistent trend of increasing number of impacts or impact magnitude with increasing weight quartile. These data may suggest age is a better predictor for increased head impact exposure rather than weight. Recently, Kerr et al. evaluated injury rates in age-only versus age and weight playing standard conditions in youth football. The results demonstrated that injury rates were similar in both age only and age and weight restricted teams, but there was a slightly larger proportion of no time loss injuries in the age and weight restricted teams and the concussion rate was lower in the age and weight restricted teams compared to the age-only teams [35]. Further research is needed to better determine if age, weight, or a combination of both have a greater influence on head impact exposure within youth football levels. This research could be important for deciding how youth football teams are formed and whether age and weight restrictions reduce injury risk.

The helmet location with the highest percentage of impacts was to the front of the helmet, which agrees with other study's findings for this age range [23]. However, the largest linear acceleration magnitude impacts were to the top of the helmet for all three levels and the largest rotational acceleration magnitudes were to the front of the helmet for levels A and B and to the back of the helmet for level C. Daniel et al. reported the 7-8 year old athletes in their study experienced higher rotational accelerations occurring in side impacts, whereas Cobb et al. reported the 9-12 year old athletes in their study experienced higher rotational accelerations occurring in frontal impacts [23, 24]. There are numerous factors that could contribute to the differences in impact locations between study populations, but could partially be due to coaching style and the tackling technique that is taught to the athletes. Additionally, the athletes in the study by Cobb et al. more closely matched the age of the athletes participating in this study, which may also contribute to more similar head impact characteristics seen between the two studies [23].

Comparing the youth football levels with published high school and collegiate data demonstrates a general trend of an increase in head impact magnitude with age and level of play. The 95th percentile linear acceleration for levels A, B, C, high school, and college were 49.4g, 51.0g, 57.9g, 57.6g, and 63g [22, 24]. On the other hand, median linear and rotational accelerations remain relatively constant between the different levels of play [22, 24]. Comparing number of impacts experienced in a season of play with high school and college athletes is difficult given the wide ranges reported in the literature [19, 20, 22, 36-39]. However, there appears to be a general trend of increasing number of head impacts in a season of play with increasing level of play [22, 39]. Variables such as length of a season, number of practices and games in a season, types of practice drills as well as many other factors can affect the number of impacts an athlete experiences in a season of play.

A few limitations should be noted about this study. First, the results are limited to 9-13 year old athletes and youth football leagues include athletes from 5-15 years old. Second, the results of this study are a limited representation of the youth football population as a whole as it is focused to a single youth football organization. Head impact exposure in additional organizations may have some variation in head impact exposure based on league-specific or organization-specific regulations for practices and competitions. This work may be expanded upon to include a multi-site study of leagues within various national organizations (i.e., Pop Warner) and demographic/cultural backgrounds. Third, the HIT system used for biomechanical data collection has some measurement error, but the error in 5DOF acceleration measurements are within the range of acceptable error for other measurement devices and methods [31].

5. Conclusion

The head impact exposure data from three sequentially increasing age and weight based levels of play over the course of four seasons demonstrates a trend of increasing magnitude and frequency of head impacts with level of play. However, there was individual variability observed among athletes, with some athletes experiencing higher magnitude and higher frequency of head impacts than athletes on higher age and weight based levels. Across all levels of play, the distribution of head impacts in competitions was of higher magnitudes than head impacts in practices, but athletes generally accumulate more impacts during practices than in competitions over the course of a season. The resulting repository of head impact data from youth football athletes will provide a better understanding of head impact exposure and may be used to inform helmet manufacturers, youth football safety regulations, and, ultimately, keep youth athletes safe.

6. Acknowledgment

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Chapter IV: Summary of Research

The research presented in this thesis has generated important contributions to the field of sport injury biomechanics, particularly in the field of concussion and brain injury research. Through the analysis of use of head impact exposure data in youth football athletes, the following aims have been completed in this thesis:

1) Head impact exposure was quantified and compared among youth football drills practiced by a single team.
2) Head impact exposure was quantified and compared among three age and weight based levels of play within a youth football league.
3) Head impact exposure was quantified and compared between practices and competitions from three age and weight based levels of play.

Characterization of subconcussive head impact exposure is vital to understanding the biomechanical basis of repetitive head trauma and when studying clinical outcomes associated with cognitive deficits and changes in the brain. A better understanding of on-field head impact exposure at the youth level can inform teams and organizations on ways to structure their practices and games to reduce head impact exposure and, ultimately, keep youth athletes safe. Research presented in Chapter II and Chapter III is expected to be published in scientific journals listed in Table 7.

Table 7: Publication plan for research outlined in this thesis.

Chapter	Topic	Journal
II	Practice Drill Head Impact Exposure Measured from a Single Youth Football Team	Medicine and Science in Sports and Exercise*
III	Head Impact Exposure in Youth Football: Comparison among Age and Weight Based Levels of Play	American Journal of Sports Medicine†

*Submitted
†Manuscript in Preparation

Scholastic Vita

Education

Virginia Tech – Wake Forest University School of Biomedical Engineering and Sciences, Winston-Salem, NC 2014 - Present

- Ph.D. Biomedical Engineering (expected May 2019)
- M.S. Biomedical Engineering (expected June 2016)
- Research Advisor: Dr. Joel Stitzel

University of Connecticut, Storrs, Connecticut 2010 - 2014

- B.S. Biomedical Engineering
- Dean's List | Cum Laude

Teaching & Tutoring Experience

BME Department, University of Connecticut, Storrs, CT September 2013 – May 2014

TA – Biomechanics & Biomaterials Lab

- Set-up lab equipment (i.e. Tinius-Olson testing machine and AMTI force platforms)
- Assisted in the instruction of junior and senior level biomaterial and biomechanics lab session

Research & Professional Experience

Center for Injury Biomechanics, Winston-Salem, NC August 2014 - Present

- Study head impact exposure in a youth football league using a head impact telemetry device. Mentor undergraduate students assisting with data collection in the study.
- Developed smoothing algorithm to improve mechanical response in finite element model of the brain.
- Study injury mechanisms in real-world motor vehicle accidents by developing crash simulations using the Total Human Model for Safety (THUMS).
- CIREN research engineer: Using biomechanics knowledge, investigate causation of serious injuries resulting from real-world motor vehicle crashes.
- Study eye injury resulting from primary blast by developing validated eye model in LS-Dyna.

Simbex, LLC. Lebanon, NH Summer 2013

- Write test plans and reports, test prototypes, design installation tool and guide for military Advanced Combat Helmet.
- Contributed to active development of InSite football head impact monitoring system and a prototype military blunt/blast head impact monitor.
- Instrumented air cannon for quantifying effect of visual disruption on human reaction time to incoming projectiles.

Musculoskeletal Modeling Lab, Storrs, CT January 2013 – May 2014

- Research knife handle design for arthritic people using a force plate and electromyography.
- Member of a BME senior design team that developed a novel device, associated computer programs, and a method to quantify the error in force platforms used in gait and balance analysis.

LPA Design, Inc. S. Burlington, VT Summer 2011

- Perform electrical & mechanical functional testing of wireless control system sub-assemblies & assemble products in fast-paced production environment.

Awards

- New England Scholar, University of Connecticut — March 2013
- Office of Undergraduate Research Student Travel Award, University of Connecticut — April 2014
- Cum Laude , University of Connecticut — May 2014
- Program Chair's Award, 52nd Annual Rocky Mountain Bioengineering Symposium — April 2015

Activities

- National Honor Fraternity Phi Sigma Pi — January 2012 – Present
  - CFO: chapter budget and cash management
- Biomedical Engineering Society — October 2011 – Present
- IEEE Engineering in Medicine and Biology Society — October 2015 – Present
  - Wake Forest University Chapter Secretary

Publications

- **Kelley ME,** Miller LE, Urban JE, Stitzel JD. "Mesh Smoothing Algorithm Applied to a Finite Element Model of the Brain for Improved Brain-Skull Interface." Biomedical Sciences Instrumentation. April 2015.
- Jones DA, Gaewsky JP, **Kelley ME**, Weaver AA, Miller AN, Stitzel JD. "Lumbar Vertebrae Fracture Injury Risk in Finite Element Reconstruction of CIREN and NASS Frontal Motor Vehicle Crashes." Traffic Injury Prevention. 2016.

Podium Presentations

- **Kelley ME**, Miller LE, Urban JE, Stitzel JD. "Mesh Smoothing Algorithm Applied to a Finite Element Model of the Brain for Improved Brain-Skull Interface." Rocky Mountain Bioengineering Symposium, Inc. Salt Lake City, UT. April 2015.
- **Kelley ME**, Urban JE, Jones DA, Miller LE, Maldjian JA, Whitlow CT, Powers AK, Stitzel JD. "Head Impact Exposure in Youth Football Over Three Seasons." 12th Annual North American Brain Injury Society Conference on Brain Injury. San Antonio, TX. April-May 2015.
- **Kelley ME**, Urban JE, Jones DA, Miller LE, Stitzel JD. "Head Impact Exposure of Youth Athletes over Multiple Seasons." 2015 BMES Annual Meeting. Tampa, FL. October 7-10, 2015.
- **Kelley ME**, Gaewsky JP, Jones DA, Miller LE, Koya B, Weaver AA, Stitzel JD. "Development and Optimization of Simplified Finite Element Reconstructions of Frontal Motor Vehicle Crashes." 43rd International Workshop on Human Subjects for Biomechanical Research. New Orleans, LA. November 8, 2015.
- Urban JE, **Kelley ME**, Davenport EM, Maldjian JA, Whitlow CT, Stitzel JD. "Cumulative Head Impact Exposure in Youth Football Players." Keystone Symposium on Traumatic Brain Injury: Clinical, Pathological, and Translational Mechanisms of TBI, Santa Fe, NM, January 2016.
- Stitzel JD, Urban JE, Miller LE, **Kelley ME**, Jones DA, Davenport EM, Whitlow CT, Powers AK, Maldjian JA. "Subconcussive Impact Exposure and Computational Modeling of the Brain Using an Atlas-Based Biomechanical Finite Element Model." International Brain Injury Association, March 2016.
- **Kelley ME**, Kane JM, Espeland MA, Miller LE, Stitzel JD, Urban JE. "Head Impact Exposure in Youth Football Practice Drills." 2016 SBES Symposium. Winston-Salem, NC. May 2016.
- Jones DA, Gaewsky JP, **Kelley ME**, Weaver AA, Stitzel JD. "Lumbar Vertebrae Fracture Injury Risk In Reconstruction Of Ciren And Nass Frontal Motor Vehicle Crashes." 2016 SBES Symposium. Winston-Salem, NC. May 2016.

Poster Presentations

- **Kelley ME**, Kaplan J, Williams J. "Quantifying Error in Force Platforms." Northeast Bioengineering Conference: Undergraduate Research Design Competition. Northeastern University, Boston, MA. April, 2014.
- **Kelley ME**, Kaplan J, Williams J. "Quantifying Error in Force Platforms." Senior Design Demonstration Day. University of Connecticut. Storrs, CT. May 2014.
- **Kelley ME**, Miller LE, Urban JE, Stitzel JD. "Improving Brain-Skull Interface through application of Mesh Smoothing Algorithm." 2015 SBES Symposium. Blacksburg, VA. May 13, 2015
- **Kelley ME**, Miller LE, Urban JE, Stitzel JD. "Improving Brain-Skull Interface through application of Mesh Smoothing Algorithm." 2015 Summer Biomechanics, Bioengineering, and Biotransport Conference. Salt Lake City, UT. June 17-20, 2015.
- Miller LE, Urban JE, **Kelley ME**, Stitzel JD. "Evaluation Of Directional Dependence Of Brain Response In Youth Athletes Using An Anatomically Accurate Finite Element Model." 2016 SBES Symposium. Winston-Salem, NC. May 2016.