Head Impact Exposure in Youth Football: Comparing Age- and Weight-Based Levels of Play

Mireille E. Kelley,^{1,2} Jillian E. Urban,^{1,2} Logan E. Miller,^{1,2} Derek A. Jones,^{1,2} Mark A. Espeland,³
Elizabeth M. Davenport,⁴ Christopher T. Whitlow,^{2,5,6} Joseph A. Maldjian,⁴ and Joel D. Stitzel^{1,2}

Abstract

Approximately 5,000,000 athletes play organized football in the United States, and youth athletes constitute the largest proportion with ~3,500,000 participants. Investigations of head impact exposure (HIE) in youth football have been limited in size and duration. The objective of this study was to evaluate HIE of athletes participating in three age- and weight-based levels of play within a single youth football organization over four seasons. Head impact data were collected using the Head Impact Telemetry (HIT) System. Mixed effects linear models were fitted, and Wald tests were used to assess differences in head accelerations and number of impacts among levels and session type (competitions vs. practices). The three levels studied were levels A ($n=39$, age = 10.8 ± 0.7 years, weight = 97.5 ± 11.8 lb), B ($n=48$, age = 11.9 ± 0.5 years, weight = 106.1 ± 13.8 lb), and C ($n=32$, age = 13.0 ± 0.5 years, weight = 126.5 ± 18.6 lb). A total of 40,538 head impacts were measured. 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 levels A ($p=0.005$) and B ($p=0.02$). There were a significantly greater number of impacts per player in a competition than in a practice session for all levels (A, $p=0.0005$, B, $p=0.0019$, and C, $p<0.0001$). Athletes at lower levels experienced a greater percentage of their high magnitude impacts (≥ 80 g) in practice, whereas those at the highest level experienced a greater percentage of their high magnitude impacts in competition. These data improve our understanding of HIE within youth football and are an important step in making evidence-based decisions to reduce HIE.

Keywords: biomechanics; football; impact frequency; impact magnitude; mild traumatic brain injury; pediatric

Introduction

THE NUMBER OF SPORT-RELATED CONCUSSIONS among the youth population, ≤ 18 years of age, occurring each year in the United States is estimated to be between 1,100,000 and 1,900,000, and football is among the sports with the highest injury rates.^{1–5} Additionally, Dompier and colleagues reported that concussions comprised 9.6% of all youth football injuries in the Youth Football Safety Study.⁶ Although concussion can be a significant injury, the majority of the head impacts that result from regular participation in football are termed “subconcussive impacts.” Repetitive subconcussive impacts do not result in clinical signs and symptoms of a concussion; however, recent studies suggest that these head impacts are of increasing concern.^{7–9} 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.^{10–14} Additionally, several studies utilizing medical imaging have found changes in white matter integrity measured from diffusion tensor imaging over the course of a single season that correlate with the amount of head impact exposure (HIE), even in the absence of a clinically diagnosed concussion.^{9,15–18} However, the nature of the relationship between HIE and white matter changes as well as the long-term implications of these changes are not yet fully understood.^{16,19} 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; however, more data are needed to better describe HIE, particularly for subconcussive impacts, within the youth level.^{11,20,21}

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 have been collected from collegiate football players, and to a lesser extent from high school players, to better understand HIE.^{22–26} With youth football athletes making up

Departments of ¹Biomedical Engineering, ³Biostatistical Sciences, and ⁵Radiology (Neuroradiology), and ⁶Clinical and Translational Sciences Institute, Wake Forest School of Medicine, Winston-Salem, North Carolina.

²Virginia Tech – Wake Forest School of Biomedical Engineering and Sciences, Winston-Salem, North Carolina.

⁴Department of Radiology, University of Texas Southwestern, Dallas, Texas.

the largest proportion of football athletes in the United States, with ~3,500,000 participants, more research is needed to characterize HIE in the youth population.^{26,27} Daniel and colleagues were the first to report HIE data of 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.²⁸ Impacts >80g were only seen in practices, not competitions.²⁸ This study was followed by Cobb and colleagues who evaluated HIE in youth football athletes, ages 9–12, participating in three different teams. Cobb and colleagues reported an average of 240 impacts measured in a season with a 95th percentile linear acceleration of 43g.²⁷ Additionally, one of the three teams studied by Cobb and colleagues experienced 37–46% fewer impacts than the other two teams, and the decrease in head impacts was partially attributed to rules implemented to reduce contact in practice.²⁷ The results from Daniel and colleagues and Cobb and colleagues have shown that HIE may increase at each level of play and that coaching style, league rules and regulations, and other factors may play a role in the HIE measured in youth athletes. A small number of other studies have also evaluated HIE at the youth level, but because of the limited size and duration of these studies, there is a need for larger population-based studies of youth athletes spanning a larger age range over multiple years.^{29,30}

Youth football leagues accommodate athletes typically ranging in age from 5 to 15 years, and because of the large variation in weight, growth, and development occurring during this time, teams are often formed based on age and/or weight requirements.³¹ Investigating HIE in sequentially increasing age- and weight-classified youth teams can provide insight into how HIE changes as youth athletes advance through the levels of play in football. The purpose of this study is to quantify HIE 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 four seasons.

Methods

This study collected on-field head impact data from athletes participating in a local youth football organization over 4 years (2012–2015). The study protocol was approved by the Wake Forest School of Medicine Institutional Review Board and participant assent and parental consent were acquired for participation in the study. Youth football players participating in a local youth football organization were prospectively recruited and enrolled in this study. The study staff worked with the organization's executive board and coaches to arrange informational meetings for the parents and players so that study representatives could describe the study and provide informed consent and assent. Study representatives also attended several existing events held by the organization including summer conditioning, sign-up nights, and equipment distribution day. Those not present during the organized events were sought out individually. Informed parental consent and subject assent was obtained from each subject by members of the study staff. Participation in the study was voluntary. Athletes also had to properly fit into a Riddell Speed Youth medium size or larger helmet to be included in the study. Levels of play are mandated by the national governing organization's age and weight requirements as shown in Table 1. The three levels included in this study will be referred to as levels A, B, and C. One team was studied at each level for each year data were collected for that level, and all 4 years of data collection were completed at the same organization.

Head impact data were collected for all pre-season, regular season, and playoff practices and competitions by instrumenting players' helmets with the Head Impact Telemetry (HIT) System head acceleration measurement device. All helmeted practices were included in the session type practice; this included both

TABLE 1. AGE AND WEIGHT REQUIREMENTS FOR EACH LEVEL OF PLAY INCLUDED IN THE STUDY

Level	Age requirements (years)	2012–2014 season Max weight ^a (lbs)	2015 Season Max weight ^a (lbs)
A	10 and under	119	124
	11	99	104
B	11 and under	134	139
	12	114	119
C	12 and under	149	159
	13	129	139

^aFive pounds are allowed at pre-competition weigh-in for all equipment.

helmet-only and padded practices. Video was recorded for all practices and competitions to verify the times that the athletes were helmeted. Impacts occurring while the players were not wearing helmets were removed from the data set. Each participant in the study was properly fitted with a Riddell Youth 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.³² In addition to the encoder, the HIT System includes a sideline base unit with a laptop computer connected to a radio receiver. Each time one of the six accelerometers in an instrumented helmet records 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. Impacts were collected using the standard HIT System processing with a peak resultant linear acceleration threshold of 10g. Data from the encoder are transmitted wirelessly 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 peak resultant rotational acceleration data were scaled by a factor of 0.648, as per Rowson and colleagues.³³ The HIT System has been described in previous literature, and has been found to reliably measure head impact exposure.^{32,34,35}

HIE was quantified in terms of impact frequency, peak head acceleration, and head impact location. Total number of impacts in a season of play as well as in each session (practice or competition) were computed. Head acceleration was described in terms of mean, 50th percentile, and 95th percentile linear and rotational acceleration. Four general locations were used to describe impact locations on the helmet: front, top, back, and side.³⁶ Inference was based on mixed effects linear models and Wald tests to assess differences in the number of impacts and linear and rotational accelerations among levels of play, session types, and year of data collection while controlling for repeated measures across seasons. The models were adjusted for confounding factors including level, impact date, and year of data collection. Because the aims were primarily descriptive, type 1 error was set at 0.05 for each inference. Statistical analysis was performed using SAS version 9.4 (SAS Institute Inc., Cary, NC).

Results

Head impact data were recorded from 97 athletes over 4 years. Sixteen of the athletes participated for more than one season, totalling 119 athlete-seasons among the three levels (level A: $n = 39$,

TABLE 2. SUMMARY OF AGE AND WEIGHT (MEAN $\pm$ STANDARD DEVIATION) OF ATHLETES PARTICIPATING IN THIS STUDY

Level	n	Player age (years) ^a	Player weight (lb) ^a	Player height (in) ^b
A	39	10.8 $\pm$ 0.7	97.5 $\pm$ 11.8	58.8 $\pm$ 2.4
B	48	11.9 $\pm$ 0.5	106.1 $\pm$ 13.8	60.0 $\pm$ 2.4
C	32	13.0 $\pm$ 0.5	126.5 $\pm$ 18.6	64.3 $\pm$ 2.8

^aComplete age and weight information was collected for 105 athletes.

^bHeight was collected for 69 athletes.

level B: $n=48$, and level C: $n=32$). The age, weight, and height aggregate data for athletes on the three levels of play are summarized in Table 2. Analysis of variance (ANOVA) showed significant differences in age ($p<0.0001$), weight ($p<0.0001$), and height ($p<0.0001$) among the three levels. Head impact data were recorded for levels A and B for all four seasons. Head impact data were recorded for level C during three of the four seasons. A total of 40,538 head impacts were measured with levels 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 participating in a full single season of play ranged from 26 to 1003 (Fig. 1A). For all three levels, peak resultant linear acceleration ranged from 10.0g 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/sec² to 8571.4 rad/sec² with a median of 975.0g rad/sec², a mean of 1120.7 rad/sec², and a 95th percentile of 2427.0 rad/sec². There were statistically significant differences in mean linear and rotational acceleration among the 4 years of data collection ($p<0.0001$ and $p<0.0001$, respectively).

The season number of head impacts was compared among levels. For level A, the mean (95% confidence interval) number of impacts per athlete measured in a single season was 331 (272, 389). For level B, the mean number of impacts was 333 (280, 386). For level C, the mean number of impacts was 364 (299, 429). There was no statistically significant difference in the mean number of total impacts in a season among levels. Generally, the mean, median, and 95th percentile total number of head impacts per athlete measured in a single season increased with increasing level of play; however, there were a number of athletes who experienced the same as or higher than the

total number of head impacts over the course of the season compared with athletes at higher levels of play, as shown in Figure 1B.

There is a trend of increasing impact magnitude with increasing level of play. For level A, the distribution of head accelerations had the lowest median, mean, and 95th percentile head accelerations compared with levels B and C (Table 3). Level C's distribution had the highest head accelerations and level B's distribution fell between that for level A and level C. Level C had significantly greater mean linear acceleration than level A ($p=0.005$) and level B ($p=0.02$). Differences in mean rotational acceleration among the three levels were not significant.

HIE was also evaluated by session type, including inter- and intra-level comparisons (Table 3). Head accelerations and number of impacts for practice, competition, and all sessions for individual athletes and averages for each level are shown in Figure 2. During competitions, level C had significantly greater mean linear acceleration than levels A ($p<0.0001$) and B ($p<0.0001$). Additionally, level C had significantly greater mean rotational acceleration during competition than levels A ($p=0.02$) and B ($p=0.02$). The distributions of linear and rotational head acceleration in practice sessions were more comparable among the three levels than in competition sessions. Although there were no significant differences in mean linear or rotational acceleration among levels during practices, the mean linear acceleration did increase with increasing level of play. Intra-level comparisons showed that distributions of linear and rotational accelerations were of higher magnitudes in competition than in practice. There was significantly greater mean linear acceleration in competition than in practice for both levels B ($p=0.03$) and C ($p<0.0001$), and significantly greater mean rotational acceleration in competition than in practice for both levels B ($p=0.0004$) and C ($p<0.0001$). There were no significant differences between head accelerations during competition and practice within level A.

The mean (95% confidence interval) number of impacts per player in a practice session for levels A, B, and C were 10.2 (9.6, 10.8), 11.6 (11.1, 12.1), and 10.4 (9.8, 11.0), respectively (Fig. 2). Level B had a significantly greater mean number of impacts per player in practice than levels A ($p=0.002$) or C ($p=0.006$). The mean number of impacts per player in a competition session for levels A, B, and C were 12.0 (10.5, 13.4), 13.4 (12.0, 14.7), and 14.6 (12.9, 16.2), respectively (Fig. 2). Level C had a significantly greater mean number of impacts per player in competition than level A ($p=0.03$). Intra-level comparisons of mean number of impacts showed significantly greater impacts per player in

FIG. 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 3. SUMMARY OF HIE DATA FOR ALL SEASON, COMPETITION, AND PRACTICE IMPACTS FOR LEVELS A, B, AND C

	Level A	Level B	Level C
Season			
Number of sessions in a season (average $\pm$ standard deviation)	39.8 $\pm$ 6.2	39.3 $\pm$ 5.7	43.0 $\pm$ 2.0
Total number of impacts			
50th Percentile	306.0	296.5	347.0
95th Percentile	568.0	674.5	762.7
Linear acceleration (g)			
Mean	23.9 (23.1 24.7) _a	24.3 (23.6 24.9) _b	25.6 (24.8 26.4) _{a, b}
50th Percentile	19.8	20.6	22
95th Percentile	49.4	51.0	57.9
Rotational acceleration (rad/sec ²)			
Mean	1099.0 (1057.1 1141.0)	1105.1 (1068.3 1141.9)	1114.6 (1069.3 1159.8)
50th Percentile	957.7	979.7	991.5
95th Percentile	2323.2	2415.7	2544.2
Competition			
Number of sessions in a season (average $\pm$ standard deviation)	10.0 $\pm$ 1.2	9.0 $\pm$ 0.0	10.3 $\pm$ 1.2
Total number of impacts			
50th Percentile	84.0	69.0	98.5
95th Percentile	244.0	260.8	328.3
Linear acceleration (g)			
Mean	24.0 (23.0 25.0) _a	24.3 (23.4 25.2) _b	27.4 (26.3 28.4) _{a, b}
50th Percentile	20.5	20.8	23.2
95th Percentile	50.9	53.3	62.8
Rotational acceleration (rad/sec ²)			
Mean	1108.8 (1055.2 1162.3) _a	1118.8 (1071.0 1166.7) _b	1210.4 (1153.0 1267.8) _{a, b}
50th Percentile	975.2	996.3	1052.4
95th Percentile	2386.7	2600.5	2856.9
Practice			
Number of sessions in a season (average $\pm$ standard deviation)	29.8 $\pm$ 5.3	30.3 $\pm$ 5.7	32.7 $\pm$ 3.1
Total number of impacts			
50th Percentile	197.0	196.5	228.5
95th Percentile	441.0	477.7	457.9
Linear acceleration (g)			
Mean	23.8 (23.0 24.6)	24.2 (23.5 24.9)	24.9 (24.0 25.7)
50th Percentile	19.6	20.6	21.5
95th Percentile	48.9	50.0	55.0
Rotational acceleration (rad/sec ²)			
Mean	1093.5 (1050.9 11136.1)	1092.5 (1055.4 1129.6)	1069.1 (1023.3 1114.8)
50th Percentile	951.0	973.5	970.9
95th Percentile	2305.20	2351.90	2393.10

Total number of impacts represents number attributed to the respective category in a single season. Means shown with 95% confidence intervals in parentheses. Mean linear and rotational accelerations in the same row that share the same subscript differ at $p < 0.05$.

HIE, head impact exposure.

competition sessions than in practice sessions for all levels (A, $p = 0.0005$; B, $p = 0.002$; and C, $p < 0.0001$).

The proportion of high magnitude impacts (i.e., $\geq 60g$, $\geq 80g$, $\geq 100g$) occurring in practice or competition differed among levels (Fig. 3). The majority of impacts within levels A, B, and C occurred in practice; only 31.7%, 28.7%, and 33.6% of impacts occurred in competitions, respectively. The majority of high magnitude impacts (i.e. $\geq 60g$, $\geq 80g$, $\geq 100g$) for levels A and B also occurred in practices. However, this trend was not evident for level C athletes, with the majority of high magnitude impacts occurring in competition rather than in practice. Of the impacts $\geq 80g$ and $100g$ within level C, 54.9% and 61.1%, respectively, occurred in competition. Ad-

ditionally, 6.2% and 3.6% of competition and practice impacts, respectively, were $\geq 60g$ for level C, whereas 2.4% and 2.2% of competition and practice impacts, respectively, were $\geq 60g$ for level A. Overall, the number of high magnitude impacts occurring in competitions increased with increasing level of play.

Lastly, we evaluated HIE by impact location (Fig. 4). The front of the helmet was the most common impact location, with impacts to the front accounting for 53.0%, 55.7%, and 46.5% of total impacts for levels A, B, and C, respectively. The impact location with the fewest impacts was the top of the helmet, with these impacts accounting for 11.2%, 9.7%, and 13.5% for levels A, B, and C, respectively. The impact location with the highest 95th percentile

FIG. 2. (Left) Mean linear acceleration versus mean rotational acceleration and (right) mean linear acceleration versus mean number of impacts per session for (top) all impacts, (middle) competition impacts, and (bottom) practice impacts in a season of play. Individual athletes and level of play averages with 95% confidence interval error bars displayed.

linear acceleration for all three levels was the top of the helmet. The impact location with the lowest 95th percentile linear acceleration was the side of the helmet. The impact location with the highest 95th percentile rotational acceleration was the front of the helmet for levels A and B, and the back of the helmet for level C.

Discussion

This study reports the largest collection of biomechanical head impact data for youth football athletes to date. The dataset includes 40,538 head impacts from youth football athletes between the ages

FIG. 3. Percentage of impacts in practice or competition for each level of play for all impacts, impacts $\geq 60g$, impacts $\geq 80g$, and impacts $\geq 100g$.

of 9 and 13 years. A diverse group of athletes with differing amounts of prior football experience and varied demographics participated in the study. The athletes are separated into increasing age- and weight-based levels of play, and provide insight into the overall HIE of youth football and how HIE changes as they progress by level athletes.

The mean total number of head impacts measured in a season increased with increasing level of play; however, the differences were not significant. This is partially because of the wide variability in total number of head impacts individual athletes experienced in a season. A wide range of values for the total number of head impacts is seen in many other similar studies of youth, high school, and college athletes.^{26,27,37–40} For example, the number of impacts for the 9–12-year-old athletes in the study by Cobb and colleagues ranged from 26 to 585, and the number of impacts for the high school athletes in the study by Broglio and colleagues ranged from 5 to 2235.^{27,37} A number of studies have shown positional differ-

ences in HIE and, although the youth athletes in this study often played multiple positions throughout the season, positional differences may contribute to differences in the number of head impacts in a season.^{37,39} Many other factors may have also contributed to the large range in total number of head impacts, including coaching styles, types of practice drills, practice structure, length of season, and athlete intensity and involvement.

Mean head acceleration increased 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 in mean linear acceleration between levels A and B, the distribution of linear acceleration shifted toward higher accelerations from level A, the youngest and lowest age and weight requirement, to level B. The mean rotational acceleration increased with level, but the differences were not significant. Although mean head accelerations were statistically compared in this analysis, similar contrasts in

FIG. 4. Ninety-fifth percentile (A) linear and (B) rotational acceleration for each level by impact location on the helmet.

95th percentile linear and rotational acceleration were also observed among levels. It should also be noted that, although the weight requirements increased from the 2012–2014 seasons to the 2015 season, there were no consistent trends or changes in head acceleration or number of impacts among the levels from the earlier seasons to the 2015 season. However, because of significant differences in head acceleration from year to year, further study is needed to evaluate the effect of varying weight requirements on HIE.

Comparing the three youth levels studied here with prior studies of high school and college athletes show that HIE continues to increase with increasing age and level of play throughout a football athlete's career. 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.^{26,28} It is noteworthy that there are significant increases in head impact magnitudes from one level to the next within a single youth organization. This suggests that all youth athletes cannot be grouped together when studying HIE and injury risk, and that more data are needed at all levels within youth football, especially at the youngest levels with athletes starting football as young as 5 years old. With increasing concern over the long-term neurological effects of repetitive head impacts, data from all levels are needed to understand athletes' exposure to head impacts over a lifetime.

HIE was also evaluated by session type. All three levels had a distribution of higher magnitude impacts in competition than in practice, which was similar to findings of other studies of youth, high school, and college football athletes.^{26,27,38} Generally, football athletes at all levels of play experience higher head accelerations during a competition session than during a practice session. For competition impacts, level C had significantly greater mean linear and rotational acceleration than levels A and B. For practice impacts, there were no significant differences in mean linear or rotational acceleration among the levels. These data suggest that the increase in head impact magnitude with increasing level of play was primarily driven by exposure to higher magnitude impacts during competition.

The percentage of high magnitude impacts occurring in competitions increased with level of play. The oldest level had more than half of their impacts ≥ 80 g occur in competitions. However, within levels A and B, the majority of impacts ≥ 60 g, 80g, and 100g still occur in practices. Additionally, the percentage of competition impacts ≥ 60 g was nearly twice the percentage of practice impacts ≥ 60 g for level C, whereas the percentage of competition and practice impacts ≥ 60 g for level A were nearly equal. These data are in agreement with trends presented in youth, high school, and college athletes, in which younger athletes experience a greater number of more severe impacts in practice whereas high school and college athletes experience a greater number of more severe impacts in games.^{28,38,41} This study shows that there is a transition of a greater proportion of more severe impacts occurring in practices to more occurring in games in football athletes between the ages of 9 and 13. These data suggest that more effort is needed to reduce exposure to high magnitude head impacts in practice, particularly at the lower levels of play; however, with increasing level of play, more effort may be needed to reduce high magnitude impacts in competition.

The number of impacts per athlete in a session 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 a significantly greater number of impacts per player in a practice session than both levels A and C. These data support that differences seen in number of impacts per player in a session among levels were driven by HIE during competition rather than during practice. Additionally, within each level, the impact frequency per

player in a competition session was significantly greater than the impact frequency per player in a practice session. Increased impact frequency on a per-session basis in competition compared with practice is typical for all age groups studied in the literature.^{28,40} However, it is important to note that a typical athlete participated in many more practice sessions than competition sessions in a season of play; therefore, for 92% of athletes who participated in this study, practices contributed to more than half of the total number of head impacts that they experienced in a season.

The helmet location with the highest percentage of impacts was the front of the helmet, which agrees with other findings for this age range.²⁷ The largest linear head acceleration impacts were to the top of the helmet for all three levels, and the largest rotational head accelerations were to the front of the helmet for levels A and B and to the back of the helmet for level C. Daniel and colleagues reported that the 7–8-year-old athletes in their study experienced higher rotational accelerations occurring in side impacts, whereas Cobb and colleagues reported that the 9–12-year-old athletes in their study experienced higher rotational accelerations occurring in frontal impacts.^{27,28} There are numerous factors that could contribute to the differences in impact locations between study populations, but these could be, in part, the result of coaching style and tackling technique taught to the athletes. Additionally, athletes in the study by Cobb and colleagues more closely matched the age of the athletes participating in this study, which may also contribute to more similar head impact characteristics between the two studies.²⁷

The 9–13-year-old youth athletes in this study generally had higher HIE, in terms of both magnitude and total number impacts, than the 9–12-year-old athletes studied by Cobb and colleagues.²⁷ The increased number of head impacts in our study population is partially the result of the increased number of sessions in a season. The athletes in the study by Cobb and colleagues participated in an average $\pm$ standard deviation of 21.8 ± 5.7 sessions in a season, whereas the level A, B, and C athletes in this study participated in 39.8 ± 6.2 , 39.3 ± 5.7 , and 43.0 ± 2.0 sessions in a season, respectively, which approaches the number of sessions typically reported in a high school season.^{26,27,40} Additionally, the distribution of linear and rotational head accelerations measured in this study, although greater in magnitude than in the study by Cobb and colleagues, was still lower than what is typically reported for high school and college athletes.^{25,26,37,38} The higher head accelerations measured in this study may be the result of differences in drills, coaching style, tackling technique, and league- or organization-specific rules.

A few limitations should be noted. First, results are limited to 9–13-year-old athletes, and youth football leagues can include athletes from 5 to 15 years old. Second, this study provides a limited representation of the youth football population as a whole, as it is focused on a single youth football organization. HIE in other organizations may have some variation 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 (e.g., Pop Warner, American Youth Football, Unaffiliated), and demographic/cultural backgrounds. Third, the HIT system used for biomechanical data collection has some error associated with acceleration measurements and impact detection. However, the errors in 5 degrees of freedom (SDOF) acceleration measurements are within the range of acceptable error for other measurement devices and methods.³⁴ Further, the analysis focused on distributions of data sets instead of individual data points, minimizing the effects of random error. Additionally, video review of all practices and games was used to

verify the times that the athletes were helmeted, but a systematic review of all impacts to visually confirm each individual data point was not completed.

The HIE data from three sequentially increasing age- and weight-based levels of play demonstrate significant differences in the magnitude and frequency of head impacts among levels of play. HIE also differed by session type between levels with more high magnitude impacts occurring in practice in the younger levels and more occurring in competition in the oldest level. Across all levels, the distribution of head impacts in competitions was of higher magnitude than that of head impacts in practices; however, athletes generally accumulate more impacts during practices than in competitions over the course of a season. These data contribute to the understanding of HIE in football, and may be used to guide evidence-based intervention efforts, such as making changes to practice structure and game rules to reduce the number of high magnitude impacts, impact frequency, and total number of head impacts, with the ultimate goal of improving safety in youth football.

Acknowledgments

Research reported in this publication was supported by the National Institute of Neurological Disorders and Stroke of the National Institutes of Health under Award Numbers R01NS094410 and R01NS082453. The National Center for Advancing Translational Sciences, National Institutes of Health, through Grant KL2TR001421 supported Dr. Jillian E. Urban. The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health. The authors give special thanks to the Childress Institute for Pediatric Trauma at Wake Forest Baptist Medical Center for providing support for this study. The authors also thank the youth football league's coordinators, coaches, parents, athletes, and athletic trainer whose support made this study possible. The authors also thank Amanda Dunn, Matt Bennett, Eliza Szuch, Danielle Rocheleau, Joeline Kane, Katie Fabian, Ana Katsafanas, Megan Anderson, and Leslie Hoyt for their valuable assistance in data collection.

Author Disclosure Statement

No competing financial interests exist.

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Address correspondence to:

Joel D. Stitzel, PhD

Wake Forest School of Medicine

575 N. Patterson Avenue, Suite 120

Winston-Salem, NC 27101

E-mail: jstitzel@wakehealth.edu