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Abstract

The relationship between head impact and subsequent brain injury for American football players is not well defined, especially for youth. The objective of this study is to quantify and assess Head Impact Exposure (HIE) metrics among youth and collegiate football players. This multiseason study enrolled 639 unique athletes (354 collegiate; 285 youth, ages 9–14), recording 476,209 head impacts (367,337 collegiate; 108,872 youth) over 971 sessions (480 collegiate; 491 youth). Youth players experienced 43 and 65% fewer impacts per competition and practice, respectively, and lower impact magnitudes compared to collegiate players (95th percentile peak linear acceleration (PLA, g) competition: 45.6 vs 61.9; 95th percentile PLA practice: 42.6 vs 58.8; 95th percentile peak rotational acceleration (PRA, rad·s⁻²) competition: 2262 vs 4422; 95th percentile PRA practice: 2081 vs 4052; 95th percentile HITsp competition: 25.4 vs 32.8; 95th percentile HITsp practice: 23.9 vs 30.2). Impacts during competition were more frequent and of greater magnitude than during practice at both levels. Quantified comparisons of head impact frequency and magnitude between youth and collegiate athletes reveal HIE differences as a function of age, and expanded insight better informs the development of age-appropriate guidelines for helmet design, prevention measures, standardized testing, brain injury diagnosis, and recovery management.

Keywords: Concussion, Sport, Biomechanics

Introduction

Participation in youth sports offers many health benefits, but there is growing concern as head injury and concussion rates continue to rise in the younger population.[2] Concussions and long-term brain injuries induced by head impacts are especially concerning in younger athletes, as they can face increased susceptibility, longer recovery times, and stunted cerebral maturation.[1,6,7,24] Additionally, underdeveloped cervical muscle strength, behavioral decision-making, and intuitive ability to anticipate impacts of younger athletes also heighten risks of head injury.[27,50] Head impacts experienced by youth have been reported to result in structural and functional changes to the brain that lead to serious long-term cognitive and behavioral deficits.[1,12,27]

There does not exist a clear relationship between head impact magnitude and consequential concussion diagnoses. It is generally understood that impacts to the head produce biomechanical forces that can result in concussions and other brain injury, but the complex variability of mechanical response yields unique injury results.[8,15,20,26,38] In

an effort to better understand the mechanisms of head impacts that lead to acute and chronic brain injury, quantification of head impact exposure (HIE) is a critical first step. In this study, HIE is defined as ''a multi-factorial term that includes the frequency of head impacts, magnitude of the impacts, impact location, and cumulative history of head impacts for an individual athlete.''[16]

When the head is directly hit or indirectly loaded, it experiences both linear and rotational acceleration.[31,43] Linear acceleration of the head has shown strong correlation to the transient intracranial pressure gradient in response to impact, which causes neurologic dysfunction.[31,38,43] Loads on the head from impact also cause differential motion between the skull and the brain, and it has been proposed that rapid head rotations result in shear forces that can deform and damage brain tissue.[31,38,43] There are also arguments supporting the relevance of impact location and the resulting direction of head motion in concussion mechanisms, as the contributions of linear and rotational accelerations vary based on the site of impact and the direction of the force.[30,41,43] The incidence of head impacts is also important when understanding athlete safety, as repetitive impacts and damage accumulation are linked to potential long-term risks, particularly concerning cognitive, neuropsychiatric, and neurodegenerative disorders.[25,36,46,48]

American football is one of the most popular, but also one of the highest concussion-producing, sports played among young athletes in the United States.[12,17,42] Past studies measuring head impacts in helmeted sports have been heavily concentrated in collegiate sports while evaluations of youth football are limited in scope due to a general lack of data. These gaps can be attributed to small sample sizes, age-dependent variability, league structure and rules, and undocumented concussion histories.[32,45,51] A comparison to collegiate data can help better interpret youth impact metrics in contrast to those of college-level play. Expanding on previous work investigating youth football head impacts and contrasting metrics to higher-level play, this observational study aims to quantify HIE consistently for both college and youth players, examining the comparative relationships between collegiate and youth football head impact frequency, magnitude, and location to bring attention to any differences and expand current efforts to inform age-appropriate play rules, equipment development, and injury management.

Materials and methods

Collegiate data were collected over four seasons (2007–2010) from three National Collegiate Athletic Association (NCAA) football teams (Brown University, Dartmouth College, and Virginia Tech) from 354 players. An earlier study analyzing collegiate head impacts has been published using these data.[15] Youth data were collected over five seasons (2015–2019) from 285 unique football players, ages 9 to 14, at three programs located in the vicinities of Brown University, Virginia Tech, and Wake Forest University. Institutional review board permission was obtained from each university for studies in the respective collegiate and youth programs, followed by player and youth parental informed consent (when appropriate) for this observational study. Each unique player from both levels was assigned an identification number, and impact data collected was considered on a per-season basis to account for participant turnover.

Players were equipped with football helmets instrumented with the Head Impact Telemetry (HIT) system (Sideline Response System, Riddell, Elyria, OH), which records head acceleration data upon head impact, determined when any one of its six linear accelerometers detects an acceleration exceeding a predetermined threshold of 14.4 g during games and practices. On each board with the accelerometer, there is a high-pass filter with cutoff frequency 1 Hz, followed by a low-pass filter with cutoff frequency 3.3 kHz. Data acquisition was triggered to record 40 ms of data at 1000 Hz, including 8 ms of pre-trigger data. The raw data was then filtered through a 250 Hz 10th order Chebyshev Type 1 filter, followed by principal component analysis to put together the acceleration data to create the resultant for the HIE metric calculations. Collected data was wirelessly transmitted to a signal receiver and laptop computer system that computes linear and rotational head acceleration and impact location using the HIT algorithm.[10,13,18] Constant contact to the head was maintained with spring-mounted accelerometers that were elastically coupled to the head, isolating them from the helmet shell to specifically take measurements from head acceleration. The HIT system has been lab-tested and measured nearly identical peak acceleration values and curve shapes compared to the Hybrid III dummy head center of gravity measurements.[35] Video validation was implemented at the youth level to confirm that

the analyzed impacts occurred during play in the specified time durations of practices and games.[8,9,11] For the collegiate data, video validation was implemented to confirm post-processing when peak linear acceleration (PLA) > 125 g.[14] Impacts for which the acceleration-time history pattern of the six linear accelerometers did not match the theoretical pattern for rigid body head acceleration (e.g. a spike in a single accelerometer signal that can result from a player removing his helmet and throwing or kicking it)[13] were also excluded.

The independent variables were level of play (youth or college) and session type (practice or competition), and the dependent variables observed were frequency (number of hits per session), impact magnitude (peak linear acceleration, peak rotational acceleration, HIT severity profile), and impact location (front, side: right and left, back, top). The dependent variables were assessed on a per-player, per-season basis. A single session was defined as a formal practice or a competition, both scrimmages and games, during which players wore protective gear; participation of a player was counted when at least one head impact was logged during the team session. Because session participation counts of competitions and practices per season differed among athletes both between and within levels, hit frequency was summarized as a per-session metric. PLA (g) was directly measured by accelerometers in the HIT system that determined the magnitude of head acceleration, and peak rotational acceleration, PRA, (rad·s^{-2}) was computed using a previously described and validated algorithm.[13] HIT severity profile (HITsp) is a non-dimensional measure that combines the weighted effects of linear and rotational accelerations with impact duration and location as a more predictive measure in concussion diagnosis than any single parameter.[23] HITsp transforms the computed head impact measures of PLA and PRA into a single latent variable using Principal Component Analysis and applies a weighting factor based on impact location.[23] It is thus used as a measure of impact severity that gives weight to factors (linear and rotational acceleration, impact duration and location) that have been deemed relevant in previous research[21,22,28,41] in predicting the likelihood of head injury.[15] Impact locations to the helmet and facemask were computed as azimuth and elevation angles in an anatomical coordinate system relative to the center of gravity of the head using our established algorithms[13,15,16] and then categorized as front, side (left and right), back,

and top. Front, left, right, and back impact locations were four equally spaced regions centered on the midsagittal plane. All impacts above an elevation angle of 65° from a horizontal plane through the center of gravity of the head were defined as impacts to the top of the helmet.[23] Impact magnitude was summarized as the 95th percentile value for each player's impacts per season.[13,15,23]

Post-processing of data excluded acceleration events with peak resultant linear head accelerations less than 9.6 g, set to eliminate non-impact events such as running or jumping. Recorded impacts for which the acceleration-time history pattern of the accelerometers did not match the theoretical pattern for rigid body head accelerations, such as a spike in a single accelerometer signal that may have resulted due to a player removing his helmet and throwing or kicking it, were also excluded.[13] These data reduction methods,[5,18,19,35] as well as the accuracy of the HIT algorithm,[10,13] have been previously verified, and laboratory tests have determined that the HIT system measures linear and rotational accelerations within ± 4% of a helmet-equipped Hybrid III dummy.[18]

Statistical Analysis

Head impact frequency and severity at youth and collegiate levels were assessed for significant differences by implementing a two-way analysis of variance followed by Tukey-Kramer post-hoc testing, using session as a within-subjects effect and level of play (youth or collegiate) as the between-subjects effect. The player was treated as a random effect.[47] Impacts per player per session, 95th percentile PLA, 95th percentile PRA, and 95th percentile HITsp were each analyzed separately to compare youth and collegiate head impact exposure. Impact location proportions for youth and collegiate players were also tested for significant differences using a Chi-square test of homogeneity using a permutation test. The permutation test is done as follows: first the Chi-square test is computed for the table that is categorized by youth status and location. Second, because the subject is the sampling unit, the labels for the player (youth or college) are permuted. The counts for each player and number of players in each group do not change, only the youth/collegiate label. Then the Chi-square test is computed on this new data set. The process is repeated 1000 times resulting in

1001 Chi-square values. The permutation test p-value is computed as the number of test statistics greater than or equal to the observed. (The minimum value of the permutation test is 1/(number of permutations + 1)). Statistical significance was set at $\alpha = 0.05$ and analyses were performed using SAS.[44] Positively skewed frequency and magnitude measures called for data summarization to be expressed as median values [25–75% interquartile range]. Log transformations were used to stabilize variance and better meet assumptions for inference. Residuals from the models were checked for normality and homogeneity of variance using graphical displays.

Results

There were 367,337 and 108,872 head impacts analyzed in this study for collegiate and youth levels, respectively. College data were collected over the span of a median of 9 competitions and 33 practices per player per season, while youth data were collected from a median of 8 competitions and 19 practices per player per season.

The median [IQR] values for head impact frequency, 95th percentile PLA, 95th percentile PRA, and 95th percentile HITsp, categorized by play level and session type, are summarized in **Table 1.**

At the college level, the median number of hits was 16.8 [9.1–29] during competition and 8.2 [4.9–14] during practice, while for youth players, the median number of hits was 7.3 [3.4–13] during competition and 5.3 [3.2–8.5] during practice. For both levels, there were more impacts in competitions than in practices, and college-level play had a higher hit count in general.

Table 1. Summary of frequency and magnitude median [IQR] values.

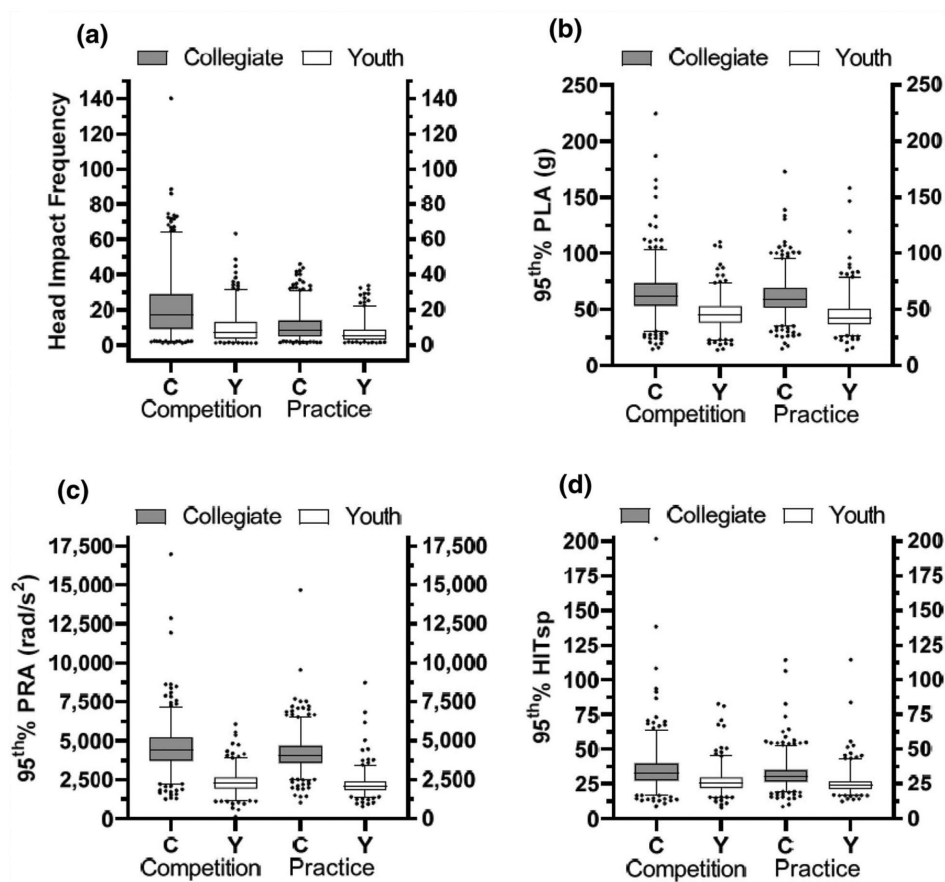| Level	Session	Frequency	95th %tile PLA (g)	95th %tile PRA (rad/s²)	95th %tile HITsp
College	Competition	16.8 [9.1–29]	61.9 [53.4–73.8]	4422 [3728–5204]	32.8 [27.4–39.4]
	Practice	8.2 [4.9–14]	58.8 [51.8–69.3]	4052 [3571–4660]	30.2 [26.7–35]
Youth	Competition	7.3 [3.4–13]	45.6 [38–53.2]	2262 [1904–2648]	25.4 [21.8–29.7]
	Practice	5.3 [3.2–8.5]	42.6 [36.9–50.8]	2081 [1827–2395]	23.9 [20.9–26.9]

Figure 1. Boxplots depicting the (a) number of impacts, (b) 95th percentile PLA (g), (c) 95th percentile PRA (rad/s²), and (d) 95th percentile HITsp experienced by players in a single season, separated by session type at collegiate (C) and youth (Y) levels.

The distribution of the number of hits per session, counted per player per season, was shown to be positively skewed, with college competition having the greatest variance, as well as more extreme outliers (**Fig. 1**a). When play level, session type, and their interaction were tested for their effects on hit frequency, results indicated statistical significance for each of the effects (Table A1—Appendix I). Pairwise Tukey-Kramer tests demonstrated a significant difference in impact frequency during competitions and practices when comparing between play levels. Log transformed head impact frequency during college competitions and practices were significantly different from that of youth competitions (Table A2). These differences can be seen
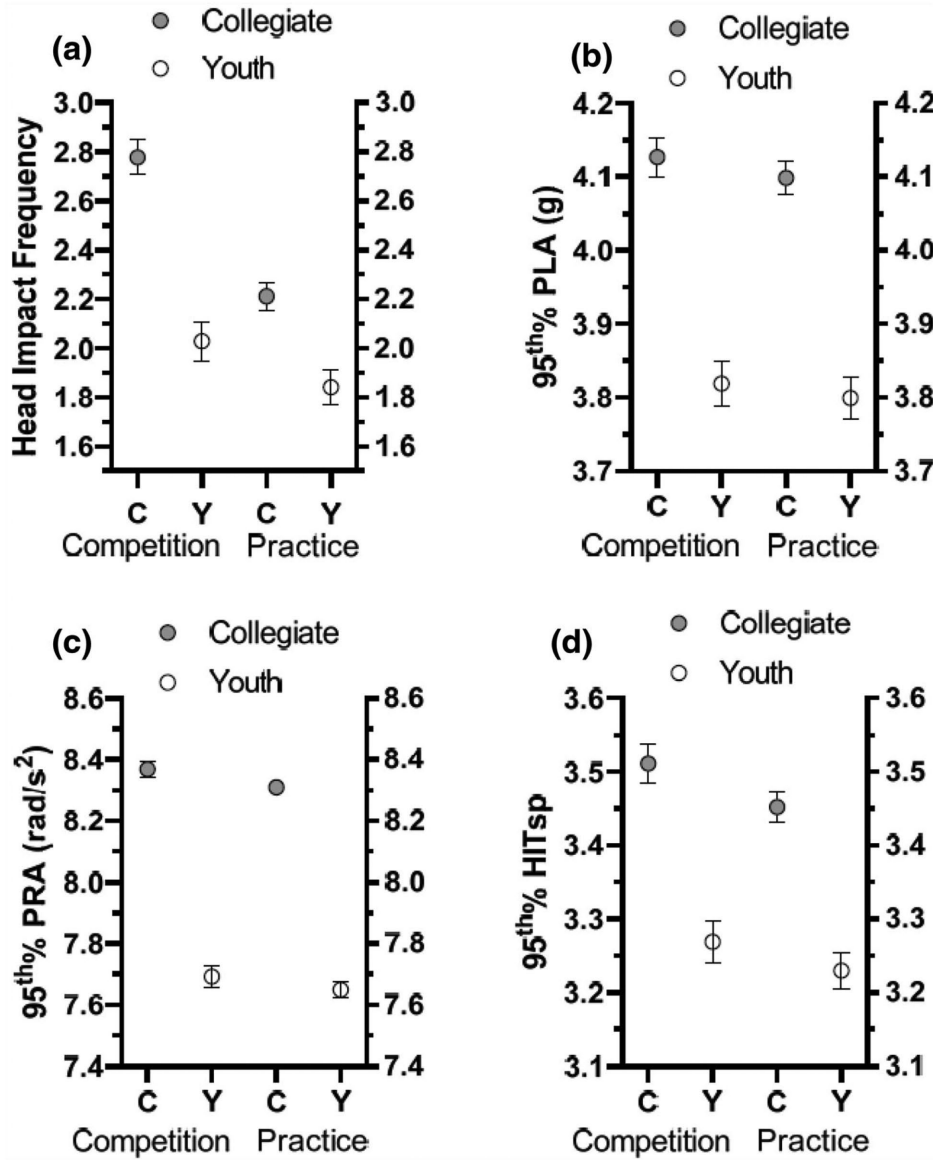
Figure 2. Least squares means for log transformed (a) hit frequency, (b) 95th percentile PLA (g), (c) 95th percentile PRA (rad/s²), and (d) 95th percentile HITsp, with 95% confidence, grouped by play level and session type.

in the least squares (LS) means plot of log-transformed hit frequencies in (**Fig. 2**a).

For college players, the 95th percentile PLA had a median value of 61.9 [53.4–73.8] g for competitions and 58.8 [51.8–69.3] g for practices, while youth athletes recorded 95th percentile PLA median values

of 45.6 [38–53.2] g during competition and 42.6 [36.9–50.8] g during practices. Peak linear acceleration magnitude was higher for both session types at the college level and impacts during competitions logged higher 95th percentile PLA for both collegiate and youth players.

The 95th percentile PLA data was positively skewed, with collegiate records, particularly in competition, displaying greater variance and greater upper outliers (Fig. 1b). There were statistically significant main effects of session type and level of play, but no significant interaction effects (Table A3). For both session types, the 95th percentile PLA was significantly different between youth and collegiate play (Table A4). The lack of interaction effect between college and youth players is shown in (Fig. 2b), the LS-means plot of log transformed 95th percentile PLA.

Collegiate 95th percentile PRA had a median value of 4422 [3728–5204] rad·s^{-2} for competitions and 4052 [3571–4660] rad·s^{-2} for practices, and youth 95th percentile PRA had median values 2262 [1904–2648] rad·s^{-2} and 2081 [1827–2395] rad·s^{-2} for competition and practice, respectively. Peak rotational acceleration magnitude was higher during competitive play at both levels, while overall, college impacts resulted in greater 95th percentile PRA.

PRA severity had greater variance and higher upper boundaries at the college level (Fig. 1c). The main effects of session type and level of play were statistically significant, and their interaction effect was not (Table A5). The 95th percentile log transformed PRA means during college competition and youth competition were significantly different, as were the means compared between college and youth practice (Table A6). Fig. 2c displays the LS-means plot of the log transformation of 95th percentile PRA, visualizing the contrast between sessions as well as collegiate and youth values.

HITsp in college play had a mean value of 32.8 [27.4–39.4] during competition and 30.2 [26.7–35] during practice, and at the youth level, HITsp mean values were 25.4 [21.8–29.7] for competition and 23.9 [20.9–26.9] for practices. Severity was greater during competition for both levels, and generally higher during collegiate play. The frequency and magnitude distributions of HITsp were shown to be right-skewed, with college competition having greater variance and upper boundary outliers (Fig. 1d). The main effects of session type and play level were significant on the log transformed 95th percentile

Table 2. Distribution of impact location by proportion at each play level; difference is expressed as College-Youth, and the proportional differences are expressed relative to college impacts.

	Back	*Front*	*Side*	*Top*
Collegiate distribution	25.86	41.30	17.47	15.37
Youth distribution	18.98	50.82	19.96	10.25
Difference (college–youth)	6.88	−9.52	−2.49	5.12
Proportional difference	0.266048	−0.23051	−0.14253	0.333116

HITsp, but the interaction effect is not (Table A7). Further, the difference in means between college and youth for each type of session, college competition versus youth competition and college practice versus youth practice, was significant for the log transformation of measures as well (Table A8). The LS-means plot in Fig. 2d displays the significant main effects of play level and session type on log transformed HITsp measures.

The distribution of all head impacts by location for each level can be seen in **Table 2,** with impacts to the front of the helmet making up the largest proportion and impacts on the top of the helmet making up the lowest percent for both college and youth athletes. Back and side impact percentages alternate, with impacts to the back of the helmet more likely in collegiate play than the sides, and hits to the sides more likely than the back during youth play.

The Chi-square statistic comparing impact location proportions between collegiate and youth levels indicates that there is sufficient evidence to conclude that the distributions of hits by location are significantly different (Table A9). Permuting the data (n = 1000) leads to greatly reduced the Chi-square statistics, suggesting the null hypothesis that there are no significant differences in the proportions should be rejected. The greatest differences are seen (Table 2) in the proportion of impacts to the top and back of the head, both of which are higher in the college population. This disparity is offset by a greater proportion of impacts to the front and side of the head in youth play.

Further observations investigating impact magnitudes by player at each location, shown in **Table 3,** reinforces the general trend that head accelerations and hit severity are greater at the college level. Impacts to the top of the head recorded the greatest PLA but the lowest PRA

Table 3. 95th percentile magnitude measures by impact location and play level, shown as median [IQR].

Level	Location	95th %tile PLA (g)	95th %tile PRA (rad·s⁻²)	95th %tile HITsp
College	Back	56.0 [46.2–67.1]	4190 [3576–5131]	21.6 [17.8–26.9]
	Front	56.3 [49.4–62.3]	4310 [3627–4911]	34.1 [29.3–38.6]
	Side	47.8 [41.2–56.8]	3635 [3129–4406]	30.1 [26.5–36.5]
	Top	70.6 [56.7–86.3]	2347 [1933–2876]	20.3 [15.4–26.1]
Youth	Back	41.8 [34.5–50.3]	2156 [1771–2593]	16.5 [14.0–19.6]
	Front	43.0 [37.9–49.3]	2175 [1896–2462]	26.1 [23.3–29.4]
	Side	34.9 [29.3–42.6]	1828 [1536–2229]	23.4 [20.5–26.8]
	Top	44.6 [34.1–57.0]	1095 [755–1434]	12.1 [9.59–15.7]

for both youth and college athletes. PRA was greatest for frontal impacts for both collegiate and youth players, with impacts to the back coming in a close second. Using HITsp as the measurement of severity indicates that impacts to the front of the helmet were most severe in both college and youth play, while top impacts were the least severe.

Discussion

This study examined head impact exposure in youth and collegiate football players, comparing frequency, magnitude, and location of impacts between the two levels of play. Given the smaller scale of research focused on younger leagues, understanding the landscape of head impacts at the youth level in contrast to collegiate play can help guide future efforts toward improved detection, management, and education regarding mild traumatic brain injuries and repeated sub-concussive impacts. Helmet design guidelines, practice structure recommendations, and competition rules to better protect players can also be updated accordingly.

Frequency and magnitude metrics, which include 95th percentile PLA, PRA, and HITsp, are greater for collegiate football head impacts during both competition and practice, compared to youth head impacts. Further, impacts to the back of the head are less likely, while impacts to the sides are more likely, for youth than for college players,

and impact location proportions are significantly different between the youth and collegiate levels.

Overall, the frequency of impacts was higher in collegiate play, which corresponds to the study by Munce et al. reporting a higher head impact frequency for college athletes.[39] Impacts were also more frequent during competition at both levels, but the incidence rate of impact during a practice session can vary depending on team-specific practice styles.[11,29] Further, the magnitude of impacts experienced by youth players was significantly lower than those by collegiate players; however, youth athletes did experience high levels of magnitude more often seen in more senior levels of play. While the distribution of hits is heavily weighted toward lower magnitude impacts, this study is in agreement with previous findings indicating the prevalence of these more severe impacts at the younger level.[11,17,39,51] Further, this study indicates that impact magnitude is greater for hits during competition than during practice, reinforcing conclusions made by Kontos et al., but differing from Daniel et al., Young et al., and Campolettano et al., who found higher levels of impact magnitude during practice, and Cobb et al., who found no significant difference between competition and practice.[9,11,17,33,51]

Central to this study is understanding the relative frequency and magnitude of youth head impacts in contrast to collegiate hits. Analysis of the impact data shows that median hit frequency is more than double, 130% higher, at the collegiate level during competition than during competitive youth sessions, and approximately 55% higher during collegiate practices than during youth practice sessions. The median 95th percentile PLA is greater in college play by 36% during competition and 38% during practice, the median 95th percentile PRA is greater in college play by 95% during both competition and practice, and the median 95th percentile HITsp is greater in college play by 29% during competition and 26% during practice. The percent difference between youth and collegiate levels is very similar for competition and practice sessions within each respective measure of magnitude; however, contrasts in frequency are more apparent, with much greater percent differences between play levels. A study by Daniel et al. examined youth and collegiate comparisons incorporating findings from previous publications and offered differing results: regardless of session type, the 95th percentile PLA was 58% higher, and the 95th

percentile PRA 27% higher, at the collegiate level in contrast to youth play.[17] The stark contrast in 95th percentile PRA percent difference can be attributed to much lower rotational acceleration collegiate measurements and younger youth athletes considered in the study by Daniel et al., which further warrants the need for continued data collection and comparison to better understand head impacts during play.[17]

Location distribution of impacts in this analysis corresponds to many previous findings. Most studies, including this one, agree that the majority of head impacts occur on the frontal aspect of the head.[11,39,51] On the other hand, Daniel et al. reported the highest proportion of impacts to the sides for youth players, citing helmet size comparable to that of collegiate players and the underdevelopment of neck muscles of younger athletes as potential reasons for higher incidence of falls to the side.[17] It is worth noting that the percent of side impacts was second to front impacts for youth players, but not for collegiate, in this study. The least common were impacts to the top of the head, as was the case for Cobb et al., but not for Daniel et al., who reported rear for youth and side for college as the least likely.[11,17] Regarding impact magnitude and location, the results of this study concurred with the findings of Cobb et al., where the greatest linear acceleration was seen for impacts to the top of the head, while the greatest rotational acceleration was seen for impacts to the front of the head. It is important to recognize patterns relating impact location and magnitude, observing unique characteristics at each level of play, to understand the biomechanics leading to head injury. Additionally, the proportions of impact by location were significantly different between youth and college players. The greater distribution of hits to the top and back during collegiate football, compared to youth play, and to the front and side for youth, compared to the college level, indicate the variation in impact locations between the two levels. Further investigation into play style and hit location can highlight the functional role and potential inadequacies of helmets, helping guide future design to best protect athletes based on level and experience of play. It can also serve to influence practice and training structures to better guide hit positioning and contact.

Continued research and comprehensive data collection on head impact exposure in youth football is necessary to create evidence-based guidelines to better understand injury exposure, concussion diagnoses,

and recovery timelines. Such work is more developed in the realm of collegiate football, with clinical concussion management by the NCAA that integrates a multimodal approach for baseline testing, diagnosis and management, computerized neuropsychological assessments, and return-to-play decision making.[3] Studies investigating brain injury in college football have clarified some of the defining characteristics of concussion diagnostic criteria and continue to work on clinical tools to assess concussion and recovery.[37] Although a strict concussion threshold is not currently known, identifying differences in factors that contribute to risk across age groups, based on impact frequency, severity, and location, are helpful in determining appropriate injury prevention and recognition practices.[34] Measurement of head impact exposure (HIE) is key in understanding the biomechanics of concussion, injury severity, and long-term consequences.[3] Learning to properly interpret the combination of metrics across age will provide better context and help guide future research in monitoring athlete impact exposure and preventing injury.

There are several limitations in this study. Comparing two play levels led to differing active play times that depended on several factors that were different in youth and collegiate football. For instance, session time during which a player was engaged can vary based on the length of a session and play length can fluctuate based on player utilization for multiple (offense and defense) positions in a single game. The total playing time of NCAA football games is 60 min, while youth football games tend to be just over half the collegiate play time, at 32 min.[40,49] The length of practices incorporating contact between players, while very variable, ranges from 45 to 180 minutes for collegiate players, while youth sessions spend around 50 minutes going through drills involving contact.[9] Tracking minutes and normalizing impact frequency based on play time may offer more detailed insight unobserved in this study. Further, while all youth players in this study were between the ages of 9 and 14, the different age ranges among youth teams were not considered. There may be confounding factors associated with the different ages of players that may have been overlooked. It is also important to acknowledge the difference in concussion and head impact safety awareness from 2007 to 2010 and from 2015 to 2019, when collegiate and youth data were collected, respectively, as changes to competition rules and practice structures have occurred. In

addition, there are measurement errors associated with the HIT system as well as limitations due to thresholds that define the data being analyzed.[11,15] Because individual measurements are not being assessed, but rather the broader distribution of head impact magnitudes, minor measurement errors do not pose serious threats to overall report accuracy. The distinct methods of video validation used to check youth and collegiate data also give rise to concerns regarding consistency in verifying the accuracy of impacts recorded. Verification only of erratic and high (PLA > 125 g) data points at the collegiate level, compared to verification of all impacts at the youth level, could have led to the inclusion of impacts that occurred when active helmeted play was not involved. Data points of high magnitude qualifying as extreme outliers (PLA>82) in combination account for 2% of collegiate impacts recorded; therefore, individual measurement outliers would not alter the group differences found and reported. Additionally, this study does not consider the type of impact in its analysis frequency and magnitudes. Understanding the source of impact can further clarify concussion kinematics and how they relate to the severity of injury experienced. The study is also not broken down by player, as head impact exposure patterns during practices and competitions were not observed at an individual level. Previous studies have reported that HIE is correlated between practice and competition, meaning athletes with greater exposure during practices also had greater exposure during competitions.[4,14,16,51] A more detailed analysis could look to investigate impact exposure patterns for each player. Another limitation is the lack of knowledge regarding concussion diagnoses from the impacts observed in this study. Moving forward, documenting longitudinal data and monitoring changes over time will be critical in improving the recognition of concussive patterns to better facilitate and improve clinical diagnoses, recovery management, and athlete health.

*   *   *   *

Supplementary Materials Appendix I includes Tables A1–A9 and is presented following the **References**.

Conflict of interest HIT System technology was developed in part under NIH R44HD40743 and research and development support from Riddell Inc (Elyria, OH). J.G.B., R.M.G., and J.J.C. have a financial interest in the instruments (HIT System, Sideline Response System; Riddell Inc) that were used to collect the biomechanical data reported in this study.

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Appendix

Table A1: Log-transformed hit frequency ANOVA

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Session	1	1520	331.39	<.0001
Youth	1	634	156.09	<.0001
Session*Youth	1	1520	84.13	<.0001

Table A2: Log-transformed hit frequency post-hoc Tukey-Kramer

Differences of Session*Youth Least Squares Means
Adjustment for Multiple Comparisons: Tukey-Kramer

Session	Youth	_Session	_Youth	Estimate	Standard Error	DF	t Value	Pr > |t|	Adj P	Alpha
Competition	College	Competition	Youth	0.7548	0.05009	930.5	15.07	<.0001	<.0001	0.05
Competition	College	Practice	College	0.5700	0.02634	1527	21.64	<.0001	<.0001	0.05
Competition	College	Practice	Youth	0.9429	0.04981	917.5	18.93	<.0001	<.0001	0.05
Competition	Youth	Practice	College	-0.1848	0.04960	906.8	-3.73	0.0002	0.0012	0.05
Competition	Youth	Practice	Youth	0.1880	0.03225	1515	5.83	<.0001	<.0001	0.05
Practice	College	Practice	Youth	0.3729	0.04932	893.7	7.56	<.0001	<.0001	0.05

Table A3: Log-transformed 95th percentile PLA ANOVA

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Session	1	1475	5.67	0.0174
Youth	1	561	346.21	<.0001
Session*Youth	1	1475	0.20	0.6585

Table A4: Log-transformed 95th percentile PLA post-hoc Tukey-Kramer

Differences of Session*Youth Least Squares Means
Adjustment for Multiple Comparisons: Tukey-Kramer

Session	Youth	_Session	_Youth	Estimate	Standard Error	DF	t Value	Pr > |t|	Adj P	Alpha
Competition	College	Competition	Youth	0.3086	0.01942	1060	15.89	<.0001	<.0001	0.05
Competition	College	Practice	College	0.02857	0.01279	1485	2.23	0.0257	0.1148	0.05
Competition	College	Practice	Youth	0.3282	0.01928	1046	17.02	<.0001	<.0001	0.05
Competition	Youth	Practice	College	-0.2800	0.01917	1033	-14.61	<.0001	<.0001	0.05
Competition	Youth	Practice	Youth	0.01962	0.01569	1468	1.25	0.2111	0.5944	0.05
Practice	College	Practice	Youth	0.2996	0.01902	1018	15.75	<.0001	<.0001	0.05

Table A5: Log-transformed 95th percentile PRA ANOVA

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Session	1	1489	23.56	<.0001
Youth	1	567	1676.33	<.0001
Session*Youth	1	1489	0.67	0.4148

Table A6: Log-transformed 95th percentile PRA post-hoc Tukey-Kramer

Differences of Session*Youth Least Squares Means
Adjustment for Multiple Comparisons: Tukey-Kramer

Session	Youth	_Session	_Youth	Estimate	Standard Error	DF	t Value	Pr > |t|	Adj P	Alpha
Competition	College	Competition	Youth	0.6773	0.01964	1107	34.49	<.0001	<.0001	0.05
Competition	College	Practice	College	0.05967	0.01330	1499	4.49	<.0001	<.0001	0.05
Competition	College	Practice	Youth	0.7198	0.01949	1092	36.93	<.0001	<.0001	0.05
Competition	Youth	Practice	College	-0.6176	0.01937	1080	-31.89	<.0001	<.0001	0.05
Competition	Youth	Practice	Youth	0.04250	0.01631	1482	2.61	0.0093	0.0457	0.05
Practice	College	Practice	Youth	0.6601	0.01922	1065	34.35	<.0001	<.0001	0.05

Table A7: Log-transformed 95th percentile HITsp ANOVA

Type 3 Tests of Fixed Effects

Effect	Num DF	Den DF	F Value	Pr > F
Session	1	1489	24.78	<.0001
Youth	1	568	223.59	<.0001
Session*Youth	1	1489	1.09	0.2958

Table A8: Log-transformed 95th percentile HITsp post-hoc Tukey-Kramer

Differences of Session*Youth Least Squares Means
Adjustment for Multiple Comparisons: Tukey-Kramer

Session	Youth	_Session	_Youth	Estimate	Standard Error	DF	t Value	Pr > |t|	Adj P	Alpha
Competition	College	Competition	Youth	0.2430	0.01866	1100	13.02	<.0001	<.0001	0.05
Competition	College	Practice	College	0.05989	0.01257	1499	4.77	<.0001	<.0001	0.05
Competition	College	Practice	Youth	0.2821	0.01852	1086	15.23	<.0001	<.0001	0.05
Competition	Youth	Practice	College	-0.1832	0.01841	1073	-9.95	<.0001	<.0001	0.05
Competition	Youth	Practice	Youth	0.03910	0.01541	1482	2.54	0.0113	0.0548	0.05
Practice	College	Practice	Youth	0.2222	0.01827	1058	12.17	<.0001	<.0001	0.05

Table A9: Table of youth by location differences. The values in the table are the total number of hits for a given value of youth and location, the deviation from what is expected under the null hypothesis of no differences and the proportion of hits at that location (these sum to 1 across the row).

Youth		location				
		Table of Youth by location				
Frequency **Deviation** **Row Pct**		**back**	**front**	**side**	**top**	**Total**
	0	94977 5775.5 25.86	151717 -7990 41.30	64183 -2086 17.47	56460 4300.9 15.37	367337
	1	20662 -5775 18.98	55324 7990.1 50.82	21727 2086.2 19.96	11158 -4301 10.25	108871
Total		115639	207041	85910	67618	476208