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Factors Affecting Head Impact Exposure in College Football Practices: A Multi-Institutional Study

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Abstract—Biomechanical data collected from head impacts in football have been used to characterize exposure and predict injury risk. This study sought to specifically quantify the factors that contribute towards player head impact exposure in college football practices. All players included in this study were outfitted with football helmets instrumented with accelerometer arrays (Head Impact Telemetry System). Head impact exposure was defined by the number of head impacts each player experienced in practice, the number of practice head impacts normalized by the number of practice sessions (practice head impact rate), and the 95th percentile linear and rotational resultant head impact accelerations. Practice head impact rate was observed to vary significantly with player position ($p < 0.0001$; $\eta^2 = 0.46$), team ($p = 0.0016$; $\eta^2 = 0.03$), and the number of game impacts ($p < 0.0001$; $\eta^2 = 0.03$), which served as a correlate for player ability. Even after controlling for practice participation, player position, team, and ability, differences between individuals accounted for 48% of the variance in head impact exposure in practice. This work demonstrates the importance of considering head impact exposure on a subject-specific basis rather than estimating head impact exposure from aggregate data.

Keywords—Concussion, Brain injury, Biomechanics.

INTRODUCTION

As many as 3.8 million sports-related concussions occur annually in the United States, with football accounting for the highest number among all sports.^{12,17,23,24,39} Biomechanical data collected from head impacts in football have been used to characterize exposure and predict injury risk. Sub-concussive head impact exposure from participation in football may also result in neurocognitive and brain changes.^{1,11,27,37,38} While most of these changes have been minor or lasted only temporarily, instances of prolonged changes have been observed.^{19,27,37}

Several biomechanical investigations have made use of helmet-mounted accelerometers to quantify player head impact exposure. Early work attached accelerometers to headbands to measure head accelerations.^{28,32,33} This technology was limited and obtrusive, interfering with normal gameplay. The collected data were of questionable quality, with linear acceleration measurements exceeding 1000 g for impacts with no injury reported.²⁸

Over the past 15 years, researchers have made use of the Head Impact Telemetry (HIT) System (Simbex, Lebanon, NH), which provides biomechanical data from head impacts through the use of helmet-mounted accelerometer arrays.^{2–4,8–10,13,15,16,20,21,26,31,34}

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Previous research using the HIT System investigated differences in head impact exposure between practices and games and found that head impact exposure varied by player position, with offensive and defensive linemen experiencing the highest frequency of impacts and running backs experiencing the highest magnitude head impacts.^{8-10,26} Efforts to relate these head impact biomechanics for predicting concussion or clinical outcomes were limited by small numbers of concussive impacts.^{18,21} While these studies were able to characterize head impact exposure at the collegiate level, the factors that contribute to head impact exposure still remain largely unquantified. Researchers have begun to use these aggregate exposure studies as a framework for predicting cumulative head impact exposure in non-instrumented players, who represent the overwhelming majority of the football-playing population, and observed negative neurological and cognitive outcomes for individuals who were predicted to have greater cumulative head impact exposure.²⁷

Player position and team are two external factors that can result in differences in head impact exposure between players who may experience different drills or different head impact configurations. Further, athletes who will play in games may experience differing levels of practice activity from their teammates that may affect head impact exposure. The objective of this study was to model practice head impact exposure in collegiate football players using factors thought to contribute towards head impact exposure. Practice represents a more controlled environment than games and the majority of head impacts and concussions actually occur in practices.^{9,23} As such, efforts to modify practice have a greater capacity to limit overall head impact exposure. Determining the specific factors associated with practice head impact exposure can help dictate future safety interventions. Head impact exposure was characterized by a player's total number of practice head impacts, 95th percentile linear and rotational resultant practice head impact accelerations, and practice head impact rate, which is calculated on a per session basis. We hypothesized that head impact exposure would not vary by player team, but that it would vary by player position. We also hypothesized that players who experienced more head impacts in games would have higher measures of practice head impact exposure than players with fewer head impacts in games. It was further hypothesized that measures of spring and pre-season practice head impact exposure would be greater than in-season practice head impact exposure.

MATERIALS AND METHODS

A total of 340 players from six National Collegiate Athletic Association (NCAA) football programs (two of which were military service academies) participated in this study during the 2015 and 2016 football seasons. Institutional review board approval was obtained, as was individual player consent. The number of players on each team from whom data were collected ranged from 46 to 65. One year of data was collected for 273 of the players, while 2 years of data were collected for the remaining 67 players.

Each player was assigned to one of eight position groups based on his primary position²²: quarterback (QB; $n = 12$), running back (RB; $n = 32$), wide receiver (WR; $n = 38$), tight end (TE; $n = 14$), offensive line (OL; $n = 64$), defensive line (DL; $n = 62$), linebacker (LB; $n = 54$), and defensive back (DB; $n = 64$). Running back consisted of all running backs, fullbacks, and halfbacks. Offensive line consisted of centers, guards, and tackles. Defensive line consisted of tackles and ends. Defensive back consisted of cornerbacks and safeties.

All players included in this study were outfitted with Riddell football helmets that were instrumented with accelerometer arrays (HIT System). The HIT System consists of a six accelerometer array, with each accelerometer mounted on an elastic base to maintain contact with the head throughout the impact, ensuring measurements are of head acceleration rather than measurements of helmet acceleration.²⁵ When an individual accelerometer channel exceeded a 14.4 g threshold, data acquisition was automatically triggered, capturing 40 ms of data, including 8 ms of pre-impact data. Resultant linear and rotational accelerations were then computed. If the resultant linear acceleration for any of these impacts was below 10 g, the impact data were not saved. This 10 g resultant acceleration threshold distinguishes between impact events and accelerations levels associated with non-impact events.²⁹

Head impact exposure was defined for each player using measures of frequency and magnitude. The total number of impacts a player experienced during practice sessions was considered as one measure of head impact exposure. Players were determined to have participated in a game or practice session if at least one head impact was experienced during that session. To control for the effect of participation level, practice head impact rate was defined as the number of practice head impacts divided by the number of practices in which a player participated. Head impact exposure magnitude was defined for each player as the 95th

percentile linear and rotational resultant head acceleration values, in g and rad/s² respectively. Previous research has shown that there is greater variance between players in 95th percentile linear and rotational resultant head acceleration values than with median acceleration values since the majority of head impacts football players experience are associated with lower magnitudes (< 20 g).^{30,35}

The number of players varied between the positions and teams considered in this study. Within players, the number of active sessions also varied. Equal variance and normality among samples could not be reasonably assumed, so rank-based transformations were conducted for analysis. Ties in the data were addressed by using the average method, which assigns the same average rank to duplicate values. ANCOVA was used to determine the effect of the factors position, team, and number of game impacts on the measures of head impact exposure, while controlling for the covariate of number of practices. Given that the level of individual player participation could heavily influence measures of head impact exposure, ANOVA was also used for analysis. Measures of head impact frequency were normalized by the number of active practice sessions for each player while measures of head impact magnitude were analyzed independent of the effect of practice participation. The proportion of the total sum of squares that each factor contributed was computed to determine each factor's contribution towards the overall variance in head impact exposure and was defined as η^2 , and type II sums of squares were computed for each factor. To account for some of the variance associated with the effects of specific position-team combinations, ANOVA was conducted that computed Type III sums of squares for the number of game impacts, team, and position factors and considered the interaction of team and position. This model did not include data from quarterbacks, as not every team had player data from quarterbacks in this dataset. Not every player at a given position may be exposed to the same practice activities across different teams, so it is

important to consider how position and team contribute together towards head impact exposure. Dunnett's modified Tukey–Kramer pairwise multiple comparison test was used for significant factors to determine which levels differed from each other. This *post hoc* test accounts for unequal variance and sample size among the different levels within a factor.¹⁴

Repeated measures ANOVA was used to compare the effect of time of season on head impact exposure. Previous research has shown differences in injury rates between the different times of the football season.¹² Only players with at least 10 practice sessions in each of the three parts of the season (spring, preseason, and in-season) were included in this analysis ($n = 64$). Spring football consisted of all practice sessions taking place in the months of March and April. Preseason football consisted of all practice sessions in the month of August. In-season football consisted of all practice sessions from September through the end of the season (December or January depending on the team). A significance level of 0.05 was used for all tests in this study. Pairwise Student's *t* tests with Bonferroni corrections were applied to those models in which time of season was found to be significant in order to determine where these temporal differences exist. The effect size for these differences was also calculated using Cohen's *d*.

RESULTS

During the 2015 and 2016 football seasons, a total of 232,941 head impacts, of which 167,321 were sustained during practice, was recorded for subjects in this study. For some teams, head impact data were only collected during the 2016 season, while the remaining teams had head impact data recorded for both the 2015 and 2016 seasons (Table 1). Most head impacts were observed to occur during practice sessions regardless of team or position, with the exception of quarterbacks (Table 2). Offensive and defensive linemen experienced more than half of all impacts for subjects included in this study.

TABLE 1. Number of head impacts experienced by team.

	# of players	# of total impacts	# of practice impacts	Percent practice impacts (%)
Team 1	65	51,894	38,998	75.1
Team 2	63	59,085	41,270	69.8
Team 3	57	21,390	18,720	87.5
Team 4	59	41,962	31,668	75.5
Team 5	50	26,296	14,024	53.3
Team 6	46	32,314	22,551	69.8
Total	340	232,941	167,321	71.8

For all teams, most impacts occurred during practice sessions rather than during scrimmages or games. Some teams (Team 1, Team 2, and Team 4) collected data over two seasons, while the remaining teams only collected data during the 2016 season.

TABLE 2. Number of head impacts experienced by position.

	# of players	# of total impacts	# of practice impacts	Percent practice impacts (%)
QB	12	3605	1628	45.2
RB	32	17,682	10,992	62.2
WR	38	17,158	11,590	67.6
TE	14	10,642	7146	67.2
OL	64	70,173	53,387	76.1
DL	62	60,465	46,716	77.3
LB	54	27,064	18,170	67.1
DB	64	26,152	17,602	67.3
Total	340	232,941	167,321	71.8

With the exception of quarterbacks, all positions experienced most head impacts during practice sessions. A representative sample of positions was obtained for this study. Offensive and defensive linemen experienced the highest number of impacts, while quarterbacks experienced the fewest number of impacts.

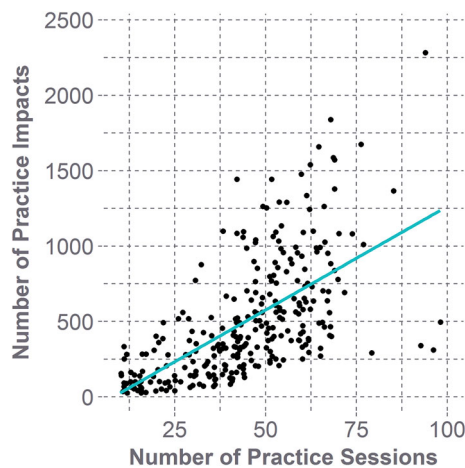


FIGURE 1. Number of head impacts experienced in practice vs. number of practice sessions participated in. As players participated in more practices, their total number of head impacts experienced in practice also increased. This simplified model was associated with a p value < 0.0001 and an adjusted $R^2 = 0.777$.

The rank of number of practice head impacts was observed to vary significantly with player position ($p < 0.0001$), the number of practices ($p < 0.0001$), team ($p = 0.0430$), and the number of game impacts ($p = 0.0005$) when using a rank-based transformation for all continuous variables. The rank of number of practices accounted for about 25% of variance in the rank of player head impacts in practice. Effectively, increased participation in practice was associated with an increase in the number of head impacts experienced by players in practice (Fig. 1). To control for the effect of participation level, ANOVA was used to assess the role of the factors of number of game impacts, team, and position on head impact exposure, with head impact frequency defined using practice head impact rate. When accounting for this, player position ($p < 0.0001$; $\eta^2 = 0.46$), team ($p = 0.0016$; $\eta^2 = 0.03$), and the

rank of number of game impacts ($p < 0.0001$; $\eta^2 = 0.03$) were all significant factors. These factors explained 52% of the variance in practice head impact rate between subjects, with the remaining 48% attributable to random variation, including individual subject differences.

To account for the potential effects of specific position-team combinations, ANOVA was conducted that computed Type III sums of squares for the number of game impacts, team, and position factors and considered the interaction of team and position. In this subset model, the interaction of team and position accounted for nearly 7% of the overall model variance. Though not a direct comparison to the ANOVA model run on the total dataset inclusive of quarterbacks, it does highlight that about 40% of the variation in head impact exposure may not be attributable to specific factors and stems from individual differences and random variation.

Player position was the factor that explained the most variance ($\eta^2 = 0.46$) in the data. Offensive and defensive linemen experienced a greater number of head impacts in practice relative to their counterparts at other positions, with the exception of tight ends. Quarterbacks experienced fewer practice head impacts than players at any other position (Fig. 2). Position was not observed to be a significant factor for 95th percentile peak linear acceleration ($p = 0.141$), though it was for 95th percentile peak rotational acceleration ($p < 0.0001$). Offensive and defensive linemen experienced lower levels of rotational acceleration than players at other positions.

Despite team testing as a significant factor, this factor explained a small amount of variance ($\eta^2 = 0.03$) in subject head impact frequency. Team 5 was associated with a lower frequency of head impacts than one team (Team 1) in this study (Fig. 3). Players on Team 5 also experienced lower magnitudes of linear acceleration ($p = 0.005$) than players on the other teams in this study. Team was not found to be a significant factor for 95th percentile peak rotational acceleration.

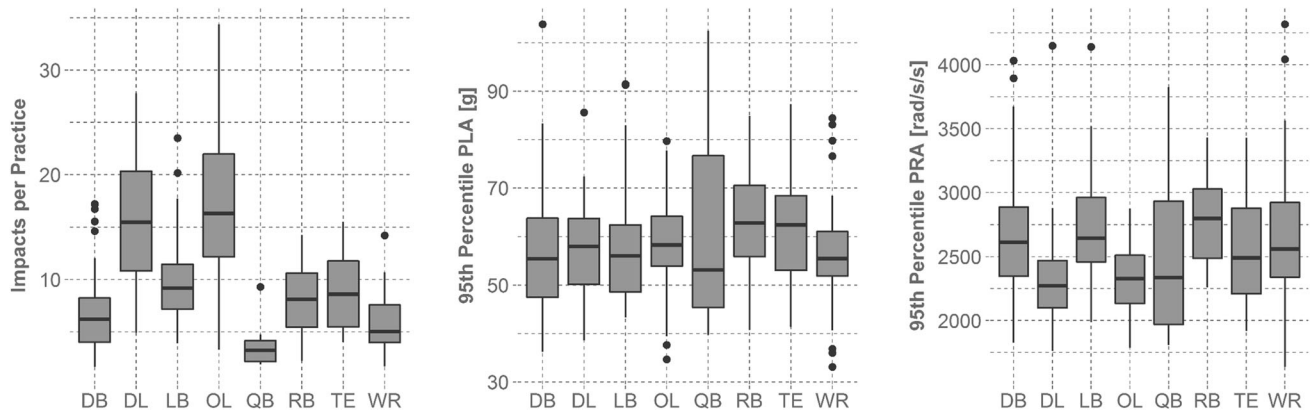


FIGURE 2. Head impact exposure by position. Impact exposure varied by position, with linemen experiencing the highest frequency of impacts. Quarterbacks experienced the fewest impacts, but exhibited the greatest interquartile range in 95th percentile linear and rotational head acceleration.

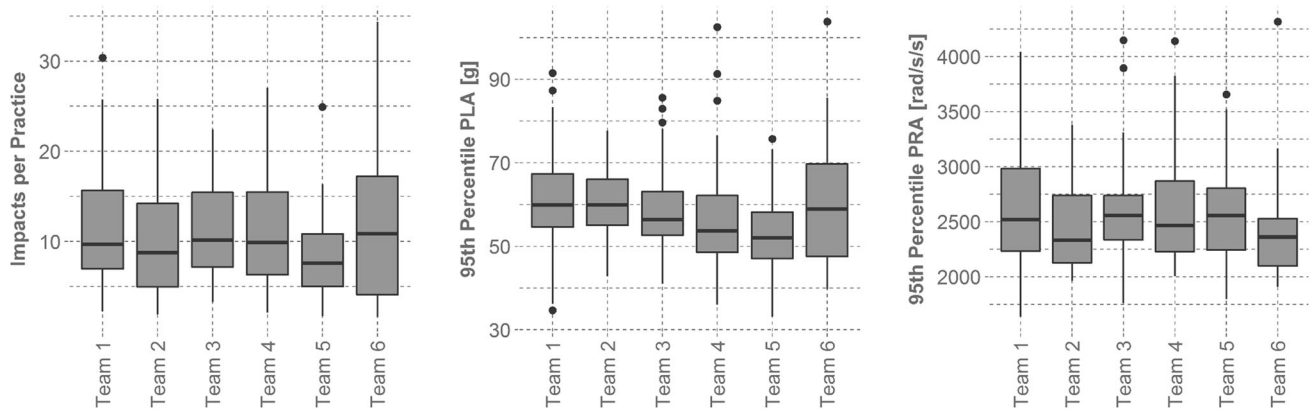


FIGURE 3. Head impact exposure by team. In general, head impact exposure did not vary between the teams in this study. Team 5 exhibited lower levels of impact frequency and 95th percentile linear acceleration relative to Team 1. There were no significant differences in 95th percentile rotational acceleration between teams.

The number of game impacts was a significant factor though it explained only 3% of overall variance in practice head impact rate. Players who experienced more head impacts in games had higher practice head impact rates. Number of game impacts was not a significant factor for either head impact magnitude measurement.

Individual head impact exposure variance was accounted for by using a repeated measures ANOVA. Time of season (preseason, spring, and in-season) was observed to be a significant factor for rank of head impact frequency ($p < 0.0001$) and 95th percentile linear head acceleration ($p = 0.002$) but not 95th percentile rotational head acceleration ($p = 0.054$). Preseason and spring practices were associated with a higher rank for practice head impact rate (Preseason: $p < 0.0001$, $d = 0.47$; Spring: $p < 0.0001$, $d = 0.80$) than in-season practices (Fig. 4).

DISCUSSION

While previous research has shown that head impact exposure for collegiate football players varies between practices and games,²⁶ the underlying factors affecting head impact exposure in practice have not been fully investigated. Researchers have recently begun to use the results of head impact exposure studies for the assessment of long-term problems.²⁷ With so few players instrumented compared to the overall population of current and former football players, these aggregate exposure measures represent gross estimates that do not consider individual variance. This individual variance, along with random variance, was found to account for 48% of variation in head impact rate for this study.

Player position was a significant factor in practice head impact rate, explaining 46% of variability in the data. Quarterbacks, who often practice in limited or no

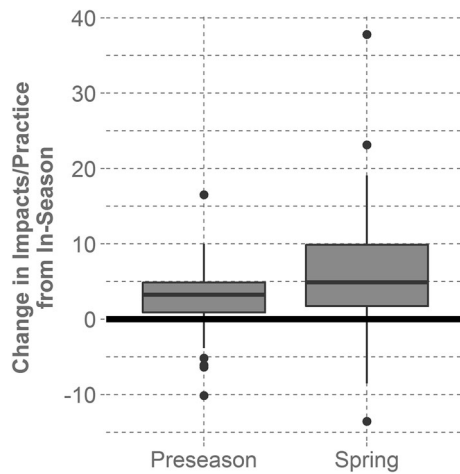


FIGURE 4. Head impact rate by time of season. Compared to the regular season, spring and preseason practices were associated with higher impact rates. Impact frequency is decreased during in-season practices, as teams must prepare to play games each week. The horizontal line at 0 on the y-axis represents no change in practice head impact rate from in-season practices.

contact situations, experienced the fewest number of head impacts among all positions. Offensive and defensive linemen experienced the highest head impact frequency of all players, though 95th percentile rotational acceleration magnitudes were lowest for linemen. Most impacts that these players experience are head-on from short closing distances, so it follows that levels of rotational head acceleration would be lower than for players at other positions with less well-described impact configurations. There were no significant differences observed between positions for 95th percentile linear head acceleration.

Team also was a significant factor in practice head impact rate, though it explained only 3% of variance in head impact exposure. One team in this study (Team 5) experienced a lower impact frequency and lower 95th percentile linear acceleration magnitude than one other team (Team 1). The differences in impact frequency and linear acceleration between Team 5 and Team 1 could stem from a difference in practice structure and intensity. Head impact exposure research at the youth football level has observed similar team effects.⁵ This skew would appear to be slight, given that impact frequency and magnitude did not vary with regard to the remaining teams in this study.

The number of game impacts was observed to be a significant factor in explaining variability in head impact rate in practice. The number of head impacts experienced in games was included in this analysis as an assumed indirect measure of player ability. It was assumed that the athletes who play the most in games would be the players with the most ability. Those athletes who play the most in games would also be

expected to sustain the most head impacts during games. While not a perfect representation of player ability, it offered a reasonable substitute that was readily available within the dataset. Injuries and other external factors can certainly affect this relationship though and should not be understated. Exposure to a greater number of head impacts in games was associated with an increase in practice head impact rate.

Specific factors were observed to explain only 52% of variation in practice head impact exposure data for the athletes in this study. The remaining 48% of variation was attributable to random variation, which includes specific position-team combinations, and individual differences in players. Recently, the individualized nature of concussion tolerance has been suggested as acceleration levels for concussions in football vary considerably. For 90% of athletes who sustained a concussion, the concussive impact was found to be among that individual athlete's top 5 highest magnitude accelerations measured.³⁶ Some of this variation may stem from biological variance or be related to individual behavioral differences. It is possible that traits like aggression or lack of inhibition which may account for variability in accelerations associated with concussion might also relate to higher levels of head impact exposure in individuals.

Head impact rate in practice was elevated for preseason and spring practices relative to in-season practice. During the season, the player depth chart has largely stabilized, with the exception of injuries or particularly strong or poor playing performance. Further, practices during the week are less severe to ensure players are ready to play in the game on the weekend. Spring and preseason practices represent a key evaluation tool for coaches to determine which athletes will play during the season. The elevated head impact rate for spring and preseason practice likely stemmed from an increased intensity of practice relative to in-season practice.

There are several limitations associated with this study. The HIT System is associated with random measurement error of $\pm 15.7\%$ for resultant linear head acceleration and $\pm 31.7\%$ for resultant rotational head acceleration. These large errors are associated with single impact measurements, and the effect of these random errors is mitigated when looking at aggregate impact data.^{6,7} While the overall group of players is representative of the positions on the football field, the composition of instrumented players for individual teams varied in this study. Players were chosen to receive instrumented helmets prior to the opening of preseason camp with the goal of achieving a representative sample of players based on position and playing time/ability. Injuries and player performance represent unknown variables that likely contributed to

some measure of variability in head impact exposure. Not all teams in this study were instrumented for the same duration of time, but measures of impact frequency were normalized on a per session basis to minimize any effects associated with these variations. Individual practice sessions may also vary, both in terms of duration and style, which is not accounted for by normalizing on a per session basis. However, regulations regarding the amount of time spent in practice likely mitigate this effect.

Head impact kinematic data were collected over two college football seasons to determine what specific factors affect head impact exposure in college football practices. There have been changes to practice structure and regulations in recent years that have worked to limit head impact exposure during practices, though preseason and spring practices were observed to result in higher impact rates than practices during the season. It was also observed that player position, team, and the number of head impacts experienced in games all contributed towards head impact exposure, but nearly half of the variance in head impact exposure was not attributable to these specific factors. This work demonstrates the importance of considering head impact exposure on a subject-specific basis rather than estimating head impact exposure from aggregate data.

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