



Published in final edited form as:

Pediatrics. 2022 November 01; 150(5): . doi:10.1542/peds.2022-057725.

Drill Intensity and Head Impact Exposure in Adolescent Football

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Abstract

BACKGROUND AND OBJECTIVES: The objective of this study was to examine head-impact exposure by intensity level and position group, and to test the hypothesis that there would be an increase in cumulative head-impact exposure between drill intensities after controlling for duration in each level with air recording the lowest frequency and magnitude and live recording the highest: air < bags < control < thud < live.

METHODS: We conducted a prospective, multisite study in 1 season with players from 3 high school football teams ($n = 74$). Each player wore a sensor-installed mouthguard, which monitored head-impact frequency, peak linear acceleration (PLA), and peak rotational acceleration (PRA). Practice drills and games were categorized by level of contact.

RESULTS: A total of 7312 impacts were recorded with a median of 67 (interquartile range:128) impacts per player. After controlling for duration, increases in head-impact outcomes by level of contact were observed (air < bags = control < thud = live). Live drills had higher cumulative head-impact frequency (45.4 ± 53.0 hits) and magnitude (PLA: 766.3 ± 932.9 g; PRA: 48.9 ± 61.3 kilorad/s²) per player than other levels ($P < .0001$). In comparison, air drills had the lowest cumulative frequency (4.2 ± 6.9 hits) and magnitude (PLA: 68.0 ± 121.6 g; PRA: 6.4 ± 13.2 kilorad/s²).

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Dr Kercher conceptualized and designed the study, coordinated and supervised data collection, conducted all data analyses, drafted the initial manuscript, and revised the manuscript; Drs Steinfeldt and Macy conceptualized and designed the study, supervised the analyses, revised the manuscript, and critically reviewed the manuscript for important intellectual content; Dr Seo supervised the analyses, revised the manuscript, and critically reviewed the manuscript for important intellectual content; Dr Kawata conceptualized and designed the study, provided the funding acquisition, supervised the analyses, revised the manuscript, and critically reviewed the manuscript for important intellectual content; and all authors approved the final manuscript as submitted and agree to be accountable for all aspects of the work.

CONFLICT OF INTEREST DISCLAIMER: The authors have indicated they have no conflicts of interest relevant to this article to disclose.

CONCLUSIONS: These data support the levels-of-contact system as a practical approach to limiting head-impact exposure in tackle football. Our findings are clinically important, because data have begun to suggest the relationship between chronic head-impact exposure and decline in brain health. Since head-impact exposure was influenced by levels of contact, regulation of the duration of certain drill intensities (eg, thud, live) may associate with reduced head-impact exposure in high school football.

High school tackle football is the most popular sport for boys in the United States, with >1 million participants annually.¹ However, participation has declined in recent years,¹ partly because of increased awareness of the risk of head injury^{2,3} and fear for its long-term outcomes. Many preliminary studies have begun suggesting that chronic exposure to head impacts, even without eliciting overt concussion symptoms,⁴ can trigger neuronal microstructural damage, altered brain activation patterns, and functional alteration.⁵⁻⁸ Although numerous rules and policies have been implemented to mitigate brain injury on the field, these changes have faced mixed outcomes. For example, college kickoff rule changes and penalizing dangerous tackling techniques in high school football appeared to decrease the number of concussions and neck injuries.^{9,10} Conversely, reduction in the number of collegiate preseason practices from 29 to 25 led to mixed results, including 1 team's average of total recorded head impacts to increase by 35%.¹¹ Thus, simply reducing the number of practice days may not be effective in minimizing head-impact exposure, defined in this study as the cumulative head impacts, peak linear acceleration (PLA), and peak rotational acceleration (PRA) experienced by participants.

USA Football, the national governing body over amateur football in the United States, has established the levels-of-contact system, which was developed to guide drill intensity in a 5 step incremental manner (air < bags < control < thud < live). A pilot study found that drill intensities correlated with cumulative head-impact exposure, where air contained the lowest number of head impacts, whereas the highest were in live.¹² This information presents a potential practical breakthrough in regulating head-impact exposure in football players. However, this study was limited by a small sample size ($N = 24$), a single high school team, and lack of control for cumulative duration spent in each drill. Understanding the role of duration spent in each drill on head-impact exposure is particularly meaningful, given that:

1. nearly all high school football coaches organize their football schedules on the basis of duration; and
2. level-of-contact guidelines would be more specific than broad restrictions on number of contact practices or contact time that erroneously treat all drills equally.

The current consensus states that the lower cumulative head-impact exposure, the safer and lower the likelihood of later-onset of neurologic disorders.¹³⁻¹⁵

To enhance generalizability of the preliminary finding, we conducted a prospective, multisite, longitudinal study in a single season to validate the previous findings in 3 football teams while addressing the previous limitations. Our primary hypothesis was that there would be an incremental increase in cumulative head-impact exposure between drill intensities after controlling for duration in each level, with air recording the lowest head-

impact frequency and magnitude, and live recording the greatest: air < bags < control < thud < live. Since frequency and sum of PLA and PRA have been shown to associate with acute and chronic changes in neurologic outcomes (eg, brain-injury blood biomarkers, diffusion tensor imaging),¹⁶⁻²¹ these kinematic variables were set as our outcomes. We also hypothesized that linemen and hybrid athletes (eg, running backs, linebackers) would have greater cumulative head-impact exposure in thud and live, compared with skill position athletes (eg, receivers, defensive backs, quarterbacks). Given that most head impacts in football are <30 g, our third hypothesis was that average head-impact magnitude would not differ between drill intensities and position groups. We further quantified head impacts by magnitude thresholds and expected high magnitude impacts to occur more frequently in thud and live compared with air, bags, and control.

METHODS

Participants

This multisite, observational study included 74 male football players at 3 high schools in the Midwest. Participants were predominantly White (88%) and non-Latino/Hispanic (92%). The study used head-impact kinematic measurement through sensor-installed mouthguards, as well as collection of detailed practice plans, video recordings, and observation of practices and games to identify levels of contact, drill types, drill durations, and video validation of head impacts throughout the 2021 football season. Inclusion criteria included being a high school student and member of the football team. These football players had to be willing to wear sensor-installed mouthguards at football practices and games. The research team obtained approval from the district school board. All participants and their legal guardians provided informed consent, and the Indiana University institutional review board approved the study protocol (1904461516).

Study Procedures

Parents and football players completed a questionnaire regarding demographics, contact sport history, and football contextual questions. During the preseason data collection, participants were custom-fitted with “boil-and-bite” mouthguards (Prevent Biometrics, Inc.). Participants wore the mouthguard for all contact practices ($n = 37-46$), scrimmages ($n = 1-2$), and games ($n = 4-12$) from preseason training camp (August 2) to the end of the season (October 29–November 5). Video of practices on Mondays, Tuesdays, and Wednesdays, as well as all games (Fridays and/or Saturdays), were recorded. Thursday’s “walk-through” practices were excluded because of being noncontact days. Video data were collected using Hudl video software (Agile Sports Technologies, Inc.). Participants’ playing positions were categorized on the basis of the previous literature^{22,23} into 3 groups as follows: 30 linemen (defensive linemen, offensive linemen), 25 hybrid (tight ends, running backs, linebackers), and 19 skill (receivers, defensive backs, quarterbacks). In accordance with USA Football levels-of-contact guidelines,²⁴ head impacts were categorized by air, bags, control, thud, and live.

Measures

Level of Contact—The 5 levels-of-contact are air, bags, control, thud, and live, with air being estimated to have the lowest intensity and live being the highest.²⁵ See the video abstract for example video of each level of contact. Air is defined as drills being run unopposed and without contact. Bags is defined as drills being run against a bag or soft-contact surface. Control is defined as drills being run at an assigned speed until the moment of contact. It does not involve tackling; rather, players stay on their feet. Thud is defined as drills being run at a competitive, fast speed through the moment of contact. It does not involve full tackling; rather, contact is above the waist and players stay on their feet and a quick whistle ends the drills. Live is defined as drills being run in game-like conditions that include live-drills during practice and real games. Live should be the only time players are allowed to fully tackle another player to the ground. Although only 1 school used the control level of contact, that school had 43 players and made up 57% of our sample.

Head-Impacts Kinematics—This study used an instrumented Prevent Biometrics Impact Monitor Mouthguard (IMM) system that incorporates data from a triaxial accelerometer (ADXL372) and gyroscope (BMG250) to provide 6-degree-of-freedom spatial and temporal estimates of linear and rotational head accelerations during impact.²⁶ When an axis of acceleration exceeds a preset threshold of 5 g to 15 g, an impact event triggers data collection, and the data are processed on-board in firmware within the mouthguard and then transmitted wirelessly over Bluetooth to a nearby mobile application, which then uploads the data to a secure, cloud-based portal. The sampling rate is 3.2 kHz, and impact data are collected for 50 milliseconds. The on-board firmware in the mouthguards can store up to 460 impact data and has internal sensors to confirm proper wearing of the mouthguard during play.^{27,28} In the current study, head impacts with PLAs >10 g were included to distinguish kinematic events, such as jumping and running, from head impacts.²⁹ The outcome measures included frequency, PLA, and PRA.

Head-Impact Validation Against Film Analysis—The goal of the film analysis was to classify that each head impact detected by IMM was either a real impact or a spurious measurement. The primary placement of the camera was at the press-box. Head-impact events recorded by the IMM were time-synchronized with video and categorized into each level of contact. Randomly stratified head-impact data, accounting for 25% of all head impacts, were equally sampled from each level of contact. An impact could be either to an athlete's head or body, because both impart acceleration to the head.³⁰ Each impact was classified as either a true positive or false positive (FP) impact. True positive impacts were defined as time-matched impact to the body or head between the IMM data and film analysis. FP impacts were defined as IMM detected an acceleration, but no impact observed in the film. FP events could be generated from actions such as running, jumping, or taking off and putting on a sensor.³¹ Positive predictive values (PPVs) or precision were computed by true positives divided by true positives plus false positives.

Data Analysis

To test the first 2 hypotheses that there would be an incremental increase in cumulative head-impact exposure between drill levels of contact and by position group, we used 1-way and

2-way repeated measures analysis of variance models on 5 levels of contact and 3 position groups, respectively. The 3 dependent variables were season-long cumulative head-impact frequency, PLA, and PRA. The independent variables were level of contact and position group. Each of our 3 dependent variables were assessed with 2 approaches:

1. as a cumulative outcome; and followed by
2. controlling for accumulated duration by dividing each outcome by the time spent in each level of contact.

Dividing by duration was done to ensure that the outcomes controlled for the cumulative duration spent in each level of contact. Without this adjustment, it would have been possible that simply spending more time in certain levels of contact may have been the primary factor driving greater cumulative head-impact exposure. The assumption of sphericity was violated as assessed by Mauchly's test ($P < .0001$), and, thus, the Greenhouse-Geisser correction was used to report within subject outputs. When significant effects were found, Tukey's post-hoc tests were used to examine where the specific head impact outcome differences occurred. For the exploratory aim, we used descriptive methods to present the frequency of head impacts that occurred in each level of contact within 3 magnitude ranges: 10 to 20 g, 20 to 60 g, and 60 to 100 g. These thresholds were selected on the basis of published head-impact kinematic research categorizing <20 g as minimal magnitude,^{32,33} and 60 g³⁴ previously being thought to be a potential threshold to induce concussion. Analyses were performed in R 4.0.3,³⁵ and the level of statistical significance was set to $P < .05$.

RESULTS

Demographics and Overall Head Impact Exposure

A total of 7312 head impacts were recorded in 74 football players throughout the season, with a median of 66.5 hits per player, PLA of 1035.1 g per player, and PRA of 62.3 kilorad/s² per player. In line with past research,³² the head-impact distribution showed a strongly positive skew, with a median PLA of 14 g (interquartile range [IQR]: 7.4–20.6) and PRA of 0.929 krad/s² (IQR: 0.107–1.751) per impact. Demographics and head-impact data are presented in Table 1.

Video Validation of Head Impacts

Of the 1785 head impacts that were selected to be reviewed for video validation, 1670 head impacts were visually confirmed, whereas 115 were not, which equates to a PPV of 93.6%.

Level-of-contact–Dependent Cumulative Head Impact Exposure

There was a statistically significant difference in head-impact exposure between levels of contact in the overall sample (F , [1.70–124.30] = 37.98, $P < .0001$, $\eta^2 = 0.34$; PLA, F [1.53–111.90] = 36.53, $P < .0001$, $\eta^2 = 0.33$; PRA, F [1.72–125.90] = 32.14, $P < .0001$, $\eta^2 = 0.31$). For impact frequency and PLA, Tukey's post-hoc tests revealed incremental increases as levels of contact intensified, except for between bags and control (air < bags = control < thud < live). For PRA, Tukey's post-hoc tests indicated incremental increases between

control, thud, and live (air = bags = control < thud < live). See Fig 1A-1C for the visual trend of the outcomes and Supplemental Table 2 for post-hoc results.

Cumulative Duration by Levels of Contact

Football players spent the greatest amount of time in the live, followed by thud, air, bags, and control. Cumulative duration is presented for the full sample, as well as separated by school in Supplemental Fig 6A and 6B. After controlling for amount of time players spent in each level of contact, cumulative head-impact frequency, PLA, and PRA were independent of duration spent in each level of contact, as demonstrated by a statistically significant differences in head-impact exposure between levels of contact (F [2.54–185.70] = 24.21, $P < .0001$, $\eta^2 = 0.25$; PLA, F [2.46–179.40] = 22.88, $P < .0001$, $\eta^2 = 0.24$; PRA, F [2.72–198.60] = 16.24, $P < .0001$, $\eta^2 = 0.18$). For instance, players spent 5144 minutes in air and had 310 total head impacts, as opposed to 6901 minutes in thud with a total of 3360 impacts. Tukey's post-hoc analysis revealed significant differences between air and bags, as well as between control and thud (air < bags = control < thud = live), meaning air had the lowest cumulative head-impact exposure. Bags and control were significantly higher than air, followed by thud and live, which had the highest head-impact exposure and were significantly higher than all other levels. See Fig 2A-2C for the visual trend of the outcomes and Supplemental Table 3 for post-hoc and analysis of variance results. Players who did not incur any recorded head impacts were not excluded from any particular drills or games because they can participate (be exposed) in any drill or game and not incur any head impacts.

Position Group Differences

The 3 position groups exhibited a similar incremental increase in head-impact frequency and magnitude by level of contact. The only significant difference in head-impact exposure within a level of contact was between the hybrid and skill position groups in live (frequency: F $P < .001$, 95% confidence interval [CI] [11.70–70.03]; PLA: $P < .001$, 95% CI [229.70–1226.00]; PRA: $P = .035$, 95% CI [1133.00–70434.00]). Although the trend was similar across position groups, the skill position group had the lowest cumulative frequency and magnitude compared with the linemen and hybrid athletes, but these within-level differences were not significant. See Fig 3A-3C for the visual trend of the outcomes and Supplemental Table 4 for head-impact kinematics for each level of contact.

Average Magnitude Per Head Impact by Levels of Contact and Position Group

Average magnitudes per head impact were similar across levels of contact and position groups, except for significant differences in the skill position group in air, which was significantly less than the average impact in 9 other groups (Fig 4). See Supplemental Table 5 for median PLA and PRA in each level of contact.

Magnitude Thresholds

The descriptive analysis of magnitude thresholds (10 to 20 g, 20 to 60 g, 60 to 100 g) identified that low and moderate magnitude impacts were most prevalent in live, followed by thud, control, bags, and air. Eight of the 9 high magnitude impacts (60 to 100 g) were

identified during the live level of contact. See Fig 5A-5C for a visual representation of these magnitude thresholds.

DISCUSSION

Because the consequences associated with chronic head impacts have begun to unravel,^{5-8,15} an exploration of practical approaches for minimizing head impacts has become increasingly important. The current study yielded 3 key findings. First, head-impact exposure (eg, cumulative number of head impacts, PLA, PRA) increased as level of contact increased (air < bags = control < thud < live), and this near stepwise trend in head-impact exposure was sustained after controlling for duration spent in each level of contact. Second, a recurring pattern emerged between position groups within most levels of contact, where linemen and hybrid athletes experienced greater head-impact exposure than the skill position group. This finding was most notable in thud and live. Third, the incremental increase in head-impact exposure was consistent across low and moderate magnitude thresholds, and the greatest number of high magnitude impacts occurred in live. Together with our previous study,¹² our data support USA Football's levels-of-contact system to guide the intensity of practice structure, while in turn regulating head-impact exposure. Simultaneously, this study sets the foundation for an interventional study to examine whether, and how effectively, the level-of-contact system can mitigate head-impact burden in adolescent football players.

Previous literature has analyzed structural aspects of tackle football and found head-impact exposure to differ on the basis of position group, coaching strategy, play type, drill type, and tackling/coaching technique.³⁶⁻³⁹ Additionally, given that individual characteristics (eg, behavioral differences, aggression) can yield up to 48% of variance in head-impact exposure,⁴⁰ it is not surprising that rule changes and policy interventions that do not address or account for structural aspects (eg, position group, drill type) related to head-impact exposure have led to inconsistent results.^{11,41,42} These challenges may be further compounded by researchers using different definitions of head-impact exposure and exposure time as the field continues to seek the most reliable metrics and research designs to inform safety policy and understand the potential for brain injury. One study examining the effect of a statewide reduction in allowable contact practices found an average decline in head-impact exposure of 42% across all players.⁴¹ In contrast, the National Collegiate Athletic Association has eliminated 2-a-day practices and reduced the number of allowable full-contact practices in the preseason from 29 to 25. However, these policy changes have led to increases in head-impact exposure by 26% after the 2-a-day practice reduction,⁴² and total number of head impacts increasing by 35% in 1 team after reducing the number of practices.¹¹ One reason for these mixed findings is that, when teams are faced with regulations reducing the number of practices, they may be more prone to conduct more intense practice drills with the remaining practice time. Thus, addressing drill intensity rather than treating all drills equally may improve this ambiguity. Our first key finding of a near stepwise increase in head-impact exposure (eg, air < bags = control < thud = live) suggests that the limitation of impact-prone practice drills may reduce overall head-impact exposure. This data are significant because athletes who are diagnosed with a concussion have shown to be exposed to frequent head impacts before the concussive event.^{22,43} This

makes a strong case that minimizing head-impact exposure, especially before games, can be done by incorporating less impact-prone drills (eg, air, bags, control) instead of thud or live.

There were 2 other key findings in this study. One was the differences in cumulative head-impact exposure by position group, where linemen and hybrid groups had greater head-impact exposure in all levels of contact compared with the skill group. Despite this visual trend, the only statistically significant group difference was between the hybrid and skill groups in live, and the limited statistical differences may be because of lack of sample size. These findings are consistent with antecedent literature,^{12,36,37,40} while demonstrating the trend within the levels-of-contact system. The final key finding was that the trend of increasing head-impact exposure was also consistent across magnitude thresholds (10 to 20 g, 20 to 60 g, 60 to 100 g), yet the differences in clinical implications of various combinations of high versus low magnitude impacts remain uncertain.

Overall, these data provide insights into more refined practice guidelines, accounting for position group and levels of contact. Specifically, quantifying cumulative head-impact exposure within the levels-of-contact system provides empirical evidence for this feasible approach to football safety guidelines. The implication for this policy strategy will require greater willingness of stakeholders (eg, coaches) to adopt the policy. An emphasis on less time in thud and live and more time in lower exposure drills such as air, bags, control may meet this required willingness of coaches in that it requires a relatively low amount of effort from coaches to implement into their practice plans, thus helping with the scalability of the strategy. However, evaluation of coaches' willingness to adopt the levels-of-contact guidelines warrants further investigation.

This study has several limitations. First, the study sample would have benefited from more racial, ethnic, and geographic diversity, along with representation from a greater number of coaching styles. A nationwide study should be the next step to validate that these results are replicable. Nonetheless, our 3 sites demonstrated the same trend, supporting the generalizability of our findings. Second, the use of cumulative head-impact kinematic/exposure metrics is inherently limited in that the metric cannot differentiate between individual combinations of head impacts (eg, 70 g + 30 g vs 50 g + 50 g). It is possible that the clinical significance of different combinations of head impacts may influence varying head-impact sequelae. Additionally, the duration variable could not differentiate between individuals who may have participated in different amounts of repetitions. Despite these measurement limitations, in combination with forthcoming advancements in our understanding of neurologic consequences associated with head impacts, this type of testable and practical hypothesis using cumulative metrics and teamwide level-of-contact durations can help researchers quantify differences in what may constitute a safe duration or number of plays between drill intensity levels and position groups.

In conclusion, empirical support for the levels-of-contact system in the current study provides further evidence that the system may present a practical means to regulate head-impact exposure. The study results point to the importance of continued research dissecting the structural elements of football practice, such as intensity level, to determine practical,

feasible, and scalable approaches to minimizing head-impact exposure while maintaining tackle football as a viable physical activity opportunity.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

FUNDING:

Supported by National Institutes of Health–National Institute of Neurological Disorders and Stroke, grant no. R01NS113950. The funder had no role in the design or conduct of this study.

ABBREVIATIONS

CI	confidence interval
FP	false positive
IMM	Impact Monitor Mouthguard
IQR	interquartile range
PLA	peak linear acceleration
PPV	positive predictive value
PRA	peak rotational acceleration

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WHAT'S KNOWN ON THE SUBJECT:

Chronic head-impact exposure can trigger neuronal microstructural damage, altered brain activation patterns, functional alteration, and early onset cognitive impairments. Evaluation of these phenomena is complex because exposure differs on the basis of competitive level, position group, playing style, and individual factors.

WHAT THIS STUDY ADDS:

These data support the use of USA Football's levels-of-contact system as a practical approach to guiding the intensity of practice structure, while warranting further investigations into structural elements of drill intensity to determine effective approaches at reducing head-impact burden.

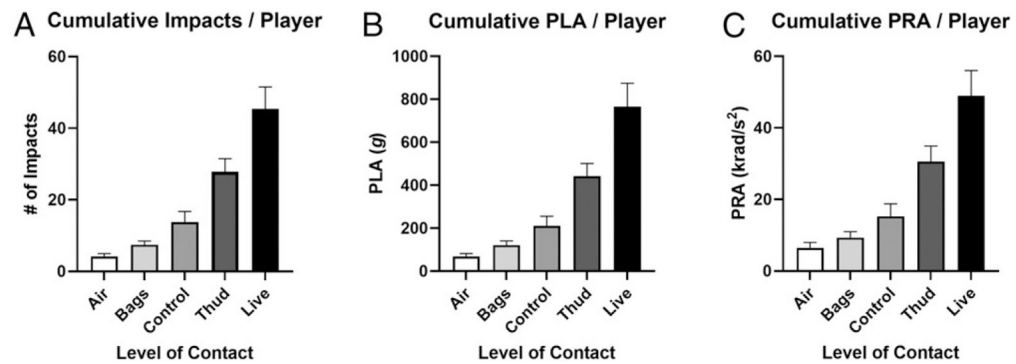


FIGURE 1.

Cumulative head-impact kinematics between levels of contact. Cumulative (A) head impact count, (B) PLA, and (C) PRA per player were influenced by the level of contact in an incremental manner, with air being the lowest and live being the highest. Data are presented as mean $\pm$ SD.

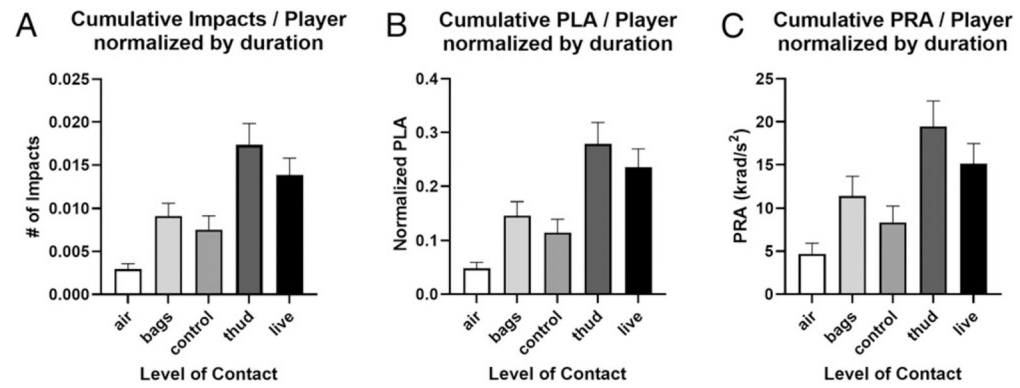
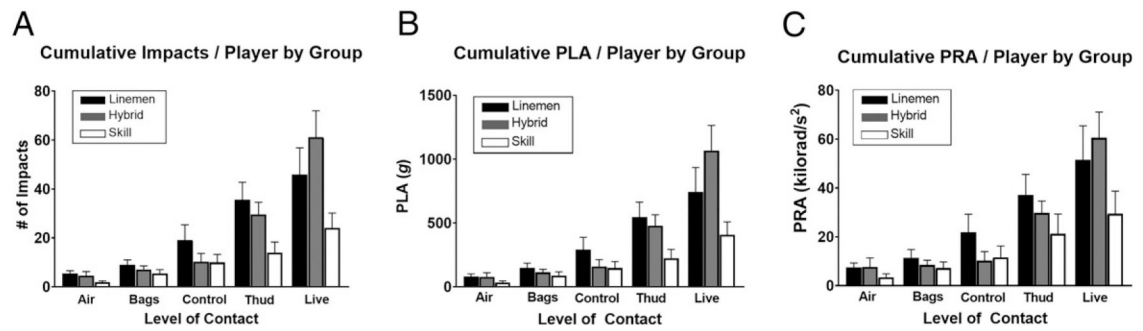


FIGURE 2.

Cumulative head-impact kinematics between levels of contact after controlling for duration in each level. Cumulative (A) head-impact count, (B) PLA, and (C) PRA per player were influenced by the level of contact. Data are presented as mean $\pm$ SD.

**FIGURE 3.**

Group-dependent cumulative head-impact exposure between levels of contact. All 3 groups shared a similar incrementally increasing pattern in cumulative head-impact kinematic outcomes per player, with air being the lowest and live being the highest. Data are presented as mean $\pm$ SD.

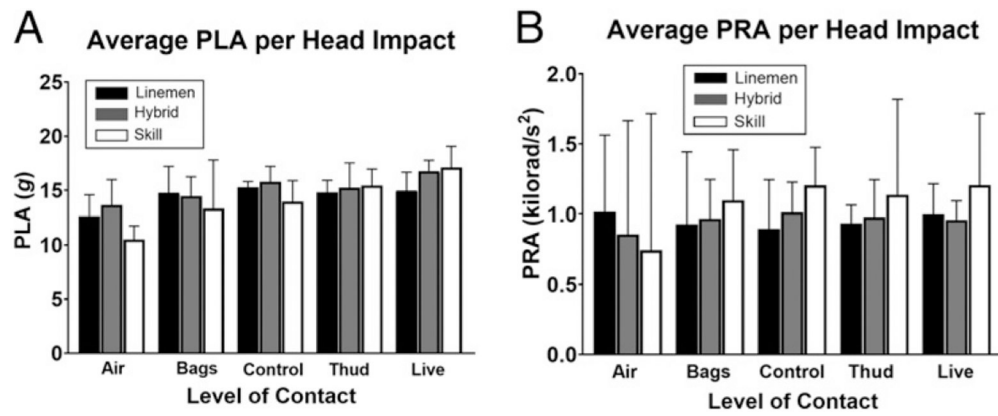


FIGURE 4.

Average head impact magnitude per impact between levels of contact and group. Average PLA per head impact (A) was influenced by the level of contact ($P < .001$), whereas average PRA per head impact (B) was not ($P = .219$) across levels of contact and position groups. Data are presented as mean $\pm$ SD.

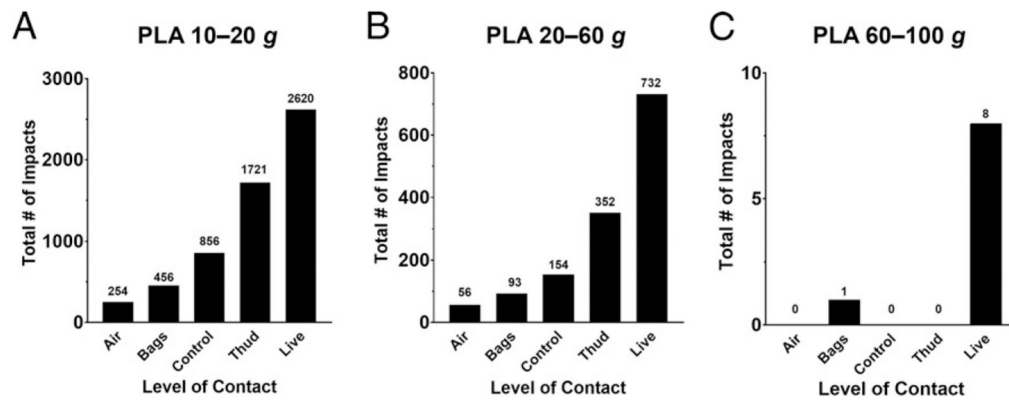


FIGURE 5.

Frequency of head impacts within various magnitude ranges. A total number of head impacts was categorized into PLA (A) 10 to 20 g, (B) 20 to 60 g, and (C) >60 g. The incrementally increasing pattern of greater head-impact exposure was observed in (A) and (B).

Video abstract.

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TABLE 1

Group Demographics and Head-Impact Kinematics

Variables	Overall	Linemen	Hybrid	Skill
<i>n</i>	74	30	25	19
Sex (%)	74 M (100)	30 M (40.5)	25 M (33.8)	19 M (25.7)
Age, y	15.9 ± 1.1	16.1 ± 1.0	15.9 ± 1.2	15.8 ± 1.2
BMI, kg/m ²	26.7 ± 5.5	30.9 ± 5.7	25.3 ± 3.1	22.1 ± 2.2
No. of previous concussion, <i>n</i> (%)				
0	63 (85.1)	27 (90.0)	22 (0)	14 (73.7)
1	10 (13.5)	3 (10.0)	3 (12.0)	4 (21.1)
2	1 (1.4)	0 (0)	0 (0)	1 (5.3)
Tackle football experience, y	5.3 ± 3.0	5.0 ± 3.0	6.1 ± 3.1	4.6 ± 2.8
Race, <i>n</i> (%)				
White	65 (87.8)	27 (90.0)	23 (92.0)	15 (78.9)
Black/African American	7 (9.5)	2 (6.7)	1 (4.0)	4 (21.1)
Asian American	0 (0)	0 (0)	0 (0)	0 (0)
American Indian or Alaska Native	0 (0)	0 (0)	0 (0)	0 (0)
Native Hawaiian or Pacific Islander	0 (0)	0 (0)	0 (0)	0 (0)
Multiracial	2 (2.7)	1 (3.3)	1 (4.0)	0 (0)
Ethnicity, <i>n</i> (%)				
Not Latino/Hispanic	68 (91.9)	27 (90.0)	24 (96.0)	17 (89.5)
Latino/Hispanic	6 (8.1)	3 (10.0)	1 (4.0)	2 (10.5)
Impact kinematics for season, median (IQR)				
Cumulative impact count	66.5 (128)	60 (136)	98 (78)	55 (62)
Cumulative PLA, g	1035.1 (1994.0)	891 (2062.2)	1715.3 (1475.0)	829.2 (839.9)
Cumulative PRA, kilorad/s ²	62.3 (116.3)	57.54 (105.3)	110.2 (108.6)	42.6 (79.3)

BMI, body mass index; IQR, interquartile range; M, male; y, year.