HHS Public Access
Author manuscript
J Appl Biomech. Author manuscript; available in PMC 2024 January 25.

Published in final edited form as:
J Appl Biomech. 2023 June 01; 39(3): 157–168. doi:10.1123/jab.2022-0196.

Characterization of head acceleration exposure during youth football practice drills

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Abstract

Many head acceleration events (HAEs) observed in youth football emanate from a practice environment. This study aimed to evaluate HAEs in youth football practice drills using a mouthpiece-based sensor, differentiating between inertial and direct HAEs. Head acceleration data was collected from athletes participating on two youth football teams (ages 11–13) using an instrumented mouthpiece-based sensor during all practice sessions in a single season. Video was recorded and analyzed to verify and assign HAEs to specific practice drill characteristics, including drill intensity, drill classification, and drill type. HAEs were quantified in terms of HAEs per athlete per minute and peak linear and rotational acceleration and rotational velocity. Mixed effects models were used to evaluate the differences in kinematics and generalized linear models

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Conflict of Interests
The authors declare that they have no known conflicts of interest. Dr. Joel D. Stitzel and Dr. Jillian E. Urban (authors) have a patent pending on the mouthpiece instrumentation utilized in this study. The results of this study are presented clearly, honestly, and without data manipulation, fabrication, or falsification.

were used to assess differences in HAE frequency between drill categories. A total of 3,237 HAEs were verified and evaluated from 29 football athletes enrolled in this study. Head kinematics varied significantly between drill categorizations. HAEs collected at higher intensities resulted in significantly greater kinematics than lower intensity drills. The results of this study add to the growing body of evidence informing evidence-based strategies to reduce head impact exposure and concussion risk in youth football practices.

Introduction

There is increasing evidence that repetitive head impacts in contact and collision sports may be associated with short- and long-term changes in cognitive function, and may influence an individual's risk of concussion. However, information remains limited regarding the relationships between youth sport participation and long-term neurological affects.[1–12] Previous studies have also concluded that youth (ages 9–12) football athletes endure head acceleration events (HAEs) similar to the magnitude of those sustained by high school or college football athletes.[13–15] In recent years, youth football has seen a decline in athlete participation with racial/ethnic minorities and adolescents from households with lower socioeconomic status being less likely to participate.[16] This has been attributed to increased public awareness of concussion risks and long-term effects of repetitive head impacts. Despite rising concerns, more than 2.5 million youth football players participate in the sport each year.[17,18] Therefore, it is critically important to accurately characterize head acceleration experienced by youth athletes to adequately inform prevention efforts.

Steps have been taken to address and assure athlete safety by some youth football organizations such as Pop Warner. These include limitations on contact in practice and exclusion of head-on blocking or tackling drills in which athletes begin more than three yards apart. Additionally, the amount of contact allowed at each practice has been reduced to only include a maximum of 1/3 of total practice time in certain organizations like Pop Warner.[19] However, Kelley et al demonstrated that teams with less player-to-player contact time may still experience higher head impact exposure due to the intensity of contact.[20] Experts have also suggested a variety of rule changes to the sport such as the prohibition of offensive and defensive lineman starting in a three-point stance and limiting full contact practice to no more than two days per week for all players.[21–23] Educational programs, such as Heads Up Football, have been adopted by some organizations with the intentions of informing coaches of the dangers of improper equipment and high intensity contact practice drills. The results of equipping coaches with strategies to decrease concussion risk in a practice environment have been positive.[14,22,24] Evaluations of strategies that can be utilized to reduce the risk of HAE exposure in contact sports found that limiting contact practice in youth football, along with rule enforcement to reduce head contact, are effective when attempting to increase athlete safety.[25] However, not all football organizations have adopted similar educations and rule changes. Most youth-football organizations operate on a community level, allowing coaches, who are often volunteers, a significant degree of freedom to structure practices as they see fit. A previous study suggested that relying on coaches at the community level to voluntarily adopt biomechanics informed interventions can result in less than satisfactory implementation.[26]

Despite the inherent risk of head injury in contact and collision sports, there is a well-documented benefit from participating in these sports, especially during adolescent development. Previous studies demonstrate that athletes participating in team sports such as football are more likely to be physically active, exhibit improved functional movement skills, and possess improved mental health, leading to better social identity and social adjustment.[27] Efforts to improve athlete safety should be informed by biomechanical evidence; therefore, further research in the subject of practice structure and specific practice drill contact characteristics is required to maximize both athlete safety and the benefits of participating in the sport of football.

Prior studies have highlighted the effectiveness of rules, regulations, and practice structure in curbing HAE exposure among athletes in the sport of football.[25,28,29] A study conducted by Kelley et al concluded that exposure to HAEs varies significantly between practice drills and that full-speed tackling and blocking drills resulted in the highest head impact magnitudes.[20,30] Campolattano et al documented the tendency for higher-magnitude HAEs to occur in practice than competitions and that practice exposure could be mitigated by modifying athlete time spent in high contact drills and even recommended the elimination of certain drills entirely.[31] Both HAE frequency and magnitude have been previously studied.[20,30,32–36] Kelley et al noted the tendency for multi-player vs player tackle drills to increase the frequency of HAEs.[30] Frequency and magnitude of HAEs contribute to the cumulative burden of head impact exposure and can influence brain health and increase concussion risk.[7,8,37–39] It is imperative that both HAE frequency and magnitude be evaluated when characterizing differences between football practice drills.

Few studies have examined the differences between HAEs among different practice drills and most have used helmet-based sensors.[11,40] Additionally, a previous study conducted by Tierney et al highlighted the importance of differentiating between contact events, including inertial (indirect) head loading events, when measuring HAE exposure in football.[41] Therefore, the objective of this study was to evaluate HAEs in youth football practice drills using a mouthpiece-based sensor. Additionally, this study sought to differentially evaluate direct and indirect HAEs across drills to better inform safety efforts to reduce head impact exposure in practice.

Methods

Head acceleration data were collected from athletes participating on two separate youth football teams (ages 11–13). The study protocol was approved by the Wake Forest University School of Medicine Institutional Review Board. Participant assent and parent/legal guardian consent was obtained prior to enrollment in the study.

Mouthpiece Sensor Fabrication:

A digital scan of the dentition of each enrolled athlete was collected (TRIOS intraoral scanners; 3Shape A/S, Copenhagen, Denmark). A 3D model was created from the digital scan and printed to create custom-fit mouthpiece sensors. A soft mouthguard overlay was integrated into the acrylic mouthpiece sensors to provide greater skull coupling and comply with mouthguard functions as recommended by football organizations. The mouthpiece sensor system is comprised of an accelerometer and an angular rate sensor mounted on a custom print circuit board to measure head kinematics with six degrees of freedom[32] and has been previously validated for kinematic measurements and used to collect data in hockey, soccer, and gymnastics.[42–45] The mouthpiece sensors were set to record data when the accelerometer exceeded 5 g on any axis for at minimum three milliseconds; data were recorded 15 milliseconds prior, and 45 milliseconds post trigger. Previous head impact sensors have used a 10 g resultant threshold to eliminate HAEs determined to be inconsequential non-impact events (e.g., running and jumping).[35,46–48] The mouthpiece sensors were set to collect data when acceleration above 5 g was detected on any axis for longer than 3 ms to maximize the number of captured HAEs by the mouthpiece.[42] Video-verification of each HAE was completed to ensure non-impact events were not included in the data set.

On-Field Data Collection:

The athletes (n = 29) were instrumented with the mouthpiece sensors for a single fall football season, including all contact practices and games. At team sessions, mouthpiece sensors were distributed to study participants. A single camera (Sony, Model: FDR-AX43; 1080p, 60 fps) was mounted in a location in close proximity to the center of the football field and elevated approximately 10 feet above the field with a clear view of all study participants. This camera was time aligned to the mouthpiece client by displaying the mouthpiece client time (HH:MM:SS) on the first frame of video. Using this time alignment, video was paired to recorded events from the mouthpiece sensors in the time window that the session was taking place. During each contact practice session, a member of the research team noted the beginning and end times for all drills. At session conclusion, all mouthpiece sensors were collected from study participants. Event data were downloaded from the devices and all devices were sanitized between sessions.

Video Review:

A custom video analysis program developed in MATLAB (MathWorks, Natick, MA) was used to independently review all events recorded by the mouthpiece sensors.[49] The exact event time as recorded by the mouthpiece sensors was viewed alongside the time-synchronized video and events were categorized using a variety of drill characteristics. The practice drill characteristics coded in this study included drill intensity, drill classification, and drill type. Drill intensity was used to categorize drills by level of contact and was evaluated according to the levels of contact defined by USA Football.[50] Drill classification was used to categorize drills by the number of athletes participating in a drill and was adapted from a study conducted by Kelley et al.[30] Drill type was created with input from the coaches of Teams A and B based upon drills that each team utilized in practice sessions. Definitions for each drill characteristic category are provided in Tables I. False events (i.e., a sensor recording due to an athlete dropping the mouthpiece sensor onto the ground or collecting an event while not participating in a practice drill or competition) identified during film review were marked and excluded from analysis. Direct HAEs (i.e., events where the helmet of the athlete was directly impacted) and indirect HAEs (i.e., events where the primary collision to the body of the athlete resulted in inertial motion of the head) were identified using video analysis. In the case that an event was unclear on video, the characteristics of the moments surrounding the event and a second opinion from another video reviewer were used to identify events with the highest degree of certainty.

Interrater reliability of video reviewers was assessed by comparing the coding of practice sessions among reviewers. The contact characteristics identified by each independent reviewer were compared against each other and Cohen's kappa was calculated.[51] The results of the interrater reliability were deemed to be acceptable (minimum agreement $\kappa > 0.60$). Any discrepancies in video review were addressed to ensure consistent event characterization across reviewers.

Signal Analysis:

The normalized linear acceleration amplitude spectra were calculated for all verified HAEs using thresholds of −30 dB and 1500 Hz were used on the peak normalized (units of dB) amplitude spectra to identify HAEs with abnormal frequency content. All HAE signal frequency content was further examined using the rotational acceleration amplitude spectra for the remaining the remaining HAEs. HAEs that exceeded the 99.9th percentile rotational acceleration amplitude at each frequency domain were excluded.

Statistical Analysis:

Following the methods described by Rich et al, peak resultant linear acceleration, rotational acceleration, and rotational velocity were calculated for each true positive event (i.e., an event that was recorded with the mouthpiece sensor and simultaneously visible on video).[42] To calculate event rates, the number of true-positive events for a given athlete was divided by the time spent in a specific drill on a given day. HAEs were further stratified by direct HAEs and indirect HAEs. Peak resultant linear acceleration, rotational acceleration, rotational velocity, and HAE rates were log-transformed for analyses due to the right skewed distribution of the data. Mixed effects models were used to evaluate differences in kinematics among drill categories (drill intensity, drill classification, and drill type), controlling for repeated measures among participants. A secondary analysis using mixed effects models was conducted to evaluate kinematics stratified by direct HAE and indirect HAE. All models were adjusted for confounding factors of team and date. HAE rates among drill categories were compared using generalized linear models, with adjustment for team and date. Due to low number of events (n) after indirect HAE and direct HAE stratification, Skelly (n = 27) and 1 on 1 Pass (n = 36) were excluded from the drill type analysis. A Bonferroni correction was applied for all statistical tests control for multiple comparisons. All statistical analyses were completed using SAS statistical analysis software (Version 9.4). Events exceeding 25 g peak resultant linear acceleration were classified as high magnitude events and the total number of events above this threshold per drill was tabulated. The 25 g threshold was chosen as it approximately represented the 95th percentile from the distribution of linear acceleration and was thus used as the cutoff for defining the top 5% of the data. Additionally, to aptly compare the results of this study to past studies, a digital threshold of 10 g peak resultant linear acceleration was applied to all data and the median and 95th percentile were reported.

Results

A total of 57,988 events were collected from twenty-nine individual athletes participating on two separate teams (Team A and Team B) over 26 and 32 practice sessions, respectively. A total of 3,268 HAEs were identified with video-verification. Using the aforementioned 99.9th percentile rotational acceleration amplitude analysis, a total of 31 events were excluded for exceeding the threshold. A total of 3,237 HAEs were associated with a real contact event; 2008 events were attributed to Team A and 1229 events were attributed to Team B. Of the 3,237 events measured by the mouthpiece sensors, 2,105 (65.0%) events were classified as indirect HAEs and 1,132 (35.0%) events were classified as direct HAEs. Peak resultant linear and rotational acceleration and rotational velocity for all practice drill characteristic categories varied among teams and over time. Overall, the median (95th percentile) peak resultant linear and rotational acceleration was 9.4 g (26.4 g) and 657 rad/s^2 (1737 rad/s^2), respectively. The median and 95th percentile peak resultant rotational velocity was 8.4 rad/s (16.6 rad/s). A total of 1472 (45.5%) HAEs were above 10 g with a corresponding median (95th percentile) peak resultant linear and rotational acceleration of 14.5 g (32.7 g) and 930 rad/s^2 (2319 rad/s^2), respectively, and peak resultant rotational velocity of 10.5 rad/s (19.2 rad/s). No events collected in this study resulted in a clinically diagnosed concussion.

Drill intensity (Table II) had a significant association with peak resultant linear acceleration ($p < 0.01$), rotational acceleration ($p < 0.001$), and rotational velocity ($p < 0.001$). Drill intensity level three practice drills had the highest 95th percentile peak resultant kinematics and highest median rotational acceleration and velocity. Practice drills conducted at drill intensity level one had the lowest mean linear acceleration and rotational velocity. Drill intensity level one drills had significantly lower mean linear acceleration than drill intensity level five and drill intensity level three drills (both $p = 0.0006$ and $p = 0.0003$ respectively). Drill intensity level three drills had significantly higher mean rotational velocity than drill intensity level one, drill intensity level two, and drill intensity level five drills (all $p < 0.001$). Additionally, drill intensity level three drills had significantly greater mean rotational acceleration than drill intensity level five drills ($p = 0.0238$). The greatest proportion of HAEs occurred at drill intensity level five (n = 2378, 73.5%), followed by drill intensity level three (n = 403, 12.4%), and drill intensity level 2 (n = 355, 11.0%).

Boxplots were used to display the differences between peak resultant linear acceleration, angular acceleration, and rotational velocity in direct and indirect HAEs by drill intensity (Figure 1). Practice drills conducted at drill intensity level four had the highest proportion of direct HAEs (44.7%), followed by drills conducted at drill intensity level three (41.2%). Practice drills conducted at drill intensity level two had the lowest proportion of direct HAEs (25.4%). Mean peak resultant rotational acceleration was highest in drill intensity level three for direct and indirect HAEs ($p < 0.001$). Direct HAEs had greater peak resultant linear acceleration, on average, across all drill intensity categories ($p < 0.001$).

Drill classification (Table III) had a significant effect on peak resultant linear acceleration ($p < 0.001$), peak resultant rotational acceleration ($p = 0.005$), and peak resultant rotational velocity ($p < 0.001$). Minimal or no player contact had the lowest number of HAEs and lowest median kinematics, while single player vs player contact had the second highest number of HAEs and median kinematics. The greatest 95th percentile for all peak resultant kinematics was observed in minimal or no player contact drills followed by single player vs player contact drills. Single player vs player contact drills had significantly greater mean kinematics than minimal or no player vs player contact drills (all $p < 0.05$).

The distribution of peak resultant linear acceleration, rotational velocity, and rotational acceleration were compared across direct and indirect HAEs as shown below in Figure 2. Direct HAEs had greater peak resultant linear acceleration, on average, compared to all drill classification categories. Single player vs player contact drills had the highest proportion of direct HAEs (36.5%), followed by multiple player vs player contact (34.2%) and minimal or no player contact drills (32.1%).

Drill type (Table IV) had a significant effect on peak resultant linear acceleration, rotational acceleration, and rotational velocity (all $p < 0.001$). Open field tackle had the highest mean linear and rotational acceleration. Open field tackle and angle tackle had significantly greater mean linear and rotational acceleration than team scrimmage, inside run, 1-on-1 block, individual, and dummy or sled (all $p < 0.001$). Angle tackle had significantly higher mean rotational velocity compared to the aforementioned drills (all $p < 0.001$). Angle tackle, open field tackle, 1-on-1 tackle, and Oklahoma were not significantly different from one another across all kinematic metrics. Significant differences in accelerations and event rate are indicated by non-overlapping 95% confidence intervals (CI).

Dummy or sled, inside run, and Oklahoma had the highest rate of HAEs per athlete. The practice drills with the lowest rate of HAEs per athlete were team scrimmage, and individual. Oklahoma had one of the highest rates of HAEs per athlete, which was significantly greater than team scrimmage ($p = < 0.001$) and individual ($p = 0.002$), but was conducted for the least amount of total time during the season. Team scrimmage, where the most cumulative time was spent throughout the season, had a significantly lower rate of HAEs per athlete than most other practice drills (all $p < 0.03$), with the exception of individual.

A pairwise comparison of kinematic measurements between drills is provided in Figure 3. Significant differences in acceleration and event rate are indicated by non-overlapping 95% confidence intervals. The practice drill type with the largest proportion of direct HAEs was 1-on-1 tackle followed by Oklahoma and open field tackle (Figure 3D). The drill types associated with the lowest proportion of direct HAEs were 1-on-1 block and dummy or sled. Events classified as direct HAE measured greater values for peak resultant linear acceleration, on average, across all drill types.

Discussion

The purpose of this study was to evaluate HAEs in youth football practice drills using a mouthpiece-based sensor that couples rigidly to the upper dentition. Because practice sessions represent a higher proportion of HAEs throughout the season[15,31,52] and practices are environments amenable to intervention, it is important to accurately characterize HAEs associated with different practice drills. The results of this study demonstrate significant differences in HAEs among practice drills in youth football. Single athlete vs athlete drills conducted at a greater closing distance (open field tackle and angle tackle) resulted in higher kinematics when compared to multiple athlete vs athlete practice drills. This study also demonstrates that multi-player vs player practice drills have higher event rates on average.

The median peak resultant linear acceleration (9.4 g, 14.6 g adjusted) recorded in this study was lower than the results reported by Kelley et al (20.2 g), Cobb et al (19 g), and Bellamkonda et al (18.2 g) in similar football practice drill studies.[14,20,52] The median rotational head acceleration recorded in this study (663 rad/s^2, 939 rad/s^2 adjusted) was comparable to the results reported by Kelley et al (962 rad/s^2), Cobb et al (890 rad/s^2), and Bellamkonda et al (1290 rad/s^2). Differences in linear acceleration are likely due to the lower 5 g trigger threshold utilized in this study compared to the commonly used 10 g threshold.[11] When limited to events over 10 g, the data are more comparable to past studies, although median peak resultant linear acceleration is still lower. Previous studies have highlighted the importance of including lower magnitude impacts (i.e. less than 10 g) as football athletes who experience low intensity events at a higher frequency often experience more frequent post-impact symptoms that may result in undiagnosed concussions.[35,36] The instrumented mouthpiece used in this study was also used by Marks et al to collect HAEs in games in addition to practices.[53] HAEs collected in games resulted in higher mean peak kinematics than HAEs collected in practices which is consistent with previous findings.[36]

Drill intensity was evaluated according to the levels of contact as defined by USA Football.[50] While several practice drills classified as drill intensity zero, in which the athlete ran unopposed and without contact through a drill, were observed throughout the season, none of these drills resulted in a HAE. Practice drills conducted at USA football's defined drill intensity level zero were often more focused on developing and improving athlete technique without the presence of contact. Practice drills conducted at drill intensity levels three to five were focused heavily on contact as a means of instruction. USA football defines drills conducted at drill intensity level three as "drills conducted at an assigned athlete speed where one athlete is pre-determined as the winner and athletes are allowed to take the opposing athlete to ground in a controlled manner".[50] Drill intensity level five drills are defined as a drill that is conducted at a competitive speed with competition-like conditions. On average, peak kinematics at drill intensity level three were highest; however, peak kinematics at drill intensity level three were only significantly greater than peak kinematics in drill intensity level one and drill intensity level two ($p < 0.01$). A greater number of HAEs were measured at drill intensity level five. This could be because the practice drills that were often categorized as drill intensity level three included angle tackle and 1-on-1 tackle, which were associated with higher kinematics compared to the other practice drills that frequently fell within drill intensity level five (team scrimmage, inside run, Oklahoma, open field tackle). Team scrimmage in particular was conducted for a larger portion of total practice time when compared to other practice drills and accounts for the higher number of HAEs recorded for drill intensity level five. Drill intensity level three measured the largest 95th percentile of 32.0 g which may indicate that athletes were subjected to higher proportion of greater magnitude events. The results of this study indicate that even with a controlled speed and pre-determined winner, such as the practice drills categorized in drill intensity level three, drills in which athletes are allowed to tackle the opposing athlete may result in higher average kinematics than drills where both athletes remain on their feet and contact remains above the waist. Because of the nature of contact involved in football games, athletes must learn how to safely block and tackle in a practice setting prior to a game. Efforts to reduce head impact exposure in practice should consider the necessity of gaining experience with contact in practice and how skills gained from drills in practice translates to on-field behaviors and skills that influence head impact exposure in a game setting.

The greatest number of HAEs were attributed to multi-player vs player contact drills while minimal or no player contact had the lowest number of impacts. This is similar to previous findings from Kelley et al in which multiple player vs player contact drills accounted for the greatest number of HAEs for five out of the six teams instrumented in the study.[30] Single player vs player contact resulted in greater mean peak resultant linear acceleration, rotational acceleration, and rotational velocity than the other drill classifications. According to past studies, reducing time spent in full-speed tackling and blocking drills like those within the single player vs player contact drill classification may not reduce overall HAE exposure.[30] Football organizations should instead consider putting more focus on interventions that reduce the speed of athlete engagement and improve contact technique. A study conducted by Asken et al examined the implications for reducing HAE exposure in practice drills.[54] The author concluded that recommending drill-specific changes based on practical considerations such as event-frequency and drill duration could improve the chance of intervention acceptance from coaches and athletes while simultaneously reducing HAE exposure. While the kinematics of the HAEs collected from practice drills in multiple player vs player contact classification were relatively low when compared to HAEs collected from practice drills in single player vs player contact classification, the volume of HAEs collected was high. Previous studies have documented the effects of cumulative exposure to concussive and sub concussive events is associated with later-life cognitive and neurobehavioral consequences.[6] Athletes should be able to develop the skills necessary to remain healthy in competitive scenarios while also being mindful of the volume of HAEs they receive during practice. Further studies could be conducted to evaluate the proper balance between multiple player vs player contact drills and single player vs player contact drills.

Mean peak resultant kinematics varied significantly among drill types. The open field tackle drill resulted in the greatest mean linear and rotational acceleration and the highest median linear and rotational acceleration. This is consistent with the results produced by Kelley et al.[20,35] When compared to 1-on-1 tackle, a similar practice drill where athletes begin less than three yards apart as opposed to greater than three yards apart, open field tackle resulted in greater peak resultant linear acceleration, on average. This is likely due to 1-on-1 tackle allowing athletes to begin the drill with a shorter distance between athletes. Previous studies documented that larger closing distance has been associated with higher kinematics.[55–57] In this study, open field tackle had the second highest total number of HAEs collected (n = 345) with only team scrimmage surpassing it (n = 1570); however, the rate of HAEs per player for open field tackle (0.16 events per player per session by session drill time) was significantly greater than that of team scrimmage (0.09 events per player per session by session drill time). The higher kinematics and rate of HAEs measured in open field tackle is likely due to athletes being allowed to hit and tackle at competition-level speeds and begin the drill with greater distance between athletes. While team scrimmage may be run at speeds consistent with that of a game, the players who begin the practice drill on the line of scrimmage start less than a yard apart and thus are less likely to experience a HAE equivalent with that experienced in open field tackle. Coaches and policy makers should be made aware of the possibility of higher magnitude HAEs and higher event rate in open field tackle and implement techniques that reduce the chances of injury and still provide the same level of simulation expected in a game.[42] It is important to understand the effect of body positioning and tackling technique to further inform decisions. Further studies could highlight the differences between HAE magnitude and event rate between teams that implement different tackling approaches and those that opt for a more traditional tackling technique approach in the same practice drills.

The dummy or sled, 1-on-1 block, and Oklahoma drills resulted in the highest rates of HAEs (0.18 events per player per minute, 0.18 events per player per minute, and 0.25 events per player per minute) when compared to other practice drills. This is likely due to the increased number of athletes participating in these drills at a time with upwards of five athletes competing in dummy or sled, upwards of ten athletes competing in a single repetition of 1-on-1 block with two athletes being paired together, and four competing in a single repetition of Oklahoma compared to the usual two in similar tackle technique practice drills.[20] Notably, Oklahoma is conducted similarly to open field tackle and 1-on-1 tackle, where the drill ends when the ball carrier is tackled to the ground; however, Oklahoma includes two blockers that are not present in open field tackle or 1-on-1 tackle. The inclusion of two blockers that begin the drill at a closer distance to each other than in open field tackle or 1-on-1 tackle could account for the lower average peak kinematics. The individual practice drill measured one of the lowest event rates (0.11 events per player per minute). Individual consisted of a variety of position specific drills that did not always use athlete contact in instruction. This variety in contact duration and implementation likely accounts for the lower event rates when compared to practice drills conducted for similar amounts of time.

Peak resultant linear acceleration and rotational acceleration were greater on average for direct HAEs than indirect HAEs, but a greater proportion of HAEs were attributed to indirect HAEs. This is contrary to the results produced by Tierney et al,[41] who found greater kinematics in indirect HAEs than direct HAEs at the collegiate level. These differences could be due to lack of athlete experience at the youth level, as most athletes participating in youth football have not learned proper tackling techniques and are still likely to lead with the head instead of the shoulder in a contact scenario. Drill intensity level one and the minimal or no player contact drill classification have similar kinematic measurements for direct and indirect HAEs which may be due to the low number of events that were recorded in these categories. However, direct HAEs recorded higher magnitudes for peak resultant linear and rotational acceleration than indirect HAEs in drill intensity, drill classification, and drill type. This is likely due to direct contact with the head of an athlete, applying a direct load to the head and increasing head movement. Further studies are needed to inform the differences between direct and indirect HAEs and the respective effects on risk of concussion in football and differentially evaluate direct and indirect events to inform efforts to reduce HAEs.

This study had several limitations. First, all data analyzed and reported in this study were gathered from two youth football teams within a single youth organization. The practice drills and teaching techniques used in this organization may vary from coaches and athletes outside of this organization may utilize different practice structures and exhibit different behaviors. Furthermore, the two youth football teams observed in this study utilized different practice structures and conducted practice drills for varying amounts of time during practice session. Previous studies have documented the tendency for older athletes participating in higher level football to receive higher magnitude HAEs and a greater total number of HAEs.[58,59] Further studies of football athletes participating in different organizations or at different levels of football (i.e., high school and college) could help to increase understanding of HAEs in practice. A low sample size of 29 athletes were instrumented, and each athlete demonstrated variation in HAE which could be attributed to athlete participation in practice and individual athlete intensity. The video review conducted to independently review each HAE included several video reviewers that may contribute to human error in video review. However, we assessed interrater reliability to ensure that each reviewer was following the protocol established for video review. Additionally, our signal analysis approach employs manual video review using linear acceleration frequency spectra and review of rotational acceleration frequency content to exclude HAEs verified on video from analyses. However, less than 1% of HAEs were removed using frequency analysis. Reducing the frequency and magnitude of HAEs may reduce the risk of concussion and effects of subconcussive head impacts in football,[1,7,8] however, the number and/or magnitude of acceleration that translates to a clinically meaningful reduction in risk is not well understood. Incorporating drills of lower exposure or identifying methods to reduce acceleration magnitudes among individual high-risk drills, will aid in reducing concussion risk as well as the cumulative burden of head impacts over time.

Conclusion

The purpose of this study was to evaluate HAEs in youth football practice drills using a mouthpiece-based sensor coupled rigidly with the upper dentition. The results of this study indicate HAEs collected at higher intensities resulted in significantly greater kinematics than lower intensity drills. Single player vs player drills with greater closing distance (open field tackle and angle tackle) were associated with the highest mean peak resultant linear acceleration and rotational acceleration. Multi-player vs player drills (team scrimmage, inside run, and Oklahoma) resulted in the largest total number of HAEs collected in practices. Notably, Oklahoma resulted in the highest rate of HAEs compared to 1-on-1 style tackling technique drills. Direct HAEs were less common than indirect HAEs but were greater in magnitude. The results of this study add to the growing body of evidence informing evidence-based strategies to reduce head impact exposure and concussion risk in youth football practices.

Acknowledgements

The authors would like to thank the youth football organizations who participated in this research. The authors thank Konstantina Strates for project management and Grace Bondurant, Sydney Rojas, Oryann Addison, Robert Treadway, Alex Riddell, Noah Rothhaar, and William Blackburn for supporting data collection and video review. This project was supported by the National Institutes of Health (NIH, NICHD K25HD101686) and the Wake Forest University School of Medicine Dean's Award. The content is solely the responsibility of the authors and does not necessarily represent the official views of the NIH. No sponsor institution was involved in the study design, data collection, analysis/interpretation, or authorship of this manuscript.

References

1. Saghafi B, Murugesan GK, Powers A, et al. Quantifying the association between white matter integrity changes and subconcussive head impact exposure from a single season of youth and high school football using 3D convolutional neural networks. Published online February 27, 2018:13. doi:10.1117/12.2293023
2. Rose SC, Yeates KO, Nguyen JT, McCarthy MT, Ercole PM, Pizzimenti NM. Neurocognitive Function and Head Impact Burden over Two Seasons of Youth Tackle Football. https://home-liebertpub-com.ezproxy.lib.vt.edu/neu. 2019;36(19):2803–2809. doi:10.1089/NEU.2019.6519
3. Talavage TM, Nauman EA, Breedlove EL, et al. Functionally-detected cognitive impairment in high school football players without clinically-diagnosed concussion. J Neurotrauma. 2014;31(4):327–338. doi:10.1089/NEU.2010.1512/ASSET/IMAGES/LARGE/FIGURE5.JPEG [PubMed: 20883154]
4. McAllister TW, Flashman LA, Maerlender A, et al. Cognitive effects of one season of head impacts in a cohort of collegiate contact sport athletes. Neurology. 2012;78(22):1777–1784. doi:10.1212/WNL.0B013E3182582FE7 [PubMed: 22592370]
5. Stemper BD, Shah AS, Harezlak J, et al. Repetitive Head Impact Exposure in College Football Following an NCAA Rule Change to Eliminate Two-A-Day Preseason Practices: A Study from the NCAA-DoD CARE Consortium. Ann Biomed Eng. 2019;47(10):2073–2085. doi:10.1007/S10439-019-02335-9/FIGURES/1 [PubMed: 31388849]
6. Montenigro PH, Alosco ML, Martin BM, et al. Cumulative Head Impact Exposure Predicts Later-Life Depression, Apathy, Executive Dysfunction, and Cognitive Impairment in Former High School and College Football Players. J Neurotrauma. 2017;34(2):328–340. doi:10.1089/NEU.2016.4413/ASSET/IMAGES/LARGE/FIGURE2.JPEG [PubMed: 27029716]
7. Davenport EM, Urban JE, Mokhtari F, et al. Subconcussive impacts and imaging findings over a season of contact sports. http://dx.doi.org/102217/cnc-2016-0003. 2016;1(4). doi:10.2217/CNC-2016-0003
8. Breedlove KM, Breedlove EL, Robinson M, et al. Detecting neurocognitive and neurophysiological changes as a result of subconcussive blows in high school football athletes. Athl Train Sports Health Care. 2014;6(3):119–127. doi:10.3928/19425864-20140507-02
9. Bazarian JJ, Zhu T, Zhong J, et al. Persistent, long-term cerebral white matter changes after sports-related repetitive head impacts. PLoS One. 2014;9(4):e94734. doi:10.1371/journal.pone.0094734 [PubMed: 24740265]
10. Bahrami N, Sharma D, Rosenthal S, et al. Subconcussive head impact exposure and white matter tract changes over a single season of youth football. Radiology. 2016;281(3):919–926. doi:10.1148/radiol.2016160564 [PubMed: 27775478]
11. Funk JR, Rowson S, Daniel RW, Duma SM. Validation of concussion risk curves for collegiate football players derived from HITS data. Ann Biomed Eng. 2012;40(1). doi:10.1007/s10439-011-0400-8
12. Rowson S, Duma SM, Beckwith JG, et al. Rotational head kinematics in football impacts: An injury risk function for concussion. Ann Biomed Eng. 2012;40(1). doi:10.1007/s10439-011-0392-4
13. Urban JE, Davenport EM, Golman AJ, et al. Head impact exposure in youth football: High school ages 14 to 18 years and cumulative impact analysis. Ann Biomed Eng. 2013;41(12). doi:10.1007/s10439-013-0861-z

14. Cobb BR, Urban JE, Davenport EM, et al. Head impact exposure in youth football: Elementary school ages 9–12 years and the effect of practice structure. Ann Biomed Eng. 2013;41(12). doi:10.1007/s10439-013-0867-6
15. Daniel RW, Rowson S, Duma SM. Head impact exposure in youth football. Ann Biomed Eng. 2012;40(4):976–981. doi:10.1007/S10439-012-0530-7 [PubMed: 22350665]
16. Macy JT, Kercher K, Steinfeldt JA, Kawata K. Fewer US Adolescents Playing Football and Public Health: A Review of Measures to Improve Safety and an Analysis of Gaps in the Literature. Public Health Reports. 2021;136(5). doi:10.1177/0033354920976553
17. Powell JW, Barber-Foss KD. Traumatic brain injury in high school athletes. J Am Med Assoc. 1999;282(10). doi:10.1001/jama.282.10.958
18. Guskiewicz KM, Weaver NL, Padua DA, Garrett WE. Epidemiology of concussion in collegiate and high school football players. American Journal of Sports Medicine. 2000;28(5). doi:10.1177/03635465000280050401
19. Pop Warner Limited Contact in Practice Rule. https://www.popwarner.com/Default.aspx?tabid=1476228.
20. Kelley ME, Kane JM, Espeland MA, et al. Head impact exposure measured in a single youth football team during practice drills. J Neurosurg Pediatr. 2017;20(5):489–497. doi:10.3171/2017.5.PEDS16627 [PubMed: 28937917]
21. New Rules to Tackle Brain Injuries in Football. Accessed March 9, 2022. https://www.healthline.com/health-news/changing-way-football-played#Six-new-rules
22. Youth Football Safety and Injury Prevention | NFL FLAG. Accessed March 9, 2022. https://nflflag.com/football-safety
23. Auerbach PS, Waggoner WH. It's time to change the rules. JAMA - Journal of the American Medical Association. 2016;316(12). doi:10.1001/jama.2016.8184
24. Protection and Prevention Strategies - Sports-Related Concussions in Youth - NCBI Bookshelf. Accessed March 9, 2022. https://www.ncbi.nlm.nih.gov/books/NBK185338/
25. Emery CA, Black AM, Kolstad A, et al. What strategies can be used to effectively reduce the risk of concussion in sport? A systematic review. Br J Sports Med. 2017;51(12). doi:10.1136/bjsports-2016-097452
26. Kroshus E, Kerr ZY, Lee JGL. Community-Level Inequalities in Concussion Education of Youth Football Coaches. Am J Prev Med. 2017;52(4). doi:10.1016/j.amepre.2016.12.021
27. Logan K, Cuff S, LaBella CR, et al. Organized sports for children, preadolescents, and adolescents. Pediatrics. 2019;143(6). doi:10.1542/PEDS.2019-0997/37135
28. Wiebe DJ, D'Alonzo BA, Harris R, Putukian M, Campbell-McGovern C. Association between the experimental kickoff rule and concussion rates in ivy league football. JAMA - Journal of the American Medical Association. 2018;320(19). doi:10.1001/jama.2018.14165
29. Beaudouin F, Reinsberger C, Meyer T. Efficacy of a football rule to prevent concussion. Br J Sports Med. 2017;51(11). doi:10.1136/bjsports-2016-097270.170
30. Kelley ME, Espeland MA, Flood WC, et al. Comparison of head impact exposure in practice drills among multiple youth football teams. J Neurosurg Pediatr. 2018;23(3):381–389. doi:10.3171/2018.9.PEDS18314 [PubMed: 30579266]
31. Campolettano ET, Rowson S, Duma SM. Drill-specific head impact exposure in youth football practice. J Neurosurg Pediatr. 2016;18(5). doi:10.3171/2016.5.PEDS1696
32. Wong RH, Wong AK, Bailes JE. Frequency, magnitude, and distribution of head impacts in Pop Warner football: The cumulative burden. Clin Neurol Neurosurg. 2014;118. doi:10.1016/j.clineuro.2013.11.036 [PubMed: 25459256]
33. Crisco JJ, Fiore R, Beckwith JG, et al. Frequency and location of head impact exposures in individual collegiate football players. J Athl Train. 2010;45(6). doi:10.4085/1062-6050-45.6.549
34. Gellner RA, Campolettano ET, Rowson S. ASSOCIATION BETWEEN TACKLING TECHNIQUE AND HEAD ACCELERATION MAGNITUDE IN YOUTH FOOTBALL PLAYERS. Biomed Sci Instrum. 2018;54(1).
35. Urban JE, Kelley ME, Espeland MA, et al. In-Season Variations in Head Impact Exposure among Youth Football Players. J Neurotrauma. 2019;36(2). doi:10.1089/neu.2018.5699

36. Campolettano ET, Gellner RA, Rowson S. High-magnitude head impact exposure in youth football. J Neurosurg Pediatr. 2017;20(6). doi:10.3171/2017.5.PEDS17185
37. Mainwaring L, Ferdinand Pennock KM, Mylabathula S, Alavie BZ. Subconcussive head impacts in sport: A systematic review of the evidence. International Journal of Psychophysiology. 2018;132(Pt A):39–54. doi:10.1016/j.ijpsycho.2018.01.007 [PubMed: 29402530]
38. Johnson B, Neuberger T, Gay M, Hallett M, Slobounov S. Effects of subconcussive head trauma on the default mode network of the brain. J Neurotrauma. 2014;31(23). doi:10.1089/neu.2014.3415
39. Kuzminski SJ, Clark MD, Fraser MA, et al. White Matter Changes Related to Subconcussive Impact Frequency during a Single Season of High School Football. American Journal of Neuroradiology. 2018;39(2). doi:10.3174/ajnr.A5489
40. Wu LC, Kuo C, Loza J, et al. Detection of American Football Head Impacts Using Biomechanical Features and Support Vector Machine Classification. Sci Rep. 2018;8(1). doi:10.1038/s41598-017-17864-3
41. Tierney GJ, Kuo C, Wu L, Weaving D, Camarillo D. Analysis of head acceleration events in collegiate-level American football: A combination of qualitative video analysis and in-vivo head kinematic measurement. J Biomech. 2020;110. doi:10.1016/j.jbiomech.2020.109969
42. Rich AM, Filben TM, Miller LE, et al. Development, Validation and Pilot Field Deployment of a Custom Mouthpiece for Head Impact Measurement. Ann Biomed Eng. 2019;47(10). doi:10.1007/s10439-019-02313-1
43. Swenson AG, Pritchard NS, Miller LE, Urban JE, Stitzel JD. Characterization of head impact exposure in boys’ youth ice hockey. Research in Sports Medicine. Published online 2021. doi:10.1080/15438627.2021.1989433
44. Filben TM, Pritchard NS, Miller LE, et al. Characterization of Head Impact Exposure in Women’s Collegiate Soccer. J Appl Biomech. 2022;38(1). doi:10.1123/jab.2020-0304
45. Pritchard NS, Urban JE, Miller LE, Lintner L, Stitzel JD. An analysis of head kinematics in women’s artistic gymnastics. Science of Gymnastics Journal. 2020;12(3).
46. Kelley ME, Jones DA, Espeland MA, et al. Physical Performance Measures Correlate with Head Impact Exposure in Youth Football. Med Sci Sports Exerc. 2020;52(2). doi:10.1249/MSS.0000000000002144
47. Mihalik JP, Bell DR, Marshall SW, Guskiewicz KM. Measurement of head impacts in collegiate football players: An investigation of positional and event-type differences. Neurosurgery. 2007;61(6). doi:10.1227/01.neu.0000306101.83882.c8
48. CC JJ, W BJ, M JT, et al. Magnitude of head impact exposures in individual collegiate football players. J Appl Biomech. 2012;28(2).
49. Rowson S, Mihalik J, Urban J, et al. Consensus Head Acceleration Measurement Practices (CHAMP): Study Design and Statistical Analysis. Ann Biomed Eng. 2022;(50):1346–1355. [PubMed: 36253602]
50. Levels of Contact as defined by USA Football. https://usafootball.com/resources-tools/coach/levels-of-contact/.
51. Gisev N, Bell JS, Chen TF. Interrater agreement and interrater reliability: Key concepts, approaches, and applications. Research in Social and Administrative Pharmacy. 2013;9(3). doi:10.1016/j.sapharm.2012.04.004
52. Bellamkonda S, Woodward SJ, Campolettano E, et al. Head Impact Exposure in Practices Correlates With Exposure in Games for Youth Football Players. J Appl Biomech. 2018;34(5):354–360. doi:10.1123/JAB.2017-0207 [PubMed: 29651910]
53. Marks M, Holcomb T, Pritchard NS, et al. Characterizing Exposure to Head Acceleration Events in Youth Football Using an Instrumented Mouthpiece. Annal of Biomedical Engineering. Published online October 23, 2022.
54. Asken BM, Brooke ZS, Stevens TC, et al. Drill-Specific Head Impacts in Collegiate Football Practice: Implications for Reducing “Friendly Fire” Exposure. Ann Biomed Eng. 2019;47(10). doi:10.1007/s10439-018-2088-5
55. Ocwieja KE, Mihalik JP, Marshall SW, Schmidt JD, Trulock SC, Guskiewicz KM. The effect of play type and collision closing distance on head impact biomechanics. Ann Biomed Eng. 2012;40(1). doi:10.1007/s10439-011-0401-7

56. Urban JE, Flood WC, Zimmerman BJ, et al. Evaluation of head impact exposure measured from youth football game plays. J Neurosurg Pediatr. 2019;24(2):190–199. doi:10.3171/2019.2.PEDS18558 [PubMed: 31075762]
57. DiGuglielmo DM, Kelley ME, Espeland MA, et al. The effect of player contact characteristics on head impact exposure in youth football games. J Appl Biomech. 2021;37(2). doi:10.1123/JAB.2020-0145
58. Kelley ME, Urban JE, Miller LE, et al. Head Impact Exposure in Youth Football: Comparing Age-and Weight-Based Levels of Play. J Neurotrauma. 2017;34(11). doi:10.1089/neu.2016.4812
59. Broglio SP, Surma T, Ashton-Miller JA. High school and collegiate football athlete concussions: A biomechanical review. Ann Biomed Eng. 2012;40(1). doi:10.1007/s10439-011-0396-0

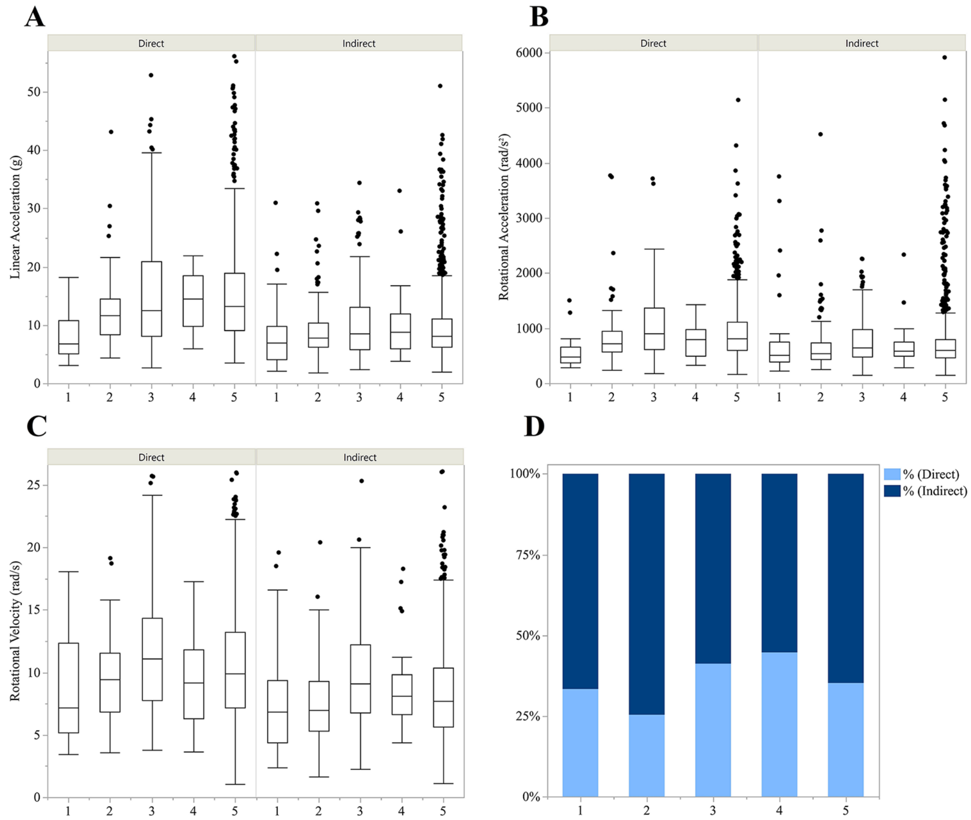

Figure 1 - (A) Peak resultant linear acceleration, (B) peak resultant rotational acceleration, (C) peak resultant rotational velocity, and (D) proportion of indirect and direct head acceleration events by drill intensity.

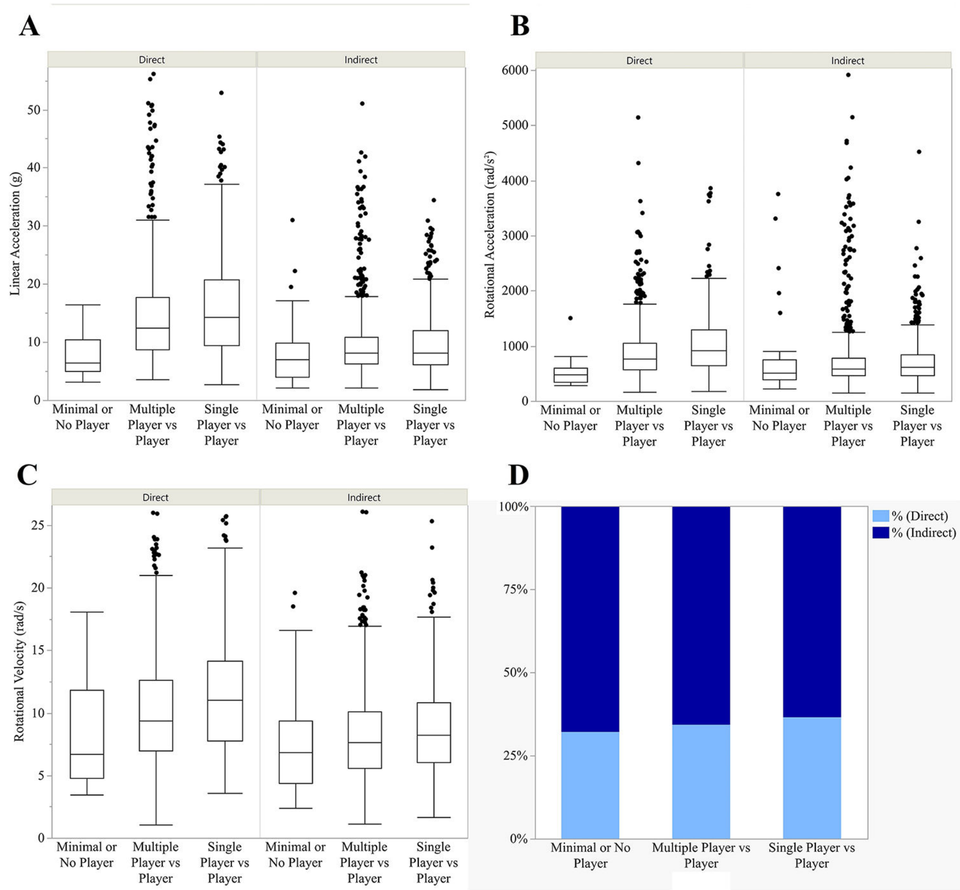

Figure 2 - (A) Peak resultant linear acceleration, (B) peak resultant rotational acceleration, (C) peak resultant rotational velocity, and (D) proportion of indirect and direct head acceleration events by drill classification.

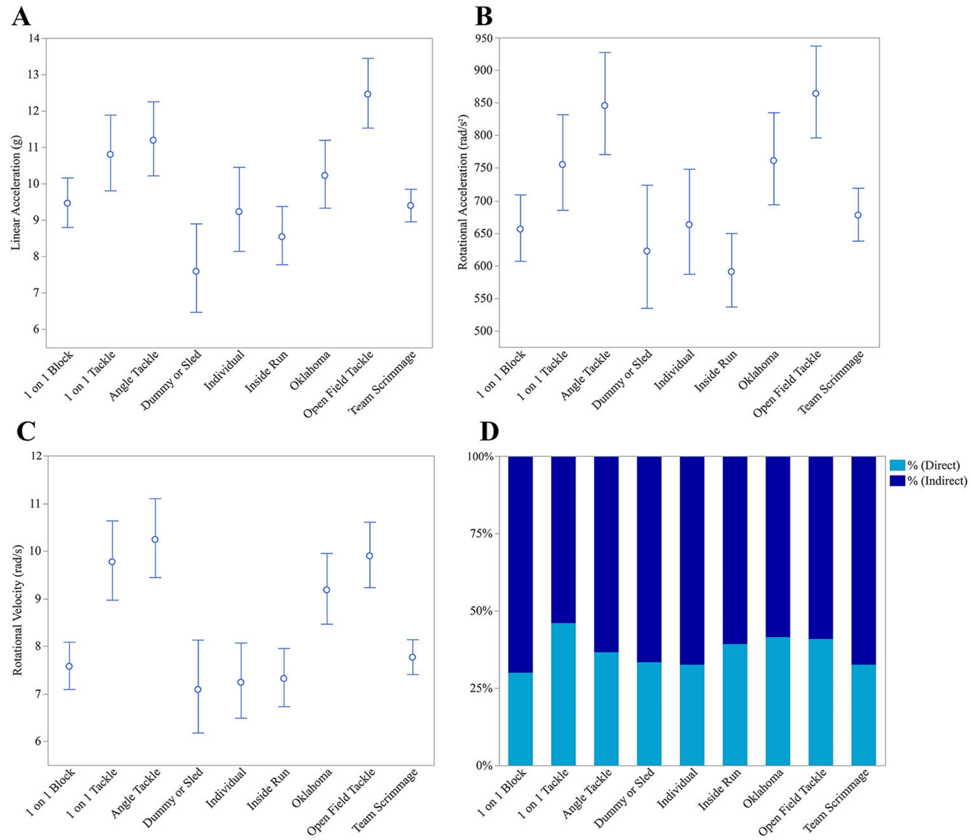

Figure 3 - (A) Peak resultant linear acceleration, (B) peak resultant rotational acceleration, (C) peak resultant rotational velocity, and (D) proportion of indirect and direct head acceleration events by drill type.

Table I:

Category descriptions for practice contact characteristics

Drill Intensity	Description
1	Athlete contacts a soft contact surface (i.e., bag)
2	Athlete is assigned a slower speed and cannot tackle
3	Athlete is assigned a slower speed and can tackle in a controlled manner
4	Athlete is assigned a competition speed and cannot tackle
5	Athlete can move through the drill as if in a competition
Drill Classification	**Description**
Minimal or No Player Contact	Athlete has minimal or no contact with equipment or another athlete (i.e., Dummy or Sled, Individual, 1-on-1 Pass)
Single Player vs Player Contact	Athlete engages in contact with one other athlete (i.e., Angle Tackle, 1-on-1 Block, 1-on-1 Tackle, 1-on-1 Pass, Open Field Tackle)
Multiple Player vs Player Contact	Athletes engage in contact with multiple other athletes (i.e., Oklahoma, Team Scrimmage, Inside Run, Skelly)
Drill Type	**Description**
1-on-1 Block	1-vs-1 blocking where 1 player blocks an opposing player
1-on-1 Pass	Players compete to catch a pass
1-on-1 Tackle	1-vs-1 tackling with 2 players starting <3 yds apart and tackle
Angle Tackle	1-vs-1 tackling 2 players starting >3 yds apart at an angle
Dummy or Sled	Player tackles or blocks a dummy or sled
Individual	Players participate in a variety of position-specific drills
Inside Run	Live scrimmage without skill players (i.e., wide receivers, cornerbacks)
Oklahoma	2-vs-2 tackling with tackler, blockers, and ball carrier in confined space
Open Field Tackle	1-vs-1 tackling with 2 players starting >3 yds apart and tackle head on
Skelly	Live scrimmage without linemen
Team Scrimmage	Live scrimmage

Table II:

Peak resultant kinematics for all HAEs by drill intensity

Drill Intensity		Linear Acceleration (g)	Rotational Acceleration (rad/s^2)	Rotational Velocity (rad/s)
(a) Level 1 ^{b,c,d,e} (n = 54)	Mean	8.1	666	7.0
	95% CI	6.9–9.4	568–780	6.1–8.0
	50 %ile	7.0	492	6.9
	95th %ile	20.2	2633	18.2
(b) Level 2 ^{a,c,d,e} (n = 355)	Mean	9.0	640	7.3
	95% CI	8.4–9.7	587–697	6.9–7.8
	50 %ile	8.4	595	7.5
	95th %ile	18.4	1356	13.8
(c) Level 3 ^{a,b,e} (n = 403)	Mean	10.5	783	9.7
	95% CI	9.8–11.2	719–853	9.1–10.3
	50 %ile	9.9	739	9.8
	95th %ile	30.2	1859	18.8
(d) Level 4 ^{a,b} (n = 47)	Mean	10.6	706	8.8
	95% CI	9.0–12.6	595–837	7.8–10.1
	50 %ile	10.7	642	8.6
	95th %ile	24.4	1451	17.2
(e) Level 5 ^{a,b,c} (n = 2378)	Mean	10.1	732	8.3
	95% CI	9.7–10.6	683–783	8.0–8.7
	50 %ile	9.5	661	8.4
	95th %ile	26.5	1787	16.7

*a-e Intensities that share the same superscript letter have peak kinematics that differ at $p < 0.05$.

Table III:

Peak resultant kinematics for all HAEs by drill classification

Drill Classification		Linear Acceleration (g)	Rotational Acceleration (rad/s^2)	Rotational Velocity (rad/s)
(a) Minimal or no Player [b,c] (n = 53)	Mean	7.4	605	7.0
	95% CI	6.3–8.7	518–706	6.1–8.0
	50th %ile	7.0	486	6.7
	95th %ile	20.3	2678	18.2
(b) Multiple Player vs Player [a,c] (n = 2082)	Mean	9.6	690	8.0
	95% CI	9.2–9.97	649–735	7.6–8.4
	50th %ile	9.2	642	8.2
	95th %ile	25.2	1712	16.2
(c) Single Player vs Player [c,b] (n = 1102)	Mean	10.5	750	8.9
	95% CI	10.0–11.0	702–801	8.4–9.4
	50th %ile	9.8	706	9.0
	95th %ile	28.1	1736	17.6

[*]a-c Classifications that share the same superscript letter have peak kinematics that differ at $p < 0.05$.

Table IV:

Frequency of HAEs and total time spent over the season by drill type

Drill Type[*]	No. of Events [% Direct, % Indirect]	Event Rate Mean	Event Rate 95% CI	Total Drill Time (min)	Total No. of Events >25g
(a) 1-on-1 Block [i]	327 [30.0, 70.0]	0.18	0.15–0.22	422	7
(b) 1-on-1 Tackle [i]	187 [46.0, 54.0]	0.17	0.13–0.21	165	18
(c) Angle Tackle [i]	186 [36.6, 63.4]	0.16	0.12–0.20	150	16
(d) Dummy or Sled [i]	51 [33.3, 66.7]	0.18	0.12–0.26	197	1
(e) Individual [g]	83 [32.5, 67.5]	0.11	0.08–0.15	479	1
(f) Inside Run [i]	199 [39.2, 60.8]	0.17	0.13–0.23	216	1
(g) Oklahoma [i,e]	234 [41.5, 58.5]	0.25	0.19–0.30	135	36
(h) Open Field Tackle [i]	345 [40.9, 59.1]	0.16	0.16–0.23	230	40
(i) Team Scrimmage [a,c,d,f,g,h]	1570 [32.5, 67.5]	0.09	0.08–0.10	2022	66

[*]a-i Drills that share the same superscript letter have mean number of events per player per minute per drill that differ at $p < 0.05$.