JOURNAL OF NEUROTRAUMA 36:1752–1757 (June 1, 2019)

DOI: 10.1089/neu.2018.6236

A Comparison of Youth Flag and Tackle Football Head Impact Biomechanics

Robert C. Lynall, Landon B. Lempke, Rachel S. Johnson, Melissa N. Anderson, and Julianne D. Schmidt

Abstract

Our purpose was to describe the youth flag football head impact burden and make comparisons with youth tackle football. Head impact frequency and magnitude (linear acceleration [g], rotational acceleration [rad/s^2]) were collected from 25 tackle and 25 flag youth football players over one season. Athlete exposure (AE) was defined as one player participating in one session. Head impact rates (IR) were calculated and impact rate ratios (IRR) were used to compare youth tackle and flag football. Random-intercept generalized logit models with odds ratios compared the probabilities of sustaining an impact with a linear acceleration of 20.00–29.99*g*, 30.00–39.99*g*, and ≥40.00*g* against the reference of 14.00–19.99*g* and an impact with a rotational acceleration of 2500.00–7499.99 rad/s^2 or ≥7500.00 rad/s^2 against the reference of ≤2499.99 rad/s^2 between youth flag and tackle football. We observed 1908 tackle football head impacts (735 in games, 38.5%) across 624 AE and 169 flag football head impacts (101 in games, 59.8%) across 255 AE. Youth tackle football players experienced higher overall IR (3.06, 95% confidence interval [CI]: 2.61, 3.58; IRR = 4.61, 95% CI: 3.94, 5.40) compared with flag football (IR = 0.66, 95% CI: 0.57, 0.78). Youth flag football players had lower odds of sustaining impacts >20*g* but higher odds of sustaining impacts between 2500.00–7499.99 rad/s^2 compared with youth tackle players. Our preliminary sample of youth flag football players sustained less frequent head impacts at higher rotational accelerations than tackle football players. Flag football is considered a limited-contact sport, but little is known about the true head impact burden. Our findings may be important for policymakers when debating potential changes to youth football participation.

Keywords: concussion; mild traumatic brain injury; repetitive head impacts; sport

Introduction

Football is a popular youth sport in the United States, with nearly one million children between the ages of six and 12 participating in tackle football and almost 900,000 children participating in flag football.[1] While tackle football may help promote physical activity and teamwork, some researchers and clinicians believe the possible negative consequences from repeated head impacts may outweigh the positives. Several advocacy groups have suggested that children under the age of 12 not participate in tackle football, but rather play flag football as an alternative. As such, some state legislators have proposed laws that would ban tackle football for children. Although none of these laws have been adopted as state policy, legislators in Illinois, California, New York, New Jersey, and Maryland have put forth similar bills that would eliminate tackle football under the age of 14.[2,3]

Several research groups have described the head impact burden in youth tackle football, with impact frequency varying considerably. Youth football players ages 12–14 sustain 275 impacts per season on average,[4] while players eight to nine years old experience about 161 impacts per season.[5] In both studies, large between-player variability was noted, and individual player season head impact average frequencies as low as nine per season[6] and as high as 372 per season[7] have been reported in other studies. Youth football players appear to sustain the majority of head impacts in a season during practices compared with games,[8] although the head impact rate is greater during games than practices when accounting for athlete exposure.[4,9,10]

There are many factors that may influence head impact magnitude in football, such as head impact location,[11] playing position,[12,13] and type of practice drill.[12,14,15] In youth football, approximately 8% of head impacts are considered high magnitude by one definition (greater than linear acceleration of 40*g*[12,14]), with an association existing between impact magnitude and on-field impact location, position, and practice drill.[12] Ninety-five percent of youth tackle football head impacts are below a range of 47–60*g* of linear acceleration and 2500–3900 rad/s^2 of rotational acceleration,[4,7,8] although 95% of impacts may be below lower thresholds for younger players (approximately 38g and 2100 rad/s^2, respectively).[5]

Department of Kinesiology, UGA Concussion Research Laboratory, University of Georgia, Athens, Georgia.

Despite these recent empirical advances toward understanding head impact exposure in youth tackle football, there are no reports detailing head impacts in youth flag football. According to the American Academy of Pediatrics, flag football is considered a limited-contact sport while tackle football is a collision sport.[16] In collision sports (a subdivision of contact sports), athletes purposely hit or collide with each other, implying a greater injury risk. Although contact with other athletes or inanimate objects is infrequent or inadvertent in limited-contact sports, some of these sports may be as dangerous as contact sports.[16]

While it is likely that the youth flag football head impact burden is less than that of tackle football, describing head impacts sustained in youth flag football may be important to determine whether it is truly a safer alternative. Policy changes aimed at eliminating youth tackle football in favor of youth flag football are based solely on tackle football head impact data.

The purpose of this study was to describe the youth flag football head impact burden in a preliminary manner and make general comparisons between youth flag and tackle football. We hypothesized youth flag football impact rates and magnitudes would be less than youth tackle football head impacts. Based on recommendations to participate in youth flag football instead of tackle football, and the American Academy of Pediatrics flag football limited-contact designation,[16] we expected to observe very few, if any, youth flag football impacts.

Patients and Methods

Twenty-five youth male tackle football players from two teams (age 10.95 ± 1.46 years; height 146.36 ± 11.89 cm; mass 45.33 ± 15.01 kg) and 25 youth male flag football players from four teams (age 8.65 ± 1.15 years; height 134.42 ± 8.74 cm; mass 34.57 ± 9.98 kg) were enrolled into this prospective cohort study. The study protocol was approved by our Institutional Review Board. All players assented to be in the study, and at least one parent or guardian provided signed informed consent. Both tackle and flag football players were a part of the same Recreation Department in the suburban southern United States.

Triax Smart Impact Monitors (SIM-G; Triax Technologies Inc., Norwalk, CT), inserted in either a headband or skullcap, were used to collect head impact biomechanics data. The SIM-G contains a triaxial accelerometer to measure linear acceleration and a triaxial gyroscope to measure rotational velocity and acceleration. The SIM-G has been used previously to record on-field head impact biomechanics in several published investigations.[17–19] Linear acceleration data are transformed to head center of gravity based on a previously published formula.[20] A $14g$ linear acceleration threshold was employed such that 10 msec of data before the impact and 52 msec after the impact were recorded once the accelerometer reached $14g$.

The SIM-G validation data are inconsistent, with investigations reporting optimal impact detection (100% of non-helmeted impacts detected and 80% of helmeted impacts detected in one study,[21] 99% of helmeted impacts detected in another study[22]) and linear acceleration validity (no difference between headform and SIM-G linear acceleration at low and medium energy impacts in one study,[23] approximately 14.25% error on average in another study[22]) while a separate investigation reported less than optimal acceleration validity (underpredicted linear and rotational acceleration in helmeted and non-helmeted condition).[24] No on-field head impact biomechanics data collection system is perfect. The SIM-G was chosen for this study because it has the ability to record head impact data from both helmeted and non-helmeted participants.

Before or during the first practice session of the season, players were fit with a Triax SIM-G and a headband or skullcap. Specific SIM-G devices were assigned to each player and were worn throughout the entire season. The SIM-G was placed inside the back of the headband or skullcap with the SIM-G positioned inferior to the occiput during all full-padded practices (helmets only walk-throughs were not recorded), scrimmages, and games for youth tackle and flag players. The SIM-G impact sensors were distributed before each session and collected after each session for charging. A member of the research team was present at every session and recorded start and end times for each event, water breaks, injury time outs, and any miscellaneous pauses in play.

Data analysis

Data went through a multistep cleaning process before being analyzed (Fig. 1). The data processing procedures were implemented to ensure that spurious impacts were not included in the final dataset. Because impact frequency was an important study outcome, we elected to take a conservative approach to data cleaning. Impacts were removed if they fell outside each defined practice or competition session time. For tackle football, the head coach required players to leave their helmets on at all times, except water breaks and between quarters. It is possible that the SIM-G could have been triggered when an athlete removed his helmet. Thus, all water break and quarter break start/end times were recorded, and any impacts that occurred during these times were removed from the analysis dataset. This was not necessary for flag football because there were no helmets.

The study team took diligent notes during all sessions, and data were excluded where any athlete removed or tampered with their SIM-G. Finally, to further ensure only real head impacts were included in the analysis dataset, individual player sessions where a large number of impacts occurred were removed. This conservative data cleaning approach was used to eliminate situations where a player may have removed/donned the headband frequently or not worn it appropriately during a session (e.g., headband fell down around their neck).

To standardize a higher than normal impact frequency, several options were explored. The most conservative approach (resulting in the strictest high frequency threshold) was to take the median number of impacts per session and add the third quartile value. Medians and corresponding third quartile impacts per session were calculated separately for tackle and flag football. Then, any player who experienced more impacts in a single session than the high frequency threshold was identified, and the data for this player for the identified session were removed from the analysis dataset.

Sessions were classified as either games or practices. Scrimmages against opposing teams that were planned in advance were considered games. Youth flag football teams often scrimmaged among themselves or against other teams unscheduled for small portions of practice. These sessions were considered practices. Impact rates (IR; number of impacts/total exposures) were calculated separately for games and practices and are presented as impacts per one athlete exposure.

Athlete exposure was defined as one player participating in one session while wearing a SIM-G. Impact rate ratios (IRR; tackle IR/flag IR) compared IR between youth tackle and flag football players overall and by session type. Games and practices were also compared within both tackle and flag youth football separately

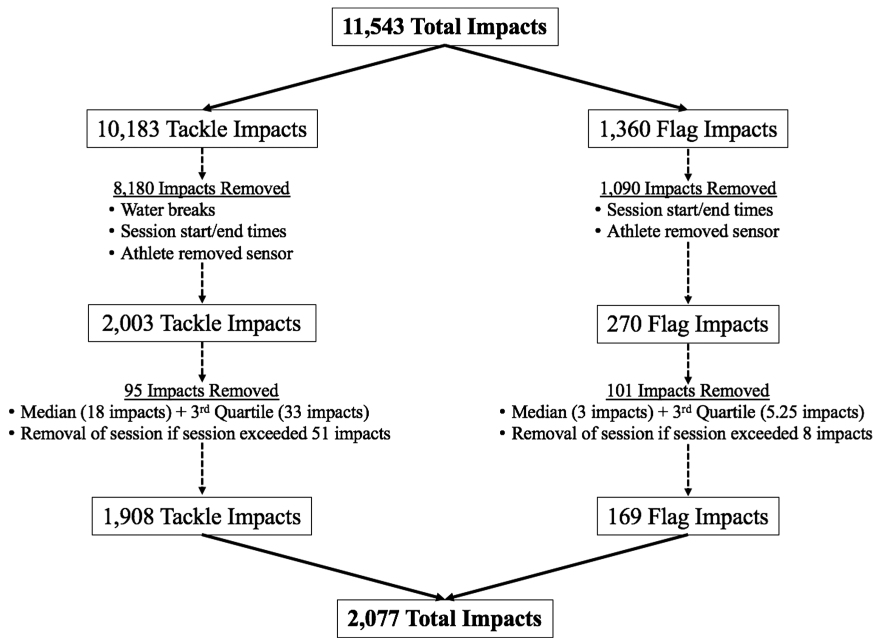

FIG. 1. Multistep data cleaning process.

using IRR, reported as game IR relative to practice IR. The IRR with corresponding 95% confidence intervals (CI) not containing 1.0 were considered statistically significant.

Impact magnitude (linear and rotational acceleration) descriptive statistics are provided along with 95th percentile values, and comparisons were made between the football cohorts utilizing previously published head impact magnitude categories.[25] Impacts were binned into four categories based on linear (14.00–19.99*g*, 20.00–29.99*g*, 30–39.9*g*, and ≥40.00*g*) and rotational acceleration (≤2499.99 rad/s^2, 2500.00–7499.99 rad/s^2, 7500.00–12,499.99 rad/s^2, and ≥12,500.00 rad/s^2). After coding the data into this binned structure, we observed only nine tackle football impacts (0.5%; 0 flag football impacts) in the ≥12,500.00 rad/s^2 bin. Thus, when exploring rotational acceleration, we collapsed the highest magnitude bin into the 7500.00–12,499.99 rad/s^2 bin, resulting in three total rotational acceleration magnitude bins. By reporting magnitude outcomes in binned categories in addition to summary accelerations (median values), we were able to provide complementary, but alternative views of the head impact data distribution.

We computed odds ratios (OR) with corresponding 95% CIs using random-intercept generalized logit models.[26] We computed the odds of sustaining an impact with a linear acceleration of 20.00–29.99*g*, 30.00–39.99*g*, and ≥40.00*g* against the reference of 14.00–19.99*g* and an impact with a rotational acceleration of 2500.00–7499.99 rad/s^2 or ≥7500.00 rad/s^2 against the reference of ≤2499.99 rad/s^2 between youth flag and tackle football groups. Independent samples *t* tests were used to compare demographics between youth football cohorts. All statistical analyses were performed using SAS 9.4 (SAS Institute, Morrisville, NC). The ORs are presented as youth flag football players relative to youth tackle football players, and any OR with a corresponding 95% CI not containing 1.0 was considered statistically significant.

Results

We collected head impact biomechanics data from 624 tackle football athlete exposures (192 in games, 30.8%) and 255 flag football athlete exposures (182 in games, 71.4%). Overall, we observed 1908 tackle football head impacts (735 in games, 38.5%) and 169 flag football head impacts (101 in games, 59.8%). The number of impacts per player in youth tackle football ranged from four to 221 (median = 71) and from one to 21 (median = 7) in youth flag football. Youth tackle football players were significantly taller ($p < 0.001$), heavier ($p = 0.005$), and older ($p < 0.001$) than youth flag football players.

Impact rates

Tackle football players experienced a significantly higher head IR during games, practices, and both sessions combined compared with flag players. Table 1 provides all IR and IRR with corresponding 95% CIs.

Youth tackle football players experienced a significantly higher IR during games compared with practices (IRR = 1.41; 95% CI: 1.29, 1.55). Youth flag football players experienced a significantly higher IR during practices, however, compared with games (IRR = 1.69; 95% CI: 1.24, 2.28).

Table 1. Impact Frequency for Youth Flag and Tackle Football Players

		No. of Impacts	*Impact rate (95% CI)*[a]	*Impact rate ratio (95% CI)*[b]
Overall	*Tackle*	1908	3.06 (2.61, 3.58)	4.61 (3.94, 5.40)
	Flag	169	0.66 (0.57, 0.78)	
Games	*Tackle*	735	3.83 (3.11, 4.71)	6.90 (5.60, 8.49)
	Flag	101	0.55 (0.45, 0.68)	
Practices	*Tackle*	1173	2.72 (2.13, 3.47)	2.91 (2.28, 3.72)
	Flag	68	0.93 (0.73, 1.19)	

Impact rate ratios with 95% confidence interval (CI) not containing 1.0 were considered statistically significant.

[a]Impact rates are calculated per one athlete exposure.

[b]Impact rate ratio is tackle relative to flag.

Impact magnitude

Linear and rotational acceleration descriptive statistics are presented in Table 2. Youth flag football players had reduced odds of sustaining linear acceleration head impacts among 20– 29.99*g* (R = 0.28; 95% CI: 0.16, 0.51), 30–39.99*g* (OR = 0.31; 95% CI: 0.17, 0.55), and ≥40*g* (OR = 0.35; 95% CI: 0.19, 0.66) compared with youth tackle football players. Youth flag football players had increased odds of sustaining rotational acceleration head impacts between 2500–7499.99 rad/s^2 (OR = 1.73 95% CI: 1.07, 2.81) but not >7500 rad/s^2 (OR = 2.28; 95% CI: 0.92, 5.67) compared with youth tackle football players. Binned linear and rotational acceleration head impact frequencies are presented in Table 3.

Discussion

We are the first to report head impact outcomes in youth flag football and to make comparisons between youth flag and tackle football. Overall, youth tackle football players experienced a higher impact rate than their flag counterparts, but flag football players had increased odds for sustaining head impacts of higher magnitude rotational accelerations. Although flag football is considered a limited-contact sport,[16] we observed numerous head impacts, both with our data collection instrumentation and anecdotally through observation while collecting data throughout the season. Understanding the head impact burden in both youth tackle and flag football is critical because policies are being crafted and proposed that may drastically change the youth football landscape.

Our hypothesis regarding youth flag football impacts was not supported by the data. Although the impact rate was low compared with youth tackle football, it was somewhat surprising that we captured 169 impacts from 25 players in a single season. Overall, youth flag football players sustained about one head impact for every two exposures, while youth tackle football players sustained about six impacts for every two exposures. It is possible that simple measures, such as enforcing existing rules, may help mitigate head impacts in youth flag football. Anecdotally, we noticed very few instances where officials stopped play or assessed a foul during player-to-player contact, even though this contact was against league rules.

Another strategy to reduce head impacts in youth flag football may be enhanced coaching in regard to pulling the opponents flag. The volunteer youth flag football coaches were limited in the time they spent with the players, which may have caused coaches to focus on other more common skills such as passing, catching, and running. Additional training focused on pulling the opponents flag without physical contact may give young athletes the tools they need to avoid potentially hazardous player-to-player contact.

Youth flag football had a lower head impact rate than tackle football. Legislators, parents, coaches, and players should be aware, however, that even though flag football is a limited-contact sport, head impacts can and do occur with some regularity. Our data must be considered preliminary because we only observed four youth flag football teams from a single Recreation Department league, but clearly future studies are needed to determine the true head impact burden in this limited-contact sport. This is important because head impact frequency in the absence of concussion has been linked to neurological changes over the course of a football season.[27–29] It is not clear, however, what head impact frequency and/or magnitude combination may lead to short- and long-term neurodegeneration.

There are many factors that may cause parents and administrators to push for youth flag football as opposed to tackle football, but

Table 2. Linear and Rotational Acceleration Descriptive Statistics for Youth Flag (N = 169 Impacts) and Tackle (N = 1908 Impacts) Football Players

	Overall		*Games*		*Practices*	
Linear accel (g)	*Flag*	*Tackle*	*Flag*	*Tackle*	*Flag*	*Tackle*
Median (range)	32.7 (16.1–100.9)	32.5 (16.0–110.0)	35.0 (16.6–100.9)	33.1 (16.0–101.1)	33.9 (16.0–68.9)	32.2 (16.0–110.0)
95th Percentile	62.9	62.3	65.8	63.2	54.9	61.5
Rotational accel (rad/s^2)	*Flag*	*Tackle*	*Flag*	*Tackle*	*Flag*	*Tackle*
Median (range)	4100.0 (1100.0–11700.0)	3200.0 (600.0–15600.0)	3800.0 (1100.0–11700.0)	3200.0 (600.0–15400.0)	4550.0 (1600.0–11100.0)	3200.0 (600.0–15600.0)
95th Percentile	9200.0	8300.0	9500.0	8000.0	9200.0	8400.0

TABLE 3. FREQUENCY OF CATEGORIZED LINEAR AND ROTATIONAL ACCELERATION BETWEEN GROUPS

	Linear acceleration (g)				*Rotational acceleration (rad/s²)*		
	14–19.99	*20–29.99*	*30–39.99*	*≥40*	*≤2499.99*	*2500–7499.99*	*>7500*
Flag % (n)	12.4 (21)	27.8 (47)	32.5 (55)	27.2 (46)	17.8 (30)	65.7 (111)	16.6 (28)
Tackle % (n)	4.3 (81)	33.6 (641)	36.1 (688)	26.1 (498)	30.6 (584)	61.2 (1167)	8.2 (157)

certainly the head impact burden is an important consideration. Before strict policies are implemented eliminating youth tackle football, additional studies should be conducted in youth flag football that further elucidate the true head impact burden.

Comparing our youth tackle football head impact rate to previous studies is challenging given methodological differences. About 62% of our observed youth tackle football impacts occurred in practices, which is similar to previous reports; impacts range from 57% to 77%.[6,10,14] We report smaller practice and game head impact rates than previous studies, however.[5,6,8,9,30] Impact frequency may be influenced by a number of factors, including coaching style,[6] age,[10,31] and skill level.[5] Data collection instrumentation and data cleaning techniques may also influence head impact rate. Our minimum threshold (14*g*) was slightly higher than the 10*g* minimum threshold commonly used with the Head Impact Telemetry System,[7,14] although various minimum thresholds have been used throughout the literature.[6,32]

We describe our data cleaning process in detail here, but many previous studies do not detail this process. This process was designed to ensure spurious impacts were removed from the analysis dataset. Although it is possible some true impacts may have been removed, we think this conservative strategy better describes the actual head impact burden in youth tackle and flag football.

We observed significantly higher youth tackle football game impact rates compared with practice impact rates, but observed the opposite with youth flag football. Our youth tackle findings are similar to previously published research indicating players experience a higher number of impacts in practice, but when exposure is accounted for, suffer a higher impact rate during games.[4,9,10] There may be several reasons why we observed the opposite trend in youth flag football players. Practices were highly unstructured, and contact was largely unregulated. Increased focus on minimizing contact and proper opponent flag pulling may help reduce youth flag football practice head impact exposure.

Another reason may be the small number of total practice exposures. In the youth flag football league we observed, athletes had about twice the exposure to game impacts as they did practice impacts, which is contrary to published tackle football outcomes and our own results here. Increased practice time, in a controlled environment, may allow the athletes to better learn proper flag football techniques, which could help reduce both game and practice head impacts.

Median head impact magnitudes were similar between cohorts. When observing binned rotational acceleration values, however, flag football players had increased odds for sustaining higher magnitude impacts compared with tackle football players. Conversely, youth tackle football players had increased odds for sustaining higher linear acceleration impacts than flag players. While only preliminary, these findings indicate there may be different head acceleration profiles for youth flag and tackle football. These head impact profiles differences may be because of helmet use in tackle football but not flag football, rule differences between tackle and flag football, or inherent behavior differences (aggressiveness, risk taking behavior, etc.) between tackle and flag football, but we can only speculate from the current study.

Future work should further explore contributions to youth tackle and flag head impact profiles so interventions, rule changes, and equipment advances can be made to mitigate head impact magnitude. It should be noted, however, that these differences could be driven by biomechanical differences between an impact sustained while wearing a helmet versus an impact sustained without a helmet. Further, the clinical consequences of different acceleration profiles are not clear, and the accuracy of such profiles is dependent on the ability of the data recording system to measure correctly head impact magnitude in both helmeted and non-helmeted scenarios.

This preliminary study has several limitations, some of which have been discussed already. We only observed a single season of two youth male tackle and four flag football teams from one Recreation Department, limiting generalizability. The youth tackle teams played in a league that spans multiple counties, however, and conforms to many standard rules in place across the country. The SIM-G validity and reliability is unclear, especially in an on-field setting. To account for some potential impact magnitude errors, we calculated binned acceleration values. We also applied and reported robust data cleaning methods to remove spurious impacts. Recording video and reviewing film to identify impacts, albeit cumbersome and time consuming, may help minimize some instrumentation limitations. Given delimitations regarding access to youth athletes, our tackle cohort was slightly older, heavier, and taller than our flag cohort on average, which could have affected some of our reported outcomes.

We are the first to report youth flag football head impact outcomes and compare these outcomes with youth tackle football. The head impact rate was substantially lower in youth flag football players compared with tackle players, but numerous head impacts did occur. Our sample of flag football players sustained less frequent, but higher rotational acceleration magnitude head impacts, relative to tackle football players. Flag football is classified as a limited-contact sport,[16] but more research is needed to understand the true head impact burden. These data may be important for policy makers when debating potential changes to the current youth football landscape.

Author Disclosure Statement

No competing financial interests exist.

References

1. Aspen Institute. *State of Play 2017: Trends and Developments.* (2017). Aspen Institute Sports & Society Program: Washington, D.C.
2. Kaplen, D.C. Youth tackle football - proposed legislation. (2018). www.brainlaw.com/youth-tackle-football/. Last accessed June 22, 2018.
3. Feldman, J. Four states considering youth tackle football bans. (2018). www.si.com/nfl/2018/04/04/four-states-consider-banning-youth-football-themmqb-newsletter. Last accessed June 22, 2018.

4. Daniel, R.W., Rowson, S., and Duma, S.M. (2014). Head impact exposure in youth football: middle school ages 12–14 years. J. Biomech. Eng. 136, 094501.
5. Young, T.J., Daniel, R.W., Rowson, S., and Duma, S.M. (2014). Head impact exposure in youth football: elementary school ages 7–8 years and the effect of returning players. Clin. J. Sport Med. 24, 416–421.
6. Kerr, Z.Y., Yeargin, S.W., Valovich McLeod, T.C., Mensch, J., Hayden, R., and Dompier, T.P. (2015). Comprehensive coach education reduces head impact exposure in American youth football. Orthop. J. Sports Med. 3, 2325967115610545.
7. Bellamkonda, S., Woodward, S.J., Campolettano, E., Gellner, R., Kelley, M.E., Jones, D.A., Genemaras, A., Beckwith, J.G., Greenwald, R.M., Maerlender, A.C., Rowson, S., Jr., Duma, S.M., Urban, J.E., Stitzel, J.D., and Crisco, J.J. (2018). Head impact exposure in practices correlates with exposure in games for youth football players. J. Appl. Biomech. 34, 354–360.
8. Munce, T.A., Dorman, J.C., Thompson, P.A., Valentine, V.D., and Bergeron, M.F. (2015). Head impact exposure and neurologic function of youth football players. Med. Sci. Sports Exerc. 47, 1567–1576.
9. Urban, J.E., Davenport, E.M., Golman, A.J., Maldjian, J.A., Whitlow, C.T., Powers, A.K., and Stitzel, J.D. (2013). Head impact exposure in youth football: high school ages 14 to 18 years and cumulative impact analysis. Ann. Biomed. Eng. 41, 2474–2487.
10. Kelley, M.E., Urban, J.E., Miller, L.E., Jones, D.A., Espeland, M.A., Davenport, E.M., Whitlow, C.T., Maldjian, J.A., and Stitzel, J.D. (2017). Head impact exposure in youth football: comparing age- and weight-based levels of play. J. Neurotrauma 34, 1939–1947.
11. Mihalik, J.P., Bell, D.R., Marshall, S.W., and Guskiewicz, K.M. (2007). Measurement of head impacts in collegiate football players: an investigation of positional and event-type differences. Neurosurgery 61, 1229–1235.
12. Campolettano, E.T., Gellner, R.A., and Rowson, S. (2017). High-magnitude head impact exposure in youth football. J. Neurosurg. Pediatr. 20, 604–612.
13. Crisco, J.J., Wilcox, B.J., Machan, J.T., McAllister, T.W., Duhaime, A.C., Duma, S.M., Rowson, S., Beckwith, J.G., Chu, J.J., and Greenwald, R.M. (2012). Magnitude of head impact exposures in individual collegiate football players. J. Appl. Biomech. 28, 174–183.
14. Campolettano, E.T., Rowson, S., and Duma, S.M. (2016). Drill-specific head impact exposure in youth football practice. J. Neurosurg. Pediatr. 18, 536–541.
15. Kelley, M.E., Espeland, M.A., Flood, W.C., Powers, A.K., Whitlow, C.T., Maldjian, J.A., Stitzel, J.D., and Urban, J.E. (2018). Comparison of head impact exposure in practice drills among multiple youth football teams. J. Neurosurg. Pediatr. 1–9. E-pub ahead of print.
16. Rice S.G., American Academy of Pediatrics Council on Sports Medicine and Fitness. (2008). Medical conditions affecting sports participation. Pediatrics 121, 841–848.
17. Lamond, L.C., Caccese, J.B., Buckley, T.A., Glutting, J., and Kaminski, T.W. (2018). Linear acceleration in direct head contact across impact type, player position, and playing scenario in collegiate women's soccer players. J. Athl. Train. 53, 115–121.
18. Caccese, J.B., Lamond, L.C., Buckley, T.A., and Kaminski, T.W. (2016). Reducing purposeful headers from goal kicks and punts may reduce cumulative exposure to head acceleration. Res. Sports Med. 24, 407–415.
19. Marchesseault, E.R., Nguyen, D., Spahr, L., Beals, C., Razak, B., and Rosene, J.M. (2018). Head impacts and cognitive performance in men's lacrosse. Phys. Sportsmed. 46. 324–330.
20. Yoganandan, N., Pintar, F.A., Zhang, J., and Baisden, J.L. (2009). Physical properties of the human head: mass, center of gravity and moment of inertia. J. Biomech. 42, 1177–1192.
21. Oeur, R.A., Karton, C., and Hoshizaki, T.B. (2016). Impact frequency validation of head impact sensor technology for use in sport. Presented at the 34th International Conference on Biomechanics in Sports, Tsukuba, Japan.
22. Cummiskey, B., Schiffmiller, D., Talavage, T.M., Leverenz, L., Meyer, J.J., Adams, D., and Nauman E.A. (2017). Reliability and accuracy of helmet-mounted and head-mounted devices used to measure head accelerations. Proceedings of the Institution of Mechanical Enggineering, Part P: Journal of Sport Engineering and Technology. 231, 144–153.
23. Karton, C., Oeur, R.A., and Hoshizaki, T.B. (2016). Measurement accuracy of head impact monitoring system in sport. Presented at: 34th International Conference on Biomechanics in Sports, Tsukuba, Japan.
24. Tyson, A.M., Duma, S.M., and Rowson, S. (2018). Laboratory evaluation of low-cost wearable sensors for measuring head impacts in sports. J. Appl. Biomech. 34, 320–326.
25. Lynall, R.C., Clark, M.D., Grand, E.E., Stucker, J.C., Littleton, A.C., Aguilar, A.J., Petschauer, M.A., Teel, E.F., and Mihalik, J.P. (2016). Head impact biomechanics in women's college soccer. Med. Sci. Sports Exerc. 48, 1772–1778.
26. Schmidt, J.D., Guskiewicz, K.M., Blackburn, J.T., Mihalik, J.P., Siegmund, G.P., and Marshall, S.W. (2014). The influence of cervical muscle characteristics on head impact biomechanics in football. Am. J. Sports Med. 42, 2056–2066.
27. Talavage, T.M., Nauman, E.A., Breedlove, E.L., Yoruk, U., Dye, A.E., Morigaki, K.E., Feuer, H., and Leverenz, L.J. (2014). Functionally-detected cognitive impairment in high school football players without clinically-diagnosed concussion. J. Neurotrauma 31, 327–338.
28. Abbas, K., Shenk, T.E., Poole, V.N., Robinson, M.E., Leverenz, L.J., Nauman, E.A., and Talavage, T.M. (2015). Effects of repetitive sub-concussive brain injury on the functional connectivity of Default Mode Network in high school football athletes. Dev. Neuropsychol. 40, 51–56.
29. Nauman, E.A., Breedlove, K.M., Breedlove, E.L., Talavage, T.M., Robinson, M.E., and Leverenz, L.J. (2015). Post-season neurophysiological deficits assessed by ImPACT and fMRI in athletes competing in American football. Dev. Neuropsychol. 40, 85–91.
30. Kelley, M.E., Kane, J.M., Espeland, M.A., Miller, L.E., Powers, A.K., Stitzel, J.D., and Urban, J.E. (2017). Head impact exposure measured in a single youth football team during practice drills. J. Neurosurg. Pediatr. 20, 489–497.
31. Cobb, B.R., Urban, J.E., Davenport, E.M., Rowson, S., Duma, S.M., Maldjian, J.A., Whitlow, C.T., Powers, A.K., and Stitzel J.D. (2013). Head impact exposure in youth football: elementary school ages 9–12 years and the effect of practice structure. Ann. Biomed. Eng. 41, 2463–2473.
32. McCuen, E., Svaldi, D., Breedlove, K., Kraz, N., Cummiskey, B., Breedlove, E.L., Traver, J., Desmond, K.F., Hannemann, R.E., Zanath, E., Guerra, A., Leverenz, L., Talavage, T.M., and Nauman, E.A. (2015). Collegiate women's soccer players suffer greater cumulative head impacts than their high school counterparts. J. Biomech. 48, 3720–3723.

Address correspondence to:
Robert C. Lynall, PhD
Department of Kinesiology
University of Georgia
330 River Road
Athens, GA 30602

E-mail: rlynall@uga.edu