Head Impact Biomechanics in Youth Flag Football

A Prospective Cohort Study

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Background: Youth flag football participation has rapidly grown and is a potentially safer alternative to tackle football. However, limited research has quantitatively assessed youth flag football head impact biomechanics.

Purpose: To describe head impact biomechanics outcomes in youth flag football and explore factors associated with head impact magnitudes.

Study Design: Cross-sectional study; Level of evidence, 3.

Methods: We monitored 52 player-seasons among 48 male flag football players (mean ± SD; age, 9.4 ± 1.1 years; height, 138.6 ± 9.5 cm; mass, 34.7 ± 9.2 kg) across 3 seasons using head impact sensors during practices and games. Sensors recorded head impact frequencies, peak linear (g) and rotational (rad/s^2) acceleration, and estimated impact location. Impact rates (IRs) were calculated as 1 impact per 10 player-exposures; IR ratios (IRRs) were used to compare season, event type, and age group IRs; and 95% CIs were calculated for IRs and IRRs. Weekly and seasonal cumulative head impact frequencies and magnitudes were calculated. Mixed-model regression models examined the association between player characteristics, event type, and seasons and peak linear and rotational accelerations.

Results: A total of 429 head impacts from 604 exposures occurred across the study period (IR, 7.10; 95% CI, 4.81-10.50). Weekly and seasonal cumulative median head impact frequencies were 1.00 (range, 0-2.63) and 7.50 (range, 0-21.00), respectively. The most frequent estimated head impact locations were the skull base (n = 96; 22.4%), top of the head (n = 74; 17.2%), and back of the head (n = 66; 15.4%). The combined event type IRs differed among the 3 seasons (IRR range, 1.45-2.68). Games produced greater IRs (IRR, 1.24; 95% CI, 1.01-1.53) and peak linear acceleration (mean difference, 5.69g; P = .008) than did practices. Older players demonstrated greater combined event–type IRs (IRR, 1.46; 95% CI, 1.12-1.90) and increased head impact magnitudes than did younger players, with every 1-year age increase associated with a 3.78g and 602.81-rad/s^2 increase in peak linear and rotational acceleration magnitude, respectively ($P \leq .005$).

Conclusion: Head IRs and magnitudes varied across seasons, thus highlighting multiple season and cohort data are valuable when providing estimates. Head IRs were relatively low across seasons, while linear and rotational acceleration magnitudes were relatively high.

Keywords: pediatric; repetitive head impact; concussion; subconcussive; sport safety; youth sport

Flag football is a rapidly growing sport in the United States across age groups and sexes,[18-20] with nearly 1 million adolescents participating each year.[30] Youth flag football has received attention because it promotes foundational team building and physical activity health benefits[26,27] while minimizing the repetitive head impacts accrued relative to traditional tackle football.[16] Repetitive head impacts before the age of 12 years have been associated with long-term neurodegenerative consequences,[1,31] although mixed evidence exists.[4,29] Regardless, promoting a physically active lifestyle early on while mitigating repetitive head impacts is an important consideration until the long-term consequences are further understood.

Flag football has been proposed by advocacy groups as a safer alternative to tackle football for children aged <12 years. Consequently, state legislators have proposed bills aimed at banning youth tackle football[9] because of the potential long-term neurodegenerative consequences.[1,31] These advocacy and legislation proposals are collectively intended to eliminate the head impact burden experienced by adolescents, but limited research has

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TABLE 1
Flag Football Player Characteristics Across Seasons

	2017 Season		2018 Season		2019 Season		Combined Seasons	
	No.	%	No.	%	No.	%	No.	%
Players	25	48.1	10	19.2	17	32.7	52	100.0
Players in previous 2 seasons	0	0.0	2	20.0	2	11.8	4	7.7
Age, y[a]	8.65	1.15	10.06	0.56	10.05	0.55	9.37	1.14
Playing level[b]								
7-8U	14	56.0	0	0	0	0	14	26.9
9-10U	11	44.0	10	100.0	17	100.0	38	73.1
Sex: male	25	100.0	10	100.0	17	100.0	52	100.0
Height, cm[a]	134.42	8.74	148.70	6.98	138.65	7.00	138.55	9.45
Mass, kg[a]	34.57	9.98	37.22	4.65	33.21	10.26	34.66	9.24
Weeks of play[c]	8	33.3	7	29.2	9	37.5	24	100.0

[a]Values are presented as mean (SD).
[b]7-8U, 7 to 8 years old; 9-10U, 9 to 10 years old.
[c]Percentage based on combined seasons.

quantitatively explored the head impact burden in youth flag football to determine its safety.[16] Flag football research is confined to sport epidemiology reports on musculoskeletal and concussion injury rates among adult-aged cohorts,[3,10] with only 1 study examining a youth cohort.[22] Although sport epidemiology research is seminal in understanding musculoskeletal and concussion injuries in flag football, the head impact rates (IRs), magnitudes, and characteristics are relatively unknown.

Only our previous study,[16] to our knowledge, has examined head impact biomechanics in a small youth flag football cohort. We found that flag football players experienced 4.6-times fewer head impacts for practices and games combined, but those head impacts demonstrated similar peak linear and higher-magnitude peak rotational acceleration as compared with those of matched tackle football players. The reported[16] IRs and magnitudes may not truly represent youth head impact biomechanics across a normative spectrum because monitoring occurred across a single season involving a single player cohort. It is possible that the observed findings may over- or underestimate the true head IRs and/or magnitudes occurring in youth flag football. This concern warrants multiseason and multicohort observation to comprehensively inform stakeholders (eg, players, parents, coaches, policy makers, clinicians, and researchers).

Our previous study[16] did not present findings related to impact location, weekly or seasonal cumulative head impact frequencies and magnitudes, or the association between these factors and head impact magnitudes. Conducting a detailed examination of head impact biomechanics can ensure flag football safety by informing stakeholders of head impact characteristics so that potential policy, equipment, or rule changes may be implemented. Therefore, the purpose of this study was to comprehensively describe head IRs, magnitudes, and characteristics across 3 seasons of youth flag football and to explore factors associated with head impact magnitudes. We hypothesized that greater head impact magnitudes and rates would be observed during games versus practices and in older versus younger age groups.

METHODS

Participants

We used a 3-year prospective cohort study to examine head impact biomechanics among youth flag football players. All players were part of the same recreation department in the United States. Data were collected across 3 fall seasons, with 25 players participating in 2017; 10, in 2018; and 17, in 2019. Four players participated in 2 seasons. Player characteristics are presented in Table 1. The study protocol was approved by our institutional review board, and all players assented to be in the study, with at least 1 parent or guardian providing informed consent for each player. This study is reported in accordance with the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) guidelines.[35]

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Head Impact Telemetry

The Triax Smart Impact Monitor (SIM-G; Triax Technologies Inc) head impact telemetry system was used to collect head impact frequencies and magnitudes and estimated impact locations during practices and games. The SIM-G was inserted into either a headband or skullcap and worn by each player inferior to his external occipital protuberance throughout the duration of each practice and competition. Each player was assigned a unique sensor and headband or skullcap. The SIM-G sensor utilized a 3-axis gyroscope to measure rotational velocity and acceleration (rad/s^2) and a low- and high-g 3-axis accelerometer to measure linear acceleration. A 14g linear acceleration threshold was established for 10 milliseconds before the impact and 52 milliseconds after the impact. Peak linear and rotational accelerations were captured during the head impact threshold time window when the accelerometer reached the 14g threshold.[16] Several publications have investigated the accuracy of the SIM-G telemetry system, reporting strong nonhelmeted and helmeted impact detection[8,21] and valid linear acceleration values as compared with a headform[11]; others, however, have reported underestimated linear and rotational acceleration values during nonhelmeted and helmeted conditions.[34] It is important to note that no on-field head impact telemetry system is perfect in comparison with the gold standard instrumented headform[5,8,28]; therefore, the optimal system should be based on the study's nature. The SIM-G telemetry system was utilized for this study because it can wirelessly record, store, and transmit real-time head impact data from nonhelmeted players and has been widely used in various sports examining head impact biomechanics.[6,14,16,33]

Data Processing and Statistical Analysis

A research team member was present at every event (practice or game) to hand out each player's unique sensor and record start and end times, water breaks, injury time-outs, and any additional pauses (eg, pauses between quarters or at halftime) in play to filter erroneous impacts recorded during these times across all 3 seasons.[16] The research team members took notes during all events, and head impacts were excluded from the data set if any player removed or tampered with his sensor for that specific time frame. The sensors were returned to a research team member, and data were extracted from each device at the end of each event.

All flag football head impacts per session were initially filtered using on-board manufacturer parameters.[14,16] Next, impacts that were time-stamped during the defined periods were removed from the data set. Finally, all head impacts were filtered by using a head impact frequency threshold derived from summing the median number of head impacts per session and adding the third-quartile impacts per session to it ($\geq$8 impacts in this study).[16] The head impact frequency threshold resulted in removing 132 impacts from 6 events across 4 players in 2017, 67 impacts from 1 event from 1 player in 2018, and 37 impacts from 2 events across 2 players in 2019. This data-filtering process was identical to that of a previous study analyzing head impact biomechanics in youth tackle and flag football players.[16]

Event types were classified as games or practices. Unscheduled scrimmages among the team or against other teams for short periods were considered practices. The IRs were derived from the number of impacts per 10 player-exposures and calculated separately for event type (games, practices, and combined), season (2017, 2018, 2019, and combined), and age group (7-8 years old [7-8U] and 9-10 years old [9-10U]). Player-exposure was defined as 1 player participating in 1 session while wearing an SIM-G. The IR ratio (IRR) compared IRs among event types, seasons, and age groups. IRRs with corresponding 95% CIs not containing 1.0 were considered statistically significant.

Descriptive statistics were assessed for player characteristics and event exposures as well as head impact frequencies, location, severities, and magnitudes. Weekly cumulative mean head impact frequencies and magnitudes were calculated across all seasons by summing the values in a 7-day period for each player, averaging the sums within each player, and then taking the average among all players.[32] Seasonal cumulative mean head impact frequencies and magnitudes were calculated identical to the way weekly data were calculated, except values were summed and averaged over the entire season.[2] Linear and rotational head impact magnitude severity frequencies were categorically binned on the basis of previously established levels.[15,16] We utilized mixed-model univariable linear regression analysis (ie, accounting for numerous head impacts deriving from a single player) using restricted maximum likelihood variance estimation to examine the effect of age, height, mass, body mass index (BMI), event type, and season year on peak linear and rotational acceleration values. Predictors from the univariable models with $P \leq .10$ (determined a priori) were then included in a mixed-model multivariable linear regression to examine each predictor variable's association with linear and rotational acceleration values while accounting for the other contributing predictors. Univariable and multivariable P values were calculated using the Satterthwaite method,[13] and multivariable coefficients of determination (R^2) were derived using the approach of Nakagawa and Schielzeth.[17] All regression model assumptions were assessed for violations before statistical interpretation. Multicollinearity was identified between season year and age ($r >$ 0.50); therefore, only age was included in the multivariable model if meeting inclusion. All statistical analyses were conducted using the R Project for Statistical Programming (Version 3.4.3)[23] with the α level set a priori at .05.

RESULTS

A total of 52 player-seasons were monitored among 48 male flag football players who participated in 1 of the 3 seasons, resulting in 24 cumulative weeks of participation. Players in the 7-8U age group (n = 14) only participated in the 2017 season, with players in the 9-10U age group (n =

TABLE 2
Head Impact Exposures, Frequencies, and Rates Across Seasons and Event Type

	2017 Season		2018 Season		2019 Season		Combined Seasons	
	No.	%	No.	%	No.	%	No.	%
Practice								
Exposure frequency[a]	73	36.3	28	13.9	100	49.8	201	100
Head impact frequency[a]	68	55.3	8	6.5	47	38.2	123	100
Impact rates per 10 exposures[b]	9.32	4.48-19.38	2.86	1.97-4.14	4.70	2.22-9.95	6.12	4.96-7.54
Game								
Exposure frequency[a]	190	47.1	70	17.4	143	35.5	403	100
Head impact frequency[a]	101	33.0	26	8.5	179	58.5	306	100
Impact rates per 10 exposures[b]	5.32	3.45-8.18	3.71	2.91-4.74	12.52	8.30-18.89	7.59	6.16-9.36
Combined								
Exposure frequency[a]	263	43.5	98	16.2	243	40.2	604	100
Head impact frequency[a]	169	39.4	34	7.9	226	52.7	429	100
Impact rates per 10 exposures[b]	6.43	4.45-9.29	3.47	2.84-4.23	9.30	6.29-13.34	7.10	4.81-10.50

[a]Percentage based on combined seasons.
[b]Range indicates 95% CI.

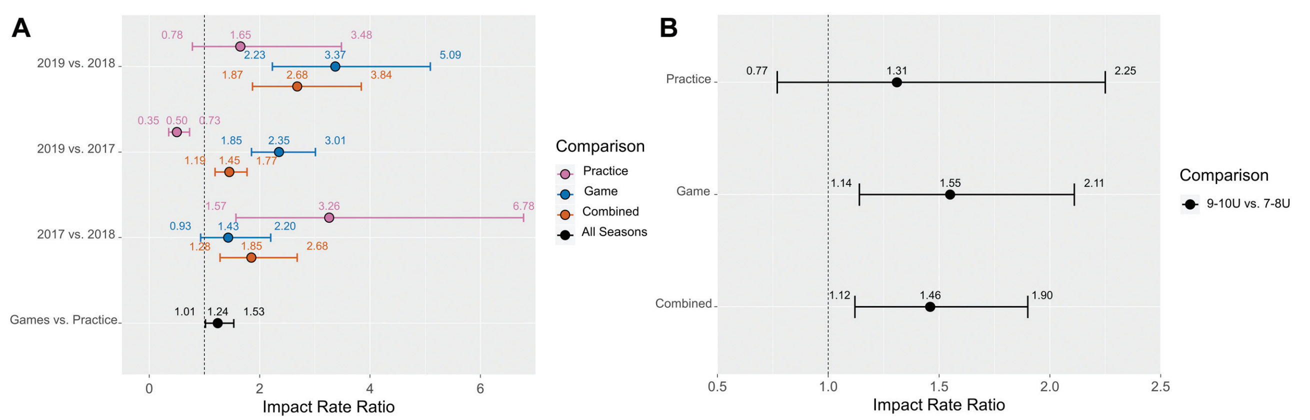

Figure 1. Head impact rate ratios (IRRs) across seasons, age groups, and event types. (A) IRRs and 95% CIs between flag football seasons for practices, games, and combined events, as well as between games and practices for all seasons. (B) IRRs between age groups for practices, games, and combined events. The factor levels before and after ‘‘vs’’ indicate the IRR numerator and denominator, respectively. 7-8U, 7 to 8 years old; 9-10U, 9 to 10 years old.

38) participating in all 3 seasons. Age, height, and mass were similar across seasons and are presented in Table 1.

Head Impact Frequencies, Rates, and Rate Ratios

Table 2 provides a summary of player-exposures, impact frequencies, and IRs across individual and combined seasons and event types. The 2017 season contributed to the largest combined-season percentage of head impact exposures (n = 263; 43.5%), and the 2019 season contributed the largest number of head impacts (n = 226; 52.7%). Head IRRs and 95% CIs between seasons for practices, games, and combined events as well as between games and practices for all seasons are presented in Figure 1A. Games resulted in significantly greater IRs than did practices when all seasons were combined (IRR, 1.24; 95% CI, 1.01-1.53). The 2019 season resulted in significantly greater game and combined-event IRs than did the 2018 season, but seasons were not statistically different for practices. The 2019 season also demonstrated significantly greater game and combined-event IRs and lower practice IRs than did the 2017 season. The 2017 season displayed significantly greater IRs for practices and combined events when compared with the 2018 season but did not differ for games.

Head IRRs and 95% CIs between age groups (9-10U vs 7-8U) are presented in Figure 1B and indicate that games (IR, 8.26 vs 5.33) and combined events (IR, 7.59 vs 5.20) resulted in significantly greater IRs for 9-10U than for 7-8U but were not statistically different for practices (IR, 6.35 vs 4.84).

TABLE 3
Head Impact Frequencies and Characteristics Across Seasons

	2017 Season		2018 Season		2019 Season		Combined Seasons	
	No.	%[a]	No.	%[a]	No.	%[a]	No.	%[b]
Sensor-estimated impact location								
Back	14	21.2	2	3.0	50	75.8	66	15.4
Front	26	46.4	6	10.7	24	42.9	56	13.1
Sides	23	45.1	0	0.0	28	54.9	51	11.9
Top	23	31.1	10	13.5	41	55.4	74	17.2
Back right	10	30.3	4	12.1	19	57.6	33	7.7
Back left	4	66.7	0	0.0	2	33.3	6	1.4
Front right	8	26.7	0	0.0	22	73.3	30	7.0
Front left	9	52.9	2	11.8	6	35.3	17	4.0
Skull base	52	54.2	10	10.4	34	35.4	96	22.4
Linear severity, g								
≤19.9	21	77.8	1	3.7	5	18.5	27	6.3
20.0-29.9	47	49.5	11	11.6	37	38.9	95	22.1
30.0-39.9	55	44.7	9	7.3	59	48.0	123	28.7
≥40.0	46	25.0	13	7.1	125	67.9	184	42.9
Rotational severity, rad/s^2								
≤2499.9	30	63.8	9	19.1	8	17.0	47	11.0
2500.0-7499.9	111	43.2	20	7.8	126	49.0	257	59.9
7500.0-12,499.9	28	25.0	4	3.6	80	71.4	112	26.1
≥12,500.0	0	0.0	1	7.7	12	92.3	13	3.0
Weekly cumulative head impact frequency								
Mean (SD)	0.83	0.59	0.49	0.42	1.65	0.33	1.03	0.66
Median (range)	0.88	0-2.63	0.43	0-1.29	1.75	1.13-2.13	1.00	0-2.63
Seasonal cumulative head impact frequency								
Mean (SD)	6.64	4.72	3.40	2.95	13.24	2.59	8.17	5.32
Median (range)	7.00	0-119.21	3.00	0-9.0	14.00	9-17	7.50	0-21.0

[a]Percentage based on combined seasons.
[b]Percentage based on all locations and severity.

Head Impact Characteristics

Table 3 provides descriptive statistics of impact locations and the average cumulative weekly and seasonal head impact frequencies. Head impact location distributions varied across seasons, with the largest combined-season frequencies being the skull base (22.4%), top of the head (17.2%), and back of the head (15.4%). Mean weekly and seasonal cumulative head impact frequencies displayed relatively high variability across seasons, and the 2017 and 2018 seasons had considerably high SDs within their players. The 2019 season had the highest cumulative head impact frequencies by week (mean ± SD, 1.65 ± 0.33 head impacts) and season (13.24 ± 2.59 head impacts). Combined-season data demonstrated that players experienced 1.03 ± 0.66 head impacts weekly and 8.17 ± 5.32 across an entire season.

Head Impact Magnitudes and Influential Factors

Linear and rotational head impact magnitude severity bins are provided in Table 3. Linear and rotational head impact severity categories were relatively heterogeneous across the seasons, with the 2017 season producing the majority of head impacts measuring ≤19.9g (n = 21; 77.8%) and ≤2499.9 rad/s^2 (n = 30; 63.8%) and the 2019 season producing the majority of head impacts measuring ≥40.0g (n = 125; 67.9%) and ≥12,500.0 rad/s^2 (n = 12; 92.3%). The highest frequencies of head impacts among the combined seasons were in the categories of ≥40.0g (n = 184; 42.9%) and 2500.0 to 7499.9 rad/s^2 (n = 257; 59.9%).

Descriptive statistics (mean, SD, median, range, and 90th percentile) are provided for linear and rotational acceleration magnitudes for each season and across event types in Table 4, and combined scatterplots and histograms for linear and rotational acceleration magnitude data points across seasons, event types, and age groups are provided in Figure 2. Similar to IRs and frequencies, head impact magnitudes were heterogeneous across seasons. Univariable mixed-model regressions identified the 2019 season as producing significantly greater peak linear (mean difference, 14.51g; $P < .001$) and rotational (mean difference, 2428.96 rad/s^2; $P < .001$) magnitudes than did the 2017 season but not the 2018 season ($P \geq .11$) (Table 5). Games resulted in 4.50g greater peak linear acceleration magnitudes than did practices ($P = .04$), but no difference was present for peak rotational magnitudes ($P = .56$). Age was identified as a significant univariable predictor for peak linear ($P = .003$) and rotational ($P = .005$) magnitudes, with every 1-year age increase resulting in 3.61g and 602.81-rad/s^2 greater head impact magnitudes. Player

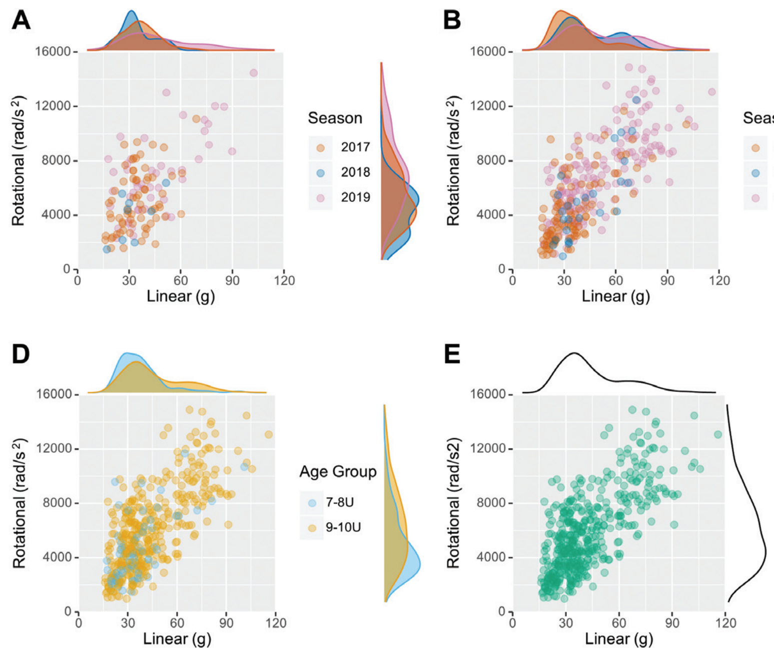

Figure 2. Linear and rotational head impact magnitudes across seasons, age groups, and overall. Peak linear and rotational acceleration magnitude scatterplot (30% shading each data point) and parallel-axis density plots for each recorded head impact for (A) practices, (B) games, and (C) combined event types across each season, as well as (D) between age groups for combined event types and (E) combined seasons and combined event types. 7-8U, 7 to 8 years old; 9-10U, 9 to 10 years old.

height and mass were not statistically significant predictors of peak linear ($P \geq .16$) or rotational ($P \geq .13$) acceleration magnitudes. BMI was not a statistically significant predictor of peak linear ($P = .07$) or rotational ($P = .33$) magnitudes but met the a priori threshold for inclusion in the linear acceleration mixed-model multivariable model.

Age, BMI, and event type were included in the multivariable model. The mixed-model multivariable regression accounted for 6% of the observed variance ($R^2 = 0.06$; 95% CI, 0.03-0.12) with age, BMI, and event type being significant predictors. Every 1-year age increase resulted in a 3.78*g* peak linear acceleration increase, every 1-unit increase in BMI resulted in a linear acceleration decrease of –0.62*g*, and games demonstrated 5.69*g* greater linear acceleration than did practices (Table 5).

Age and season year were significant univariable predictors of rotational acceleration magnitudes. Given the multicollinearity between the age and season-year outcomes ($r > 0.5$), only 1 variable could be added to the regression model, ultimately resulting in the multivariable model not being possible (Table 5).

DISCUSSION

Our study aimed to comprehensively describe head IRs, magnitudes, and characteristics across 3 seasons of youth flag football, with our findings providing current insights into the head impact burden. Overall, head IRs, magnitudes, and characteristics varied across the 3 seasons. The combined-season outcomes may provide better estimates into the true flag football head impact burden. Factors such as age and event type (practices, games, and combined) were associated with IRs and head impact magnitudes. Our findings highlight the importance of examining multiple seasons or larger cohorts to truly understand head impact biomechanics outcomes and provide evidence-based insights to stakeholders (eg, players, parents, coaches, policy makers, clinicians, and researchers).

Head impact frequencies and exposures ranged widely across seasons, which contributed to the observed IR variability (Table 2, Figure 2A). This variability is likely attributed to the relatively small sample sizes monitored, but these findings highlight the importance of utilizing multiple seasons or studying larger cohorts when providing IR estimates to help guide stakeholder decisions. Although there were between-season differences, IRs remained consistently low across seasons and event types, ranging between 2.86 and 12.52 per 10 player-exposures. Relatively low IRs were also present among the older (9-10U) and younger (7-8U) cohorts. There were statistically higher IRs among the 9-10U cohort during games and combined event types (Figure 1B). However, the respective IRs between 9-10U and 7-8U for games (8.26 vs 5.33) and combined events (7.59 vs 5.20) are likely not clinically meaningful given the minimal differences. Despite IRs being relatively low and not meaningfully different between age groups, it is still critical that all stakeholders understand that head impacts do occur in youth flag football.

Only our previous study[16] has reported head IRs in youth flag football, which limits our ability to compare

TABLE 4
Head Impact Magnitude Summaries Across Event Type and Season

	2017 Season	2018 Season	2019 Season	Combined Seasons
Practices				
Linear acceleration, *g*				
Mean (SD)	34.7 (11.1)	31.9 (10.7)	45.9 (20.8)	38.8 (16.4)
Median (range)	33.9 (16.0-68.9)	29.5 (17.0-51.3)	39.0 (17.8-102.3)	34.8 (16.0-102.3)
90th percentile	48.1	45.4	76.0	60.7
Rotational acceleration, rad/s^2				
Mean (SD)	5088.2 (2223.9)	3912.5 (1805.1)	7024.0 (2912.4)	5751.4 (2681.7)
Median (range)	4550.0 (1600-11,100)	4350.0 (1500-6400)	6658.0 (2314-14,478)	5367.0 (1500-14,478)
90th percentile	8200.0	5840.0	11,171.0	9200.0
Games				
Linear acceleration, *g*				
Mean (SD)	35.0 (15.6)	43.0 (16.2)	50.3 (21.5)	44.6 (20.5)
Median (range)	32.3 (16.6-100.9)	34.9 (23.5-71.7)	44.4 (17.9-115.7)	37.8 (16.6-115.7)
90th percentile	59.3	66.0	80.3	75.7
Rotational acceleration, rad/s^2				
Mean (SD)	4437.6 (2480.0)	5165.4 (2968.1)	7047.7 (3029.8)	6026.2 (3099.5)
Median (range)	3800.0 (1100-11,700)	4500.0 (1000-12,500)	6678.0 (1172-14,897)	5600.0 (1000-14,987)
90th percentile	8300.0	9900.0	11,098.0	10,174.0
Combined events				
Linear acceleration, *g*				
Mean (SD)	34.9 (14.0)	40.4 (15.7)	49.4 (21.4)	43.0 (19.6)
Median (range)	32.7 (16.0-100.9)	32.6 (17.0-71.7)	43.0 (17.8-115.7)	37.0 (16.0-115.7)
90th percentile	51.7	64.4	79.4	73.1
Weekly cumulative				
Mean (SD)	28.9 (20.9)	19.6 (19.4)	81.0 (15.0)	44.2 (32.1)
Median (range)	27.2 (0-90.4)	14.5 (0-61.0)	83.8 (56.0-102.8)	38.8 (0-102.8)
Seasonal cumulative				
Mean (SD)	231.5 (167.2)	137.2 (135.6)	651.9 (116.1)	350.8 (258.4)
Median (range)	217.6 (0-723.0)	101.7 (0-427.0)	670.1 (448.4-882.6)	299.2 (0-822.6)
Rotational acceleration, rad/s^2				
Mean (SD)	4699.4 (2394.9)	4870.6 (2767.0)	7042.7 (2999.4)	5947.5 (2985.2)
Median (range)	4100.0 (1100-11,700)	4350.0 (1000-12,500)	6668.0 (1172-14,897)	5571.0 (1000-14,897)
90th percentile	8220.0	9190.0	11,205.0	10,101.0
Weekly cumulative				
Mean (SD)	3896.0 (3250.8)	2365.7 (2506.3)	11,574.3 (2286.5)	6111.9 (4777.7)
Median (range)	3662.5 (0-14,287.5)	1771.4 (0-8200)	11,732.5 (7976.6-15,407.3)	4181.3 (0-15,407.3)
Seasonal cumulative				
Mean (SD)	31,168.0 (26,006.6)	16,560.0 (17,544.3)	93,066.9 (17,604.3)	48,594.9 (38,460.0)
Median (range)	29,300.0 (0-114,300.0)	12,400.0 (0-57,400.0)	93,860.0 (63,812.4-123,258.7)	33,450.0 (0-123,258.7)

findings. We utilized the same SIM-G head impact telemetry system in our previous study[16] and identified flag football IRs per 10 player-exposures to be 9.3, 5.5, and 6.6 for practices, games, and combined events, respectively, while our present combined-season IRs were 6.1, 7.6, and 7.1, respectively. These findings provide updated IRs for youth flag football player stakeholders to consider as sports participation grows and safety decisions are being made.

In our previous study,[16] IRRs between youth flag and tackle football demonstrated that tackle players experienced 2.9, 6.9, and 4.6 times more impacts in practice, games, and combined events, respectively. To elucidate potentially important differences between youth tackle and flag football, we substituted the findings presented here and compared them with tackle football IRs.[16] With the additional data from 3 full youth flag football seasons, we observed approximately 4.4-, 5.1-, and 4.3-times greater IRs in youth tackle than in flag football. These findings may be useful to provide an updated viewpoint on the head IR comparisons being made between youth tackle and flag football and ultimately indicate that flag football players still experience considerably fewer head impacts than do tackle football players.

Head impact magnitudes across the 3 seasons were relatively heterogeneous within and between seasons, as exemplified by larger SDs and wide ranges (Table 4). Wide variance in impact magnitudes is a common occurrence in football head impact biomechanics studies.[2,24,25,32] We observed median peak linear acceleration to be 37.0*g* and rotational acceleration to be 5571.0 rad/s^2 for combined event types and seasons. Previous research among youth tackle football players has reported median linear

TABLE 5
Mixed-Model Regressions for Linear and Rotational Acceleration Magnitudes[a]

	Linear Acceleration, g				Rotational Acceleration, rad/s^2: Univariable	
	Univariable		Multivariable			
	Estimate ± SE	P Value	Estimate ± SE	P Value	Estimate ± SE	P Value
Age, y	3.61 ± 1.16	**.003**[b]	3.78 ± 1.05	**.001**	602.81 ± 208.37	**.005**[b]
Height, cm	0.23 ± 0.16	.16			45.18 ± 29.31	.13
Mass, kg	–0.13 ± 0.13	.31			–4.88 ± 25.32	.85
Body mass index	–0.53 ± 0.29	.07[b]	–0.62 ± 0.25	**.02**	–55.30 ± 56.19	.33
Event type: practice vs game	–4.50 ± 2.18	**.04**[b]	–5.69 ± 2.12	**.008**	192.77 ± 330.77	.56
Season year						
2018 vs 2017	5.48 ± 3.45	.11			79.91 ± 581.21	.89
2019 vs 2017	14.51 ± 1.87	**<.001**[b]			2428.96 ± 351.82	**<.001**[b]
R^2 (95% CI)[c]			0.06 (0.03-0.12)			

[a]Flag football players, N = 48; head impact count, n = 429. Bold P values indicate statistically significant predictors ($P \leq .05$). Age and season year are presented with multicollinearity; therefore, only age was considered for multivariable modeling. Age, however, was the only significant univariable predictor for rotational acceleration, resulting in no multivariable model.
[b]Only univariable predictors with $P \leq .10$ were included in the mixed-model multivariable regressions.
[c]R^2 values were derived from the Nakagawa and Schielzeth[17] approach for mixed-model regressions.

accelerations ranging from 17g to 32.5g[7,12,16] and median rotational accelerations from 890 to 3200 rad/s^2.[12,16] Our previous work[16] also identified that youth flag football players had 2.3-greater odds of sustaining a rotational head impact between 2500 and 7499.9 rad/s^2 than did youth tackle football players. Our current findings suggest that youth flag football players sustain greater-magnitude head impacts relative to youth tackle football players, which is concerning and should not go unnoticed. It is important to note that previous studies using head impact telemetry systems employed minimum impact thresholds between 8g and 14g.[2,7,12,16,24,25,32] Various minimal thresholds could skew head impact magnitude data and make comparisons among studies using different methodologies difficult. Regardless, researchers and stakeholders should be aware that youth flag football players may experience significantly fewer head impacts compared to youth tackle players but at potentially greater linear and rotational magnitudes.

We aimed to provide exploratory insights into factors contributing to peak linear and rotational magnitudes in youth flag football to understand and mitigate these factors where possible. Findings from the multivariable mixed-model peak linear acceleration regression demonstrated that age, BMI, and event type were significant predictors of linear accelerations (Table 5). Every 1-year age increase contributed to 3.78g, every 1–BMI unit increase resulted in –0.62g, and practices had –5.69g versus games. Age was a significant predictor for peak rotational acceleration, with every 1-year increase resulting in 602.8 rad/s^2. Our findings indicated that older age and competitions contribute to increased linear and rotational magnitudes, while BMI is likely a negligible factor given the small linear-magnitude change. Just 6% of the linear acceleration variance and 4% of the rotational acceleration variance were explained overall, indicating that numerous other factors contribute to the impact magnitudes players experience. Future research should examine head impact magnitude contributors to identify augmentable risk factors and promote sports safety.

The interaction between impact frequency and magnitude may play a key role in potential long-term neurodegenerative effects from repeated head impacts.[1,31] To try to understand this interaction, previous research among tackle football players has provided metrics quantifying the weekly and seasonal head impact frequencies and magnitudes to quantify a cumulative head impact burden.[2,24,25,32] Employing the same methodology here, we found that flag football players experienced a median 1.0 head impact per week and 7.5 head impacts per season, although high variance and ranges were present (Table 3). The mean combined event–type weekly and seasonal cumulative linear magnitudes were 44.2g and 350.8g, respectively, while the mean rotational magnitudes were 6111.9 and 48,594.9 rad/s^2, respectively (Table 4). These findings are substantially smaller than those of the median seasonal impact frequency[25] of youth tackle football of 150 and the seasonal cumulative linear acceleration of 4100g.[24] These metrics equate to youth tackle football's having an approximately 20-fold greater seasonal head impact frequency and 11-fold increase in seasonal cumulative linear accelerations experienced as compared with our youth flag football findings. Previous research among youth tackle football has not examined weekly cumulative magnitudes or any weekly or seasonal rotational magnitudes, limiting the current comparisons. It is important to note that no research to date has established whether greater head IRs, greater head impact magnitudes, or a combination of these are the critical contributors associated with short- or long-term neurodegenerative consequences.[1,4,29,31] Our findings, however, may provide important insights to the youth flag football head impact burden as future research surrounding short- and long-term neurodegenerative consequences evolves.

Limitations

Our study has inherent limitations in some of the outcomes and general applicability of our findings. First, head impact locations were not video verified and were derived only from sensor estimates. The Triax SIM-G sensor has mixed evidence on its accuracy.[8,11,21] No on-field head impact telemetry system is perfect in comparison with the gold standard instrumented headform.[5,8,28] This is a consistent and important limitation when interpreting head impact biomechanics outcomes from any study. Second, these data were collected from the same recreation department and among 7- to 10-year-old male players; thus, our findings may not be generalizable to other geographical areas, players of different ages, or female players. Third, we utilized an established event-based head impact–filtering method rather than using video verification. Video verification has been proposed as the on-field gold standard; however, no method used is perfect. Video verification may exclude numerous true head impacts from analysis because they could not be fully described or confirmed using film (eg, camera view obstructed by other players), thereby head impact frequencies and magnitudes may be underestimated.

CONCLUSION

Youth flag football players experienced 7.10 head impacts per 10 player-exposures across the combined seasons, indicating that head impacts occur at a relatively low rate. Linear and rotational acceleration head impact magnitudes were concerningly high among the seasons. Whether high IRs, high-magnitude head impacts, or both are associated with long-term neurodegenerative consequences is undetermined and requires future research. Older age was associated with greater peak linear and rotational acceleration magnitudes, while games were associated with greater peak linear acceleration magnitudes. Cumulatively, our findings provide current insights into youth flag football head IRs, magnitudes, and risk factors for high-magnitude impacts so that stakeholders may gain evidence-based insights into this rapidly growing sport.

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