

Effects of Sex and Event Type on Head Impact in Collegiate Soccer

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Background: The effects of head impact in sports are of growing interest for clinicians, scientists, and athletes. Soccer is the most popular sport worldwide, but the burden of head impact in collegiate soccer is still unknown.

Purpose: To quantify head impact associated with practicing and playing collegiate soccer using wearable accelerometers.

Study Design: Descriptive epidemiological study.

Methods: Mastoid patch accelerometers were used to quantify head impact in soccer, examining differences in head impact as a function of sex and event type (practice vs game). Seven female and 14 male collegiate soccer players wore mastoid patch accelerometers that measured head impacts during team events. Data were summarized for each athletic exposure, and statistical analyses evaluated the mean number of impacts, mean peak linear acceleration, mean peak rotational acceleration, and cumulative linear and rotational acceleration, each grouped by sex and event type.

Results: There were no differences in the frequency or severity of head impacts between men's and women's soccer practices. For men's soccer, games resulted in 285% more head impacts than practices, but there were no event-type differences in mean impact severity. Men's soccer games resulted in more head impacts than practices across nearly all measured impact severities, which also resulted in men's soccer games producing a greater cumulative impact burden.

Conclusion: Similar to other sports, men's soccer games have a greater impact burden when compared with practices, and this effect is driven by the quantity rather than severity of head impacts. In contrast, there were no differences in the quantity or severity of head impacts in men's and women's soccer practices. These data could prompt discussions of practical concern to collegiate soccer, such as understanding sex differences in head impact and whether games disproportionately contribute to an athlete's head impact burden.

Keywords: head injuries/concussion; football (soccer); biomechanics (general); subconcussion; accelerometer

American football garners the most attention regarding sports-related concussion (SRC), but clinicians and researchers recognize SRC is also a problem in other contact sports such as soccer. Men's and women's soccer has a concussion incidence that repeatedly appears in top 5 lists of college and high school sports.^{12,17} One study found that 62.7% of college soccer players reported symptoms of concussion at least once in the previous season, while only 19.8% of those players were aware of suffering a concussion.¹⁰

Fortunately, most head impacts do not result in concussion, but many studies suggest that multiple "subconcussive" head impacts can cause functional and

structural damage to the brain. Subconcussion was recently defined as a "cranial impact that does not result in known or diagnosed concussion on clinical grounds."¹ In the short term, subconcussion can lead to decreased resistance to concussion,^{2,13} impaired cognition,⁴ changes in brain functional connectivity,^{19,38} and disruption of the brain white matter.^{9,25} In the long term, subconcussion may increase risk for neurodegenerative disorders, such as amyotrophic lateral sclerosis, Alzheimer disease, Parkinson disease, and chronic traumatic encephalopathy.^{24,31} Research investigating subconcussion in soccer has demonstrated correlations with cognitive dysfunction,^{25,44} changes in brain white matter,^{22,25} and abnormalities in brain metabolites, possibly reflecting demyelination and/or inflammation.²³ However, confirming links between these outcomes and subconcussive impacts is difficult because many effects may have

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subclinical symptomatology and/or develop over a long time course.

Concerns over the detrimental effects of subconcussion have driven a movement to quantify head impacts in both collision and contact sports. Quantification of head impact in sport does not directly address the possible short- and long-term effects of these impacts, but analysis of circumstances related to these impacts can identify focus areas for cumulative impact reduction. Accurately quantifying head impacts could also aid the identification of true short- and long-term effects related to subconcussion. Much research has been done in American football,^{4-7,11,27,29,33,35} but the burden of head impact a typical soccer player experiences is relatively unknown. Some studies have attempted to quantify the severity of head impact in soccer, but most of these measurements have occurred outside live-play situations. Helmet-based accelerometers have measured header acceleration in a laboratory setting,³⁰ video analysis and biomechanical reconstruction have studied head impacts caused by player contact with instrumented dummies,⁴² and a modified helmet-based accelerometer has recorded head impacts in controlled scrimmages.¹⁶ Progress in biomechanical sensor miniaturization has produced accelerometers that can be worn unobtrusively in unhelmeted sports to quantify head impact during live play. Recent studies have used a mastoid patch sensor to quantify head impact in college women's soccer,^{26,28,32} but no studies have quantified head impact in college men's soccer. The present study uses mastoid patch accelerometers to quantify head impact in male and female collegiate soccer, describing differences in subconcussive head impact as a function of sex and event type (practice vs game).

METHODS

Participants

A cohort of 7 female and 12 male soccer players (mean \pm SD age, 20.43 \pm 1.27 and 20.33 \pm 1.23 years, respectively) wore head impact sensors during official team events. Participants were volunteers from 2 Division I soccer teams (roster sizes of 24 women and 34 men). Data from female soccer players were collected during spring practice. Data from male soccer players were collected during spring practice ($n = 5$), fall competitive seasons ($n = 1$), or both ($n = 6$). No athlete had a history of developmental or neurological disorder or severe traumatic brain injury. All participants gave written informed consent.

Biomechanical Measurements

Study participants wore the xPatch (X2 Biosystems) on the skin covering their mastoid process (left or right side was decided by the athlete). The xPatch accelerometer used in the present study appears in 9 published studies,^{**} 3 of which test biomechanical validity in different settings.^{8,28,43} Wu et al⁴³ compared in vivo performance of the xPatch against video capture in a simulated low-impact soccer setting; that study examined 10 impacts (mean acceleration, 9.3g), 1 impact location, 1 mastoid placement location, and 1 xPatch device. The xPatch overestimated individual linear and rotational accelerations in 1 subject (normalized root mean squared error [RMSE] of 120% for peak linear acceleration [PLA] and 290% for peak rotational acceleration [PRA]), likely related to the unique viscoelastic properties of that individual's soft tissues. As a prelude to a live-play soccer study, McCuen et al²⁸ evaluated xPatch performance on a Hybrid III headform; this study examined 250 impacts, spread over 5 impact locations, in 2 mastoid placement locations, including data from 5 different xPatch devices. McCuen et al²⁸ also found significant xPatch measurement error related to individual impacts (RMSE of 34% for PLA and 50% for PRA). However, McCuen et al²⁸ also looked at aggregate performance over large numbers of impacts and concluded, "average values over a large number of acceleration events can be determined with good accuracy." The present study uses the xPatch in this manner.

Using a Hybrid III headform model, Cummiskey et al⁸ performed the most thorough comparison to date of the reliability and accuracy of helmet-mounted and head-mounted accelerometer systems. Five commercially available accelerometer systems were tested directly against each other, including the xPatch and the Head Impact Telemetry System (HITS)—the most commonly used accelerometer system in studies of American football.⁸ Cummiskey et al⁸ delivered 140 impacts across 7 impact locations to evaluate each device and sensor location. RMSE was calculated for each device, sensor location, and impact location by comparing with values generated from accelerometers inside the Hybrid III headform, to which the devices were attached. The xPatch did produce considerable error across impact locations (RMSE of 8%-58% for PLA and 11%-350% for PRA), but across devices, sensor locations, and impact locations, the xPatch produced RMSEs that were considerably lower than, or at least comparable to, the RMSE produced by the HITS.

**References 8, 20, 26, 28, 32, 33, 36, 37, 43.

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Ethical approval for this study was obtained from the University of Virginia Institutional Review Board for Health Sciences Research.

Cummiskey et al⁸ do rightly point out that the RMSE for the xPatch could have been underestimated in their study as the Hybrid III headform does not realistically mimic the skin surface, which could shift in response to a head impact and increase measurement error.

The sensor was to be worn during all official team practices and home games, although athletes maintained the right to refuse at each event. The xPatch contains a triaxial high-impact linear accelerometer and a triaxial gyroscope to capture 6 degrees of freedom for linear and rotational accelerations. Impact to the body or head can result in head acceleration; however, for simplicity, we will henceforth refer to impacts that result in head acceleration as “head impacts.” If the accelerometer exceeded a predetermined 10g resultant linear acceleration threshold, 100 ms of data (10 ms pretrigger and 90 ms posttrigger) from each accelerometer and gyroscope were recorded to onboard memory. Raw accelerometer data were then transformed to calculate PLA and PRA at the head center of gravity by X2 Biosystems’ Injury Monitoring System using a rigid body transformation for PLA and a 5-point stencil for PRA. X2 Biosystems’ proprietary algorithm attempts to remove false impacts by comparing the waveform of each impact to a reference waveform using cross-correlation and rejects those that fall below a correlation threshold.

Impacts with a resultant PLA less than 10g were removed. Impact data were time filtered to include only impacts that occurred during a practice or game. Impact burden measures, PLA sum, and PRA sum, were calculated per athletic exposure (a single practice or game) by summing each impact linearly weighted by its severity, first used by Broglio et al⁵ as a measure of “cumulative impact burden.” There is currently no widely accepted metric specifically for the quantification of cumulative impact burden. Many studies that quantify impact burden use the summation of a metric that was developed for individual impacts.^{5,9,11,28,33,36,39} This study chose to use PLA sum and PRA sum due to their ease of calculation and to match similar studies with the same accelerometer.^{28,33,34} All participants’ recorded practices were included in the analysis. To account for the high variability of playing time between participants in games, an athlete needed to play more than 45 minutes in the game for the event to be included in the analysis. Hereafter we will refer to these athletes as “starters.” Using this procedure, men’s soccer totaled 49 game starts. Females were only assessed during spring practice and thus did not have game data. Data from 3 additional male soccer players was not included in the analyses because only fall practice data were collected, disallowing their data to be included in either the sex or event-type analyses.

Statistical Methods

Categorical scaled data were summarized by frequencies and percentages, while continuous scale data were summarized by mean, standard deviation, median, and range of the empirical distribution.

Analyses of Sex Differences in Practice. Analysis of sex differences only used the participants’ spring practice data to avoid the confound of including men’s soccer fall

practices, which were not collected in the women’s soccer team. A negative binomial generalized estimate equation (GEE) model compared mean number of impacts per soccer practice between female and male soccer players. The GEE model included a single indicator variable that distinguished females from males. Since each player participated in multiple practices, each player’s impact data were considered a cluster of nonindependent observations in the GEE analysis. The sandwich variance-covariance estimator of Huber¹⁸ and White⁴¹ estimated the GEE model variance-covariance matrix. The GEE version of the Wald test tested the null hypothesis that mean number of impacts per soccer practice was the same for females and males. A 2-sided $P \leq .05$ decision rule was the criterion to reject the null hypothesis.

Average PLA per impact per soccer practice (PLA/impact/practice) was analyzed on the natural logarithmic scale via a Gaussian GEE model. Natural logarithmic transformation rescaled the data to a more symmetric (bell-shaped) distribution. We tested the null hypothesis that geometric mean PLA/impact/event is the same for females and males. A 2-sided $P \leq .05$ rejection rule was used as the null hypothesis criterion.

Average PRA per impact per practice event (PRA/impact/practice) was analyzed on the natural logarithmic scale in exactly the same way as PLA per impact data to compare men’s and women’s practices.

Analyses of Event-Type Differences for Male Soccer Starters. Analysis of event-type differences only used practice data from male soccer players with available game data for comparison (players 13, 15, 18, and 19), aforementioned “starters.” Differences in number of impacts and impact forces experienced by male soccer starters during practice and game events were analyzed in the same way as practice impact frequency and practice mean impact force data. The major difference was that these analyses focused on athletic event type and not sex.

A negative binomial GEE model analyzed the number of impacts per event causing linear acceleration greater than 10g, 20g, 30g, 40g, 50g, 60g, 70g, 80g, and 90g. Two indicator variables were utilized: 1 to distinguish practices and games and 1 to distinguish the 9 different PLA thresholds. Although these “thresholds” might be more correctly termed “cut-points,” we retain the nomenclature from studies with similar analyses in football³⁵ to facilitate comparison. Indicator variables for event type by PLA threshold interaction were modeled. To account for intraplayer measurement correlation, the GEE model variance-covariance matrix was unstructured. The GEE version of the Wald test tested the global hypothesis that impact was uniformly (across all PLA thresholds) the same for practices and games. Wald tests additionally examined, on per PLA threshold bases, event-type differences in mean number of impacts per event in which the PLA was greater than the defined threshold. Bonferroni correction was applied to all pairwise tests to keep the simultaneous type I error rate ≤ 0.05 .

Analysis of PRA Threshold. A negative binomial GEE model analyzed the number of impacts per practice event where players experienced PRA greater than 0 rad/s², 2000 rad/s², 4000 rad/s², 6000 rad/s², 8000 rad/s², 10,000 rad/s²,

TABLE 1
Event Summary for Captured Spring Practices per Subject, Including Mean Number of Impacts, Geometric Mean Peak Linear Acceleration (PLA), and Geometric Mean Peak Rotational Acceleration (PRA) per Athletic Event for Men's and Women's Soccer

Player ID	Sex	Position	Practices, n ^a	Mean Impacts per Practice, n	Geometric Mean PLA, g	Geometric Mean PRA, rad/s ²
1	Female	Goalkeeper	22	5.2	20.1	2923.5
2	Female	Midfield	21	3.4	19.3	2993.6
3	Female	Forward/Defense	20	4.2	18.2	3067
4	Female	Midfield	15	7.1	20	3952.1
5	Female	Forward	20	9.3	18.1	2821.2
6	Female	Forward/ Midfield	19	2.8	16.7	2458.3
7	Female	Goalkeeper	20	8.3	21.5	4144
Mean (SD) or geometric mean			19.6 (2.2)	5.7 (2.3)	19.1	3115.4
Median			20	5.2	19.3	2993.6
Range			15-22	2.8-9.3	16.7-21.5	2458.3-4144.0
8	Male	Goalkeeper	18	14.4	24.3	4843.1
9	Male	Defense	13	8.2	20.3	3373.7
10	Male	Defense	11	1.1	34.3	5974.3
11	Male	Midfield	16	5.1	19.2	3264.5
12	Male	Midfield	8	3.1	24.4	4096
13	Male	Defense	16	5.4	18.4	3232.2
14	Male	Midfield	16	3.9	18.1	3212.7
15	Male	Forward	14	4.4	18.7	3245.9
16	Male	Midfield	15	1.9	17.3	3108.4
17	Male	Defense	13	6.6	23.7	4272.9
18	Male	Defense	16	29.3	16.8	3377.5
Mean (SD) or geometric mean			14.2 (2.82)	8.2 (8.0)	20.5	3687.1
Median			15	5.1	19.2	3373.7
Range			8-18	1.1-29.3	16.8-34.6	3108.4-5974.3

^aThere were a total number of 137 and 156 practices included for men and women, respectively.

12,000 rad/s², and 14,000 rad/s². The GEE analysis was identical to the PLA threshold analysis.

PLA sum and PRA sum are measures of impact burden that are severity-weighted linear summations of all head impacts for an athletic event.^{5,28,33} The Cox proportionate hazard model compared empirical cumulative distributions for PLA and PRA sum per event between practices and games. This approach accounted for intra-player measurement correlation in the null hypothesis test.

Analyses of Women's Soccer Practices with a 20g Threshold. Analyses that closely matched the methods of McCuen et al²⁸ were performed to aid direct comparison with their results. Mean number of impacts per practice, mean peak linear acceleration, and mean peak rotational acceleration were calculated as previously described with 3 differences. First, any impacts with a PLA less than 20g were removed. Second, X2 Biosystems' proprietary algorithm that attempts to remove false impacts was not used to identify and remove possible spurious impacts. Third, an arithmetic mean, rather than a geometric mean, was used for the calculation of mean PLA and PRA values.

SAS version 9.4 software (SAS Institute Inc) was used for statistical analyses, and Spotfire S plus software (TIBCO Inc) was used for graphic displays.

RESULTS

Results include 649 athletic exposures (AEs) from 7 female and 12 male collegiate soccer players. Based on roster sizes of 24 women and 34 men, the recruitment rate for women was 29.2% and for men was 35.3%. There were 38 women's spring practices. For men, there were 41 spring practices, 79 fall practices, and 11 fall home games. There were 137 captured women's practices and 331 captured men's practices, corresponding to respective practice capture rates of 54.5% and 39.4%. There were 24 captured men's soccer home games, corresponding to a game capture rate of 49.0%. Tables 1 and 2 contain a detailed summary of the athletic events.

In practices, male and female soccer players did not differ in total number of impacts (>10g) they received (mean impacts/event, 8.2 [95% CI, 4.52-15.0] and 5.7 [95% CI, 4.2-7.7], respectively; $P = .290$), mean PLA of impacts (geometric mean PLA/impact/event, 20.5g [95% CI, 18.3-22.8] and 19.1g [95% CI, 17.9-20.3], respectively; $P = .260$), or mean PRA of impacts (geometric mean PRA/impact/event, 3687.1 rad/s² [95% CI, 3268.0-4159.9] and 3115.4 rad/s² [95% CI, 2737.3-3545.9], respectively; $P = .061$) (Figure 1).

For male soccer starters, there were more impacts (>10g) in games than practices (mean impact/event, 39.5 [95% CI, 17.2-90.8] and 10.2 [95% CI, 5.4-19.0], respectively; $P < .001$).

TABLE 2

Event Summary for Captured Practices and Games per Male Soccer Players Who Played More Than 45 Minutes in the Game, Including Mean Number of Impacts, Geometric Mean Peak Linear Acceleration (PLA), and Geometric Mean Peak Rotational Acceleration (PRA) per Athletic Event^a

Player ID	Sex	Position	Practices, n	Mean Impacts per Practice	Geometric Mean PLA, g	Geometric Mean PRA, rad/s ²
13	Male	Goalkeeper	50	5.5	17.4	2290.3
15	Male	Defense	43	6.2	18.4	2625.5
18	Male	Defense	50	19.8	16.6	2795
19	Male	Midfield	32	7.7	19	3337.2
Mean (SD) or geometric mean			43.8 (8.5)	10.2 (6.2)	16.7	2693.7
Median			46.5	7	17.9	2710.3
Range			32-50	5.5-19.8	16.6-19.0	2290.3-3337.2
Player ID	Sex	Position	Games, n	Mean Impacts per Game	Geometric Mean PLA, g	Geometric Mean PRA, rad/s ²
13	Male	Goalkeeper	7	20.9	18.3	2589.8
15	Male	Defense	7	18	20.9	2726.6
18	Male	Defense	8	82.5	15	2675.3
19	Male	Midfield	2	8.5	14	2494.1
Mean (SD) or geometric mean			6	39.5 (31.3)	17.1	2649.3
Median			7	19.4	16.7	2632.6
Range			2-8	8.5-82.5	14.0-20.9	2494.1-2726.6

^aThere were a total of 175 and 24 practices and games included, respectively.

Games were not different from practices in mean PLA per impact (geometric mean PLA/impact/event, 17.1g [95% CI, 13.8-21.2] and 16.7g [95% CI, 15.4-18.1], respectively; $P = .728$) or mean PRA per impact (geometric mean PRA/impact/event, 2649.3 [95% CI, 2548.0-2754.6] and 2693.7 [95% CI, 2204.5-3291.5], respectively; $P = .809$) (Figure 2).

Global tests of number of impacts above PLA thresholds 10g to 90g and PRA thresholds 0 to 14,000 rad/s² demonstrate differences between men's soccer practices and games (both $P < .001$). Threshold-by-threshold post hoc pairwise comparisons showed event type differences in mean number of impacts at several individual linear and rotational acceleration thresholds after Bonferroni correction. Overall differences were driven by greater numbers of impacts during games for impacts above PLA thresholds 10g ($P < .001$), 20g ($P < .001$), 30g ($P < .001$), 40g ($P = .004$), 50g ($P = .008$), 60g ($P = .001$), 70g ($P < .001$), and 80g ($P = .005$) and all PRA thresholds 2000 to 14,000 rad/s² (all $P < .001$). Few events included >90g impacts, resulting in a smaller sample size and reduced statistical power above 90g ($P > .999$) (Figure 3, A and B and Appendix Table A1). With regard to cumulative distribution of impact burden (PLA sum and PRA sum) per AE, men's games resulted in more impact burden than practices (both $P < .001$) (Figure 3, C and D).

For women's practices, using the 20g threshold changed the mean number of impacts per practice to 4.0 and resulted in a mean PLA of 41.3g and PRA of 7234 rad/s².

DISCUSSION

This pilot study was performed using mastoid patch accelerometers to quantify head impacts in college

soccer, specifically to describe any differences in subconcussive head impact as a function of sex or event type (game vs practice). While most head impacts do not result in concussion, the hypothesized effects of subconcussion on brain structure^{9,25,44} and function,^{4,19,25,36,38} coupled with their proposed role in increasing susceptibility to neurodegenerative disorders,^{24,31} suggest that quantification of subconcussion may be important for assessing soccer's overall safety. This study is the first to quantify subconcussive head impacts in live-action men's collegiate soccer and to compare them with similar measurements from women's collegiate soccer.

In spite of hypothesized differences between male and female soccer players, no significant differences were present in the number or severity of head impacts during practices. One might expect men, who are on average larger, faster, and more aggressive, to experience more head impacts and a greater mean impact severity than women. Alternatively, less-developed neck muscles can result in greater resultant head acceleration after head impact,¹⁴ which may predispose women to experience head impacts of greater severity.⁴⁰ Men experienced an average of 8.2 impacts per practice, with mean PLA of 20.5g per impact and PRA of 3687.1 rad/s² per impact; women experienced an average of 5.7 impacts per practice, with mean PLA of 19.1g per impact and PRA of 3115.4 rad/s² per impact. If the trends became significant in a larger sample size, the result would suggest that men experience more impacts per practice and greater severity impacts than women.

For male soccer starters, there were significantly more impacts in games (39.5 impacts/event) than during practices (10.2 impacts/event), but no difference in average severity of impacts in games (PLA, 17.1g; PRA, 2649.3 rad/s²) when

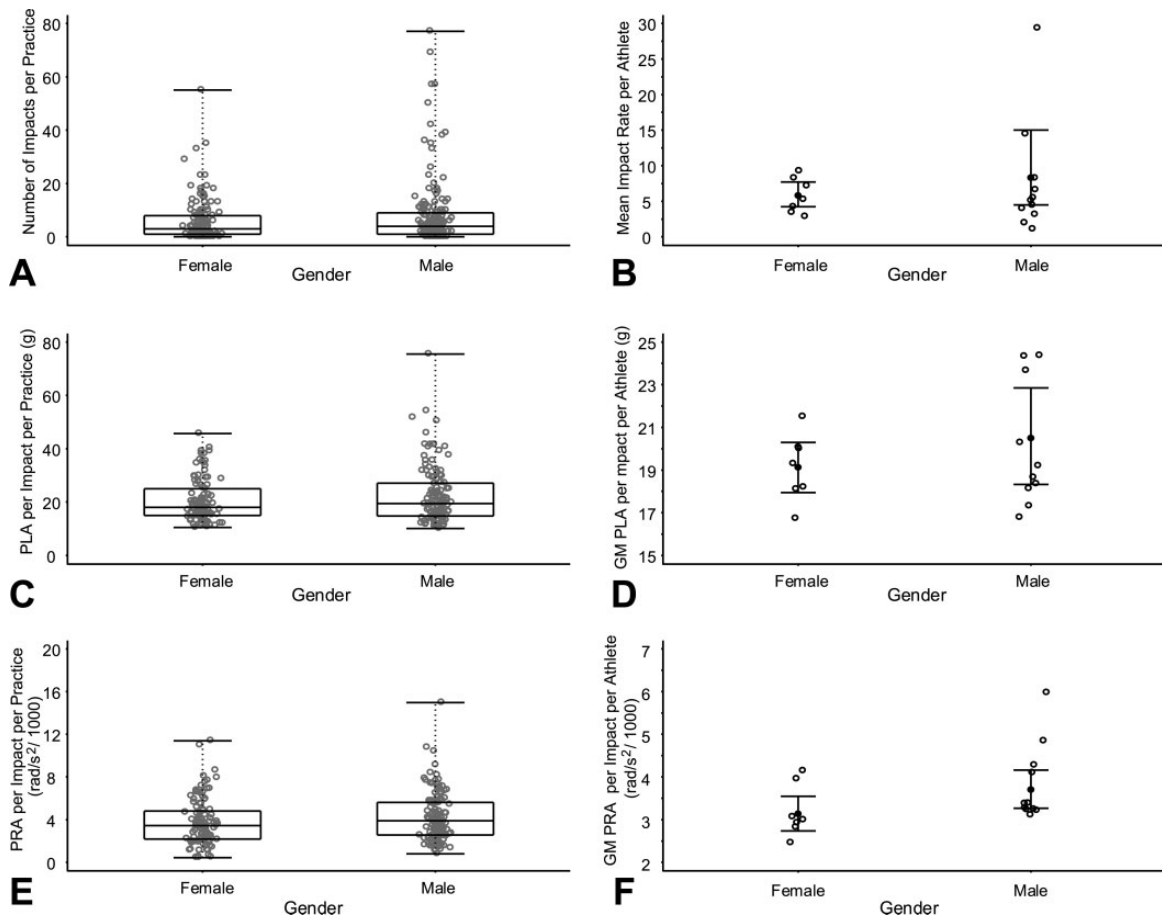


Figure 1. (A) Empirical distributions for the number of impacts per practice, (C) mean peak linear acceleration (PLA) per impact per practice, and (E) mean peak rotational acceleration (PRA) per impact per practice for female and male soccer players. (B) Mean number of impacts per practice per athlete, (D) geometric mean (GM) PLA per impact per athlete, and (F) GM PRA per impact per athlete for female and male soccer players. Closed circles in B identify the mean of the distribution. Closed circles in D and F identify the GM of the distributions. Open circles identify player-specific means in B and player-specific GMs in D and F, and the vertical lines in B identify the 95% CI for the mean and the vertical lines in D and F identify the 95% CI for the GM. No significant differences were found for any comparison between male and female practice events.

compared with practices (PLA, 16.7g; PRA, 2693.7 rad/s²). The number of impacts was 2.78 to 6.25 times greater for games than practices (depending on the PLA or PRA threshold), with nearly all impact severities showing statistically significant differences. Increases in number of impacts also result in a greater total impact burden for games compared with practices. It may be unsurprising that games result in more impacts than practices, but many would also expect a concomitant increase in impact severity, which was not found. This finding of increased quantity but not severity of impacts for games compared with practices seems to hold true across several other studies^{26,28} and sports.^{33,34} Furthermore, the stability of this difference across several impact severity thresholds demonstrates that the increased frequency is not dependent on a specific arbitrary threshold. This relationship further suggests that the causes of head impact do not differ between practices and games but occur less frequently. Future studies utilizing accelerometers and video recording could identify the causes

of these head accelerations, which would inform impact-reduction strategies.

Others have tried to estimate the frequency of head impact through self-report²⁵ and head impact severity through video analysis and biomechanical reconstruction⁴² or by using a helmet-based accelerometer system in a controlled setting.^{16,30} In the present study, we estimate a male soccer starter experiences an average of 2133 impacts per year (using mean impacts per practice and per game, adjusted by 120 official team practices and 23 games). This estimate is higher than self-reported estimates of annual head impact (median, 432) from headers in adult amateurs but within the reported range (32-5400)²⁵; the present study includes head impacts other than headers, and self-report can be unreliable. Video reconstruction of player-to-player impacts has shown arm-to-head contact resulted in mean PLA of 20.4g to 21.3g and mean PRA of 1445 to 1611 rad/s², and head-to-head contact resulted in mean PLA of 35.1g to 86.7g and mean PRA of 2770 to 7033 rad/s², depending on

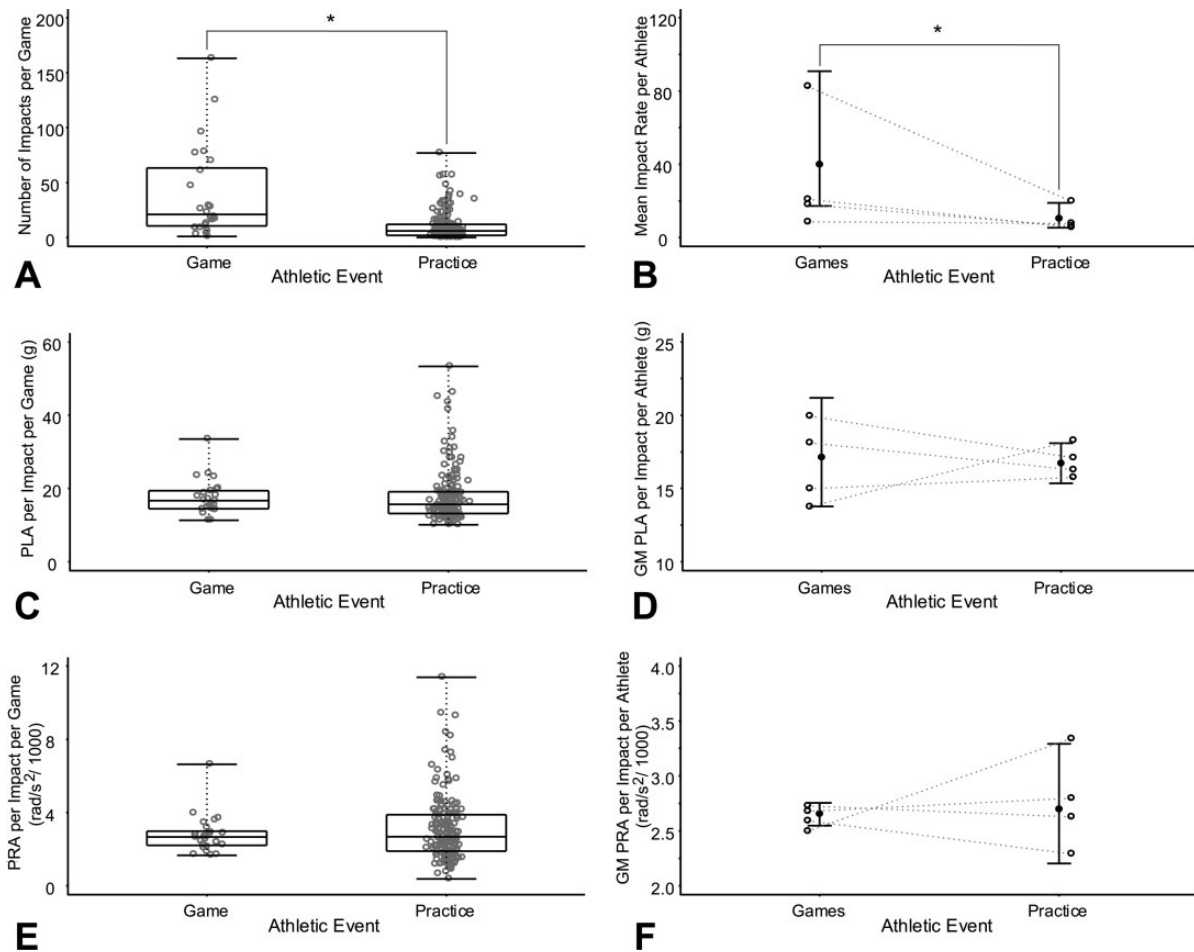


Figure 2. (A) Empirical distributions for the number of impacts per athletic event (AE), (C) mean peak linear acceleration (PLA) per impact per AE, and (E) mean peak rotational acceleration (PRA) per impact per AE for male soccer players’ games and practices. (B) Mean number of impacts per AE per athlete, (D) geometric mean (GM) PLA per impact per athlete, and (F) GM PRA per impact per athlete for male soccer players’ games and practices. Closed circles in B identify the mean of the distribution. Closed circles in D and F identify the GM of the distributions. Open circles and dotted lines identify player-specific means in B and player-specific GMs in D and F, and the vertical lines in B identify the 95% CI for the mean and the vertical lines in D and F identify the 95% CI for the GM. Compared with practices, men’s games resulted in more impacts per event. There was no difference in the mean PLA or mean PRA per impact per event. * $P < .05$.

impact speed and direction.⁴² Hanlon and Bir¹⁶ used a modified accelerometer suite from a helmet-based system to measure severity of head impacts during short scrimmages, reporting a mean PLA of 19.4g and PRA of 1666.8 rad/s² for nonheader impacts. In the present study, mean PLA per impact for all players ranged from 16.7g to 34.3g, and PRA per impact ranged from 2458.3 to 5974.3 rad/s². Previous studies were mostly simulations of specific types of head impacts, and it is not surprising they do not reflect a soccer player’s full range of impact types. The present data most closely align with the mean severity for nonheader impacts reported by Hanlon and Bir.¹⁶

Recent studies^{26,28,32} have used the xPatch accelerometer in collegiate female soccer players. McCuen et al²⁸ reported a mean 3.5 impacts per practice for college female soccer players, with a mean PLA of 37.7g and PRA of 7297 rad/s². Press and Rowson³² reported a mean 1.69 impacts per

practice and 2.16 impacts per game for college female soccer players, with a mean PLA of 20g and PRA of 4541 rad/s² per practice and a mean PLA of 32g and PRA of 7126 rad/s² per game. Lynall et al²⁶ did not report the number of impacts per player per practice. Instead, they reported number of impacts summed across players per practice (40.10 impacts per practice) or across practices per player (36 impacts per player), with a mean PLA of 12.78g and PRA 2183 rad/s². For games, Lynall et al²⁶ reported 7.16 impacts per player per 90 game minutes, with a mean PLA of 12.51g and PRA of 2093 rad/s².

While these values are different from each other and our reported values, some of the discrepancies between the studies are likely driven by methodological differences. First, McCuen et al²⁸ used a 20g threshold, compared with the 10g threshold used in the present study. When data from the present study are processed using similar methods

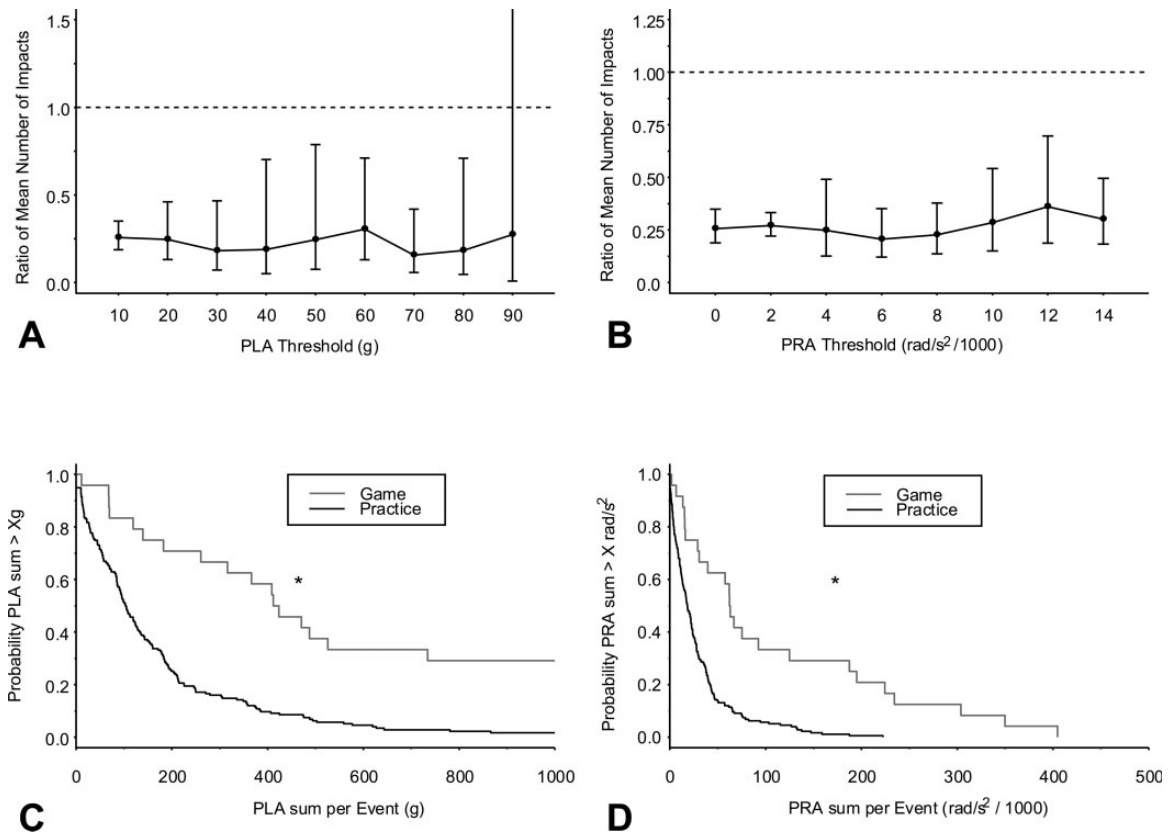


Figure 3. Graphs showing the ratio of means for comparing the mean number of impacts greater than the (A) peak linear acceleration (PLA) or (B) peak rotational acceleration (PRA) thresholds between men’s soccer games and practices (see Appendix Table A1). Data points identify the mean impact rate ratio (eg, practice:game) and vertical lines identify the Bonferroni-corrected 95% CI. Dotted lines identify the line of equality (ie, ratio equals 1). Empirical cumulative distributions for (C) PLA sum and (D) PRA sum for men’s soccer games and practices. Event-type differences in the number of impacts were present at nearly all linear and rotational acceleration thresholds. Compared with practices, men’s soccer games resulted in greater PLA sum and PRA sum per event. *Bonferroni-corrected $P < .05$.

to McCuen et al,²⁸ women’s means change to 4.0 impacts per practice, with a mean PLA of 41.3g and PRA of 7234 rad/s². Their decision to discard impacts <20g was made to eliminate head accelerations of uncertain physiologic significance, such as those caused by kicks and hard stops. However, since the lower limit of physiological relevance is not known, this study analyzed all impacts recorded by the sensor, which triggered at a linear acceleration of 10g. Many biomechanical head impact studies in sport use a 10g threshold,²¹ which enables wider comparison with the existing literature across sports. Press and Rowson³² only included head accelerations that were directly caused by head-to-ball, head-to-player, or head-to-ground impacts. This restriction likely resulted in the exclusion of a large number of head accelerations translated to the head by body-to-ground, body-to-body, or body-to-ball impacts, leading to a lower number of included impacts than the present study.

In contrast to helmet-based accelerometers, mastoid patch sensors are not integral to required soccer equipment. Therefore, sensor application was an additional step for the athlete, but it was quick and easily integrated into team routines. This study includes 15 male and 7 female soccer players,

corresponding to recruitment rates of 35.3% for men and 29.2% for women, consistent studies in football.^{3,5,11,15,29,33} Practice (41.9% for men, 54.5% for women) and game capture rates (49.0% for male starters) fall below typical values for football, likely due to the sensor not being part of mandatory equipment. Our AE capture rate was comparable to use of the same sensor in a football cohort.³³ The majority of missed events were from athletes forgetting or declining the sensor and not from events where the entire team was missed. There was no discernable pattern to missed events that would cause concern that a vital feature of head impact exposure was omitted. The exception is men’s soccer games where only home games were captured; any inherent difference between home and away games was not characterized.

Limitations

Several factors could affect the generalizability of comparisons between sex and event types. This study reports findings from only 1 men’s and 1 women’s soccer team. Both teams were from the National Collegiate Athletic Association (NCAA) Division I, but the results could be affected by the

caliber of the 2 soccer teams, both of which happened to reach the national championship game in the study year. In football, head impact can be affected by the style of offensive play,²⁷ and a similar effect of playing style could be possible for our soccer teams. Within each team, the results could also be skewed by the subset of athletes who participated in the study; this small sample could disproportionately include more aggressive players, which would result in an overestimation of head impact, or vice versa. Our event-type analysis is more susceptible to this type of outlier or selection bias due to our sample of only 4 male soccer starters in competition. Both of these limitations reduce the generalizability of these results to other soccer players and teams. Additionally, event-type analyses were not done for women's soccer due to the inclusion of their practice season only. The inability to compare across event type in women's soccer or compare sex differences in games also limits the generalizability of our findings. It is possible that female soccer players experience different event-type effects or sex differences could be present during games that did not exist in practices.

We believe the transformed values reported by *all* head impact sensors in live-play settings should be viewed skeptically, as they probably do not reflect the "ground truth" biomechanical forces experienced by the brain. The xPatch data for individual hits is almost certainly noisy, and the absolute values reported by these sensor systems should not carry too much influence. However, if the errors are random or systematic, then relative comparisons across situations and groups with large numbers of impacts are valid. The present study addresses this limitation by testing relative impact comparisons (eg, men vs women and game vs practice) rather than focusing on the absolute values reported. While these differences are statistically significant, more work needs to be done to determine whether these differences are physiologically significant.

CONCLUSION

This pilot study indicates men's and women's soccer practices result in a similar number of head impacts, and these head impacts have similar average severity. In men's soccer, there are significantly more head impacts in games than in practices, but these head impacts have similar average severity. While the physiologic significance of concussion is unclear, most people would agree that limiting unnecessary head contact is beneficial to athletes. Some of the open questions that could be addressed by further quantification of subconcussive head impacts include effects of competition level (youth to professional), playing style, incorporation of protective equipment, or sex differences in games.

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REFERENCES

- Bailes JE, Petraglia AL, Omalu BI, Nauman E, Talavage T. Role of subconcussion in repetitive mild traumatic brain injury. *J Neurosurg*. 2013;119:1235-1245.
- Baugh CM, Kiernan PT, Kroshus E, et al. Frequency of head impact-related outcomes by position in NCAA Division I collegiate football players. *J Neurotrauma*. 2015;32:314-326.
- Beckwith JG, Greenwald RM, Chu JJ, et al. Head impact exposure sustained by football players on days of diagnosed concussion. *Med Sci Sports Exerc*. 2013;45:737-746.
- Breedlove EL, Robinson M, Talavage TM, et al. Biomechanical correlates of symptomatic and asymptomatic neurophysiological impairment in high school football. *J Biomech*. 2012;45:1265-1272.
- Broglio SP, Eckner JT, Martini D, Sosnoff JJ, Kutcher JS, Randolph C. Cumulative head impact burden in high school football. *J Neurotrauma*. 2011;28:2069-78.
- Broglio SP, Sosnoff JJ, Shin S, He X, Alcaraz C, Zimmerman J. Head impacts during high school football: a biomechanical assessment. *J Athl Train*. 2009;44:342-349.
- Crisco JJ, Wilcox BJ, Beckwith JG, et al. Head impact exposure in collegiate football players. *J Biomech*. 2011;44:2673-2678.
- Cummiskey B, Schmittmiller D, Talavage TM, et al. Reliability and accuracy of helmet-mounted and head-mounted devices used to measure head accelerations [published online August 3, 2016]. *J Sports Eng Technol*. doi:10.1177/1754337116658395.
- Davenport EM, Whitlow CT, Urban JE, et al. Abnormal white matter integrity related to head impact exposure in a season of high school varsity football. *J Neurotrauma*. 2014;31:1617-1624.
- Delaney JS, Lacroix VJ, Leclerc S, Johnston KM. Concussions among university football and soccer players. *Clin J Sport Med*. 2002;12:331-338.
- Eckner JT, Sabin M, Kutcher JS, Broglio SP. No evidence for a cumulative impact effect on concussion injury threshold. *J Neurotrauma*. 2011;28:2079-2090.
- Gessel LM, Fields SK, Collins CL, Dick RW, Comstock RD. Concussions among United States high school and collegiate athletes. *J Athl Train*. 2007;42:495-503.
- Guskiewicz KM, McCrea M, Marshall SW, et al. Cumulative effects associated with recurrent concussion in collegiate football players: the NCAA Concussion Study. *JAMA*. 2003;290:2549-2555.
- Gutierrez GM, Conte C, Lightbourne K. The relationship between impact force, neck strength, and neurocognitive performance in soccer heading in adolescent females. *Pediatr Exerc Sci*. 2014;26:33-40.
- Gysland SM, Mihalik JP, Register-Mihalik JK, Trulock SC, Shields EW, Guskiewicz KM. The relationship between subconcussive impacts and concussion history on clinical measures of neurologic function in collegiate football players. *Ann Biomed Eng*. 2012;40:14-22.
- Hanlon EM, Bir CA. Real-time head acceleration measurement in girls' youth soccer. *Med Sci Sports Exerc*. 2012;44:1102-1108.
- Hootman JM, Dick R, Agel J. Epidemiology of collegiate injuries for 15 sports: summary and recommendations for injury prevention initiatives. *J Athl Train*. 2007;42:311-319.
- Huber PJ. The behavior of maximum likelihood estimates under non-standard conditions. In: *Proceedings of the Fifth Berkeley Symposium on Mathematical Statistics and Probability*. Vol. 1. Berkeley, CA: University of California Press; 1967:221-233.
- Johnson BD, Neuberger T, Gay M, Hallett M, Slobounov S. Effects of subconcussive head trauma on the default mode network of the brain. *J Neurotrauma*. 2014;31:1907-1913.
- Kerr ZY, Hayden R, Dompier TP, Cohen R. Association of equipment worn and concussion injury rates in National Collegiate Athletic Association football practices. *Am J Sports Med*. 2015;43:1134-1141.
- King D, Hume P, Gissane C, Brughelli M, Clark T. The influence of head impact threshold for reporting data in contact and collision sports: systematic review and original data analysis. *Sports Med*. 2016;46:151-169.
- Koerte IK, Ertl-Wagner B, Reiser M, Zafonte R, Shenton ME. White matter integrity in the brains of professional soccer players without a symptomatic concussion. *JAMA*. 2012;308:1859-1861.

23. Koerte IK, Lin AP, Muehlmann M, et al. Altered neurochemistry in former professional soccer players without a history of concussion. *J Neurotrauma*. 2015;32:1287-1293.
24. Lehman EJ, Hein MJ, Baron SL, Gersic CM. Neurodegenerative causes of death among retired National Football League players. *Neurology*. 2012;79:1970-1974.
25. Lipton ML, Kim N, Zimmerman ME, et al. Soccer heading is associated with white matter microstructural and cognitive abnormalities. *Radiology*. 2013;268:850-857.
26. Lynall RC, Clark MD, Grand EE, et al. Head impact biomechanics in women's college soccer. *Med Sci Sports Exerc*. 2016;48:1772-1778.
27. Martini D, Eckner J, Kutcher J, Broglio SP. Subconcussive head impact biomechanics: comparing differing offensive schemes. *Med Sci Sports Exerc*. 2013;45:755-761.
28. McCuen E, Svaldi D, Breedlove K, et al. Collegiate women's soccer players suffer greater cumulative head impacts than their high school counterparts. *J Biomech*. 2015;48:3729-3732.
29. 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;61:1229-1235.
30. Naunheim RS, Standeven J, Richter C, Lewis LM. Comparison of impact data in hockey, football, and soccer. *J Trauma*. 2000;48:938-941.
31. Omalu BI, DeKosky ST, Hamilton RL, et al. Chronic traumatic encephalopathy in a National Football League player: part II. *Neurosurgery*. 2006;59:1086-1092.
32. Press JN, Rowson S. Quantifying head impact exposure in collegiate women's soccer. *Clin J Sport Med*. 2017;27:104-110.
33. Reynolds BB, Patrie J, Henry EJ, et al. Practice type effects on head impact in collegiate football. *J Neurosurg*. 2016;124:501-510.
34. Reynolds BB, Patrie J, Henry EJ, et al. Quantifying head impacts in collegiate lacrosse. *Am J Sports Med*. 2016;44:2947-2956.
35. Rowson S, Broolinson G, Goforth M, Dietter D, Duma S. Linear and angular head acceleration measurements in collegiate football. *J Biomech Eng*. 2009;131:061016.
36. Svaldi DO, McCuen EC, Joshi C, et al. Cerebrovascular reactivity changes in asymptomatic female athletes attributable to high school soccer participation [published online January 26, 2016]. *Brain Imaging Behav*. doi:10.1007/s11682-016-9509-6.
37. Swartz EE, Broglio SP, Cook SB, et al. Early results of a helmetless-tackling intervention to decrease head impacts in football players. *J Athl Train*. 2015;50:1219-1222.
38. Talavage TM, Nauman E, Breedlove EL, et al. Functionally-detected cognitive impairment in high school football players without clinically-diagnosed concussion. *J Neurotrauma*. 2010;31:327-338.
39. 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;41:2474-2487.
40. Vasavada AN, Danaraj J, Siegmund GP. Head and neck anthropometry, vertebral geometry and neck strength in height-matched men and women. *J Biomech*. 2008;41:114-121.
41. White H. A heteroskedasticity-consistent covariance matrix estimator and a direct test for heteroskedasticity. *Econometrica*. 1980;48:817-838.
42. Withnall C, Shewchenko N, Gittens R, Dvorak J. Biomechanical investigation of head impacts in football. *Br J Sports Med*. 2005;39(suppl 1):i49-i57.
43. Wu LC, Nangia V, Bui K, et al. In vivo evaluation of wearable head impact sensors. *Ann Biomed Eng*. 2016;44:1234-1245.
44. Zhang MR, Red SD, Lin AH, Patel SS, Sereno AB. Evidence of cognitive dysfunction after soccer playing with ball heading using a novel tablet-based approach. *PLoS One*. 2013;8:e57364.

APPENDIX

TABLE A1

Comparison of the Mean Number of Impacts/Event With Force $>X_g$ or $>X_{rad}/s^2$ Between Practice and Game Events for Men's Soccer Starters, Expressed as a Ratio of Means^a

G-Force Threshold	Ratio	Mean Rate Ratio	Lower 95% CL	Upper 95% CL	Unadjusted P value	Bonferroni Lower 95% CL	Bonferroni Upper 95% CL	Bonferroni P value
10	Practice:game	.26	0.21	0.32	<.001	0.19	0.35	<.001
20	Practice:game	.25	0.16	0.38	<.001	0.13	0.46	<.001
30	Practice:game	.18	0.09	0.35	<.001	0.07	0.47	<.001
40	Practice:game	.19	0.07	0.48	<.001	0.05	0.7	.004
50	Practice:game	.25	0.11	0.56	0.001	0.08	0.79	.008
60	Practice:game	.3	0.17	0.55	<.001	0.13	0.71	.001
70	Practice:game	.16	0.08	0.31	<.001	0.06	0.42	<.001
80	Practice:game	.18	0.07	0.48	.001	0.05	0.71	.005
90	Practice:game	.27	0.03	2.91	.283	0.01	7.74	1

PRA Threshold	Ratio	Mean Rate Ratio	Lower 95% CL	Upper 95% CL	Unadjusted P value	Bonferroni Lower 95% CL	Bonferroni Upper 95% CL	Bonferroni P value
0	Practice:game	.26	0.21	0.32	<.001	0.19	0.35	<.001
2000	Practice:game	.27	0.23	0.31	<.001	0.22	0.33	<.001
4000	Practice:game	.25	0.15	0.4	<.001	0.13	0.49	<.001
6000	Practice:game	.21	0.14	0.3	<.001	0.12	0.35	<.001
8000	Practice:game	.23	0.16	0.33	<.001	0.14	0.38	<.001
10000	Practice:game	.29	0.18	0.45	<.001	0.15	0.54	<.001
12000	Practice:game	.36	0.23	0.58	<.001	0.19	0.7	<.001
14000	Practice:game	.3	0.21	0.43	<.001	0.18	0.5	<.001

^aBoth event types must have at least one impact greater than a given threshold to perform the comparison.