Sport- and Gender-Based Differences in Head Impact Exposure and Mechanism in High School Sports

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Background: Repeated head impacts sustained by athletes have been linked to short-term neurophysiologic deficits; thus, there is growing concern about the number of head impacts sustained in sports. Accurate head impact exposure data obtained via head impact sensors may help identify appropriate strategies across sports and between genders to mitigate repetitive head impacts.

Purpose: To quantify sport- and gender-based differences in head impact rate and mechanism for adolescents.

Study Design: Cohort study; Level of evidence, 2.

Methods: High school female and male varsity soccer, basketball, lacrosse, and field hockey (female only) teams were instrumented with headband-mounted impact sensors during games over 2 seasons of soccer and 1 season of basketball, lacrosse, and field hockey. Video review was used to remove false-positive sensor-recorded events, and the head impact rate per athlete-exposure (AE) was calculated. Impact mechanism was categorized as equipment to head, fall, player to head, or head to ball (soccer only).

Results: Male players had significantly higher head impact rates as compared with female players in soccer (3.08 vs 1.41 impacts/AE; rate ratio, 2.2 [95% CI, 1.8-2.6]), basketball (0.90 vs 0.25; 3.6 [2.6-4.6]), and lacrosse (0.83 vs 0.06; 12.9 [10.1-15.8]). Impact mechanism distributions were similar within sports between boys and girls. In soccer, head to ball represented 78% of impacts, whereas at least 88% in basketball were player-to-player contact.

Conclusion: Across sports for boys and girls, soccer had the highest impact rate. Male high school soccer, basketball, and lacrosse teams had significantly higher head impact rates than did female teams of the same sport. For girls, basketball had a higher head impact rate than did lacrosse and field hockey, and for boys, basketball had a similar impact rate to lacrosse, a collision sport. Sport differences in the distribution of impact mechanisms create sport-specific targets for reducing head impact exposure.

Keywords: head injuries/concussion; pediatric sports medicine; injury prevention; football (soccer); basketball; lacrosse

A concussion occurs every 20 seconds in the United States.[9,16] Adolescents are particularly vulnerable to concussion because they frequently participate in sporting and recreational activities and have slower recovery periods than do adults.[24,54] Additionally, there is growing concern for the neurologic effects of repetitive head impacts in sports even without a diagnosed injury.[2,28] Repeated head impacts have been linked with several short-term neurophysiologic deficits in neurocognitive performance, postural control, and ocular reflexes.[17-19] Accurate head impact exposure and mechanism data may help identify appropriate strategies to mitigate repetitive head impacts and lower risk of acute injury.

Concussion and head impact exposure research in sports has primarily been focused on male American football players[34]; however, female athletes have higher concussion rates than do male athletes in equivalent sports—for example, in soccer (2.8-3.4 vs 1.9-2.0 concussions per 10,000 athlete-exposures [AEs]) and basketball (2.0-2.1 vs 0.8-1.6)[20,27,43]—and higher peak kinematics in equivalent soccer headers (linear acceleration, 17.9g vs 14.7g; angular acceleration, 1038.9 vs 656.6 rad/s^2).[4,5] Furthermore, female athletes have a higher concussion symptom burden, longer symptom duration, and worse vestibular ocular deficits.[11,32,46] Despite a higher concussion rate and symptom burden among female athletes, efforts to understand the

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frequency of head impacts to reduce exposure have rarely included female athletes: a systematic review of head impact kinematic studies revealed that only 1 in 5 included female athletes,[34] and direct male to female comparisons are rare in studies of ice hockey, soccer, and lacrosse.[29,41,52] As a result, we have limited knowledge of head impact exposure differences between genders for similar sports.

Play characteristics, such as speed of play, level of contact, and rules, vary across sports and between genders, thus influencing specific impact mechanisms. Impact mechanism and scenario are directly related to the severity of head kinematics and occurrence of injury.[6] Head-to-head contact in soccer creates higher peak linear accelerations than intentionally heading the ball,[23] and a majority of concussions in soccer are due to player-to-player contact.[10] Specific changes to sporting equipment often stem from identification of frequent injury mechanisms. For example, the most common concussion impact mechanisms in the National Football League have inspired design challenges for position-specific helmets to mitigate injuries.[26] Studying the distribution of head impact mechanisms and associated impact rate is needed across all sports for male and female athletes to develop sport- and gender-specific rule and protective equipment strategies to mitigate head impact exposure.

Head impact sensors—which contain accelerometers and gyroscopes in a mouthguard, headband, skin patch, or helmet—offer the opportunity to quantitatively measure head impact exposure. Previous research highlighted that sensor recordings can be triggered by nonimpact events (eg, player dropping detached sensor); therefore, video confirmation of head impact sensor data is necessary to attain an accurate head impact exposure measure in sports.[13,37,38] Individual sports differ in equipment, gameplay, rules of the game, and playing surface, thus contributing to differences in sensor attachment method and novel sources of false-positive acceleration events.[13,37,38] To compare head impact exposure across sports, quantification of false positives in multiple sports using the same head impact sensor is needed.

To address these gaps and move toward sport-specific strategies to mitigate repetitive head impacts, this study quantified the head impact exposure and impact mechanism using a single head impact sensor, the headband-mounted Triax Smart Impact Monitor (SIM-G; Triax Technologies, Inc), and rigorous video confirmation methods. The aim was to quantify sport- and gender-based differences in head impact rate and mechanism in high school soccer, basketball, lacrosse, and field hockey (female only).

METHODS

A prospective observational cohort study design was used to investigate head impacts in high school varsity soccer, basketball, lacrosse, and field hockey teams during the 2017 and 2018 seasons. The current study received institutional review board (IRB) approval. Review head impact sensor data was conducted under a waiver of consent. Head impact sensor usage was part of participation on that school's soccer team, independent of the study, and no clinical procedures were conducted with those athletes. Clinical details (ie, concussion diagnosis) were collected under a separate IRB, in which subjects provided informed consent.

Athletes were recruited from a single suburban private high school in the Philadelphia region as part of a larger concussion study. Two seasons of male and female soccer were studied and 1 season of each of the following: male and female basketball, male and female lacrosse, and female field hockey. All teams were varsity level in grades 9 to 12. Throughout this study, *gender* was used rather than *sex*, as biological sex was not collected; rather, gendered team sport participation was studied.

Head Impact Sensor: Triax Smart Impact Monitor

All participants were assigned Triax SIM-G head impact sensors throughout the entire season as described previously.[37] Sensors were worn during regular and postseason games by all players on the teams. Sensors were secured in a neoprene headband and positioned just above the greater occipital protuberance and worn identically in helmeted and unhelmeted sports (Figure 1). The SIM-G device comprises a high-g and low-g triaxial accelerometer for linear acceleration measurement ($3g$-$150g$) and a triaxial gyroscope for angular velocity measurement at 1000 Hz.[48] An event recording is triggered by a $16g$ linear acceleration threshold, and the sensor stores time series data from 10 milliseconds preimpact to 52 milliseconds postimpact.

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Figure 1. Lacrosse athlete wearing the Triax Smart Impact Monitor (Triax Technologies, Inc) headband-mounted sensor. Photo courtesy of Children's Hospital of Philadelphia.

Triax has a processing algorithm that labels each sensor-recorded event as either a "valid" or a "spurious" impact.[48] The algorithm was not used to remove sensor recordings for the current study, and the algorithm accuracy was assessed. The SIM-G has been evaluated for accuracy in human head surrogate linear impactor events[15,49] and on-field head impact counts.[23,37] As an impact counter, the SIM-G consistently recorded >85% of head impacts in 2 human head surrogate studies, and the video confirmation process described here is designed to remove false positives in real-life settings.[15,36]

Before the warm-ups of each game, sensors were confirmed to be functional and connected with the central data collection SKYi box before distribution. After the game, collection of sensor data on the SKYi box was terminated, and sensors were returned to study staff and deactivated. Data were uploaded to the cloud, processed by proprietary manufacturer software (false-positive algorithm turned off), and downloaded with event and time identifiers for video review.

Video Recording and Analysis of Head Impact Events

For each sport, video footage was captured specifically for this study from a single-camera view (Sony HD Camcorder CX405) located close to the midpoint of the field/court. The videographer (C.M.H., D.A.P.) panned the camera to follow the action of the ball with approximately one-third of the field in view for soccer, lacrosse, and field hockey and half the court in basketball. For boys' lacrosse, 3 additional stationary cameras were added opposite to the videographer to capture the offensive half, defensive half, and substitutions. Video footage was recorded in high definition 1080p with a 16:9 aspect ratio at 60 frames per second. Video and sensor data were aligned by filming a few seconds of a world clock website (timeanddate.com).

Video review of all sensor-recorded events was used to identify actual head impact events as described previously for soccer[37] and to describe impact mechanism (ie, the cause of head contact). Sensor-recorded events were removed if the associated player was off the field or out of frame during the event time. Remaining sensor-recorded events were reviewed to categorize each event as an impact event (eg, ball striking the head), trivial event (eg, player adjusting headband), or nonevent (eg, player stationary and not touching headband). The impact mechanism of each confirmed head impact event was then categorized as follows: equipment to head (ie, sporting equipment striking the head of a player), fall (ie, player falling to the ground after losing balance), player to head (eg, athlete struck by another player's arm, head), or head to ball (ie, intentional heading of the ball, exclusive to soccer). Fall events included direct impact events with the head striking the ground and indirect head acceleration events initiated by a player falling without head-to-ground contact. Player-to-head events included another player striking the head and player-to-player body contact without head contact.

Statistical Analysis

Video review was conducted by sport and gender to identify proportions of event type (ie, nonevents, trivial events, and impact events) among sensor-recorded events. Video-confirmed head impact data were then summarized by sport and gender. Individual 2×3 Fisher exact tests were performed to determine significant differences ($P < .05$) in the distribution of sensor-recorded event types between female and male teams within each sport and between sports within each gender. Sensor data were included for all athletes, including those sustaining an injury during a game. Impact mechanism (ie, equipment to head, fall, player to head, and head to ball) was described and detailed by sport and gender. Impact rates were calculated as impacts per AE. A single AE was defined as an athlete entering a single game with an active sensor. AEs were quantified by recording the number of players who actively participated in the game that day via video review and substitution tracking. AEs were excluded if a player's sensor was inactive or removed by the athlete during the game. Head impact rate ratios with 95% CIs were calculated to determine impact rate differences between female and male teams within each sport and between sports within each gender.

RESULTS

A total of 169 athlete seasons were studied from 124 athletes (56 girls, 68 boys) who participated in this study. Data were collected from 104 games and 1211 AEs (Table 1) across soccer, basketball, lacrosse, and field hockey. Two athletes sustained a concussion during filmed games while wearing active sensors. Clinical data of the 2 athletes who sustained concussions were not included in this study as the focus was on head impact rate and mechanism.

TABLE 1
Athlete Participation[a]

	All Sports			Soccer		Basketball		Lacrosse		Field Hockey
	Total	Female	Male	Female	Male	Female	Male	Female	Male	Female
Seasons	9	5	4	2	2	1	1	1	1	1
Games	104	55	49	18	23	14	10	12	16	11
Athlete seasons	169	82	87	34	44	12	13	15	30	21
Athlete-exposures	1211	509	702	195	338	100	92	109	272	105

[a]Values are presented as No.

TABLE 2
Reduction of Sensor-Recorded Events During Game Times to Video-Confirmed Head Impact Events by Sport and Gender[a]

	All Sports			Soccer		Basketball		Lacrosse		Field Hockey
Sensor-Recorded Events	Total	Female	Male	Female	Male	Female	Male	Female	Male	Female
During verified game times	13,388	3740	9648	1758	5038	364	801	1323	3809	295
With on-field players[b]	5094 (38)	1655 (44)	3439 (36)	1191 (68)	1584 (31)	161 (44)	149 (19)	255 (19)	1706 (45)	48 (16)
With players in field of view[b]	3552 (27)	778 (21)	2774 (29)	565 (32)	1328 (26)	81 (22)	123 (15)	102 (8)	1323 (35)	30 (10)
Impact events[c]	1658 (47)	308 (40)	1350 (49)	275 (49)	1041 (78)	25 (31)	83 (67)	7 (7)	226 (17)	1 (3)
Trivial events[c]	508 (14)	266 (34)	242 (9)	207 (37)	189 (14)	36 (44)	16 (13)	19 (19)	37 (3)	4 (13)
Nonevents[c]	1386 (39)	204 (26)	1182 (43)	83 (15)	98 (7)	20 (25)	24 (20)	76 (75)	1060 (80)	25 (83)

[a]Values are presented as No. (%).
[b]Percentage calculated relative to number of sensor-recorded events during verified game times.
[c]Percentage calculated relative to events with players in the field of view.

TABLE 3
Percentage of Sensor-Recorded Events Correctly Classified by the SIM-G Algorithm

	Soccer		Basketball		Lacrosse		Field Hockey
Video-Confirmed Event	Female	Male	Female	Male	Female	Male	Female
Impact	77.5	68.0	56.0	45.8	71.4	69.0	100.0[a]
Trivial	43.5	61.4	63.9	68.8	63.2	48.6	75.0
Nonevent	62.7	69.4	65.0	75.0	69.7	19.6	96.0
All	62.8	67.2	61.7	54.5	68.6	28.9	93.3

[a]Only 1 impact. SIM-G, Triax Smart Impact Monitor (Triax Technologies, Inc).

Video Confirmation: False Positives and Algorithm Accuracy

A total of 13,388 sensor-recorded events were recorded during verified game times (Table 2); however, this number was reduced to 5094 (38%) when accounting for players on the field/court at the time of the recorded event and to 3552 (27%) for on-field/court players in the video frame of view. The Triax proprietary sensor event-processing algorithm was evaluated for impact, trivial, and nonevents by sport and gender. Overall, the processing algorithm had a 52% accuracy (Table 3). The algorithm correctly classified 68% of video-confirmed impact events as true head impacts, and the algorithm correctly classified 54% and 31% of trivial and nonevents, respectively, as "spurious" recordings. Accuracy ranged from 28.9% to 93.3% by sport. Owing to poor accuracy, algorithm classification was not used to remove sensor recordings for head impact rate and mechanism analyses, and all sensor-recorded events were video reviewed via the methods described.

The number of sensor-recorded events are presented by sport and gender, and video-confirmed sensor events are categorized into impact, trivial, or nonevents (Table 2). Male teams had significantly different distributions of observable event types than did female teams in soccer, basketball, and lacrosse (all $P < .001$). For male sports, the proportion of observable events significantly differed across all sports (all $P < .001$). For female sports, the proportions significantly differed for all sports (all $P < .005$) apart from lacrosse and field hockey, which had similar distributions of sensor event types ($P = .688$). Trivial and nonevents were removed for head impact rate and

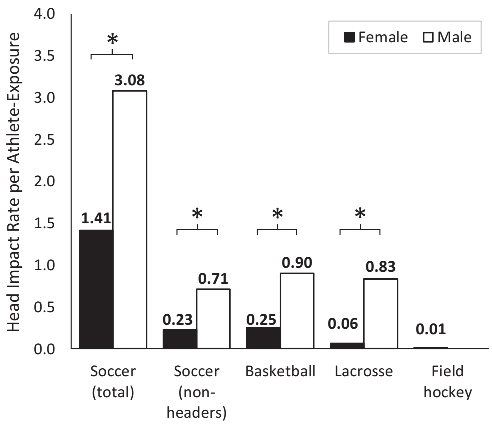

Figure 2. Head impact rates per athlete-exposure. For soccer, the impact rate is presented as all impacts and all non–head to ball impacts (ie, equipment to head, fall, and player to head). For all other sports, the bars represent all impacts. *Boys had a higher impact rate as compared with girls in soccer (rate ratio [95% CI], 2.2 [1.8-2.6]), nonheaders in soccer (3.1 [2.6-3.7]), basketball (3.6 [2.6-4.6]), and lacrosse (12.9 [10.1-15.8]).

TABLE 4
Comparison of Head Impact Rate Ratios Across Sports by Gender[a]

Sport Comparison	Female	Male
Soccer (total)		
Basketball	**5.6 (4.3-7.0)**	**3.4 (2.6-4.2)**
Lacrosse	**22.0 (16.8-27.1)**	**3.7 (3.1-4.3)**
Field hockey	**148.1 (112.9-183.2)**	NA
Soccer (nonheaders)		
Basketball	0.9 (0.7-1.1)	**0.8 (0.6-1.0)**
Lacrosse	**3.5 (2.7-4.3)**	**0.9 (0.7-1.0)**
Field hockey	**23.7 (18.1-29.3)**	NA
Basketball		
Lacrosse	**3.9 (2.8-4.9)**	1.1 (0.8-1.3)
Field hockey	**26.3 (19.1-33.4)**	NA
Lacrosse		
Field hockey	**6.7 (4.9-8.6)**	NA

[a]Data are presented as rate ratio (95% CI). Bold values indicate significant rate ratio difference. NA, not applicable.

mechanism analysis; therefore, only video-confirmed head impacts were used.

Head Impact Rates per AE: Gender- and Sport-Based Differences

Overall, the confirmed head impact rate in girls was relatively low as compared with that in boys in the same sport (Figure 2). Boys had a significantly higher impact rate than did girls in soccer (rate ratio [95% CI], 2.2 [1.8-2.6]), nonheaders in soccer (3.1 [2.6-3.7]), basketball (3.6 [2.6-4.6]), and lacrosse (12.9 [10.1-15.8]). A gender-based comparison for field hockey was not possible, as it was played only by female athletes. The head impact rate was very low, with 1 confirmed head impact event for the entire season.

Within each gender, there were differences in head impact rate across sports. For boys, the impact rate in soccer was >3 times higher than that in basketball and lacrosse; however, when intentional headers exclusive to soccer were removed, the impact rate was slightly lower than that in basketball and lacrosse (Table 4). Male basketball and lacrosse did not differ in impact rate. For female sports, soccer had a substantially higher impact rate than did basketball, lacrosse, and field hockey. All rates were significantly different. After soccer, female basketball had the next-highest head impact rate, followed by lacrosse and field hockey. After intentional headers exclusive to soccer were removed, the impact rate in female soccer was similar to that in basketball but remained higher than that in lacrosse and field hockey.

Sport-Specific Head Impact Mechanism Distribution

Impact mechanisms for video-confirmed head impacts were detailed by sport and gender (Table 5). Intentional head-to-ball impacts were removed from intersport impact mechanism distribution calculations because intentional headers were exclusive to soccer. Given the low number of confirmed head impacts in a few sports (eg, female lacrosse), no statistical comparisons were made. Impact mechanism distribution was similar between genders in soccer, basketball, or lacrosse. Head-to-ball impacts represented 78% of total impacts in soccer, and 36% of player-to-head impacts

TABLE 5
Distribution of Impact Mechanism Across Sports and Between Genders[a]

	Soccer		Basketball		Lacrosse		Field Hockey
Impact Mechanism	Female	Male	Female	Male	Female	Male	Female
Equipment-to-head	2 (5)	9 (4)	1 (4)	3 (4)	3 (43)	65 (29)	0 (0)
Fall	18 (41)	111 (46)	2 (8)	4 (5)	1 (14)	33 (15)	0 (0)
Player-to-head	24 (55)	120 (50)	22 (88)	76 (92)	3 (43)	128 (57)	1 (100)
Intentional head-to-ball	231	801	NA	NA	NA	NA	NA
Total	275	1041	25	83	7	226	1

[a]Data are presented as No. (%). NA, not applicable.

occurred from players challenging to head the ball. Soccer and basketball equipment-to-head impacts were all contact with the ball and occurred infrequently. Similarly, male lacrosse had a low proportion of equipment-to-head impacts from contact with the ball (2%), and female lacrosse had no impacts from ball contacts. The majority of equipment-to-head impacts were attributed to stick-to-head contact. Due to head-to-ball impacts being exclusive to soccer, percentages were not calculated for head-to-ball to facilitate a direct comparison across sports of impact mechanism distribution of equipment-to-head, fall, and player-to-head.

DISCUSSION

This study uniquely quantifies head impact rates and mechanisms in 4 sports, comparing boys and girls in 3 of the 4. Despite the popularity of basketball and field hockey, with >24 million US participants[47] and significant concussion rates,[27,43] this is the first study using head impact sensors to quantify head impact exposure in these 2 sports. Importantly, this study used the same sensor for all sports to facilitate accurate comparisons while accounting for sensor behavior and false-positive rates.

Sport-Based Differences in Head Impact Rates

Cross-sport analysis of head impact rates is extremely rare,[39] especially when video confirmation methods are applied, but this study uniquely analyzed multiple high school sports to characterize head loading across sports. For boys and girls, soccer had the highest impact rate, with nearly 80% of impacts being intentional headers. In this study, head impact rates per AE were in the range of previous studies employing video confirmation methods. However, variability introduced by level of play, sensor choice, and sensor recording threshold has created a wide range of head impact rates: female soccer (0.4-3.3 impacts/AE),[30,33,38,42,44,45] male soccer (1.3-2.4 impacts/AE),[33,44,45] female lacrosse (0.1-0.3 impacts/AE),[8,13,25] and male lacrosse (0.7-1.9 impacts/AE).[7,13,25,35,51] Head impact rates were markedly lower than rates in sensor studies without video or visual reviewer techniques: female soccer (2.9-5.7 impacts/AE),[29,40] male soccer (31.1-39.5 impacts/AE),[39,40] female lacrosse (9.2 impacts/AE),[41] and male lacrosse (5.5-11.5 impacts/AE).[31,39,41] Generally, previous studies have found that soccer has higher impact rates than does lacrosse. This study similarly found that male and female soccer had higher rates than did lacrosse while employing the same sensor and methods across sports, which created a strong, direct comparison.

Basketball had a higher head impact rate than did lacrosse and field hockey for girls and a similar impact rate to that of lacrosse for boys; furthermore, for both genders, these impact rates were similar to or higher than nonheader soccer impact rates. The similarity in impact rate between male basketball and lacrosse was unexpected, given that male lacrosse is classified as a collision sport and requires the use of a helmet. Male and female basketball have substantial concussion rates,[27,43] yet this is the first study employing head impact sensors to analyze basketball. Most head impacts in basketball were due to player-to-player contact, indicative of the physicality of the game, small court dimensions relative to other sports, and close player proximity. Basketball seasons typically have more games in a single season than do lacrosse and soccer, so cumulative head impact exposure per player may be even higher than that in those sports. It is important to note that while head impact rates may be similar among sports, further analyses are required to quantify the magnitude of head impacts. Such analyses may reveal important differences among the sports that relate to injury risk. However, these findings do point to the need for investigation to understand head impact exposure and acute concussion risk in basketball.

The low impact rate (<1 impact every 10 games) in female high school lacrosse and field hockey highlights that these teams had a low cumulative head impact exposure for the season studied. Further research is needed on injury mechanisms to reconcile the low number of impacts recorded with in-game concussion rates in female lacrosse (8.6 per 10,000 AEs) and field hockey (4.1 per 10,000 AEs).[27] Although head contact may be uncommon in these sports, the head impact events are frequently caused by contact with hard surfaces (ie, ball, stick, or ground), which may be more likely to cause injury than may the common impacts observed in other sports.

Gender-Based Differences in Head Impact Rates

Overall, male athletes in this study had impact rates 2 to 13 times higher than those of their female counterparts in all sports. Lacrosse had the largest difference between genders, which was consistent with previous studies using head impact sensors and appropriate video confirmation methods: Cortes et al[13] (high school, 15 times higher) and Le et al[25] (National Collegiate Athletic Association Division III, 5.7 times higher). A higher impact rate in male lacrosse was expected because a higher level of contact is allowed (eg, checking) and male players wear more protective equipment (eg, helmets). Rules decreasing contact in male lacrosse may reduce total head impact exposure.

Higher impact rates for boys persisted in basketball and soccer: 2 sports that are similar in rules and equipment between male and female players. In soccer, male players had an impact rate >2 times higher than that of female players, which was consistent with gender-based comparisons found at the youth (1.5 times higher)[44] and collegiate (2.2 times higher)[45] levels. With this study, gender-based differences in basketball were quantified for the first time; the male head impact rate was 3.6 times higher than that for female athletes in this study. In soccer and basketball, the nature of the game is similar between boys and girls; therefore, impact rate differences may be attributable to differences in aggression, physicality, and speed of play.[22] Further research is needed to understand how total head impact exposure, time between impacts, and impact characteristics including severity influence injury risk.

Impact Mechanisms by Sport

Within a given sport, the distribution of impact mechanism was similar between boys and girls. There were, however, key differences across sports in common impact mechanisms. Unique to soccer is the intentional use of the head to contact the soccer ball; nearly 80% of male and female soccer head impacts were intentional headers. To minimize the role of this scenario in the game, US soccer eliminated all heading for players aged <12 years to reduce total head impact exposure.[50] Further research is needed to understand the short-term effects of soccer heading and how to safely teach heading technique.[17-19] Player contact is responsible for 71% of head injuries in soccer.[10] Rule changes, such as disallowing raised arms/elbows while heading, may reduce the number of head impacts that occur when challenging another player to head a ball in the air, which accounted for 36% of player-to-head impacts. After removing head-to-ball impacts, approximately 45% of head impacts in soccer were caused by falls, which is higher than that in either basketball (~6%) or lacrosse (~15%).

Lacrosse had a higher proportion of equipment-to-head impacts than did other sports because of the introduction of a stick, with intentional contact with the stick permitted in male lacrosse. Stick-to-head impacts are already penalized; therefore, enforcement of existing rules may be a focus. There is discussion of introducing helmets to female lacrosse to reduce the severity of stick-to-head impacts.[3,12,14] Female lacrosse had a significantly lower impact rate (0.06 impacts/AE) than did male lacrosse (0.83 impacts/AE) because of rule differences. Wearing a helmet may allow a more aggressive game that has the unintended consequence of increasing total head impact exposure; however, directed helmet design and continued strict enforcement of the rules can maintain lower head impact rates while decreasing stick-to-head impact severity.[1]

False-Positive Identification via Algorithm and Video Confirmation

The Triax SIM-G proprietary classification algorithm to remove nonimpact sensor-recorded events was previously shown to be ineffective.[37] Similar results across sports were found in this study: the algorithm correctly classified 68% of video-confirmed impact events as true head impacts and 54% and 31% of trivial and nonevents as "spurious," respectively. As a result, head impact exposure would have been overestimated if only algorithm filtering was used, as a significant number of false-positive recordings would have been included. Therefore, algorithms should be used cautiously.

The results of this study confirmed previous work emphasizing the necessity of video confirmation in head impact sensor research to remove nonimpact sensor-recorded events.[13,33,37,38] In this study across all sports, 73% of sensor events recorded during verified game times were removed because players were off the field or out of view of the camera. In addition, 53% of the remaining impacts were removed because they were false-positive recordings. Sport-specific video confirmation techniques should be implemented to ensure that all sensor-recorded events are verifiable; for example, football may require more cameras to capture impacts away from the ball.[53]

Limitations

Several limitations of the current study exist. First, this study reported impact rates but not magnitude. All impacts above the sensor recording threshold were treated equivalently. It is possible that sports with similar impact rates may experience a differential injury rate owing to differences in the magnitude of impacts that they sustain. Head impact kinematics across sports and between genders will be analyzed in future studies to delineate the differential risk. This study's focus on impact rate provides targets for interventions in reducing the overall exposure that youth experience in sports. Second, a single private high school was studied. Impact rates may not be representative of all high school varsity athletics, including other schools with different sport cultures and levels of competitiveness and/or skill, and the results do not reflect other levels of sport (eg, middle school, collegiate). Third, a headband-mounted Triax SIM-G with a 16*g* recording threshold was used for this study. A sensor with a different threshold would influence the number of impacts recorded, so impact rates must be interpreted in the context of the threshold in this study.[21] However, a strength of this study was that the same sensor with the same threshold was used for all sports. Future studies should observe the same sports using a different sensor to confirm trends and results. Fourth, a single-camera view was used for video confirmation for all sports except male lacrosse. The camera field of view encompassed approximately one-third to one-half of the field/court and followed the action of the play. Therefore, a portion of sensor-recorded events (away from the ball) were unable to be observed, and some impacts in the far corners of the playing surface were difficult to observe, as previously detailed.[37] However, as most head impacts are plays on or near the ball, it is likely that these unobserved sensor-recorded impacts are trivial or nonevents and not actual head impacts. Furthermore, to minimize the number of unobserved sensor-recorded events in male lacrosse, multiple camera views were used to film the full field throughout the game. Fifth, sensors were ensured to be functioning and worn before each game. However, as headbands may have fallen off or batteries may have died during the game, some impacts may not have been captured. Last, throughout this article, *gender* was used rather than *sex*, as biological sex was not collected; rather, gendered team sport participation was studied. The male/female differences observed in this study may be due to gameplay differences between the gendered teams rather than biological sex.

CONCLUSION

This study used the same sensor across sports and between genders to quantify head impact rates across several popular high school sports, some of which had never been studied. The results emphasized the need to employ rigorous video confirmation to remove false-positive head impact sensor recordings for an accurate account of head impact exposure. Overall, soccer had the highest impact rate for male and female athletes across the sports studied, which was attributed to the role of intentional headers. High school male sports consistently had higher impact rates than did female soccer, basketball, and lacrosse. For girls, basketball had a higher head impact rate than did lacrosse and field hockey, which were generally very low, and for boys, impact rates for basketball were similar to those of lacrosse. Further research is needed to understand how the head impact rates observed in this study relate to acute neurologic sequelae and if gender-based differences in rates correspond to neurologic outcome differences. Sport-specific mechanism findings produced head impact exposure mitigation targets, such as minimizing stick-to-head contact in lacrosse. Additional research is needed to understand how differences in impact characteristics (eg, severity, direction) among mechanisms influence injury risk. Overall, the data provided in this study provide an objective quantification of head impact exposure across sports and between genders that can be useful in anticipatory guidance for clinicians to provide to patients as they consider sport participation.

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