Characterizing Verified Head Impacts in High School Girls' Lacrosse

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Background: Girls' high school lacrosse players have higher rates of head and facial injuries than boys. Research indicates that these injuries are caused by stick, player, and ball contacts. Yet, no studies have characterized head impacts in girls' high school lacrosse.

Purpose: To characterize girls' high school lacrosse game-related impacts by frequency, magnitude, mechanism, player position, and game situation.

Study Design: Descriptive epidemiology study.

Methods: Thirty-five female participants (mean age, 16.2 ± 1.2 years; mean height, 1.66 ± 0.05 m; mean weight, 61.2 ± 6.4 kg) volunteered during 28 games in the 2014 and 2015 lacrosse seasons. Participants wore impact sensors affixed to the right mastoid process before each game. All game-related impacts recorded by the sensors were verified using game video. Data were summarized for all verified impacts in terms of frequency, peak linear acceleration (PLA), and peak rotational acceleration (PRA). Descriptive statistics and impact rates were calculated.

Results: Fifty-eight verified game-related impacts $\geq 20g$ were recorded (median PLA, 33.8*g*; median PRA, 6151.1 rad/s^2) during 467 player-games. The impact rate for all game-related verified impacts was 0.12 per athlete-exposure (AE) (95% CI, 0.09-0.16), equivalent to 2.1 impacts per team game, indicating that each athlete suffered fewer than 2 head impacts per season $\geq 20g$. Of these impacts, 28 (48.3%) were confirmed to directly strike the head, corresponding with an impact rate of 0.05 per AE (95% CI, 0.00-0.10). Overall, midfielders (n = 28, 48.3%) sustained the most impacts, followed by defenders (n = 12, 20.7%), attackers (n = 11, 19.0%), and goalies (n = 7, 12.1%). Goalies demonstrated the highest median PLA and PRA (38.8*g* and 8535.0 rad/s^2, respectively). The most common impact mechanisms were contact with a stick (n = 25, 43.1%) and a player (n = 17, 29.3%), followed by the ball (n = 7, 12.1%) and the ground (n = 7, 12.1%). One hundred percent of ball impacts occurred to goalies. Most impacts occurred to field players within the attack area of the field (n = 32, 55.2%) or the midfield (n = 18, 31.0%). Most (95%) impacts did not result in a penalty.

Conclusion: The incidence of verified head impacts in girls' high school lacrosse was quite low. Ball to head impacts were associated with the highest impact magnitudes. While stick and body contacts are illegal in girls' high school lacrosse, rarely did such impacts to the head result in a penalty. The verification of impact mechanisms using video review is critical to collect impact sensor data.

Keywords: head impacts; female; lacrosse; wearable sensors; verification; video analysis

Girls' lacrosse is the fastest growing sport among National Federation of State High School Associations member schools, with nearly 270,000 girls participating in high schools nationwide in 2013 to 2014.[29] The 12 team players, including the goalkeeper, participate using a crosse (lacrosse stick) to advance a ball toward an opponent's goal. Despite having shared origins with boys' lacrosse, girls' lacrosse is a distinct sport with rules designed to limit physical contact between players and, unlike the boys' game, does not permit intentional stick or bodily contact. Although girls' lacrosse requires a mouth guard and protective eyewear, rules do not mandate helmets or other protective equipment. The incidence of concussions in girls' lacrosse has been reported to be the second highest among all girls' high school sports, with the majority of concussions being sustained during games as opposed to practices.[23,39] Research suggests that about 35% of game-related injuries in girls' lacrosse occur to the head, with most resulting from illegal contact with a stick or another player.[7,38,39] The sport's rising popularity, combined with anecdotal reports of increasingly aggressive game play,[5,9]

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has contributed to growing concerns about not only concussions but also repetitive head impacts.[6,7,17,21,39]

While the potential adverse effects of repetitive concussions have been suggested, much remains to be understood about the consequences of chronic exposure to nonconcussive repetitive head impacts.[3] Crisco and colleagues[11] defined "head impact exposure" as a broad term that incorporates athlete-exposure (AE) and impact frequency, magnitude, and location along with cumulative measures of head impacts. Numerous studies have attempted to quantify head impact exposure using helmet-based accelerometers in male collision sports such as football[2,12] and ice hockey.[4,26,33] To date, fewer studies have used these methods to examine head impact exposure in female sports such as soccer[18,24,32,37] or lacrosse.[34] Recently, Reynolds et al[34] used wireless accelerometer technology to examine the frequency and magnitude of head impacts among elite female collegiate lacrosse players. However, no study has combined wearable accelerometer technology with video analysis to provide detailed information regarding player position, mechanism, or game play characteristics associated with head impacts in girls' lacrosse. Combining wearable accelerometer technology with video analysis may also help reduce the overestimation of head impact events measured by wearable sensors alone.[9,32]

To date, little is known regarding head impacts in girls' lacrosse or the characteristics of game play in which impacts occur. Therefore, the aim of this study was to quantify exposure and describe impacts based on player position, mechanism, and game play characteristics in girls' high school lacrosse players by combining wearable accelerometer technology with video analysis for verification purposes.

METHODS

Design and Participants

Data were prospectively gathered from 2 girls' high school varsity lacrosse teams (N = 35; mean age, 16.2 ± 1.2 years; mean height, 1.66 ± 0.05 m; mean weight, 61.2 ± 6.4 kg) that participated in this study during the 2014 and 2015 spring seasons. Participants were between 14 and 19 years old and an active member of a high school girls' lacrosse team. All player positions were included (goalie: n = 3; defender: n = 9; midfielder: n = 13; attacker: n = 10). A typical girls' lacrosse team formation involves 4 attackers, 4 defenders, 3 midfielders, and 1 goalie playing at one time. The research protocol was approved by the George Mason University Institutional Review Board before initiation of this study. Written informed parental consent and participant assent were obtained for all players.

Impact Event Monitoring

Game-related impacts were prospectively monitored using wearable sensors (xPatch; X2 Biosystems) that were time synchronized with game video. Before each game, a trained member of the research team affixed the wearable sensor associated with a distinctive player identification number to each player's head, behind the right ear on the skin covering the mastoid process, using an adhesive cloth tape. Participants wore the wearable sensor throughout the entirety of each game. The wearable sensor is composed of a triaxial accelerometer and a triaxial gyroscope, enabling the collection of linear acceleration and angular velocity. If a sensor exceeded a predetermined 10*g* linear acceleration threshold, 100 ms of data (10 ms before and 90 ms after the head acceleration event) were saved to onboard memory. The measurement error of the xPatch wearable device is reported as high as 50% for peak resultant linear and angular acceleration.[24] Recent studies have examined the accuracy of the xPatch wearable device compared with video-recorded impacts, demonstrating high false-positive rates and the need to cross-verify head impact events using video.[9,32]

Consistent with prior lacrosse research,[7,9] video of all varsity girls' lacrosse games was digitally recorded by a trained member of the research team using a high-definition camcorder (XA10 HD; Canon USA). Before each game, a sensor assigned as a "dummy sensor" was time synchronized with all active wearable sensors and the camcorder using a laptop computer. At the start of each game, coinciding with the game official's audible whistle and the start of the game clock, the videographer displayed a visual marker showing the date and start time of each game. Simultaneously, the dummy sensor was struck in full view of the camera. These procedures synchronized game, camcorder, and sensor times. At the conclusion of each game, all time synchronization procedures were repeated, and all sensors were immediately removed from the players and turned off.

Data Processing

After each game, all wearable sensor data were uploaded to a secure server using Concussion and Head Injury Management Software (X2 Biosystems). Raw sensor data were then transformed to the head's center of gravity by using a rigid-body transformation for peak linear acceleration (PLA) and a 5-point stencil for peak rotational acceleration (PRA). All wearable sensor data were then exported to Excel (Microsoft

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Corp). Similar to McCuen and colleagues,[24] we limited our analyses to impacts ≥20*g* to remove low acceleration events (10*g*-19*g*) commonly associated with physical activities of game play (eg, jumps, hard stops, cuts) and unlikely to result in deleterious neurophysiological changes.

Impact Event Analysis

All game-related impacts ≥20*g* recorded by the wearable sensors were reviewed and verified using video. A review of each impact consisted of approximately 60 seconds of game play immediately before and after the time stamp associated with the event recorded by the sensor. An impact was considered verified if it met criteria previously described by Cortes and colleagues.[9] Each verified impact was then coded for characteristics of game play (eg, game segment, field location, penalty called), player activity (eg, shooting, ball handling), and impact incident (eg, impact mechanism, location on body, preparedness for impact) using video analysis methodology previously used for high school girls' lacrosse.[7]

Statistical Analysis

Data were summarized by player and game play characteristics for all verified impacts. Descriptive statistics (frequency, median, and interquartile range) for PLA and PRA were calculated to characterize all verified game impacts ≥20*g*.[20] Additionally, impact rates per player game with corresponding 95% CIs were calculated. The impact rate was calculated as the number of verified impacts divided by the number of AEs. The formula for calculating the impact rate is as follows:

$$\text{Impact Rate} = \frac{\sum \text{verified impacts} \geq 20\text{g}}{\sum \text{AEs}}.$$

All analyses were calculated using SPSS V22.0 (IBM Corp).

RESULTS

Impact Frequency and Magnitude

During the 2014 and 2015 seasons, 35 female participants were instrumented with wearable sensors, and video was captured during 28 games. Across the 2 seasons, there were a total of 467 wearable sensor–instrumented player games with a mean of 17 players wearing a sensor per game. A total of 58 impacts ≥20*g* recorded by the wearable sensors were verified using video analysis. Overall, the median PLA and PRA of the verified impacts were 33.8*g* and 6151.1 rad/s^2, respectively, and the impact rate was 0.12 per AE per team game (95% CI, 0.09-0.16) (Table 1). These data corresponded with a mean exposure of 1.7 impacts ≥20*g* for each player per season. Overall, this suggests that a mean of 2.1 verified impacts per team ≥20*g* occurred during each game. No game-related concussions were reported during this 2-year study. See the Appendix for the distribution of all impacts (available in the online version of this article).

Impacts by Player Position

Midfielders sustained the most impacts (n = 28, 48.3%), followed by defenders (n = 12, 20.7%), attackers (n = 11, 19.0%), and goalies (n = 7, 12.1%) (see the Appendix). Although goalies experienced the fewest number of impacts during the season, they experienced the highest rate (0.23/AE) of impacts per player-game. Goalies also demonstrated the highest median PLA and PRA (38.8*g* and 8535.0 rad/s^2, respectively). Among field players, midfielders had the highest rate of impacts (0.15/AE) and attackers the lowest (0.08/AE). When examining the magnitude of impacts among field players, attackers demonstrated the highest median PLA and PRA (37.8*g* and 8351.3 rad/s^2, respectively). Complete descriptive information for impacts by player position can be seen in Table 1.

Impact Mechanism and Location

The most common impact mechanisms were contact with a stick (n = 25, 43.1%) and a player (n = 17, 29.3%), followed by the ball (n = 7, 12.1%) and the ground (n = 7, 12.1%). The definitive impact mechanism was unable to be determined in 2 cases (3.4%). Each of these 2 cases occurred during a loose ball situation in which the wearable sensor measured an impact and the player was seen holding her head immediately after. Because the ball was on the ground in clear view during each loose ball situation, we reason that these impacts likely resulted from either a stick or player contact. However, because of the number of athletes attempting to pick up the loose ball, the camera view was obstructed, and we could not definitively determine the mechanism. Although with the fewest number of impacts, ball contact demonstrated the highest median PLA and PRA (38.8*g* and 8534.9 rad/s^2, respectively). All ball impacts were sustained by goalies. When examining the magnitude of impacts among all other known impact sources, ground contact demonstrated the second highest PLA and PRA (37.5*g* and 6676.2 rad/s^2, respectively). See Table 1 for additional information regarding impact mechanisms.

Impact Location

Using video analysis of the 58 verified impacts enabled the determination of the body location where the initial force was imparted. While most impacts resulted from a direct contact to the head (n = 28, 48.3%), more than one-third (n = 22, 37.9%) struck another area of the body (torso: 17.2%; shoulder: 20.7%). The median PLA and PRA for all verified direct impacts to the head (n = 28) were 38.7*g* and 6783.7 rad/s^2, respectively, as compared with those measured at other body locations (28.0*g* and 5611.5 rad/s^2, respectively). Restricting our analyses of verified head impacts to only field players demonstrated that the majority of head impacts among field players (n = 21) resulted from

TABLE 1
Girls' High School Lacrosse Game Impacts by Position and Mechanism[a]

	n	AE	IR/AE (95% CI)	PLA, Median (IQR), *g*	PRA, Median (IQR), rad/s^2
Position					
Attacker	11	131	0.08 (0.03-0.13)	37.8 (23.7-50.1)	8351.3 (4645-10,423.7)
Midfielder	28	176	0.15 (0.10-0.22)	32.0 (23.5-41.1)	6025.5 (4224.7-7176.3)
Defender	12	129	0.09 (0.04-0.14)	26.8 (22.8-52.2)	4411.6 (3966.5-10,093.5)
Goalie	7	31	0.23 (0.06-0.40)	38.8 (36.2-57.09)	8535.0 (4522.4-10,347.9)
Mechanism					
Ball	7	436	0.02 (0.00-0.03)	38.8 (36.2-57.1)	8534.9 (4522.4-10,347.9)
Stick	25	436	0.06 (0.03-0.08)	31.4 (23.0-41.9)	5601.8 (4127.7-7772.7)
Player	17	436	0.04 (0.02-0.06)	28.3 (23.4-38.2)	6633.6 (4153.4-8682.3)
Ground	7	436	0.01 (0.00-0.03)	37.5 (23.8-53.1)	6676.2 (4683.7-9451.9)
Total	58	467	0.12 (0.09-0.16)	33.8 (23.6-44.6)	6151.1 (4186.6-8708.6)

[a]Two impacts were not included because of an unknown mechanism. AE, athlete-exposure; IQR, interquartile range; IR, impact rate; PLA, peak linear acceleration; PRA, peak rotational acceleration.

TABLE 2
Girls' High School Lacrosse Head Impacts by Location[a]

Location	n	AE	IR/AE (95% CI)	PLA, Median (IQR), *g*	PRA, Median (IQR), rad/s^2
Back	3	436	0.01 (0.00-0.01)	51.1 (28.5-95.5)	6790.4 (4839.0-9194.1)
Front	10	436	0.03 (0.00-0.04)	40.3 (34.9-53.7)	8504.2 (4943.3-10,091.4)
Side	10	436	0.03 (0.00-0.04)	32.3 (23.7-58.6)	5565.3 (3889.4-8754.2)
Top	1	436	0.00 (0.00-0.01)	27.1	6464.7
Total	28	467	0.05 (0.00-0.10)	38.7 (26.4-56.3)	6783.7 (4562.8-9969.7)

[a]Four impacts were not included because of an unknown location. AE, athlete-exposure; IQR, interquartile range; IR, impact rate; PLA, peak linear acceleration; PRA, peak rotational acceleration.

stick contacts (n = 11, 52.4%), followed by player contacts (n = 5, 23.8%). Most of these impacts occurred to the side (n = 9, 42.9%), followed by the front (n = 4, 19.0%) of the head. Collectively, our findings suggest that a mean of 1.1 verified head impacts per team ≥20*g* occurred during each game. Table 2 provides additional information regarding impact locations.

Team Game Play

An evaluation of the time of game revealed that impacts were nearly evenly divided between the first (n = 32, 55.2%) and second (n = 26, 44.8%) halves of game play. Similarly, impacts were nearly evenly distributed between when teams were engaged in offensive (n = 24, 41.4%) and defensive (n = 25, 43.1%) game situations. All remaining impacts (n = 9, 15.5%) occurred during face-off/draw game situations. Within both offensive and defensive game situations, field players sustained similar proportions of impacts by mechanism. Most resulted from stick contacts (offense: n = 12, 50.0% vs defense: n = 13, 52.0%), followed by player contacts (offense: n = 8, 33.3% vs defense: n = 9, 36.0%) and then ground contacts (offense: n = 4, 16.7% vs defense: n = 3, 12.0%). An inspection of the location on the playing field where impacts occurred revealed that most impacts occurred to field players within the attack area of the field (n = 32, 55.2%) or the midfield (n = 18, 31.0%).

Individual Game Play

An analysis of individual field player activity revealed that most often players did not have possession of the ball (without possession: n = 37, 72.5% vs with possession: n = 14, 27.5%) at the moment of impact. The majority of impacts without possession were sustained by midfielders (n = 19, 37.3%), and mechanisms were evenly divided between stick (n = 13, 35.1%) and player (n = 12, 32.4%) contacts. In comparison, midfielders (n = 9, 64.3%), followed by attackers (n = 5, 35.7%), accounted for most impacts among players with possession of the ball. The mechanism of impact for players with possession of the ball most commonly resulted from stick (n = 12, 85.7%) contacts. The median PLA and PRA for head impacts sustained by players with possession of the ball were higher than those without possession of the ball (37.5*g* and 6164.5 rad/s^2, respectively, vs 29.4*g* and 6137.7 rad/s^2, respectively). Overall, the most common field player activities at the time of impact were defending (n = 14, 19.6%), chasing a loose ball (n = 10, 19.6%), or ball handling (n = 9, 17.6%). Table 3 shows the distribution of impacts by position and player activity. Finally, of the 44 stick and player impacts (≥20*g*) verified using video analysis, only 2 penalties were awarded.

TABLE 3
Verified Impacts for Team and Individual Game Play[a]

Game Play	Field Player Position, n (%)			
	Attacker	Midfielder	Defender	Total
Game segment				
First half	7 (13.7)	15 (29.4)	6 (11.8)	28 (54.9)
Second half	4 (7.8)	13 (25.5)	6 (11.8)	23 (45.1)
Field location				
Attack area	6 (11.8)	16 (31.4)	10 (19.6)	32 (62.7)
Behind goal	1 (2.0)	0 (0.0)	0 (0.0)	1 (2.0)
Inside 12-m arc	2 (3.9)	4 (7.8)	5 (9.8)	11 (21.6)
Inside 8-m arc	0 (0.0)	2 (3.9)	2 (3.9)	4 (7.8)
Other	3 (5.9)	10 (19.6)	3 (5.9)	16 (31.4)
Midfield area	5 (9.8)	11 (21.6)	2 (3.9)	18 (35.3)
Out of bounds	0 (0.0)	1 (2.0)	0 (0.0)	1 (2.0)
Player activity				
Without possession	6 (11.8)	19 (37.3)	12 (23.5)	37 (72.5)
Passing/receiving	1 (2.0)	5 (9.8)	2 (3.9)	8 (15.7)
Defending	1 (2.0)	5 (9.8)	8 (15.7)	14 (27.4)
Loose ball	4 (7.8)	4 (7.8)	2 (3.9)	10 (19.6)
Draw	0 (0.0)	5 (9.8)	0 (0.0)	5 (9.8)
With possession	5 (9.8)	9 (17.6)	0 (0.0)	14 (27.5)
Shooting	1 (2.0)	4 (7.8)	0 (0.0)	5 (9.8)
Ball handling	4 (7.8)	5 (9.8)	0 (0.0)	9 (17.6)

[a]All percentages were calculated from 51 total impacts sustained by field players. All goalie impacts (n = 7) occurred on defense and were within the crease area of the goal.

DISCUSSION

This study is the first to characterize verified head impacts sustained in girls' varsity high school lacrosse games. Our primary finding suggests that the incidence of verified head impacts occurring during girls' varsity high school lacrosse game play was quite low, with approximately 2 impacts $\geq$20*g* occurring during each team game. Our findings also suggest that each athlete likely suffered fewer than 2 head impacts per season $\geq$20*g*. Consistent with prior epidemiological and video analysis research, most impacts occurred to field players and resulted from stick contact, followed by player contact.[7,23,39] The PLA magnitudes observed in this study were considerably greater than those reported in women's collegiate lacrosse.[32] Yet, no concussions were reported during this 2-year study. Nonetheless, despite all stick and player contacts being illegal in high school girls' lacrosse, we found that the majority (95%) of these impacts did not result in a penalty. Collectively, our data suggest that high school girls' lacrosse players suffered considerably fewer head impacts, but possibly of a higher magnitude, than those reported among women's collegiate lacrosse players.[34]

Impact Frequency, Location, and Magnitude

Our findings suggest that impacts $\geq$20*g* in high school girls' lacrosse are relatively infrequent. Considerably fewer impacts (2.1 impacts $\geq$20*g* per team game) occurred during a girls' varsity high school lacrosse game than among women's collegiate lacrosse[34] (9.2 impacts per team game). However, the number of impacts in girls' high school lacrosse is similar to that reported in girls' high school soccer[24] (2.8 impacts per team game). When describing the number of verified impacts in this study as a rate, the incidence of impacts was negligible (0.12/AE). It is interesting to note that not all impacts measured by the wearable sensors directly struck the head. In fact, video analysis revealed that only about one-half of verified impacts directly struck a player's head, with the remaining impacts striking the shoulder or torso. Collectively, our findings suggest that the impact rate for verified head impacts per AE was 0.05 (95% CI, 0.00-0.10). This suggests that a mean of 1.1 verified head impacts per team $\geq$20*g* occurred during each game.

The findings demonstrated the median PLA (33.8*g*) and PRA (6151.1 rad/s^2) of verified impacts to be considerably greater than recently reported in women's collegiate lacrosse[34] (14.7*g* and 2327.6 rad/s^2, respectively) but less than reported among girls' high school soccer players (37.6*g* and 6792.6 rad/s^2, respectively).[24] No concussions were reported during this 2-year study, which seems sensible, as our PLA findings (98.7*g*; 95% CI, 82.4-115.0) were considerably less than ranges associated with diagnosed concussions reported in a recent systematic review and meta-analysis by Brennan et al[5] examining concussions in male athletes. This same study reported PRA results (5776.7rad/s^2; 95% CI, 4583.5-6969.7) associated with concussions to be slightly less than measured in our study.[5] O'Connor and colleagues[30] suggested that caution be exercised when making comparisons between biomechanical studies examining head impacts, as research is biased toward male patients and thus has limited generalizability to female patients. Collectively, our findings suggest that high school girls' lacrosse players suffered somewhat fewer head impacts, but of similar magnitudes, than reported during game play among other female sports.

Impact by Player Position

Differences in the nature and frequency of impacts by player position have been well documented in male sports such as American football, ice hockey, and lacrosse.[11,12,25,27,33] Previous research examining women's collegiate lacrosse did not report impact frequency by player position.[34] Recently, Press and Rowson[32] studied women's collegiate soccer players and reported that head impact frequency varied by position. Specifically, they found that midfielders sustained the greatest and goalkeepers the fewest number of impacts. Our findings were similar, as midfielders sustained the most (48.3%) and goalies the fewest (12.1%) impacts. However, when accounting for AEs, we found goalies to have the highest impact rate of all positions. Among field players, we found midfielders to have the highest rate of impacts, followed by defenders and finally attackers. These findings support prior research indicating that positions requiring athletes to compete in all offense, defense, and transition aspects of the game (eg, midfield) have greater opportunities for sustaining an impact.

Impact Mechanism

Consistent with prior research,[7,23,39] we found that the most common mechanism of impacts in girls' high school lacrosse game play was caused by a stick, followed by player contacts. Although previous studies have reported ball contact as a common mechanism of concussions in women's lacrosse,[7,14,15,19,22,23,31,39] no ball impacts were sustained by field players in this study, suggesting that these may be relatively infrequent events. Interestingly, ball contacts generated the highest PLA magnitudes in this study and were sustained by goalies, the only girls' lacrosse players required to wear a men's lacrosse helmet. All but one of these impacts occurred to the helmet's face mask. Considered collectively, the PLA magnitudes for all verified stick, player, and ground impacts occurring to field players measured during actual game play in this study were lower than previously reported biomechanical reconstructions in the laboratory.[8,10,28,35] This finding is supported by previous research reporting that head injuries caused by stick and player contacts in girls' high school lacrosse most commonly resulted from incidental rather than intentional contact.[7] We hypothesize that this discrepancy is likely attributable to differences between laboratory reconstructions and live game play.

Impacts and Game Play

An analysis of game situations demonstrated that a similar number of impacts occurred during offensive and defensive game situations. Additionally, we found that most impacts occurred within the offensive or defensive thirds of the field, which suggests that players may have greater exposure to impacts during settled offensive and defensive game play as compared with unsettled game play or during transitions. An evaluation of individual field player activity preceding an impact revealed that in the majority (72.5%) of cases, either midfield or defense players did not have possession of the ball. Most frequently, these players were struck by a stick or another player while defending or chasing a loose ball. In cases where the player possessed the ball, the majority of impacts occurred to midfield or attack players struck by a stick while ball handling.

Our findings regarding stick and bodily impacts are noteworthy because, according to the sport's governing body (US Lacrosse), irrespective of intentionality, all stick and body contacts are illegal in girls' high school lacrosse.[38] Despite this fact, the overwhelming majority (95%) of impacts to the head did not result in a penalty. This finding is consistent with previous research that reported that in the majority of girls' lacrosse injuries, no penalty is called.[7] The findings also support and extend those that questioned collegiate players' capacity to self-monitor the location of their stick relative to other players.[15] Likewise, our finding of a large proportion of midfielders struck by a stick or another player while defending or chasing a loose ball supports previous research reporting that players may be positioning themselves in hazardous situations to deny an opponent the opportunity to possess, pass, or shoot the ball.[7] Collectively, our findings reinforce the fact that despite perceived intent or game play situations, infractions such as dangerous checking, checking to the head, slashing, obstruction of the free space to goal or "shooting space," illegal shots, and dangerous follow-through should be vigilantly enforced by coaches and officials. Data from this and prior studies suggest that efforts to investigate knowledge and enforcement of rules and other interventions are warranted. Recently, protective headgear designed specifically for girls' and women's lacrosse was introduced as optional equipment. Advocates suggest that headgear use may decrease the severity of impacts to the head,[1,13] whereas opponents argue that headgear use may result in player risk compensation,[16] causing more aggressive game play behaviors and an increased risk of injuries.[13] Future research should evaluate the consequences of the introduction of headgear on both injuries and game play. As no participants in this study wore headgear, our findings may serve as a baseline for future research evaluating the effectiveness of headgear and any potential changes in game play in girls' high school lacrosse.

Limitations

This study comprises a relatively small convenience sample and does not necessarily represent head impacts for all high school girls' varsity lacrosse players in the United States. Caution should be exercised when generalizing findings for PLA and PRA to all girls' high school lacrosse game play. As with all wearable devices, the sensor used in this study may be susceptible to measurement errors. Prior studies have examined the measurement error associated with the wearable sensor used in this study in both laboratory and field settings.[9,24,32,34,36] Collectively, these and other studies suggest that users should not rely solely on data from wearable sensors to accurately assess the direction, location, and magnitude of impacts sustained by players. Despite these limitations, wearable sensors, if integrated with other sources of data (eg, video), can produce valuable data that are otherwise unavailable and can be used to study head impacts in the sport of lacrosse.

CONCLUSION

Our findings suggest that the incidence of verified impacts occurring during girls' varsity high school lacrosse game play was quite low, with approximately 2 impacts $\geq 20g$ occurring during each team game. However, despite all stick and player contacts being illegal in high school girls' lacrosse, few penalties were called, suggesting that better enforcement of existing rules prohibiting stick and player contacts may be effective.

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REFERENCES

1. ASTM International. ASTM F3137-15: standard specification for headgear used in women's lacrosse (excluding goalkeepers). Available at: http://dx.doi.org/10.1520/F3137-15. Accessed August 23, 2016.
2. 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(4):737-746.
3. Belanger HG, Vanderploeg RD, McAllister T. Subconcussive blows to the head: a formative review of short-term clinical outcomes. *J Head Trauma Rehabil*. 2016;31(3):159-166.
4. Brainard LL, Beckwith JG, Chu JJ, et al. Gender differences in head impacts sustained by collegiate ice hockey players. *Med Sci Sports Exerc*. 2012;44(2):297-304.
5. Brennan JH, Mitra B, Synnot A, et al. Accelerometers for the assessment of concussion in male athletes: a systematic review and meta-analysis. *Sports Med*. 2017;47(3):469-478.
6. Carter EA, Westerman BJ, Lincoln AE, Hunting KL. Common game injury scenarios in men's and women's lacrosse. *Int J Inj Contr Saf Promot*. 2010;17(2):111-118.
7. Caswell SV, Lincoln AE, Almquist JL, Dunn RE, Hinton RY. Video incident analysis of head injuries in high school girls' lacrosse. *Am J Sports Med*. 2012;40(4):756-762.
8. Clark JM, Hoshizaki TB. The ability of men's lacrosse helmets to reduce the dynamic impact response for different striking techniques in women's field lacrosse. *Am J Sports Med*. 2016;44(4):1047-1055.
9. Cortes N, Lincoln AE, Myer GD, et al. Video analysis verification of head impact events measured by wearable sensors [published online May 1, 2017]. *Am J Sports Med*. doi:10.1177/0363546517706703.
10. Crisco JJ, Costa L, Rich R, Schwartz JB, Wilcox B. Surrogate headform accelerations associated with stick checks in girls' lacrosse. *J Appl Biomech*. 2015;31(2):122-127.
11. Crisco JJ, Wilcox BJ, Beckwith JG, et al. Head impact exposure in collegiate football players. *J Biomech*. 2011;44(15):2673-2678.
12. Crisco JJ, Wilcox BJ, Machan JT, et al. Magnitude of head impact exposures in individual collegiate football players. *J Appl Biomech*. 2012;28(2):174.
13. De Lench B. ASTM standard for women's lacrosse helmet: beginning of debate about whether good for game, not end. Available at: http://www.momsteam.com/helmets/concussions-in-girls-lacrosse-should-helmets-be-mandatory. Accessed April 17, 2017.
14. Diamond PT, Gale SD. Head injuries in men's and women's lacrosse: a 10 year analysis of the NEISS database. National Electronic Injury Surveillance System. *Brain Inj*. 2001;15(6):537-544.
15. Dick R, Lincoln AE, Agel J, et al. Descriptive epidemiology of collegiate women's lacrosse injuries: National Collegiate Athletic Association Injury Surveillance System, 1988-1989 through 2003-2004. *J Athl Train*. 2007;42(2):262.
16. Hagel B, Meeuwisse W. Risk compensation: a ''side effect'' of sport injury prevention? *Clin J Sport Med*. 2004;14(4):193-196.
17. Hall C, Friel K, Dong M, et al. Epidemiology of injuries in the elite level female high school lacrosse player. *Res Sports Med Print*. 2013;21(3):229-239.
18. Hanlon EM, Bir CA. Real-time head acceleration measurement in girls' youth soccer: *Med Sci Sports Exerc*. 2012;44(6):1102-1108.
19. Hinton RY, Lincoln AE, Almquist JL, Douoguih WA, Sharma KM. Epidemiology of lacrosse injuries in high school–aged girls and boys: a 3-year prospective study. *Am J Sports Med*. 2005;33(9):1305-1314.
20. King D, Brughelli M, Hume P, Gissane C. Assessment, management and knowledge of sport-related concussion: systematic review. *Sports Med*. 2014;44(4):449-471.
21. Lincoln AE, Caswell SV, Almquist JL, et al. Effectiveness of the women's lacrosse protective eyewear mandate in the reduction of eye injuries. *Am J Sports Med*. 2012;40(3):611-614.
22. Lincoln AE, Hinton RY, Almquist JL, Lager SL, Dick RW. Head, face, and eye injuries in scholastic and collegiate lacrosse: a 4-year prospective study. *Am J Sports Med*. 2007;35:207-215.
23. Marar M, McIlvain NM, Fields SK, Comstock RD. Epidemiology of concussions among United States high school athletes in 20 sports. *Am J Sports Med*. 2012;40(4):747-755.
24. 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(13):3720-3723.
25. Mihalik JP, Guskiewicz KM, Marshall SW, Blackburn JT, Cantu RC, Greenwald RM. Head impact biomechanics in youth hockey: comparisons across playing position, event types, and impact locations. *Ann Biomed Eng*. 2012;40(1):141-149.
26. Mihalik JP, Guskiewicz KM, Marshall SW, Greenwald RM, Blackburn JT, Cantu RC. Does cervical muscle strength in youth ice hockey players affect head impact biomechanics? *Clin J Sport Med*. 2011;21(5):416-421.
27. Miyashita T, Diakogeorgiou E, Marrie K, Danaher R. Frequency and location of head impacts in Division I men's lacrosse players. *Athl Train Sports Health Care*. 2016;8(5):202-208.
28. Morse JD, Franck JA, Wilcox BJ, Crisco JJ, Franck C. An experimental and numerical investigation of head dynamics due to stick impacts in girls' lacrosse. *Ann Biomed Eng*. 2014;42(12):2501-2511.
29. National Federation of State High School Associations. 2013-14 high school athletics participation survey results. Available at: http://www.nfhs.org/ParticipationStatics/PDF/2013-14_Participation_Survey_PDF.pdf. Accessed January 9, 2017.
30. O'Connor KL, Rowson S, Duma SM, Broglio SP. Head-impact–measurement devices: a systematic review. *J Athl Train*. 2017;52(3):206-227.
31. Otago L, Adamcewicz E, Eime R, Maher S. The epidemiology of head, face and eye injuries to female lacrosse players in Australia. *Int J Inj Contr Saf Promot*. 2007;14(4):259-261.

32. Press JNB, Rowson S. Quantifying head impact exposure in collegiate women's soccer. *Clin J Sport Med*. 2017;27(2):104-110.
33. Reed N, Taha T, Keightley M, et al. Measurement of head impacts in youth ice hockey players. *Int J Sports Med*. 2010;31(11):826-833.
34. Reynolds BB, Patrie J, Henry EJ, et al. Quantifying head impacts in collegiate lacrosse. *Am J Sports Med*. 2016;44(11):2947-2956.
35. Rodowicz KA, Olberding JE, Rau AC. Head injury potential and the effectiveness of headgear in women's lacrosse. *Ann Biomed Eng*. 2014;43(4):949-957.
36. Siegmund GP, Guskiewicz KM, Marshall SW, DeMarco AL, Bonin SJ. Laboratory validation of two wearable sensor systems for measuring head impact severity in football players. *Ann Biomed Eng*. 2016;44(4):1257-1274.
37. Svaldi DO, McCuen EC, Joshi C, et al. Cerebrovascular reactivity changes in asymptomatic female athletes attributable to high school soccer participation. *Brain Imaging Behav*. 2017;11(1):98-112.
38. US Lacrosse. 2016 women's rulebook. Available at: http://www.uslacrosse.org/portals/1/documents/pdf/participants/players/2016-womens-rulebook.pdf. Accessed April 5, 2016.
39. Xiang J, Collins CL, Liu D, McKenzie LB, Comstock RD. Lacrosse injuries among high school boys and girls in the united states academic years 2008-2009 through 2011-2012. *Am J Sports Med*. 2014;42(9):2082-2088.