Published in final edited form as:
Res Sports Med. 2023 ; 31(6): 772–786. doi:10.1080/15438627.2022.2042294.

QUANTIFYING HEAD IMPACT EXPOSURE, MECHANISMS AND KINEMATICS USING INSTRUMENTED MOUTHGUARDS IN FEMALE HIGH SCHOOL LACROSSE

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Abstract

Current debate exists regarding the need for protective headwear in female lacrosse. To inform this issue, the current study quantified head impact exposure, mechanisms and biomechanics in female lacrosse using instrumented mouthguards. A female high school varsity lacrosse team of 17 players wore the Stanford Instrumented Mouthguard (MiG) during 14 competitive games. Video footage was reviewed to remove false-positive recordings and verify head impacts, which resulted in a rate of 0.32 head impacts per athlete-exposure. Of the 31 video-confirmed head impacts, 54.8% were identified as stick contacts, 38.7% were player contacts and 6.5% were falls. Stick impacts had the greatest peak head kinematics. The most common impact site was the side of the head (35.5%), followed by face/jaw (25.8%), forehead (6.5%), and crown (6.5%). Impacts to the face/jaw region of the head had significantly ($p<0.05$) greater peak kinematics compared to other regions of the head, which may be due to the interaction of the impacting surface, or the lower jaw, and the sensor. The current study provides initial data regarding the frequency, magnitude and site of impacts sustained in female high school lacrosse. A larger sample size of head impact data in female lacrosse is required to confirm these findings.

Keywords

general sports trauma; head injuries/concussion; injury prevention; pediatric sports medicine

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Disclosure statement
The authors confirm no financial interest or benefit has arisen from the direct applications of this research.

Introduction

Originally played by Native Americans in the 17th century (Fisher, 2002), the modern game of lacrosse is colloquially known as the 'fastest game on two feet' due to the speed at which the ball can be moved down the field (Wiener, 2017). Lacrosse is played by males and females at the youth, high school, collegiate and professional levels. However, due to differences in history, rules and equipment, male and female lacrosse are considered to be different sports (Wiser, 2014). For example, female lacrosse is typically played without helmets and has rules that restrict intentional body and stick contact between players on opposing teams (Barber-Foss et al., 2018). Despite such differences, female lacrosse is a fast-paced contact sport and as such there are opportunities for head impacts and, therefore, head injury (Powell, 2001). Current debate exists regarding the need for enhanced protective equipment to more closely mimic that worn by male lacrosse players (Caswell et al., 2020; Comstock et al., 2020; Cooley et al., 2019). In order to inform policy discussions and rule changes for improved protection, it is important to accurately quantify exposure, mechanisms and biomechanics of head impacts in female lacrosse.

Several studies have focused on quantifying head impact exposure rates in female lacrosse measured in athlete-exposures, which is typically defined as a single player participating in a single sporting session (Huber et al., 2021a). Reynolds et al. (2016) monitored head impacts in female collegiate lacrosse games using the xPatch (X2 Biosystems), which is a skin patch sensor that is worn over the mastoid process, and reported the mean number of head impacts above 10 *g* ranged from 0.1 to 16.0 per athlete-exposure. However, video confirmation was not performed, which is necessary to remove false positives from head impact sensor data, and therefore these rates are likely elevated (Patton et al., 2020b). In a subsequent study of female collegiate lacrosse, Le et al. reported a video-confirmed head impact rate of 0.28 per athlete-exposure for female collegiate lacrosse players wearing xPatch sensors with a recording trigger threshold of 10 *g* (Le et al., 2018). In addition, stick (48%) and player contact (34%) were reported as the most common head impact mechanisms. Studies have also monitored head impacts in high school female lacrosse using the xPatch with a recording trigger threshold of 20 *g* (Caswell et al., 2020; Caswell et al., 2017; Cortes et al., 2017). Caswell et al. (2017) video-confirmed 58 head impacts resulting in a rate of 0.12 per athlete-exposure with the most common head impact mechanism being stick (43%), followed by player contact (29%). In a subsequent study, Caswell et al. (2020) reported a relatively higher rate of 0.31 video-confirmed head impacts per athlete-exposure and found player contact (53%) and stick (40%) to be the most common mechanisms of head impact. More recently, Huber et al. (2021b) used the SIM-G headband-mounted sensor (Triax Technologies) with a recording trigger threshold of 16 *g* to calculate video-confirmed head impact exposure for several high school sports. Female lacrosse had a head impact exposure of 0.06 per athlete-exposure, which was significantly lower than the rates for female soccer and basketball of 1.41 and 0.25 per athlete-exposure, respectively. In addition, equipment-to-head (43%) and player-to-head (43%) were reported to be the most common mechanisms. Similarly, Cecchi et al. used the SIM-G to monitor head impacts in collegiate club lacrosse and reported a video-confirmed impact rate of 0.07 per athlete-exposure and that half the impacts were stick, whereas the other half were player contacts (Cecchi et al., 2021). The relatively large range of head impact exposure rates previously reported for female lacrosse (i.e. 0.06–0.31 impacts per athlete-exposure) likely depends on age and level of competition (i.e. high school vs collegiate), sensor (i.e. xPatch vs SIM-G) and recording trigger threshold (i.e. 10 *g* vs 16 *g* vs 20 *g*). Large variability in head impact exposure rates has been found in other sports; for example, head impact exposure rates for female soccer ranging from 0.4 to 3.3 impacts per athlete-exposure (Huber et al., 2021b).

In addition to exposure rates, quantifying head impact kinematics in female lacrosse is critical to developing injury mitigation strategies. There have been limited previous efforts in this area using the xPatch in high school female lacrosse (Caswell et al., 2020; Caswell et al., 2017; Cortes et al., 2017). Caswell et al. (2017) reported median peak linear and angular accelerations of 33.8 *g* and 6151 rad/s^2, respectively. More recently, Caswell et al. (2020) reported a median peak linear acceleration of 26.4 *g* and a mean peak angular velocity of 25.3 rad/s. Laboratory studies have demonstrated that sensors fixed to dentition, i.e. instrumented mouthguards and mouthpieces, more accurately record the kinematics of the head compared to other sensor systems, e.g. xPatch and SIM-G sensors (Kieffer et al., 2020; Liu et al., 2020; Tyson et al., 2018). Such accuracy differences were attributed to differences in sensor-skull coupling, which have previously been quantified during a study of soccer heading (Wu et al., 2016b). Compared to the instrumented mouthguard, peak linear and angular accelerations were over-predicted by both skin patch and headgear-mounted sensors. As a result, the kinematics reported in previous studies using the xPatch likely overestimate the true kinematics of the head.

Therefore, the aim of the current study was to quantify the head impact biomechanics, by impact mechanism and site, of female high school lacrosse players during games using an instrumented mouthguard, employing rigorous video-confirmation methodology. By accurately quantifying the head impact exposure, kinematics and mechanisms in female high school lacrosse, targeted injury preventions can be developed, such as rule changes and protective equipment.

Methods

A prospective observational study of an adolescent female varsity lacrosse team from a suburban high school was conducted. Players wore the Stanford Instrumented Mouthguard (MiG) sensor during competitive games for the 2019 season. The current study was approved by the Children’s Hospital of Philadelphia Internal Review Board (IRB-17-013875 and IRB-18-015750).

The MiG sensor provides researchers with the ability to collect head impact measurements *in vivo* (Camarillo et al., 2013; L. C. Wu et al., 2016b). The triaxial linear accelerometer measures linear acceleration at 1000 Hz up to 400 g and the triaxial gyroscope measures angular velocity at 8000 Hz up to 70 rad/s. Both the accelerometer and gyroscope are positioned in front of the incisors. When the linear acceleration measured in any of the three axes exceeds 20 *g*, the MiG sensor records the linear accelerations and angular velocities for all three unique axes for a duration of 200 ms (pre-trigger, 49 ms; post-trigger, 150 ms). Each of these sensor-recorded events is timestamped with 1 s resolution, which enables synchronization with timestamped video footage. The MiG couples rigidly to the skull through the upper teeth, which have submillimeter motion with respect to the skull (Wu et al., 2016b). In addition, the MiG sensor is designed to isolate the sensors from lower jaw movements, which prevents the introductions of large measurement errors (Kuo et al., 2016). Validation tests performed in dummies (Camarillo et al., 2013; Kuo et al., 2016; Liu et al., 2020), cadavers (Kuo et al., 2016), and human subjects (Wu et al., 2016b) have shown that the recordings of the MiG sensor are highly correlated with reference values for linear acceleration, angular velocity and angular acceleration. In a field study of collegiate American football using the MiG sensor, it was reported that 83% of sensor-recorded events were false positives (Wu et al., 2018). An algorithm to identify and remove false positives from the dataset was developed and found to be effective; however, the algorithm was not used in the current study owing to the differences between collegiate male American football and high school female lacrosse. Rather, rigorous video confirmation described below was used to remove false positives.

Prior to the start of the season, dental impressions were taken of enrolled participants, from which subject-specific MiG sensors were manufactured by OPRO Ltd (Hemel Hempstead, UK). In addition to the MiG sensors, identical mouthguards without the instrumentation were also manufactured for each participant. These ‘dummy’ mouthguards were distributed to enrolled players before the season to be worn during scrimmages and practices to check, and familiarize players with, the fit of the MiG sensor. Before the start of each competitive game, MiG sensors were distributed to enrolled players. Video footage from games was captured from a single camera view located close to the midpoint of the lacrosse field from an elevated vantage point. Video footage was recorded in high-definition 1080p with a 16:9 aspect ratio at 60 frames per second. Before the start and end of each half, a few seconds of a world clock website was filmed (timeanddate.com), which provided a timestamp for the video footage. The world clock was compared to the computer clock that was used to collect data from the MiG sensors to allow time synchronization of the video and sensor data. Recording was done such that approximately one-third of the lacrosse field was captured in the video footage and the videographer panned the camera to follow the action of the ball. After the game, MiG sensors were collected, cleaned and assessed for damage (e.g. excessively chewed) and functionality. If a MiG sensor was found to be damaged and/or nonfunctioning, it was retired and a replacement sensor was manufactured. Prior to each game, the battery of each MiG sensor was charged by induction and previously collected data were downloaded using a Bluetooth connection.

As per previously published methods by Patton et al. (2021b, 2021c, 2020c), the video data were reviewed by a research staff member with prior video analysis experience to identify and remove sensor-recorded events with timestamps occurring before the start of the game, after the end of the game and during halftime and timeouts. Any sensor-recorded events associated with players who were not on the field at the time or who were on the field but outside the camera frame at the time were also excluded. The remaining sensor-recorded events were categorized as either a head impact event (e.g. player impacted in the head by the stick of an opposing player), trivial event (e.g. player removing MiG sensor from mouth) or non-event (e.g. player stationary with MiG in mouth). Head impact events were independently reviewed by two research staff members to identify the mechanism and characteristics, which were subsequently discussed to reach a consensus agreement. If consensus could not be reached, a third reviewer independently reviewed the head contact event. For each head impact event, the mechanism was coded as stick contact, player contact, ball contact or fall. In addition, head impacts were coded as either direct or indirect. An indirect head impact was one in which there was no observable contact to the head, but the head was inertially loaded by an impact to the body. A direct head impact involved observable contact to the head and the impact site of each direct impact event was additionally coded as face/jaw, forehead, crown, side or rear.

To calculate head impact exposure, the total number of head impacts for the team was divided by the total number of athlete-exposures. An athlete-exposure was defined as a single player participating in a single game with a functioning sensor. Head impact exposure was evaluated for thresholds of 10, 16 and 20 *g* for comparison with previously reported values.

As per previous studies using the MiG sensor (Liu et al., 2020), the raw kinematic data were filtered at 160 Hz with a 4th order Butterworth filter and the angular velocity data were down-sampled to the same time sequence as the linear acceleration data. Angular acceleration was calculated using a five-point stencil derivative of angular velocity. Linear acceleration data from the MiG sensor were transformed to the center of gravity of the head via the following equation:

$$a_{CG} = a_{MiG} + \omega \times (\omega \times r) + \acute{\omega} \times r$$

where a_{CG} is the linear acceleration of the center of gravity of the head, a_{MiG} is the linear acceleration of the MiG sensor, ω is angular velocity of the head, $\acute{\omega}$ is angular acceleration of the head and r is distance between the MiG sensor accelerometer and the center of gravity of the head for a 50th percentile male. Subject-specific transformations were not performed as a previous pilot study of high school female soccer players found there was no significant difference in linear accelerations transformed from the MiG sensor data using subject-specific measurements and the anthropometrics from the 50th percentile male (Patton et al. 2020a). Resultant linear acceleration and angular velocity were calculated by adding axis-specific data in quadrature.

Head impacts were considered true positives, whereas trivial events and non-events were considered false positives. Precision (i.e. positive predictive value) was calculated per the following equation:

$$Precision = \frac{True\ Positives}{True\ Positive + False\ Positives}$$

Descriptive statistics were used to describe the peak head kinematics (i.e. linear acceleration, angular velocity and angular acceleration) stratified by impact mechanism and impact site. Differences in peak head kinematics by impact mechanism and impact site were tested using a Kruskal-Wallis test; an alpha value of <0.05 was used for determining statistical significance. Post-hoc comparison of estimated difference in medians by impact site group was conducted using quantile regression analysis and Bonferroni correction for multiple comparisons. Analyses were performed using SAS statistical software, version 9.4 (SAS Institute Inc., Cary, NC, USA).

Results

Sensor and video data were recorded for 17 female high school varsity lacrosse players (mean age 16.8 ± 1.4 years) during 14 games. A total of 97 athlete-exposures were recorded as not every player participated in every game. MiG sensors were confirmed to be working for all 97 athlete-exposures. A total of 797 events were recorded by the MiG sensors worn by players who were on the lacrosse field during game times within the frame of the camera, of which 31 (3.9%), 167 (21.0%) and 599 (75.2%) were identified from video review as head impacts, trivial events and non-events, respectively. Therefore, in the absence of any classification algorithm, the MiG sensor had a precision of 3.9%. The 31 video-identified impact events were recorded by the MiG sensors of 9 players. No video-confirmed impact events were associated with a diagnosed concussion. The pooled average head impact rate was 0.32, 0.25 and 0.21 per athlete-exposure for recording trigger thresholds of 10, 16 and 20 *g*, respectively (Table 1).

Of the 31 video-confirmed impact events, 17 (54.8%) were identified as stick contacts, 12 (38.7%) were player contacts and 2 (6.5%) were falls. None of the video-confirmed impact events involved the ball-to-head contact. The most common impact site was the side of the head (11, 35.5%), followed by face/jaw (8, 25.8%), forehead (2, 6.5%), and crown (2, 6.5%). In addition, eight impacts (25.8 %) were indirect (i.e. to the body) and there were no impacts to the rear of the head.

For all 31 video-confirmed head impacts, the median (interquartile range) peak linear acceleration, angular velocity and angular acceleration values were 27.6 *g* (15.5–40.4 *g*), 8.8 rad/s (6.8–14.9 rad/s) and 3258 rad/s^2 (1550–4593 rad/s^2), respectively. There were no significant differences for peak head kinematics across head impact mechanism (Figure 1). Impacts to the face/jaw region had significantly ($p<0.05$) greater peak kinematics than impacts to other regions of the head (Figure 2). Two stick impacts to the jaw were associated with substantial peak kinematics: 122.1 *g*, 43.9 rad/s and 12301 rad/s^2; 103.8 *g*, 36.3 rad/s and 12610 rad/s^2.

Discussion

Female lacrosse is typically played without helmets and has rules that restrict intentional body and stick contact between players on opposing teams. Current debate exists regarding the need for enhanced protective headwear similar to that worn by male lacrosse players. To inform policy discussions and rule changes for improved protection, this study used head impact data from instrumented mouthguards to quantify head impact exposure, mechanism and biomechanics for female high school lacrosse.

The current study used rigorous video confirmation methods and found a pooled average head impact rate of 0.32 per athlete-exposure in female high school lacrosse using an evaluation threshold of 10 *g*. Such a rate compares well to the value of 0.28 for female collegiate lacrosse reported by Le et al. (2018) using the xPatch sensor with a 10 *g* recording trigger threshold. When the evaluation threshold was analytically increased to 16 and 20 *g* in the current study, the head impact rate decreased to 0.25 and 0.21 per athlete-exposure, respectively. This was expected as an increase in evaluation threshold results in a decrease in the number of impacts recorded and, therefore, a decrease in head impact rate. For peak linear accelerations above 20 *g*, the head impact rate of 0.21 per athlete-exposure falls within the range of previously reported median head impact rates of 0.12–0.31 per athlete-exposure (Caswell et al., 2020; Caswell et al., 2017; Cortes et al., 2017). In contrast, the two previous studies using the SIM-G headband sensor and a recording trigger threshold of 16 *g* reported head impact rates of 0.06–0.07 per athlete-exposure (Huber et al. 2021b, Cecchi et al. 2021), which was much lower than the rate of 0.25 per athlete-exposure in the current study using a 16 *g* evaluation threshold. Such differences may be due to the differences in sensor design or the size of the team and coaching style. For example, if a team has a large number of players on the bench and those players enter the game, albeit for a short time, the number of athlete-exposures will be increased and the impact rate decreased compared to a team with fewer substitutions and thus players participating in a game (Huber et al., 2021a). One strategy to overcome this limitation is to record actual playing time for each player and calculate head exposure rates per player-hour. In this study, however, substitution times were not recorded to permit such a calculation. Future head impact exposure studies in lacrosse should collect this additional information.

The head impact rate from the current study was relatively low compared to head impact rates reported in male collegiate and high school lacrosse: 0.7–1.9 head impacts per athlete-exposure (Caswell et al., 2019; Cortes et al., 2017; Huber et al., 2021b; Le et al., 2018; O'Day et al., 2017; Vollavanh et al., 2018). Such a finding is likely due to the differences in contact rules between the two sports: stick checking and body contact are allowed in male lacrosse, but not in female lacrosse (Putukian et al., 2014). Although changes to checking rules have been made for male lacrosse, including harsher penalties for body checking to a player in a defenseless position and intentional impacts to the head, face or neck, the incidence of concussion was not reduced in games (Guillaume et al., 2021). Previous studies comparing head impact exposures between female and male lacrosse using the same sensor support these findings. Le et al. (2018) reported that male collegiate lacrosse players were twice as likely to sustain head impacts compared to female players. More recently, Huber et al. (2021b) found that male high school lacrosse players sustained significantly more head impacts per athlete-exposure compared to female players.

Direct impacts to the head comprised approximately three-quarters of all video-confirmed impacts in the current study. Such a finding contrasts with the previous results of Caswell et al. (2020, 2017) who reported that 26–48% of impacts directly struck the head of female high school lacrosse players. Direct head impacts in the current study also had significantly greater median peak linear accelerations (29.5 *g* vs 21.3 *g*) and peak angular velocities (9.9 rad/s vs 7.1 rad/s) compared to indirect impacts. Such a finding is expected as relatively greater head kinematics are easier to generate from a direct head impact compared to inertially loading the head from an indirect head impacts that is attenuated by the body (Ommaya et al., 1970). The aim of the defending team in some collision sports, such as rugby or American football, is to halt or reverse the motion of a ball-carrying opponent by tackling the body, which can result in substantial peak head kinematics, particularly rotation (Jadischke et al., 2018; Tierney & Simms, 2017). In contrast, the rules in female lacrosse do not allow forceful body contact, such as cross-checking (Putukian et al., 2014). The relatively low number of, and peak kinematics associated with, indirect head impacts in the current study suggest that current rules are effective in limiting aggressive body contact to the female high lacrosse players. However, it is unknown if this result is generalizable across other lacrosse teams and levels of play.

Stick impacts are reportedly the most common mechanism of head injury in female lacrosse (Caswell et al., 2012; Diamond & Gale, 2001; Hinton et al., 2005; Lincoln et al., 2007; Marar et al., 2012; Marshall et al., 2015; Otago et al., 2007). The current study found that most head impacts involved contact with a stick (54.8%), which supports the findings of previous studies (Caswell et al., 2017; Cecchi et al., 2021; Huber et al., 2021b; Le et al., 2018). In addition, stick impacts were found to have the greatest peak linear and angular head kinematics. In female lacrosse, any contact to the head from a stick results in a penalty (Putukian et al., 2014); however, it is clear that stick impacts still occur. In 2017, US Lacrosse allowed the optional wearing of helmets in female lacrosse, which US Lacrosse refer to as ‘headgear’, that meet the ASTM International standard (ASTM International, 2015). The performance requirements of the standard involve shock absorption, ball impact and deformation tests that are designed to represent specific impacts most frequently seen in female lacrosse (Acabchuk & Johnson, 2017). Previous laboratory studies have found that male lacrosse helmets reduce head impact kinematics for stick impacts to anthropomorphic test device (ATD) headforms by female lacrosse volunteers (Clark & Hoshizaki, 2016; Crisco et al., 2015; Rodowicz et al., 2014). More recently, female lacrosse helmets that meet the ASTM International standard have been tested for drop tower (Kelshaw et al., 2019), impulse hammer (McIver et al., 2019) and pendulum (Bowman et al., 2020) impacts; however, no laboratory study has investigated stick impacts to female lacrosse helmets. In a recent field study, Caswell et al. (2020) monitored the head impacts of female high school lacrosse players over two seasons: the players did not wear helmets for the initial season, but wore helmets for the following season. For direct head impacts, it was reported that helmet use was not significantly associated with reductions in peak linear acceleration or peak angular velocity of the head.

The median peak linear acceleration of 27.6 *g* from the current study was slightly lower than the value of 33.8 *g* reported by a previous study in high school female lacrosse that used the xPatch (Caswell et al., 2017; Cortes et al., 2017). A subsequent study using the xPatch in high school female lacrosse reported a median peak linear acceleration of 26.4 g (Caswell et al., 2020) similar to the value from the current study. Similarities between kinematics measured by instrumented mouthguard and xPatch were unexpected as a study of soccer heading by human subjects found that a skin patch sensor over-predicted the peak linear acceleration measured by an instrumented mouthguard (Wu et al., 2016b). When comparing angular kinematics, the median peak angular velocity and acceleration reported by the current study (8.8 rad/s and 3258 rad/s^2, respectively) were much lower than the median values reported previously by studies in high school female lacrosse that used the xPatch: peak angular velocity, 25.3 rad/s (Caswell et al., 2020); peak angular acceleration, 6151 rad/s^2 (Caswell et al., 2017). This finding supports the previous study of Wu et al.

(2016b) who reported that a skin patch sensor over-estimated the peak rotational kinematics recorded by an instrumented mouthguard by up to 290%.

Impacts to the face/jaw region of the head had significantly higher peak kinematics compared to impacts to the other regions of the head. Such a difference was partially driven by two stick impacts that struck the jaw regions that resulted in sensor recordings exceeding 100 *g* and 12,000 rad/s^2. No concussion curves have been developed for youth female unhelmeted sports, but Sayre et al. reported on two cases of concussion to collegiate female lacrosse players (Sayre et al., 2019). The first was a stick impact to the front of the head with peak linear and angular accelerations of 15.8 *g* and 2693 rad/s^2, respectively. The second was a stick impact to the side of the head with relatively higher peak linear and angular accelerations: 76.5 *g* and 11,976 rad/s^2, respectively. Such data highlights the improbable magnitudes of the two impacts to the jaw in the current study. Although it is possible to generate large peak angular head kinematics from impacts to the jaw, e.g. punches to the chin in boxing (Holbourn, 1943), it is also the location of the MiG sensor. A recent study using a headband-mounted SIM-G sensor in youth male soccer found that impacts to the rear of the head were associated with the greatest peak kinematics (Patton et al., 2021c). As the sensor was located at the rear of the headband, it was suggested that perhaps direct contact with the sensor was responsible for the relatively high peak kinematics. This finding was supported by a recent laboratory study that used a soccer ball heading model to compare the kinematics recorded by the SIM-G sensor to those recorded by a youth ATD reference (Patton et al., 2021a). It was found that impacts to the rear of the ATD headform had the highest peak linear and angular kinematic compared to the other impact sites. Kuo et al. (2016) investigated the effects of the lower jaw on measurements from the MiG sensor in the laboratory using cadaver heads. The cadavers had unconstrained lower jaws, which closed on the sensor during helmeted drop tests resulting in large errors in angular kinematics. However, when the MiG sensor was redesigned to isolate the sensors from lower jaw movements, root mean square errors for all kinematics measures were reduced below 15%. The MiG sensor version used in the current study incorporates this improvement; however, studies using instrumented mouthguards should interpret direct impacts to the jaw with caution.

The main limitation of the current study was the sample size of the video-confirmed head impacts. Although 797 events were recorded by the MiG sensors worn by players who were on the lacrosse field during game times within the frame of the camera, rigorous video-confirmation methods resulted in only 31 head impacts for analysis, which is within the range reported by previously published studies (Caswell et al., 2020; Caswell et al., 2017; Cecchi et al., 2021; Huber et al., 2021b; Le et al., 2018). While only a single camera view, panning to the action of the game, was used for video confirmation, it is unlikely that there were many true impacts outside of the camera frame as female lacrosse, unlike sports such as American or Australian football, does not typically have player-to-player contact 'off the ball'. The calculation of head impact rate using athlete-exposure as a denominator has limitations as per the previously detailed example of team size and coaching style. As substitution timepoints were not identified in the current study, head impacts per player-hour was not calculated. A previous study has identified the limitations of current sensors in terms of the bandwidths to accurately capture the kinematics of unhelmeted cadaver impacts

(Wu et al., 2016a); however, the impacts had durations of approximately 3 ms and peak linear accelerations of over 200 *g*. The data in the current study is more comparable to the helmeted dummy linear impactor data from the Wu et al. (2016a) study, which had impact durations of approximately 10 ms and peak linear accelerations of approximately 50 g. Therefore, minimal attenuations in peak kinematics based on bandwidth limitations were assumed for the impacts reported in the current study. Despite this, typical errors associated with numerical differentiation of gyroscopic data to obtain angular acceleration are expected (Bussone et al., 2017).

The current study is the first to use instrumented mouthguards in lacrosse, which have been demonstrated by validation studies (Camarillo et al., 2013; Kuo et al., 2016; Liu et al., 2020; Wu et al., 2016b) to have greater accuracy compared to other approaches (e.g. skin patch or headband-mounted sensors) used by all previous lacrosse studies. Given this context and the fact that high school female lacrosse is substantially understudied (Patton et al., 2020b), this initial quantification of head impact exposure for this cohort contributes important knowledge to the field of sport injury prevention despite the small sample. Future work should be directed towards the collection of a larger sample size of impacts in female lacrosse to confirm the estimates of head impact rate, per athlete-exposure and player-hour, and determine if the significant results of the current study reflect a true effect.

Current debate exists regarding the need for more enhanced protective headwear in female lacrosse. Contributing to the state of knowledge informing this issue, the current study quantified head impact exposure, mechanisms and biomechanics in female lacrosse using instrumented mouthguards. The head impact rate of 0.32 per athlete-exposure for female high school lacrosse was comparable to previous studies in female high school lacrosse and relatively lower than rates reported for male lacrosse. Most impacts involved head contact with a stick, which had the greatest peak linear and angular head kinematics. Impacts to the face/jaw region of the head had significantly higher peak kinematics compared to impacts to the other regions of the head, which may be due to the interaction of the impacting surface, or the lower jaw, and the sensor. The current study provides initial data on the frequency, magnitude and site of impacts sustained in female high school lacrosse, which are important considerations when designing effective protective headwear and developing valid performance standards (McIntosh et al., 2011). A larger sample size of head impact data in female lacrosse is required to confirm these findings.

Acknowledgements

The authors thank members of the research team for their contributions to data collection and analysis: Ronni Kessler, Fairuz Mohammed, Valerie Lallo and Katie Simms. The authors also thank David Camarillo and members of the Stanford University CamLab for their collaboration and support: August Domel, Yuzhe Liu and Nicholas Cecchi. In addition, the authors thank the students and parents from the Shipley School for their participation and appreciate the support from the Shipley School administration and athletic department: Michael Turner, Steve Piltch, Mark Duncan, Katelyn Taylor, Dakota Carroll, Kimberly Shaud and Kayleigh Jenkins.

Funding details

This work was supported by the Pennsylvania Department of Health under Grant (SAP100077078) and the National Institute of Neurologic Disorders and Stroke of the National Institutes of Health (R01NS097549 and R24NS098518). The content of this original research is solely the responsibility of the authors and does not necessarily represent the official views of the Pennsylvania Department of Health and/or the National Institutes of Health.

Data availability

Data available upon reasonable request.

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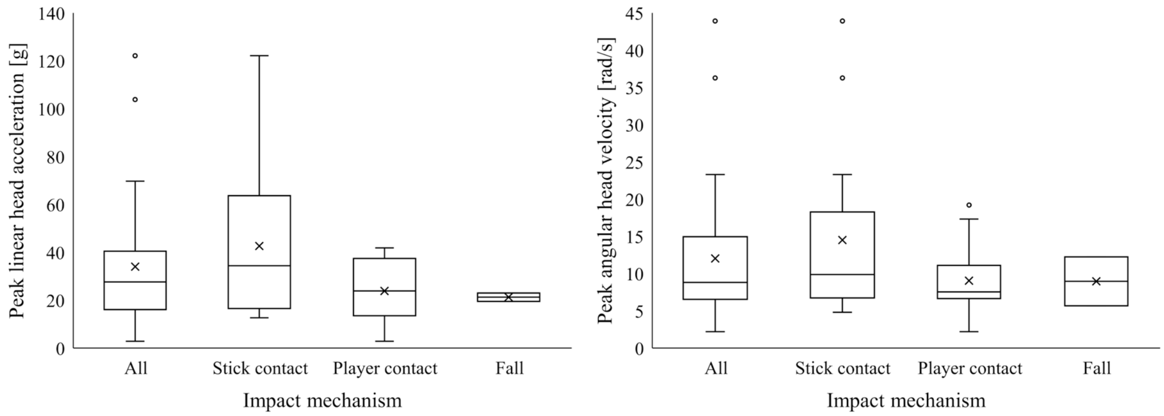

Figure 1:

Peak linear accelerations (left) and peak angular velocities (right) across different impact mechanisms. There were no significant differences for peak head kinematics across head impact mechanism.

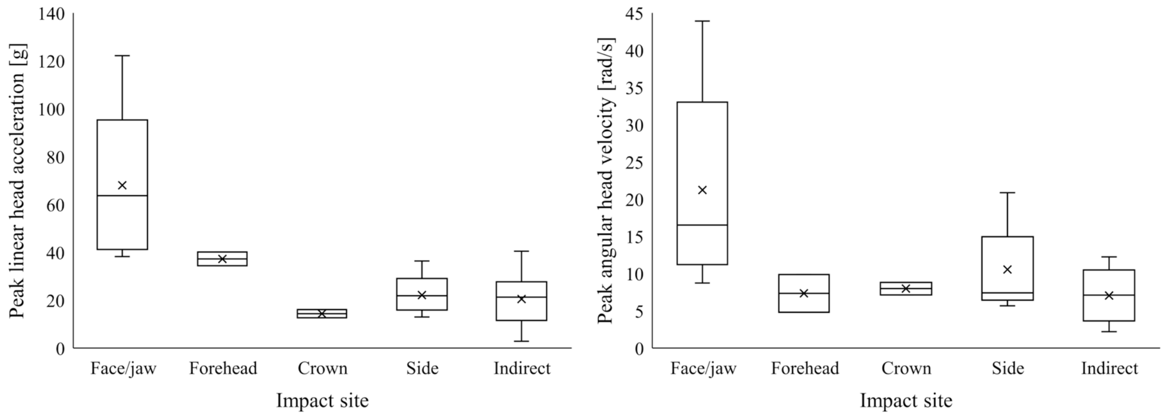

Figure 2:

Peak linear accelerations (left) and peak angular velocities (right) across different impact sites. Impacts to the face/jaw region had significantly ($p<0.05$) greater peak kinematics than impacts to other regions of the head.

Table 1:

Video-confirmed impact rates in female lacrosse.

Study	Level	Sensor	Recording trigger threshold [g]	Athlete-exposures	Video-confirmed impacts	Impact rate per athlete-exposure
Caswell et al. (2017)	High school	xPatch	20	467	58	0.12
Le et al. (2018)	Collegiate	xPatch	10	99	28	0.28
Caswell et al. (2020)	High school	xPatch	20	649	204	0.31
Huber et al. (2021)	High school	SIM-G	16	109	7	0.07
Cecchi et al. (2021)	Collegiate	SIM-G	16	81	6	0.06
Current study	High school	MiG	10	97	31	0.32