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Quantifying Head Impacts in Collegiate Lacrosse

Bryson B. Reynolds, BS*, James Patrie, MS*, Erich J. Henry, BS*, Howard P. Goodkin, MD, PhD*, Donna K. Broshek, PhD*, Max Wintermark, MD†, and T. Jason Druzgal, MD, PhD*‡
Investigation performed at the University of Virginia, Charlottesville, Virginia, USA

*University of Virginia, Charlottesville, Virginia, USA

†Stanford University, Palo Alto, California, USA

Abstract

Background: Concussion and repetitive head impact in sports has increased interest and concern for clinicians, scientists, and athletes. Lacrosse is the fastest growing sport in the United States, but the burden of head impact in lacrosse is unknown.

Purpose: The goal of this pilot study was to quantify head impact associated with practicing and playing collegiate lacrosse while subjects were fitted with wearable accelerometers.

Study Design: Descriptive epidemiology study.

Methods: In a single year, a collegiate cohort of 14 women's and 15 men's lacrosse players wore mastoid-patch accelerometers to measure the frequency and severity of head impacts during official practices and games. Average impact severity, mean number of impacts, and cumulative acceleration were evaluated, stratified by sport and event type.

Results: Men's and women's collegiate lacrosse players did not significantly differ in the number of head impacts received during games (11.5 for men vs 9.2 for women) or practices (3.1 vs 3.1). Men's lacrosse players had significantly higher average head acceleration per impact during games compared with women (21.1g vs 14.7g) but not during practices (21.3g vs 18.1g). For both men and women, more impacts occurred during games than during practices (men, 11.5 vs 3.1; women, 9.2 vs 3.1), but impact severity did not significantly differ between events for either sport (men, 21.1g vs 21.3g; women, 14.7g vs 18.1g).

Conclusion: The study data suggest a higher impact burden during games compared with practices, but this effect is driven by the quantity rather than severity of impacts. In contrast, sex-based effects in impact burden are driven by average impact severity rather than quantity. Data collected from larger multisite trials and/or different age groups could be used to inform ongoing debates, including headgear and practice regulations, that might appreciably affect the burden of head impacts in lacrosse.

Clinical Relevance: While most head impacts do not result in a clinical diagnosis of concussion, evidence indicates that subconcussive head impacts may increase susceptibility to concussion and contribute to long-term neurodegeneration.

‡ Address correspondence to T. Jason Druzgal, MD, PhD, University of Virginia, PO Box 800170, Charlottesville, VA 22908, USA (tjd4m@virginia.edu).

Keywords

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Some 1.6 to 3.8 million concussions or mild traumatic brain injuries occur in the United States each year,²⁷ and sportsrelated concussion (SRC) constitutes at least 20% of all concussions.⁴⁴ Concussion is generally defined as a blow to the head that results in a variable set of 1 or more clinical signs (eg, loss of consciousness, vomiting, imbalance) and symptoms (eg, headache, dizziness, amnesia, confusion, visual disturbance).³⁵ SRC is now recognized as a widespread public health problem, garnering attention from medical professionals, scientific researchers, and the media. Most of the media attention originates from the popularity of American football, which has been shown to have the highest or second highest incidence of concussion among collegiate sports.^{9,13,20,23}

Although football receives the most attention for SRC, there is increasing recognition that SRC is a problem in other high-impact sports, such as lacrosse. Men's and women's lacrosse are two of the most rapidly growing contact sports in the United States and, respectively, have the fourth and third highest concussion rates in men's and women's collegiate sports.²³ Lacrosse players have a higher concussion incidence than their counterparts in basketball, field hockey, wrestling, volleyball, cheerleading, track and field, baseball, and softball.^{9,30,33,49} The primary cause of SRC in men's lacrosse is player body contact, but SRC in women's lacrosse primarily results from head contact with the lacrosse stick.^{8,15,16,29,31} Several differences between men's and women's lacrosse gameplay may account for the difference in the primary concussion cause, including the amount of contact allowed and the extent of protective equipment used. Regardless of the differences between men's and women's lacrosse, head impact has become an increasing concern for both groups.

Fortunately for the athletes, the majority of head impacts do not result in the clinical diagnosis of a concussion, but an increasing concern is that multiple "subconcussive" head impacts might cause short-term or longterm functional and structural damage to the brain. In a recent review, subconcussion was defined as a "cranial impact that does not result in known or diagnosed concussion on clinical grounds."¹ Evidence indicates that shortterm changes related to subconcussion include increased susceptibility to subsequent concussion,^{2,3,21} decreased cognitive function,⁴ altered brain gray matter functional connectivity,^{25,43} and changes in brain white matter microstructure.^{14,32} Over the long term, subconcussion has been linked to retired football players' increased risk of developing neurodegenerative disorders, such as amyotrophic lateral sclerosis, Alzheimer's disease, Parkinson's disease, and chronic traumatic encephalopathy.^{28,38}

Given the potential importance of subconcussive head impacts, an increasing movement is being made to quantify their frequency and severity in all high-impact sports. Previous studies using helmet-based accelerometers indicate that collegiate football players can have more than a thousand head impacts in a typical season,²² but the frequency and severity of head impact experienced by a typical lacrosse player remain unknown. Some studies of head impact in lacrosse have attempted to infer similar data from laboratory-based biomechanical reconstructions¹⁰ or video capture of live lacrosse play.^{8,29} Recent advances in

biomechanical sensor technology have miniaturized accelerometers enough that they can be unobtrusively attached to the mastoid process with an adhesive patch, theoretically expanding the number of sports in which head impact can be measured during live play. The goal of the present study is to use a nonhelmeted mastoid-patch accelerometer to collect head impact data during live play in a cohort of men's and women's collegiate lacrosse players. The collected data were used to investigate sport differences in head impact between men's and women's lacrosse, separated by the athletic event types of practices and games.

METHODS

Participants

In 2014, a cohort of 14 women's and 15 men's lacrosse players (mean $\pm$ SD age, 20.29 $\pm$ 0.91 and 20.33 $\pm$ 1.11 years, respectively) wore head impact sensors during official practices and games. Participants were volunteers from two National Collegiate Athletic Association (NCAA) Division I lacrosse teams, with a roster size of 29 for women and 45 for men. No athlete had a history of developmental or neurological disorder or severe traumatic brain injury. The University of Virginia's Institutional Review Board for Health Science Research approved the research protocol, and all study participants gave written informed consent.

Biomechanical Measurements

Study participants wore the xPatch impact sensing skin patch (X2 Biosystems) on the skin covering their mastoid process (left or right side as decided by the athlete). A mastoid-patch accelerometer can be deployed in both helmeted and nonhelmeted sports. Although helmets are required in men's lacrosse, women's lacrosse players wear only protective eyewear. The xPatch allows for men's and women's lacrosse to be compared by use of the same biomechanical sensor. The sensor was to be worn during all official team practices and games, although athletes maintained the right to refuse at each event. The xPatch contains a triaxial high-impact linear accelerometer and a triaxial gyroscope to capture 6 degrees of freedom for linear acceleration and rotational velocity. Impact to the body or head can result in head acceleration; however, for simplicity we henceforth refer to impacts that result in acceleration of the head as *head impacts*. If an accelerometer exceeded a predetermined 10g linear acceleration threshold, 100 milliseconds of data (10 ms pretrigger and 90 ms posttrigger) from each accelerometer and gyroscope were recorded to onboard memory. Raw accelerometer data were then transformed to calculate peak linear acceleration (PLA) and peak rotational acceleration (PRA) at the head's center of gravity by X2 Biosystems' Injury Monitoring System using a rigid-body transformation for PLA and a 5-point stencil for PRA. False impacts are removed by X2 Biosystems' proprietary algorithm, which compares the waveform of each impact to a reference waveform using cross-correlation. Impacts with resultant peak linear acceleration less than 10g were removed. Impact data were then time filtered to include only impacts that occurred during a practice or game. Impact burden measurements, PLA sum, and PRA sum were calculated per athlete exposure (AE; a single practice or game event) by summing each impact linearly weighted by its severity.⁵ During the study period, 78 official women's practices and 87 official men's practices took place. All participants' recorded practices were included in the analysis. To account for highly

variable playing time between participants in games, an athlete needed to play more than 33% of the game for the event to be included in the analysis. Hereafter we refer to these athletes as *starters*. With this procedure, participants totaled 131 game starts for women and 63 game starts for men. Individual events (practices or games) that resulted in a number of impacts, PLA sum, or PRA sum greater than the 99th percentile for all lacrosse events were identified as outliers and removed from subsequent analysis.

Statistical Analyses

Data Summarization—Categorical scaled data were summarized by frequencies and percentages, whereas continuous scale data were summarized by the mean, standard deviation, median, and range of the empirical distribution. SAS version 9.4 (SAS Institute Inc) was used to conduct the statistical analyses. Graphic displays were created with statistical software Spotfire S plus (TIBCO Inc).

Analyses of Sex-Based Differences in Practice Events

Impacts per Practice Event.: A negative binomial generalized estimate equation (GEE) model was used to compare between female and male lacrosse players the number of impacts per lacrosse practice that the players experienced. With regard to model specification, the GEE model included only a single indicator variable, which distinguished female lacrosse players from male lacrosse players. Since each player participated in several practices, each player's impact data were considered a cluster of potentially nonindependent observations in the GEE analysis. The sandwich variance-covariance estimator of Huber and White^{24,46} was used to estimate the GEE model variance-covariance matrix. With respect to hypothesis testing, the GEE version of the Wald test was used to test the null hypothesis that mean number of impacts per practice was the same for females and males, and a 2-sided P .05 decision rule was used as the null hypothesis test rejection criterion.

Analysis of PLA per Impact.: Average PLA per impact per practice event was analyzed on the natural logarithmic scale via a Gaussian GEE model. The natural logarithmic transformation was applied to rescale the data to a scale in which the measurement distributions were more symmetric in shape (ie, bell-shaped). Indicator variables in the GEE model, individual player clustering, sandwich variance-covariance estimator, null hypothesis, and rejection rule were the same as the impacts per practice event analysis.

Analysis of PRA per Impact.: Average PRA per impact per practice event was analyzed on the natural logarithmic scale in exactly the same way as the PLA per impact data.

Analysis of PLA Threshold.: A negative binomial GEE model was used to analyze the number of impacts per practice event in which the lacrosse player experienced a linear acceleration greater than 10g, 20g, 30g, 40g, 50g, 60g, 70g, 80g, 90g, and 100g. With regard to the GEE model specification, 2 indicator variables were used, 1 variable to distinguish between female and male lacrosse players and 1 variable to distinguish between the 10 different g-force thresholds. A set of indicator variables for sex by g-force threshold interaction was also a component of the model specification. To account for intraplayer measurement correlation, the GEE model variance covariance matrix was specified in the

unstructured form: that is, a variance-covariance matrix form that places no restriction on the variance-covariance structure. With regard to hypothesis testing, the GEE version of the Wald test was used to test the global hypothesis that for practice events, g-force impact was uniformly (ie, across all g-force thresholds) the same for the female and the male lacrosse players. Wald tests were additionally used to examine, on a per g-force threshold basis, sex-based differences in the mean number of impacts per practice event in which the g-force was greater than the defined threshold. A Bonferroni correction was applied to all pairwise tests as a means to restrict the simultaneous type I error rate to 0.05.

Analysis of PRA Threshold.: A negative binomial GEE model was used to analyze the number of impacts per practice event in which the lacrosse player experienced a PRA greater than 0, 2000, 4000, 6000, 8000, 10,000, 12,000, and 14,000 rad/s². The GEE analysis was conducted in exactly the same way as the analysis of PLA threshold.

Analysis of PLA Sum and PRA Sum per Practice Event.: PLA sum and PRA sum are measures of impact burden that are severity-weighted linear summations of all head impacts for an athletic event⁶ that theoretically attempt to quantify the accumulation of subconcussive damage. Researchers using the Head Impact Telemetry (HIT) system have also used cumulative versions of the HIT severity profile (HITsp) and multiple risk-weighted estimates to quantify impact burden, but these metrics were designed for the HIT system^{5,14,18,45} and therefore were inappropriate to use with xPatch. The GEE version of the Cox proportionate hazard model was used to compare the empirical cumulative distribution for PLA sum per practice between female and male lacrosse players as well as to compare the empirical cumulative distribution of PRA between female and male lacrosse players. This approach was used so that the intraplayer measurement correlation would be accounted for in the null hypothesis test that the underlying PLA sum per practice cumulative distribution is the same for female and male lacrosse players.

Analyses of Event Type Differences—Differences in the number of impacts experienced by the lacrosse players and differences in impact forces experienced by the players during practice and game events were analyzed in the same way as the practice impact frequency data and the practice impact force data. The only major differences were that this set of analyses focused on the athletic event type and not sex and also focused only on the lacrosse players who were designated as starters.

Analyses of Sex-Based Differences in Game Events—Sex-based differences in the number of impacts experienced by the players during lacrosse games and sex-based differences in the impact forces experienced by the players during lacrosse games were analyzed in the same way as the practice impact frequency data and practice impact force practice data. Again, the only major differences were that this set of analyses focused on game event as opposed to practice events and also focused on the lacrosse players who were designated as starters.

RESULTS

Participants

Results include data from 1757 AEs from 14 women's and 15 men's collegiate lacrosse players during their 2014 competitive season. On the basis of roster sizes of 29 women and 45 men, the recruitment rate for the women was 48.3% and for the men was 33.3%. The women's season entailed 78 practices and 21 games, and the men's season entailed 87 practices and 16 games. There were 719 captured practices for women and 944 captured practices for men, corresponding to practice capture rates of 65.8% for women and 72.3% for men. There were 57 captured games for women and 37 captured games for men, corresponding to game capture rates of 43.5% for female starters and 58.7% for male starters. Table 1 contains a detailed number of all captured AEs.

Sex-Based Differences in Practices

In practices, no differences were found between women's and men's lacrosse players in total number of impacts ($>10g$) they received (mean impact/event, 3.1 [95% CI, 2.1–4.7] and 3.1 [95% CI, 2.4–4.0], respectively; $P = .993$) (Figure 1A), average PLA of the impacts (geometric mean PLA/impact/event, 18.1g [95% CI, 16.1g–20.4g] and 21.3g [95% CI, 19.1g–23.9g], respectively; $P = .051$) (Figure 1B), or average PRA of the impacts (geometric mean PRA/impact/event, 3077.1 rad/s² [95% CI, 2620.2–3613.6 rad/s²] and 3754.9 rad/s² [95% CI, 3147.2–4479.9 rad/s²], respectively; $P = .099$) (Figure 1C). However, global tests of number of impacts above PLA thresholds of 10g to 100g and PRA thresholds of 0 to 22,000 rad/s² demonstrated significant differences between men's and women's lacrosse practices (both $P < .001$). Threshold by threshold post hoc pairwise comparisons showed significant sex-based differences in mean number of impacts at several individual linear and rotational acceleration thresholds after Bonferroni correction. The overall differences were primarily driven by a higher number of impacts for men's lacrosse players for impacts above PLA thresholds of 20g ($P < .001$), 30g ($P = .005$), and 40g ($P = .035$) and PRA thresholds of 4000 rad/s² ($P < .001$), 6000 rad/s² ($P = .001$), and 8000 rad/s² ($P = .030$) (Figure 1D and Appendix Table A1, available online at <http://ajsm.sagepub.com/supplemental>). Fewer practices included high-severity impacts, which resulted in smaller sample size and reduced statistical power at higher thresholds. No differences were found in cumulative distribution of impact burden (PLA sum and PRA sum) per AE for women's and men's lacrosse practices ($P = .137$ for PLA sum and $P = .053$ for PRA sum) (Figure 1, E and F).

Event Type Differences

In both women's and men's lacrosse, significantly more impacts ($>10g$) occurred in games than in practices ($P < .001$ for both) (Figure 2A). The average PLA and PRA per impact did not differ between games and practices for either men's or women's lacrosse (Bonferroni-corrected PLA, $P > .999$ and $P = .068$; PRA, $P > .999$ and $P = .255$, respectively, for men and women) (Figure 2, B and C).

A global test of number of impacts above PLA thresholds 10g to 60g demonstrated a significant difference between games and practices for both women and men ($P < .001$ for both). A global test of number of impacts above PRA thresholds 0 to 14,000 rad/s²

demonstrated a significant difference between games and practices for men but not women ($P < .001$ and $P = .641$, respectively). Threshold by threshold post hoc pairwise comparisons showed significant event type differences in mean number of impacts at several individual linear and rotational acceleration thresholds after Bonferroni correction. The overall differences were driven by higher number of impacts in games at a low PLA threshold of $10g$ ($P < .001$) and low PRA thresholds of 0 rad/s^2 and 2000 rad/s^2 (both $P < .001$) for women's lacrosse (Figure 3A and Appendix Table A2) and across nearly all PLA thresholds of $10g$ ($P < .001$), $20g$ ($P < .001$), $30g$ ($P < .001$), $40g$ ($P < .001$), $50g$ ($P = .002$), and $60g$ ($P = .001$) and PRA thresholds of 0 , 2000 , 4000 , 6000 , 8000 , $10,000$, and $12,000 \text{ rad/s}^2$ (all $P < .001$) for men's lacrosse (Figure 3B and Appendix Table A3). Fewer events included high-severity impacts, which resulted in smaller sample size and reduced statistical power at higher thresholds.

Significant differences were noted in the cumulative distribution of impact burden per AE between games and practices for both women's and men's lacrosse (PLA sum, $P = .019$ and $P > .001$; PRA sum, $P = .029$ and $P < .001$, respectively, for women and men) (Figure 3, C-F).

Sex-Based Differences in Games

In games, no differences were noted between women's and men's lacrosse starters in the number of impacts they received (mean impacts per event, 9.2 [95% CI, $4.5\text{--}18.5$] and 11.5 [95% CI, $8.3\text{--}16.0$], respectively; $P = .568$) (Figure 4A). However, men and women did significantly differ in average PLA per impact (geometric mean PLA/impact/ event, $14.7g$ [95% CI, $12.5g\text{--}17.3g$] and $21.1g$ [95% CI, $18.2g\text{--}24.5g$], respectively; $P = .006$) (Figure 4B) and in average PRA per impact (geometric mean PRA/impact/ event, 2327.6 rad/s^2 [95% CI, $1723.2\text{--}3143.9 \text{ rad/s}^2$] and 3603.1 rad/s^2 [95% CI, $2638.5\text{--}4920.3 \text{ rad/s}^2$], respectively; $P = .048$) (Figure 4C), with men receiving 43.5% higher average PLA ($21.1g$ vs $14.7g$) and 54.8% higher average PRA (3603.1 vs 2327.6 rad/s^2) per impact.

Global tests of number of impacts above PLA thresholds $10g$ to $100g$ and PRA thresholds 0 to $14,000 \text{ rad/s}^2$ demonstrated significant differences between women's and men's lacrosse games (both $P < .001$). Threshold by threshold post hoc pairwise comparisons showed significant sexbased differences in mean number of impacts at several individual linear and rotational acceleration thresholds after Bonferroni correction. The overall differences were driven by a higher number of impacts for men's lacrosse starters for impacts above PLA thresholds of $20g$ ($P < .001$), $30g$ ($P < .001$), and $40g$ ($P = .009$) and PRA thresholds of 2000 rad/s^2 ($P = .043$), 4000 rad/s^2 ($P < .001$), 6000 rad/s^2 ($P < .001$), 8000 rad/s^2 ($P = .010$), $10,000 \text{ rad/s}^2$ ($P < .001$), and $12,000 \text{ rad/s}^2$ ($P = .008$) (Figure 4D and Appendix Table A4). Fewer games included high-severity impacts, which resulted in smaller sample size and reduced statistical power at higher thresholds. No significant difference was noted in cumulative distribution of linear impact burden per AE for women's and men's lacrosse games ($P = .095$) (Figure 4E), but a significant difference was found in cumulative distribution of rotational impact burden per AE ($P = .027$) (Figure 4F).

DISCUSSION

This study was performed to investigate sport differences in head impact between men's and women's lacrosse and event type differences between practices and games within each sport. To accomplish this task, we used a nonhelmeted mastoid-patch accelerometer to collect head impact data during live play in a cohort of men's and women's collegiate lacrosse players. While the vast majority of head impacts do not result in concussion, the hypothesized short-term and long-term detrimental effects of subconcussion on brain function^{4,25,43} and structure,^{14,32} coupled with their proposed role in increasing susceptibility to neurodegenerative disorders,^{28,38} suggest that quantification of subconcussion in a sport may be important for assessing the sport's overall safety. Previous studies have tried to estimate the frequency and severity of subconcussive head impacts in lacrosse from analysis of biomechanical reconstructions¹⁰ and video capture of live events.^{8,29} This is the first study to directly quantify subconcussive head impacts in live action collegiate lacrosse.

Differences Between Sex and Event Type

Our data indicated that across event types, the difference in head impact between men's and women's lacrosse lies in the average severity of impacts rather than the number of impacts experienced. An average impact in a men's lacrosse game has a 43.5% greater linear acceleration and 54.8% greater rotational acceleration than an average impact in women's lacrosse games, and men's practices show trends in the same direction ($P = .051$ and $.099$). Although we found no significant difference in the number of impacts between sexes when using our 10g threshold, if we used a 20g, 30g, or 40g threshold, men's lacrosse did result in a higher number of head impacts compared with women's lacrosse. These differences in severity of head impact are possibly driven by size and strength difference of the sexes, differences in rules of the sport, differences in equipment, or a combination of factors.

When restricting analyses to only players who started games, we found that across sex, games resulted in more impacts per AE compared with practices, but similar average impact severity. Analysis at multiple impact thresholds reveals that for women's lacrosse these differences are only present at lower thresholds of 10g and 20g, but for men's lacrosse these differences are apparent at all thresholds tested (10g-60g). PLA sum and PRA sum also demonstrated event type differences, with athletes of both sexes experiencing higher impact burden in games relative to practices. As predicted, games had a higher impact burden compared with practices, but this effect was driven by the quantity rather than severity of impacts. In contrast, the effect of sex on impact burden is driven by average impact severity rather than quantity.

A prominent debate in lacrosse concerns whether women's lacrosse players should use helmets similar to those required in men's lacrosse. This study provides some factual data for that debate but does not make a clear case for either side. Men's and women's lacrosse players receive similar numbers of head impacts, but head impacts experienced by women's lacrosse players are of lower severity even though these players use only protective eyewear and do not wear helmets. While subconcussion is gaining interest in athletic, medical, and scientific communities, it is unknown what levels of head impact quantity or severity are physiologically relevant. Larger, more comprehensive studies are needed to further explore

the levels of head impact in men's and women's lacrosse and how they compare with other contact sports.

Practical Issues of Data Collection

Unlike helmet-based sensors typically used in football, the mastoid-patch sensor is not embedded in any required lacrosse equipment. Thus, sensor application represented an additional step in an athlete's routine but was easily integrated into the teams' routines. In theory, the sensors could be self-applied by the athlete, but in the present study, sensors were applied by study personnel to ensure consistency of placement and to maximize athlete compliance.

This study includes data from 14 women's and 15 men's lacrosse players in a single season. Our recruitment rates of 33.3% for men and 48.3% for women fall into the range of published studies using helmeted accelerometers in football.^{3,6,11,18,19,22,37} Our practice capture rates (72.3% for men, 65.8% for women) and game capture rates (58.7% for men starters, 43.5% for women starters) fall below typical values for football. Helmet-based accelerometer systems have a higher AE capture rate because of their inclusion in mandatory equipment; that is, for athletes to participate in a football practice or game, they must wear a helmet. Our AE capture rate was comparable with another study that used the same mastoid-patch sensor in a football cohort.³⁹ In our study, the athletes had the right of refusal for each athletic event; forgetting or declining the sensor caused most of the missed events in the present study.

Limitations

This pilot study reports findings from 1 men's and 1 women's team over the course of 1 lacrosse season. In a small sample, results can be affected by the team selection; in football, head impact can be affected by the style of offensive play,³⁴ and a similar effect of playing style is possible for our lacrosse teams. The subset of athletes recruited from each team or the subset of events captured could also skew the results; if our small sample size disproportionately included more aggressive players or events, then the results could be an overestimate of head impact, or vice versa. The analysis of games involved 9 starters in total, which could allow 1 or 2 outliers to drive effects. The men's lacrosse starters were 3 midfielders and 1 attacker and thus were not a representative sample of the various lacrosse positions. Thus, the finding of more impacts in games than practices should be considered preliminary, but this finding is consistent with accelerometer studies of other contact sports including football^{7,11,34,39,47} and soccer.³⁶

The xPatch accelerometer used in the present study appears in 4 published studies,^{36,39,42,48} of which 2 studies tested biomechanical validity in different settings.^{36,48} In 2016, Wu et al⁴⁸ compared in vivo performance of the xPatch against video capture in a simulated low-impact soccer setting; that study examined 25 impacts, 1 impact location, 1 mastoid placement location, and 1 xPatch device. In a single subject, the investigators found that the xPatch overestimated individual linear and rotational accelerations in ways likely related to the unique viscoelastic properties of that individual's soft tissues. In 2015, as prelude to a liveplay soccer study, McCuen et al³⁶ evaluated xPatch performance on a Hybrid 3

headform; this study examined 250 impacts, spread over 5 impact locations, in 2 mastoid placement locations, including data from 5 different xPatch devices. McCuen et al found significant xPatch measurement error related to individual impacts (root mean squared error of ~50% for individual PLA and PRA values). However, these authors also looked at aggregate performance over larger numbers of impacts and concluded that “average values over a large number of acceleration events can be determined with good accuracy.”³⁶

Another study that used the same mastoid accelerometer in collegiate football³⁹ found that the number and linear severity of head impacts compared favorably to published data using helmet-based accelerometers.^{7,12,17,37,40,41} But in the same football study,³⁹ discrepancies existed between rotational severity of head impact measured by the mastoid accelerometer and similar published data from helmeted systems. We believe that the transformed values reported by all head impact sensors in live play settings should be viewed skeptically, as they probably do not reflect the “ground truth” biomechanical forces experienced by the brain. The xPatch data for individual hits are almost certainly noisy, but if the errors are systematic, relative comparisons across situations and groups with large numbers of impacts should still be valid. The design of this study acknowledges this issue by testing hypotheses comparing relative situations (eg, men vs women and game vs practice) rather than focusing on the absolute values reported.

The reported number and average severity of head impacts are highly affected by the choice of a minimum inclusion threshold. Since the lower bound of physiological significance for subconcussive impacts is not yet established, a threshold needs to minimize recording of head accelerations caused by running and jumping but record all impacts to the body or head that result in head acceleration. McCuen et al,³⁶ who used the same sensor in women’s soccer, chose a threshold of 20g to exclude head accelerations caused by hard kicks, but this is potentially an issue specific to soccer. In 2016, King et al²⁶ reviewed the impact thresholds used in 52 biomechanical studies of head impact in sport and found that 10g was the most common threshold, used in 42% of the publications, and that moving the threshold from 10g to 20g removed 62% of the impacts and increased the average PLA by 64%. These authors argued that since the best impact threshold for injury outcomes has not been established and the largest proportion of studies used a 10g threshold, future studies should use a 10g threshold to maximize comparison to existing literature.²⁶ In light of these studies, we believe that the choice of a 10g threshold strikes the appropriate balance between including as many head impacts as possible, excluding the vast majority of nonimpact accelerations, and maintaining a high degree of comparability within the field. Despite the recommendation by King et al, we performed sex and event type comparisons for number of impacts at multiple linear and rotational acceleration thresholds to determine whether effects were limited to specific thresholds.

CONCLUSION

This pilot study indicates that men’s lacrosse games have a higher average impact severity than women’s lacrosse games, but both sports result in a similar number of head impacts. Both sports show more impacts in games than during practices but with no differences in average impact severity. The clinical relevance of subconcussion is the subject of ongoing

research, but most people would agree that limiting unnecessary head contact is beneficial to athletes. The results of this study show how accelerometer data might address head impact hypotheses of practical relevance to lacrosse, such as differences in the burden of impact experienced by men compared with women or practices compared with games. However, larger, multisite studies may be needed to develop the level of understanding of head impact frequency and severity in lacrosse that currently exists in football. In particular, we note open questions in lacrosse with regard to how subconcussive head impacts are affected by school level, playing style, practice structure, and level of protective equipment.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1.

Empirical distributions for women's and men's lacrosse players: (A) number of impacts per practice, (B) mean peak linear acceleration (PLA) per impact per practice, and (C) mean peak rotational acceleration (PRA) per impact per practice. (D) Mean number of impacts at multiple linear acceleration thresholds for practices. Empirical cumulative distributions for (E) PLA sum and for (F) PRA for practices.

Figure 2.

(A) Mean number of impacts per athletic event, (B) geometric mean peak linear acceleration (PLA) per impact per athletic event, and (C) geometric mean peak rotational acceleration (PRA) per impact per athletic event for women's and men's lacrosse starters. Closed circles identify the (A) mean or (B, C) geometric mean of the distributions; open circles and dotted lines identify player-specific (A) means or (B, C) geometric means; and error bars in identify 95% CIs for the (A) mean or (B, C) geometric mean.

Figure 3.

Mean number of impacts at multiple linear acceleration thresholds for (A) women's and (B) men's lacrosse starters. Peak linear acceleration (PLA) sum empirical cumulative distributions for (C) women's and (D) men's lacrosse starters, and peak rotational acceleration (PRA) sum empirical cumulative distributions for (E) women's and (F) men's lacrosse starters.

Figure 4.

Empirical distributions for women's and men's lacrosse starters: (A) number of impacts per game, (B) mean peak linear acceleration (PLA) per impact per game, and (C) mean peak rotational acceleration (PRA) per impact per game. (D) Mean number of impacts at multiple linear acceleration thresholds for games. Empirical cumulative distributions for (E) PLA sum and for (F) PRA for games.

Table 1Summary of Captured Athletic Events per Subject^a

Player Summary		Practice Summary			Game Summary		
Player No.	Position	No. of Captured Events	Mean No. of Impacts	Mean PLA/Impact/Event, <i>g</i>	No. of Captured Events	Mean No. of Events	Mean PLA/Impact/Event, <i>g</i>
Women's lacrosse							
1	Attack	21	11.9	14.3	—	—	—
2	Midfield	72	1.6	16.6	13	2.1	14.3
3	Attack	71	5.4	13.9	17	16.0	13.7
4	Defense	14	1.8	26.4	—	—	—
5	Defense	73	4.6	16.2	—	—	—
6	Defense	64	1.5	19.3	—	—	—
7	Defense	56	1.2	26.0	4	0.5	45.4
8	Midfield	17	3.8	18.6	—	—	—
9	Defense	23	2.2	18.5	—	—	—
10	Goalie	51	1.2	29.4	—	—	—
11	Goalie	63	1.0	23.7	8	0.1	15.1
12	Midfield	72	6.7	16.1	—	—	—
13	Midfield	62	2.4	16.8	—	—	—
14	Attack	60	1.8	16.4	15	14.7	13.3
Mean ± SD (range)		51.4 ± 22.4 (14–73)	3.1 ± 5.8 (1.0–11.9)	18.1 ^b (14.2–31.8)	11.4 ± 5.3 (4–17)	9.2 ± 7.5 (0.5–16.0)	14.7 ^b (13.3–45.4)
Men's lacrosse							
1	Midfield	47	2.6	21.8	4	13.5	26.3
2	Attack	60	2.5	27.2	—	—	—
3	Midfield	73	3.3	22.4	—	—	—
4	Attack	77	3.8	23.5	11	12.1	23.2
5	Attack	21	8.0	26.4	—	—	—
6	Defense	63	2.0	15.7	—	—	—
7	Defense	63	2.0	24.6	—	—	—
8	Midfield	63	3.9	21.5	—	—	—
9	Midfield	66	1.4	18.7	11	6.4	20.4
10	Midfield	74	3.0	20.5	—	—	—
11	Defense	59	1.4	21.7	—	—	—
12	Midfield	81	5.9	14.8	—	—	—
13	Midfield	74	5.5	17.3	11	15.4	17.7
14	Defense	67	2.1	31.2	—	—	—
15	Defense	56	1.3	24.9	—	—	—
Mean ± SD (range)		62.9 ± 14.6 (21–81)	3.1 ± 4.8 (1.3–8.0)	21.3 ^b (14.8–31.2)	9.2 ± 3.5 (4–11)	11.5 ± 3.6 (6.4–15.4)	21.1 ^b (17.7–26.3)

^aPLA, peak linear acceleration.

^bReported as the geometric mean of the measurement distribution, where the geometric mean is a location parameter of the measurement distribution similar to the mean and median of the measurement distribution

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