Comparative Analysis of Head Impact in Contact and Collision Sports

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Abstract

As concerns about head impact in American football have grown, similar concerns have started to extend to other sports thought to experience less head impact, such as soccer and lacrosse. However, the amount of head impact experienced in soccer and lacrosse is relatively unknown, particularly compared with the substantial amount of data from football. This pilot study quantifies and compares head impact from four different types of sports teams: college football, high school football, college soccer, and college lacrosse. During the 2013 and 2014 seasons, 61 players wore mastoid patch accelerometers to quantify head impact during official athletic events (i.e., practices and games). In both practices and games, college football players experienced the most or second-most impacts per athletic event, highest average peak resultant linear and rotational acceleration per impact, and highest cumulative linear and rotational acceleration per athletic event. For average peak resultant linear and rotational acceleration per individual impact, college football was followed by high school football, then college lacrosse, and then college soccer, with similar trends in both practices and games. In the four teams under study, college football players experienced a categorically higher burden of head impact. However, for cumulative impact burden, the high school football cohort was not significantly different from the college soccer cohort. The results suggest that head impact in sport substantially varies by both the type of sport (football vs. soccer vs. lacrosse) and level of play (college vs. high school).

Keywords: adult brain injury; epidemiology; head trauma; pediatric brain injury; subconcussion

Introduction

WITH AN ESTIMATED 750,000 sports-related concussions each year in the United States,^{1,2} concussion is increasingly recognized as a widespread public health issue by medical professionals, scientists, and the media. Although the specific definition is evolving, concussion generally involves a rapid acceleration of the head followed by a variable set of clinical signs (e.g., loss of consciousness, vomiting, imbalance) and symptoms (e.g., headache, dizziness, amnesia, confusion, visual disturbance).³ And although American football has captured the majority of recent media attention relating to head injury in sports, most contact and collision sports involve some risk of concussion. The relative incidence of concussion among several different high school and collegiate sports has been well studied.^{4–8} In a recent epidemiologic study of sports-related concussion in National Collegiate Athletic Association (NCAA) athletes, football has the second highest overall incidence of concussion for noncombat male sports; soccer and lacrosse are fourth and fifth, with similar overall concussion inci-

dence.⁷ An earlier study comparing high school and college sports found that the incidence of concussion in high school football was considerably lower than that in college football, but comparable to that in college soccer.⁵ However, the relatively high concussion incidence rates have caused rising concerns about brain injury in all collision and contact sports.

Separate from the issue of concussion, there are growing concerns about effects of repetitive “subconcussive” head impacts. One review defined subconcussion as a “cranial impact that does not result in a concussion on clinical grounds.”⁹ There is a growing body of evidence indicating that these repeated subconcussive head impacts might cause anatomical and/or physiological damage to an athlete’s brain. Research has suggested that subconcussion, over the short term, leads to increased susceptibility to concussion,^{10–12} decreased cognitive function,^{13–15} altered functional connectivity in brain gray matter,^{16–18} and changes in the microstructure of brain white matter.^{15,19–21} Over the long term, subconcussion has been linked to increased risk for neurodegenerative disorders, such as amyotrophic lateral sclerosis, Alzheimer’s disease, Parkinson’s

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disease, and chronic traumatic encephalopathy.^{22–26} In parallel with concerns about concussion, concerns about subconcussion that originated in studies of football are starting to extend to other contact and collision sports. However, it remains undetermined what level of subconcussive head impact quantity and/or severity is physiologically significant, and the relative burden of subconcussion experienced in different live play sport settings remains unknown.

Despite unknown significance, concern about the detrimental effects of subconcussion has fueled a movement to quantify head impacts in contact and collision sports. There are dozens of studies analyzing head impact in American football, using both laboratory simulations/recreations^{27–33} and live play biomechanical measurements.^{13,34–52} A much smaller number of studies have quantified head impact in soccer and lacrosse, primarily using self-report questionnaires,¹⁵ video analysis,^{31,53,54} and/or laboratory simulations/recreations.^{55–59} No published studies present live play biomechanical data in lacrosse, and only one study has reported head impact measured during live play in soccer.⁶⁰ No studies have quantified subconcussion in multiple sports with the same biomechanical sensor and directly compared the sports' quantity and severity of head impacts.

Recent advances in biomechanical sensor technology have miniaturized accelerometers enough so that they can be attached unobtrusively to the mastoid process with an adhesive patch, expanding the number of sports in which head impact can be measured during live play. The present study compares biomechanical sensor data collected during one season for each of the following sports teams: college football (CF), high school football (HF), college lacrosse (CL), and college soccer (CS). These sports each have a comparatively high concussion incidence,^{4–8} with football typically having the most of all male sports. However, the relative amount of subconcussive head impact in these sports is unknown, although football is widely assumed to have the highest subconcussive burden of all noncombat sports. The collected data are used to quantitatively investigate head impact differences among these teams during practices and games.

Methods

Participants

During 2013 and 2014, 16 CF players, 15 HF players, 15 CL players, and 15 CS players (mean [SD] age: 20.1 [1.3] years, 16.5 [1.2] years, 20.1 [1.1] years, and 20.2 [1.3] years, respectively) wore head impact sensors during official practices and games of their respective sport. College participants were volunteers from Division I teams, and HF players were from a small private high school. No athlete had a history of developmental or neurological disorder, or moderate to severe traumatic brain injury.

Standard protocol approvals, registrations, and patient consents

The University of Virginia Institutional Review Board for Health Science Research approved the research protocol. All participants gave written informed consent; if a participant was <18 years old at the time of enrollment, a parent or legal guardian also gave written informed consent.

Biomechanical measurements

Study participants wore the xPatch impact sensing skin patch (X2 Biosystems, Seattle, WA) on the skin covering their mastoid process (left or right side was decided by the athlete) (Fig. 1A).

Impact to the body or head can result in head acceleration; however, for simplicity we will henceforth refer to impacts that result in acceleration of the head as “head impacts.” The sensor was to be worn during all official team practices and games (soccer players only wore sensors for home games), although the athletes maintained the right to refuse at each event. The xPatch contains a triaxial high impact linear accelerometer and a triaxial gyroscope to capture six degrees of freedom for linear and rotational accelerations (1 kHz sampling rate). If an accelerometer exceeded a pre-determined 10g linear acceleration threshold, 100 ms of data (10 ms pre-trigger and 90 ms post-trigger) from each accelerometer and gyroscope were recorded to onboard memory. Raw accelerometer data were then transformed to calculate peak resultant linear acceleration (PRLA) and peak resultant rotational acceleration (PRRA) at the head center of gravity by X2 Biosystems' Injury Monitoring System using a rigid body transformation for PRLA and a five point stencil for PRRA. False impacts were removed by X2 Biosystems' proprietary algorithm, which compares the waveform of each impact to a reference waveform using cross-correlation. Impacts with peak resultant linear acceleration <10g were removed. Impact data were then time filtered to include only impacts that occurred during a practice or game. Impact burden measures, PRLA sum, and PRRA sum were calculated per athletic exposure (a single practice or game event) by multiplying each impact by its linear or rotational severity and then summing them over each athletic event (e.g., impacts of 10g, 10g, 20g, and 30g result in a PRLA sum of 70g), as in the study by Broglio and coworkers.⁶¹ Studies investigating the biomechanical validity of the xPatch have found appreciable error in the measurement of PRLA and PRRA in individual impacts,^{60,62} which is discussed further in the Limitations section. However, comparing relative values between two conditions with large numbers of impacts per condition has been demonstrated to provide reliable composite results.⁶⁰ Individual impact severity values reported by any head impact sensor should be considered approximate.

Game data

All players participated in practices but not all players participated in every game. To account for this issue, athletes needed to meet a minimum playing time threshold for a game to include that player's data in the game analysis. Because of differences in substitution patterns and the structure of the playing time for each sport, the thresholds are necessarily different. To be counted as a game player, a CF athlete needed to participate in at least one play, a college lacrosse (CL) player needed to play >33% of the game, and a soccer player needed to play >45 min in the game for the event to be included in the analysis. Detailed records of playing time were not available for HF players, but on the small team under study, most players played at least some part of the game; therefore, all recorded HF games were analyzed. Additional supplementary analyses were performed that included all recorded game events, without any minimum playing time threshold for inclusion, to investigate whether the inclusion criteria substantially biased the results.

Statistical analysis

Data summarization. Categorical scaled data were summarized by frequencies and percentages, whereas continuous scale data were summarized either by the mean and standard deviation, or by the geometric mean, the median, and range of the empirical distribution.

Impacts per practice event. A negative binomial generalized estimate equation (GEE) model was utilized to compare the number of impacts per practice that the players experienced among CF, HF, CL, and CS. With regard to model specification, the

FIG. 1. Picture of an athlete wearing the xPatch (A). Graph showing impact rates per athletic event, according to sport and event type (B). Geometric mean peak resultant linear acceleration (PRLA) (g) (C) and peak resultant rotational acceleration (PRRA) (rad/sec² / 1000) (D) per individual impact. Black circles identify the mean impact rate or geometric mean peak resultant acceleration per impact, and vertical lines identify the 95% CI. Brackets with an asterisk indicate that the indicated sports differed at the $p \leq 0.05$ Bonferroni-corrected level of statistical significance for that measure.

GEE model only included a single indicator variable, which distinguished players from different teams. Because each player participated in several practices, each player's impact data were considered a cluster of potentially non-independent observations in the GEE analysis. The sandwich variance-covariance estimator of Huber and White^{63,64} was utilized 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 the mean number of impacts per practice was the same for all teams, and a two sided $p \leq 0.05$ decision rule was used as the null hypothesis test rejection criterion.

Analysis of PRLA per impact. Average PRLA per impact per practice event was analyzed on the natural logarithmic scale via a Gaussian GEE model. The natural logarithmic transformation was applied in order to rescale the data to a scale in which the measurement distributions were more symmetric in shape (i.e., bell shaped). With regard to model specification, the GEE model included one indicator variable that distinguished players from different teams. Because each player participated in several practices, each player's PRLA data were considered a cluster of potentially non-independent observations in the GEE analysis. The sandwich variance-covariance estimator of Huber and White^{63,64} was utilized to estimate the GEE model variance-covariance matrix. With re-

spect to team differences in geometric mean PRLA per impact per practice, we tested the null hypothesis that the geometric mean was the same for players from different teams. A two sided $p \leq 0.05$ rejection rule was used as the null hypothesis criterion.

Analysis of PRRA per impact. Average PRRA per impact per practice event was analyzed on the natural logarithmic scale in exactly the same way as the PRLA per impact data.

Analysis of PRLA threshold. A negative binomial GEE model was utilized to analyze the number of impacts per practice in which a player experienced an impact with PRLA >10g, 20g, 30g, 40g, 50g, 60g, 70g, 80g, 90g, and 100g. With regard to the GEE model specification, two indicator variables were utilized, one to distinguish among players from different teams, and one to distinguish between the 10 different PRLA thresholds. A set of indicator variables for team by PRLA threshold interaction was also a component of the model specification. To account for *intra-player* measurement correlation, the GEE model variance covariance matrix was specified in the unstructured form; that is, a variance-covariance matrix form that placed no restriction of the variance-covariance structure. With regard to hypothesis testing, the GEE version of the Wald test was utilized to test the global hypothesis that for practice events, the number of impacts per PRLA threshold

was uniformly (i.e., across all PRLA thresholds) the same for the players from different teams. Wald tests were additionally used to examine on a per-PRLA threshold basis, team differences in the mean number of impacts per practice event in which the PRLA 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 be ≤ 0.05 .

Analysis of PRRA threshold. A negative binomial GEE model was utilized to analyze the number of impacts per practice event in which the athletes experienced a peak resultant rotational acceleration >0 rad/sec², 2000 rad/sec², 4000 rad/sec², 6000 rad/sec², 8000 rad/sec², 10,000 rad/sec², 12,000 rad/sec², and 14,000 rad/sec². The GEE analysis was conducted in exactly the same way as the PRLA threshold analysis.

Analysis of the cumulative impact burden per practice event. Impact burden measures, PRLA sum and PRRA sum, were calculated per athletic exposure (a single practice or game event) by summing each impact linearly weighted by its severity as a measure of “cumulative impact burden.”⁶¹ There is currently no widely accepted metric specifically for the quantification of cumulative impact burden. Many studies that try to quantify impact burden use the summation of a metric that was developed for individual impacts.^{19,44,51,60,61,65,66} study chooses to use PRLA sum and PRRA sum, for their ease of calculation, and to match similar studies with the same accelerometer.^{60,67} The GEE version of the Cox proportionate hazard model was used to compare the empirical cumulative distribution for PRLA sum per practice between players from different teams as well as to compare the empirical cumulative distribution of PRRA between players from different teams. This approach was utilized so that the *intra-player* measurement correlation would be accounted for in the null hypothesis test that the underlying PRLA sum per practice cumulative distribution is the same for players from different teams.

Analyses of team differences in game events. Team differences in the number of impacts experienced by the players during games, and team differences in the impact forces experienced by the players during games were analyzed in the same way as the practice impact frequency data and practice impact force practice data. The only major differences were that this set of analyses focused on game events as opposed to practice events, and that this set of analyses focused only on the athletes who had game data that met the aforementioned inclusion criteria. To account for differences that were possibly caused by different game inclusion criteria for the teams, additional analyses were performed with the same inclusion criteria used for all teams: the athlete wore the sensor during the game event. Hereafter, this analysis will be referred to as: “all games included” analysis. Table S1 contains a detailed account the “all games included” athletic exposures (see online supplementary material at <http://www.liebertpub.com>).

Software package. SAS version 9.4 (SAS Institute Inc., Cary, NC) was used to conduct the statistical analyses. Graphic displays were created with the statistical software of Spotfire S plus (TIBCO Inc., Palo Alto, CA).

Results

Participants

Results include data from 788 practices and 102 games from CF, 369 practices and 104 games from HF, 943 practices and 37 games from CL, and 480 practices and 28 games from CS. Table 1 contains a detailed account of all captured athletic exposures.

Number of impacts per event

For practices, CF resulted in the most impacts per athlete per event, followed by CS, followed by HF, and then CL (mean impacts/practice: 13.2, 95% CI: [10.3, 16.9]; 7.4, 95% CI [5.1, 10.9]; 5.3, 95% CI [3.3, 8.5]; and 3.1, 95% CI [2.4, 4.0], respectively). However for games, CS > CF > HF > CL (mean impacts/game: 31.1, 95% CI: [15.3, 63.0]; 24.2, 95% CI [17.4, 33.8]; 14.3, 95% CI [9.2, 22.3]; and 11.5, 95% CI [8.3, 16.0], respectively). Pairwise comparisons show Bonferroni-corrected significant differences in the ratio of means (RoM) for number of head impacts per event for HF:CF practices (RoM: 0.41, $p=0.012$), CL:CF practices (RoM: 0.24, $p<0.001$), CL:CS practices (RoM: 0.42, $p=0.001$), and CL:CF games (RoM: 0.47, $p=0.010$) (Fig. 1B). Analysis with all games included did not add or remove any significant team differences in number of impacts per game (Fig. S1A) (see online supplementary material at <http://www.liebertpub.com>).

Geometric mean PRLA per event

For practices, CF resulted in the highest geometric mean PRLA per athlete per event, followed by HF, followed by CL, and then CS (geometric mean PRLA/practice: 26.8g, 95% CI: [25.0, 28.7]; 25.2g, 95% CI [23.4, 27.2]; 21.3g, 95% CI [19.9, 22.8]; and 18.5g, 95% CI [17.2, 19.9], respectively). The same order held true for games, CF > HF > CL > CS (geometric mean PRLA/game: 29.3g, 95% CI: [26.0, 32.9]; 27.1g, 95% CI [25.2, 29.1]; 21.1g, 95% CI [18.6, 24.0]; and 17.6g, 95% CI [15.7, 19.8], respectively). Pairwise comparisons show Bonferroni-corrected significant differences in the ratio of geometric mean PRLA per event for CL:CF practices (RoM: 0.80, $p<0.001$), CS:CF practices (RoM: 0.69, $p<0.001$), CS:HF practices (RoM: 0.74, $p<0.001$), CS:CL practices (RoM: 0.87, $p<0.001$), CL:HF practices (RoM: 0.85, $p<0.001$), CL:CF games (RoM: 0.72, $p=0.003$), CS:CF games (RoM: 0.60, $p<0.001$), CS:HF games (RoM: 0.65, $p<0.001$), and CL:HF games (RoM: 0.78, $p=0.009$) (Fig. 1C). Analysis with all games included resulted in lost significance between CL:CF (RoM: 0.84, $p=0.259$) and CL:HF (RoM: 0.89, $p=0.682$) games and increased effects between CS:CL (RoM: 0.74, $p=0.004$) games in geometric mean PRLA per game (Figure S1B).

Geometric mean PRRA per event

For practices, CF resulted in the highest geometric mean PRRA per athlete per event, followed by HF, followed by CL, and then CS (geometric mean PRRA/practice: 5140.0rad/sec², 95% CI [4676.4, 5649.5]; 4327.1rad/sec², 95% CI [3817.9, 4811.2]; 3817.9, 95% CI [3470.1, 4200.5]; and 2960.4rad/sec², 95% CI [2674.2, 3277.2], respectively). The same order held true for games, CF > HF > CL > CS (geometric mean PRRA/game: 5805.8rad/sec², 95% CI [5030.9, 6700.0]; 4796.6rad/sec², 95% CI [4056.2, 5672.1]; 3603.1rad/sec², 95% CI [2756.6, 4709.4]; and 2713.8rad/sec², 95% CI [2617.9, 2813.2], respectively). Pairwise comparisons showed Bonferroni-corrected significant differences in the ratio of geometric mean PRRA per event for all practices HF:CF (RoM: 0.84, $p<0.001$), CL:CF (RoM: 0.74, $p<0.001$), CS:CF (RoM: 0.58, $p<0.001$), CS:HF (RoM: 0.68, $p<0.001$), CS:CL (RoM: 0.78, $p<0.001$), CL:HF (RoM: 0.88, $p=0.036$), and CL:CF games (RoM: 0.62, $p=0.018$), CS:CF games (RoM: 0.47, $p<0.001$), and CS:HF games (RoM: 0.56, $p<0.001$) (Fig. 1D). Analysis with all games included resulted in lost significance between CL:CF games (RoM: 0.74, $p=0.052$) and increased effects between CS:CL games (RoM: 0.72, $p=0.011$) in geometric mean PRRA per game (Fig. S1C).

TABLE 1. SUMMARY FOR EACH SUBJECT'S CAPTURED ATHLETIC EVENTS

Participant number	Position	Practice summary				Game summary			
		Number of events	Mean hits per practice	Geometric mean PRLA per hit per practice (g)	Geometric mean PRRA per hit per practice (rad/sec ²)	Number of events	Mean hits per game	Geometric mean PRLA per hit per game (g)	Geometric mean PRRA per hit per game (rad/sec ²)
CF1	FB	57	9.5	34.8	6411.6	12	13.6	35	7165.6
CF2	FB	61	13.8	29.1	5098.3	8	12.3	33.1	6250.8
CF3	SS	48	18.3	32.7	6708.6	9	32.2	32.5	7148.4
CF4	DT	63	18.2	25.6	5408.3	3	10	20.8	4439.1
CF5	WR	56	5.6	24	4794.5	10	19.6	27.2	5203
CF6	LB	32	15.2	23.8	4267.5	7	23.7	27.4	5084.8
CF7	FS	23	8.2	25.1	5206.1	-	-	-	-
CF8	DE	58	13.4	27.5	5471.7	11	15.3	32.4	5878.3
CF9	WR	60	9.4	17.8	2593.3	8	33	17.1	3084.7
CF10	DT	41	23.2	25.8	4890.9	4	36	27.2	5253.6
CF11	T	29	15.6	23.5	4698.1	1	23	31.6	4427.4
CF12	TE	50	6.5	21.5	4617.9	8	20.3	26.2	5341.6
CF13	DT	63	27.1	32.3	6432.8	11	55.5	33.5	7519.2
CF14	LS	39	4.2	22.1	5056.5	1	1	15.2	3644.7
CF15	CB	60	8.8	29.7	5128.7	-	-	-	-
CF16	LB	48	10.7	45.7	9239.5	9	17.4	35.1	7087.9
Mean (SD) or GM [†]		47.0 (12.9)	13.8 (12.3)	27.2 [†]	5212.9 [†]	7.3 (3.6)	24.2 (13.2)	29.3 [†]	5805.8 [†]
Median		50.5	12	25.7	5113.5	8	19.9	29.5	5297.6
Range		(22, 61)	(4.2, 27.1)	(17.8, 45.7)	(2593.3, 9239.5)	(1, 12)	(1, 55.5)	(15.2, 35.1)	(3084.7, 7519.2)
HF1	WR and CB	14	3.6	24.9	4136.7	3	13.3	29.8	6335.1
HF2	WR and FS	20	2.2	29.1	4443.8	5	2.6	29.8	6708.8
HF3	WR and CB	28	1.6	26.3	4743.5	10	16.2	30.2	5484.4
HF4	QB	31	1.1	26.3	3309.3	10	3.3	22.4	3105.7
HF5	DL	24	1.4	30.4	7022.9	8	3.3	33.9	9023.3
HF6	OL and LB	20	6.2	25.8	4403.1	6	31	26.3	3745.7
HF7	WR and CB	22	2.7	24.7	4506.8	5	2.4	21.7	2723.4
HF8	WR	26	4.7	31	6433.7	10	4.3	29.7	5765.6
HF9	WR	33	3.2	21.6	2568.3	9	38.1	25.6	4736.6
HF10	G	38	8.2	21.9	4761.9	9	17.6	25.4	4896.5
HF11	OL and DT	19	5.3	23	4316.6	6	28	33.2	6224.4
HF12	C	29	16.8	27.1	5590.3	6	27.3	25.6	4134.9
HF13	LB	21	1.8	20.4	2942.1	5	5.2	26.5	4890.2
HF14	OL and DL	23	6.1	23.1	4085.9	7	2.6	24.8	2947.1
HF15	RB and WR	21	3.3	23.4	3441.8	7	14.6	25.8	5357.9
Mean (SD) or GM [†]		24.6 (6.2)	4.8 (7.5)	24.9 [†]	4307.8 [†]	7.1 (2.2)	14.3 (11.9)	27.1 [†]	4796.6 [†]
Median		23	3.3	24.9	4403.1	7	13.3	26.3	4896.5
Range		(14, 38)	(1.1, 16.8)	(20.4, 31.0)	(2568.3, 7022.93)	(3, 10)	(2.4, 38.1)	(21.7, 33.9)	(2723.4, 9023.3)
CL1	Midfield	47	2.6	21.8	3959.3	4	13.3	26.3	4377.4
CL2	Attack	60	2.5	27.2	4883	-	-	-	-
CL3	Midfield	73	3.3	22.4	4099.8	-	-	-	-
CL4	Attack	77	3.8	23.5	4614	11	12.1	23.2	4591.8
CL5	Attack	20	7	26.4	5996.7	-	-	-	-
CL6	Midfield	63	2	15.7	2222.8	-	-	-	-
CL7	Midfield	63	2	24.6	4323.6	-	-	-	-
CL8	Midfield	63	3.9	21.5	4052.7	-	-	-	-
CL9	Midfield	66	1.4	18.7	3212.8	11	6.4	20.4	3627.4
CL10	Midfield	74	3	20.5	4201.7	-	-	-	-
CL11	Midfield	59	1.4	21.7	4015	-	-	-	-
CL12	Midfield	81	5.9	14.8	1938.5	-	-	-	-
CL13	Midfield	74	5.5	17.3	2796.1	11	15.4	17.7	2438.5
CL14	Defense	67	2.1	31.2	5806.9	-	-	-	-
CL15	Defense	56	1.3	24.9	4594.8	-	-	-	-
Mean (SD) or GM [†]		24.6 (6.2)	3.1 (4.4)	21.3 [†]	3751.9 [†]	9.3 (3.5)	5.5 (6.1)	24.6 [†]	4350.7 [†]
Median		23	2.6	21.8	4099.8	11	2.4	24.7	4365
Range		(14, 38)	(1.3, 7.0)	(14.8, 31.2)	(1938.5, 5996.7)	(4, 11)	(0, 10.8)	(14.4, 33.3)	(947.2, 6687.6)

(continued)

TABLE 1. (CONTINUED)

Participant number	Position	Practice summary				Game summary			
		Number of events	Mean hits per practice	Geometric mean PRLA per hit per practice (g)	Geometric mean PRRA per hit per practice (rad/sec ²)	Number of events	Mean hits per game	Geometric mean PRLA per hit per game (g)	Geometric mean PRRA per hit per game (rad/sec ²)
CS1	Goalkeeper	18	14.4	24.3	4843.1	-	-	-	-
CS2	Defense	13	8.2	20.3	3373.7	-	-	-	-
CS3	Defense	11	1.1	34.3	5974.3	-	-	-	-
CS4	Midfield	16	5.1	19.2	3264.5	-	-	-	-
CS5	Midfield	8	3.1	24.4	4096	-	-	-	-
CS6	Defense	50	5.5	16.3	2290.3	7	20.9	18.1	2589.8
CS7	Midfield	52	6.5	15.2	2115.1	-	-	-	-
CS8	Forward	43	6.2	17.1	2625.5	7	18	19.9	2726.6
CS9	Midfield	49	3.4	18.6	3354.8	-	-	-	-
CS10	Defense	46	5.7	18.4	2759.8	5	17	19.7	2825.6
CS11	Defense	50	19.8	15.7	2795	7	71	15.1	2817
CS12	Goalkeeper	30	7	19.5	3544.7	-	-	-	-
CS13	Defense	27	5.7	17.3	2852	-	-	-	-
CS14	Goalkeeper	35	5	15.9	2366.2	-	-	-	-
CS15	Goalkeeper	32	7.7	18.3	3337.2	2	8.5	13.7	2494.1
Mean (SD) or GM [†]		32.0 (15.9)	7.4 (9.6)	17.8 [†]	2862.1 [†]	5.6 (2.2)	31.1 (23.2)	17.6 [†]	2713.8 [†]
Median		32	5.7	18.4	3264.5	7	18	18.1	2726.6
Range		(8, 52)	(1.1, 19.8)	(15.2, 34.3)	(2115.1, 5974.3)	(5, 7)	(8.5, 71.0)	(13.7, 19.9)	(2494.1, 2825.6)

For each athlete, the following information is provided: player position, number of captured events for each event type, mean number of impacts for each event type, geometric mean peak resultant linear acceleration (PRLA) per impact per event, and peak resultant rotational acceleration (PRRA) per impact per event.

[†]Geometric mean.

CF, college football; HF, high school football; CL, college lacrosse; CS, college soccer; FB, fullback; SS, strong safety; DT, defensive tackle; WR, wide receiver; LB, linebacker; FS, free safety; DE, defensive end; T, offensive tackle; TE, tight end; LS, long snapper; TB, tailback; CB, corner back; QB, quarterback; DL, defensive line; OL, outside linebacker; G, offensive guard; C, center; RB, running back.

Number of impacts above thresholds

For practices, the distributions for number of impacts per athlete per event, with respect to multiple linear and rotational acceleration thresholds, differed among CF, HF, CS, and CL ($p < 0.001$ for all pairwise comparisons) (Fig. 2 A,B). Threshold by threshold post-hoc pairwise ratio of means comparisons showed sport differences in the mean number of impacts per practice at several linear and rotational acceleration thresholds after Bonferroni correction (Fig. 2 C,D and Table S2) (see online supplementary material at <http://www.liebertpub.com>).

Compared with CF practices, trends across multiple PRLA and PRRA thresholds have practices for HF at ~26%, CS at ~18%, and CL at ~11% the number of CF impacts, with the percentage generally dropping as the thresholds increase. For games, the distributions for number of impacts per athlete per event, with respect to multiple linear and rotational acceleration thresholds, differed among CF, HF, CS, and CL ($p \leq 0.017$ for all pairwise comparisons) (Fig. 3 A,B). Threshold by threshold post-hoc pairwise ratio of means comparisons showed sport differences in the mean number of impacts per game at several linear and rotational acceleration thresholds after Bonferroni correction (Fig. 3 C,D and Table S3) (see online supplementary material at <http://www.liebertpub.com>).

Compared with CF games, trends across multiple PRLA and PRRA thresholds have games for HF at ~54%, CS at ~42%, and CL at ~20% the number of CF impacts, with the percentage generally decreasing as the thresholds increase. Analysis with all games included resulted in lost significance between HF:CF games

($p = 0.332$) in the distributions for number of impacts per athlete per event, with respect to multiple linear acceleration thresholds (Fig. S2A) (see online supplementary material at <http://www.liebertpub.com>).

Analysis with all games included did not add or remove any significant team differences in the distributions for number of impacts per athlete per event, with respect to multiple rotational acceleration thresholds (Fig. S2B). Threshold by threshold post-hoc pairwise ratio of means comparisons showed changes in sport differences in the mean number of impacts per game at some linear and rotational acceleration thresholds after Bonferroni correction (Fig. S2 C,D and Table S4) (see online supplementary material at <http://www.liebertpub.com>).

Cumulative impact load per event

The Kaplan–Meier forms of the cumulative distributions for impact burden (a summation of the impacts that are each weighted by severity) per athletic exposure are shown in Figure 4 A and B with regard to linear acceleration, and in Figures 4 C and D with regard to rotational acceleration. During practice, linear acceleration cumulative distributions differed among all pairwise comparisons (Bonferroni corrected $p \leq 0.05$) with the exception of the comparison of HF-to-CS, with the median of the linear acceleration distribution being greatest for CF (277.3g, 95% CI [249.4, 309.6]), followed by HF (63.1g, 95% CI [56.0, 73.5]) and CS (84.9g, 95% CI [73.0, 94.9]), and then CL (41.6g, 95% CI [36.8, 46.9]) (Fig. 4A). During games, linear acceleration cumulative distributions differed for comparisons of CF-to-CS, CF-to-CL, CS-to-CL,

FIG. 2. Graphs of the mean number of impacts greater than the peak resultant linear acceleration (PRLA) (A) or peak resultant rotational acceleration (PRRA) (B) threshold for college football (CF), high school football (HF), college lacrosse (CL), and college soccer (CS) practices. Vertical lines identify the 95% CI for the mean number of impacts per practice greater than threshold. Graphs show the ratio of means for comparing the mean number of impacts greater than the PRLA (C) or PRRA (D) threshold between CF practices and HF, CL, and CS practices. Data points identify the mean impact rate ratio (e.g., HF:CF practices) and vertical lines identify the Bonferroni-corrected 95% CI. Dotted line identifies the line of equality (i.e., ratio equals 1).

and HF-to-CL (Bonferroni corrected $p \leq 0.05$), but not between any other pairwise comparisons, with CL resulting in the lowest linear acceleration distribution (median: CF-567g, 95% CI [453, 691]; CS-410g, 95% CI [261, 471]; HF-202g, 95% CI [128, 302]; CL-101g, 95% CI [55, 144]) (Fig. 4B). Analysis with all games included resulted in lost significance between CF-to-CS games in cumulative linear impact load per event (Fig. S3A) (see online supplementary material at <http://www.liebertpub.com>).

During practice, rotational acceleration cumulative distributions also differed between all pairwise comparisons (Bonferroni corrected $p \leq 0.05$) with the exception of the comparison of HF-to-CS, again with the median of the rotational acceleration distribution being greatest for CF (53,800 rad/sec²; 95% CI [47,200, 61,700]), followed by HF (11,200 rad/sec²; 95% CI [9,200, 13,400]) and CS (13,900 rad/sec²; 95% CI [11,800, 16,300]), and then CL (7,600 rad/sec²; 95% CI [6,800, 8,600]) (Fig. 4C). During games, rotational acceleration cumulative distributions differed for comparisons of CL-to-CS, CL-to-HF, and CL-to-CF (Bonferroni corrected $p \leq 0.05$), but not between any other pairwise comparisons, again with CL resulting in the lowest rotational acceleration distribution median (median: CF-111,800 rad/sec², 95% CI [90,200, 139,700]; CS-61,700 rad/sec², 95% CI [33,300, 68,600]; HF-

41,800 rad/sec², 95% CI [29,300, 59,700]; CL-40,200 rad/sec², 95% CI [27,300, 55,000]) (Fig. 4D). Analysis with all games included did not add or remove any significant team differences in cumulative linear impact load per event (Fig. S3B)

Discussion

This study quantitatively describes differences in head impact frequency and severity during live play of CF, HF, CS, and CL. While the majority of these impacts do not result in a clinical diagnosis of concussion, the hypothesized short-term and long-term effects of repetitive subconcussive head impacts on brain structure^{14,15,19,21} and function,^{13,15–17} coupled with their proposed role in increasing susceptibility to neurodegenerative disorders,^{22,23} suggest that quantification of subconcussion may be important for assessing each sport's overall safety. Previous studies have measured the frequency and severity of subconcussive head impacts in these sports, but methodological differences in impact measurement or estimation have generally made it difficult to compare their results. This is the first study to use the same biomechanical sensor to quantify subconcussion in disparate sports to provide data for a direct comparison among them.

FIG. 3. Graphs of the mean number of impacts greater than the peak resultant linear acceleration (PRLA) (A) or peak resultant rotational acceleration (PRRA) (B) threshold for college football (CF), high school football (HF), college lacrosse (CL), and college soccer (CS) games. Vertical lines identify the 95% CI for the mean number of impacts per game greater than threshold. Graphs show the ratio of means for comparing the mean number of impacts greater than the PRLA (C) or PRRA (D) threshold between CF games and HF, CL, and CS games. Data points identify the mean impact rate ratio (e.g., HF:CF games) and vertical lines identify the Bonferroni-corrected 95% CI. Dotted line identifies the line of equality (i.e., ratio equals 1).

CF has the most impacts per practice and second most per game, as well as the highest average linear and rotational impact severity. These high values for CF cause it to have the highest impact burden (PRLA and PRRA sum per event) of all of the quantified teams. HF has the third most impacts per event, but an average linear and rotational impact severity per game and average linear impact severity per practice that is on par with CF. CS has the second most impacts per practice and most impacts per game, but has the lowest average linear and rotational impact severity. Interestingly, HF's moderate impact rate with high average impact severity and CS's high impact rate with low average impact severity results in statistically equivalent impact burden curves. CL has the fewest impacts per event and the third lowest average linear and rotational impact severity per practice and per game. Ultimately, the low impact rate and relatively low impact severity causes CL to have the lowest impact burden in both practices and games.

The ratio of means plots at multiple linear and rotational acceleration thresholds for practices and games shows that differences in the number of impacts per event are consistent across multiple thresholds. The exception is CS, which experienced a sharp drop in the number of impacts as the linear acceleration threshold increased from 10g to 20g. At 10g, CS is second to, or

higher than CF in number of impacts per event (CS:CF RoM = 0.56/practice, 1.28/game), but is much lower at 20g (CS:CF RoM = 0.21/practice, 0.49/game). McCuen and coworkers hypothesized that head accelerations of 10–20g in soccer could be caused by “hard stops, cuts, and hard kicks.”⁶⁰ Both football and lacrosse have hard stops and cuts, but hard kicks are unique to soccer, and may be responsible for the higher proportion of low severity head accelerations in soccer. Although these head accelerations may not be caused by a direct impact to the head, the lower limits of physiological relevance for head acceleration is not known; therefore, this study analyzed all impacts recorded by the sensor, which triggers at 10g.

The present study has several notable points of agreement and disagreement with published live play data using the helmet-based Head Impact Telemetry System (HITS) in football. CF's 13.2 impacts per practice and 24.2 impacts per game are a little higher than the reported range for CF from Crisco and coworkers: 4.8–7.5 impacts per practice and 12.1–16.3 impacts per game.⁴³ CF's PRLA per impact of 26.8g and 29.3g for practices and games, respectively, are similar to published values for PRLA per impact in CF, which range from 20.5g to 32.0g,^{34,37,42,45} but CF's PRRA per impact of 5140.0 rad/sec² and 5805.8 rad/sec² for practices and

FIG. 4. Graphs showing cumulative distributions per event for the peak resultant linear acceleration (PRLA) sum during practices (**A**) and games (**B**) and for the peak resultant rotational acceleration (PRRA) sum during practices (**C**) and games (**D**). The cumulative distribution is expressed as cumulative probability for observing a single athletic exposure PRLA or PRRA sum greater than X. Curves with different lowercase letters (**a–c**) differed at the $p \leq 0.05$ Bonferroni-corrected level of statistical significance.

games, respectively, is substantially higher than the published values for PRRA per impact in CF which range from 1355 rad/sec² to 1400 rad/sec².^{42,45} Similarly, HF's 5.3 impacts per practice and 14.3 impacts per game are similar to published values for HF, which range from 3.1 to 10.7 impacts per practice and 15.7 to 28.7 impacts per game.^{41,49,61,65} HF's PRLA per impact of 25.2g and 27.1g for practices and games, respectively, were also similar to published values in HF, which range from 21.9g to 28.6g,^{41,49,51,61,65,68} but HF's PRRA per impact values, 4327.1 rad/sec² for practices and 4796.6 rad/sec² for games, are more than double the highest published values in HF, which range from 973 rad/sec² to 1777 rad/sec².^{41,49,51,61,65,68} The difference between the presented data and the published data could reflect true head impact differences in our population; however, it is more likely the result of measurement differences between the xPatch and HITS, with xPatch likely overestimating PRRA values. HITS is a helmet-mounted sensor system that was used to collect most of the published football data, but its helmet-mounted nature does not allow for use in non-helmeted sports such as lacrosse and soccer.

CS's impact data values of 7.4 impacts per practice with an average PRLA and PRRA per impact of 18.5g and 2960.4 rad/sec², and 31.1 impacts per game with an average PRLA and PRRA per impact of 17.6g and 2713.8 rad/sec² differ with some of the published data for soccer. One study used a modified accelerometer suite from HITS, and measured head impacts during a small number of scrimmages; they reported an average PRLA and PRRA

per impact of 19.4g and 1666.8 rad/sec² for non-header impacts.⁵⁸ McCuen and coworkers also used the xPatch sensor to measure head impacts during high school (girls') and college (women's) soccer, and they reported an average PRLA and PRRA per impact of 37.6–39.3g and 7523–7713 rad/sec².⁶⁰ However, these differences are likely driven by their decision to use a minimum threshold of 20g in their analysis; because the distribution of head impact severities is highly weighted toward lower values, differences in the minimum threshold can have large effects on the calculated average severity values.⁶⁹ This reality makes it difficult to compare published results from biomechanical studies of head impact, as the minimum threshold is arbitrarily set for each study (although 10g, 15g, or 20g thresholds seem to be most common). In the present study, we chose to use the default 10g setting of the device, as the minimum threshold for physiologically significant impacts is unknown. Further, a plurality of biomechanical head impact studies in sport use a 10g threshold,⁶⁹ which enables wider comparison with the existing literature across sports.

The most current analysis on the epidemiology of sports-related concussion in college sports reports that CF, CS, and CL have concussion incidence rates of 30.07, 9.69, and 9.31 concussions per 10,000 games, and 4.20, 1.75, and 1.95 concussions per 10,000 practices, respectively.⁷ If the incidence of concussion is tied to head impact exposure, it would follow that one of the head impact metrics would mirror concussion incidence, with football much higher than soccer and lacrosse but with similar values for soccer

and lacrosse. CF indeed has the highest number of impacts per event, but for impacts per game, CS is close to CF and much higher than CL. CF also has the highest average PRLA and PRRA per impact, which is significantly higher than for CS and CL for both practices and games. CS and CL are differentiable in average PRLA and PRRA per impact in practices but not in games. Median PRLA and PRRA sum per game is 567g and 111,800 rad/sec² for CF, 410g and 61,700 rad/sec² for CS, and 219g and 40,200 rad/sec² for CL. Median PRLA and PRRA sums per practice are 277.3g and 53,800 rad/sec² for CF, 84.9g and 13,900 rad/sec² for CS, and 41.6g and 7,600 rad/sec² for CL. Although none of these metrics exactly mirror the relative concussion rates, average impact severity comes closest to matching the pattern of concussive risk in these sports.

Limitations

Several factors could affect the generalizability of the comparisons among these teams. This study reports findings from only one CF team, one HF team, one CL team, and one CS team. The college teams were Division I, with a national championship men's soccer team, a top 20 men's lacrosse team, and an unranked football team. The HF team was from a small private school in the Virginia Independent Schools Athletic Association Division II. In football, head impact can be affected by the style of offensive play,⁴⁹ and given that in this study only one team represents each sport, the results could be affected by team selection (i.e., less elite lacrosse or soccer teams could result in lower head impact values, and/or more competitive football teams could result in higher head impact values). Considering that CF had the highest impact burden, HF and CS tied in the middle, and CL had the lowest, it would stand to reason that choosing more competitive football teams or less competitive soccer and lacrosse teams would only further differentiate the teams' head impact values.

The xPatch accelerometer used in the present study appears in eight published studies,^{60,62,65,66,70-73} three of which test biomechanical validity in different settings.^{60,62,73} Wu and coworkers compared the *in vivo* performance of the xPatch against video capture in a simulated low-impact soccer setting; that study examined 25 impacts, one impact location, one mastoid placement location, and one xPatch device. In one subject, they found the xPatch overestimated individual linear and rotational accelerations (normalized root-mean-squared error [RMSE] of 120% for PRLA and 290% for PRRA) in ways likely related to the viscoelastic properties of that individual's soft tissues.⁶² Using a Hybrid III headform model, Cummiskey and coworkers performed the most thorough comparison to date comparing the reliability and accuracy of helmet-mounted against head-mounted accelerometer systems.⁷³ The study included both the commonly used HITS and the xPatch, among other helmet- and head-mounted accelerometer systems. Cummiskey and coworkers delivered 140 impacts across seven impact locations to evaluate each device and sensor location. The xPatch did produce considerable error across impact locations (RMSE of 8–58% for PRLA and 11%–350% for PRRA), but across devices, sensor locations, and impact locations, the xPatch produced RMSE that were considerably lower than, or at least comparable with, the RMSE produced by the HITS.⁷³ The Hybrid III system used by Cummiskey and coworkers does not account for xPatch measurement error caused by skin displacement,⁶² nor does it account for HIT system measurement error caused by differential helmet fitment.⁷⁴

As a prelude to a live play soccer study, McCuen and coworkers⁶⁰ evaluated xPatch performance on a Hybrid III headform; this study

examined 250 impacts, spread over five impact locations, in two mastoid placement locations, and included data from five different xPatch devices. McCuen and coworkers also found significant xPatch measurement error related to individual impacts (RMSE of ~50% for individual PRLA and PRRA values). However, McCuen and coworkers also looked at aggregate performance over larger numbers of impacts and concluded, “average values over a large number of acceleration events can be determined with good accuracy.”⁶⁰ The present study uses the xPatch in this manner. In support of this claim from McCuen and coworkers, a separate publication studying CF with the same xPatch sensor⁶⁶ reported head impact quantities and linear acceleration severities comparable with those in similar studies using helmet-based systems.^{36,37,41,42,45} But in the same study, discrepancies existed between rotational severity of head impact measured by the mastoid accelerometer and similar published data from helmeted systems. The high PRRA values reported by the xPatch, relative to published values, could be a result of the xPatch overestimating rotational acceleration values. Results from Wu and coworkers⁶² indicate that PRRA overestimation may be caused by movement of the skin under the xPatch.

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; however, if the errors are systematic or random, comparison across situations and groups with large numbers of impacts should still be valid. The present study addresses this limitation by testing relative impact comparisons (college vs. high school and football vs. soccer vs. lacrosse) rather than focusing on the absolute values reported.

Conclusion

This study demonstrates how a mastoid patch accelerometer can be deployed in a variety of helmeted and non-helmeted sports to collect head impact data that can be used to compare the relative subconcussive head impact burden in each sport. Although the concept of subconcussion is drawing increased attention from the scientific, medical, and athletic communities, it is still unclear how subconcussion relates to concussion incidence, and what levels of subconcussive head impact are physiologically relevant. However, the variety and gravity of the research-supported consequences of subconcussion make the head impact profile of each sport (impacts/event, PRLA/impact, PRLA sum/event) an important aspect in the evaluation of a sport's risk, just as the incidence of concussion or knee injuries has been for decades. In response to concerns about subconcussion, governing bodies for multiple sports are actively investigating ways to reduce their athletes' unnecessary head contact. CF players may experience the highest values for nearly every head impact metric; however, there is also a wide range of head impacts that can occur among different contact or collision sports. Level of play (high school vs. college) and type of sport (football vs. soccer vs. lacrosse) each have sizable effects on head impact values, indicating that larger and more comprehensive studies are still needed for each sport at every level of play to understand the amount of head impact experienced by the athletes. Open topics that could be addressed by large-scale quantification of head impact in sport include determining the effects of: competition level (youth to professional), gender in similar sports, player position, rule changes, and changes to protective equipment. This information could be useful in reducing the head impact across all contact and collision sports.

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Author Disclosure Statement

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