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Research Article

The Effect of Soccer and Lacrosse Participation and Video Verified Head Impact Biomechanics on Clinical Concussion Measures

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ABSTRACT

Neurocognitive changes have been found in participants of contact sports without documented concussions, raising concerns regarding the long-term consequences of subconcussive head impacts in sport. However, sex comparisons of neurocognitive change without reported concussions have not been completed for soccer or lacrosse athletes. Our purpose was to determine changes in clinical measures of cognitive function in uninjured collegiate lacrosse and soccer players. Men's soccer (N=23), women's soccer (N=36), men's lacrosse (N=28) and women's lacrosse (N=31) players wore xPatch head impact monitoring sensors for all practices and games. Sensors measured peak linear accelerations and peak rotational accelerations, allowing for daily density calculations. Participants completed the Sport Concussion Assessment Tool 3 and Immediate Post-Concussion and Cognitive Testing at the beginning and end of the season. For women, multiple statistically significant relationships were identified [decreased reaction time with increased cumulative peak linear acceleration (r_s=-0.30, *P*=0.03), peak linear acceleration daily density (r_s=-0.31, *P*=0.04), and peak rotational acceleration daily density (r_s=-0.31, *P*=0.03) and also Immediate Post-Concussion and Cognitive Testing symptom change increased with increased cumulative peak linear acceleration (r_s=-0.38, *P*=0.008) and cumulative peak rotational acceleration (r_s=-0.37, *P*=0.009)]. For men, cognitive change scores, specifically concentration, had the only statistically significant relationship with cumulative peak rotational acceleration (r_s=0.32, *P*=0.02). Men had a greater number of changes over the course of the season compared to women; however, the changes did not appear related to head impact biomechanics. Women had many statistically significant correlations between head impacts and deterioration in some constructs, especially symptoms.

Highlights

i. Men had a greater number of changes over the course of the season; however, the changes noted did not appear related to head impact biomechanics.
ii. Women had several statistically significant correlations between head impacts and deterioration in some constructs, especially symptoms and reaction time.
iii. We also noted statistically significant changes over the course of the season, but these were likely attributed to the learning effects of the tests utilized.

Introduction

Sport-related head injuries and impacts are significant health problems in the United States. Approximately 10,560 sport-related concussions (SRCs) are reported per year in 25 National Collegiate Athletic Association (NCAA) sports (4.47 injuries per 10,000 athlete exposures

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(AE)) [1]. Soccer and lacrosse are contact sports that have been shown to have a high rate of SRC [1]. The overall rate of SRC was 6.31 per AE for women and 3.44 per AE for men's soccer players [1]. There has been a growing body of evidence supporting differences in SRC profile and recovery between men's and women's athletes. Women tend to sustain more SRCs when playing the same (or similar) sports and it has been reported that woman athletes have a longer duration of symptoms [1-6].

In recent years, in addition to SRCs, there has been growing interest in the effect of subconcussive head impacts on neurological health. Cumulative subconcussive impacts have been of interest in elucidating a potential relationship to the progression of brain injury in athletes [7-9]. While previous studies have shown cognitive changes as measured by functional magnetic resonance imaging (fMRI) and EEG following participation in football, such findings have not been consistently replicated in football or other sports such as soccer and lacrosse [7, 10-12]. Head impact biomechanics of lacrosse players have been found to correlate with BESS scores [13]. However, balance and symptoms have been found to remain stable without clinically meaningful change after competing in contact and non-contact sports [14].

Soccer and lacrosse are both popular sports played by men and women of all ages. While soccer is the most popular sport world-wide, in the United States, there has been a large increase in participation in lacrosse for both men and women [15]. The rules for lacrosse differ for men's and women's athletes [16, 17]. Men's lacrosse is considered a collision sport, where body checks are allowed (although direct contact to the head is not). Whereas, for women, body checking is not allowed. Because of rule differences, male athletes are required to wear helmets with facemasks, mouth guards, shoulder pads, elbow pads, and gloves. Women athletes are required to wear a very limited amount of protective equipment – eye protection and mouth guards only. Despite the differences, the SRC rate for NCAA women's lacrosse athletes is reportedly higher than men (5.21/AE vs. 3.81/AE) [6].

Due to the risk of exposure to head impacts in both soccer and lacrosse, and the concerns for neurocognitive changes due to these impacts, the purpose of the current study was to determine whether there are changes in clinical measures of cognitive function, despite the absence of a concussion diagnosis, after a single season of collegiate lacrosse and soccer for men and women. We also examined whether head impacts were related to cognitive changes over a single season. We hypothesized that clinical measures would diminish following a single season of either lacrosse or soccer. In addition, we hypothesized that those participants with higher head impact burdens would experience more diminished neurocognitive scores.

Materials and Methods

I Participants

We recruited collegiate men's soccer (N=23, age=19.7±1.3 years, height=181.55±5.93 cm, mass=76.71±10.90 kg), women's soccer (N=36, age=19.6±1.3 years, height=165.04±5.20 cm, mass=62.84±6.37 kg), men's lacrosse (N=28, age=20.8±1.1 years, height=180.61±5.63 cm, mass=81.23±5.71 kg) and women's lacrosse (N=31, age=20.1±1.0 years, height=166.03±5.10 cm, mass=63.45±7.26 kg) players from NCAA Division III varsity athletics during two athletic seasons (N=112 total participants). Participants were sent a recruitment email if they were 18 years or older and currently listed on the roster for each team. We included data from participants who completed baseline and post-season tests and did not sustain a concussion during the data collection period.

II Neurocognitive Testing and Instrumentation

The SCAT3 assesses patients' current symptoms for SRC and contains the Standardized Assessment of Concussion (SAC), which is a cognitive screening assessing orientation, immediate memory, delayed recall and concentration, and the modified Balance Error Scoring System (BESS). The SCAT3 has been shown to be reliable and sensitive [18]. The symptom score (range=0-22) defines how many symptoms the patient reports out of 22 and the symptom severity score (range =0-132) sums the severity of each symptom, on a scale of 0=none at all to 6=severe. The SAC has a maximum score of 30 points, where one point is deducted for each incorrect response. Higher score indicates better cognitive function. The SAC has been previously validated in an athletic population, and it was found to have 95% sensitivity and 76% specificity in identifying injured vs. non-injured athletes [19]. Reliability has also been demonstrated [18]. The modified BESS is used to assess static postural stability. The intraclass reliability coefficient of the modified BESS was reported to be 0.60-0.88 [20]. The SCAT3 and modified BESS were administered individually in a quiet room by the same athletic trainer.

The ImPACT test is a computer-based test that provides 4 proprietary composite scores: verbal and visual memory, visual-motor speed, and reaction time. ImPACT has been compared and validated using other neuropsychological measures in both uninjured and concussed subjects and has been found to be reliable [21-25]. The verbal and visual memory scores are computed from several sub-modules (a higher composite score is better), reaction time is based on the average response time of three modules (a lower number indicates a faster reaction time), and visual-motor speed is the weighted average of an interference task of memory paradigms (a higher composite score is better). ImPACT was administered in small group settings by the same athletic trainer.

We used the xPatch (X2 Biosystems, Seattle, WA, USA) to collect head impact kinematic data. The xPatch overestimates both linear and rotational accelerations but is more accurate than other head and helmet-mounted sensors that were available at the time of data collection [26, 27]. Since we were collecting data with unhelmeted participants during sports participation, we selected the xPatch sensor, as this is secured directly to the head and could be placed in the same location for all participants.

III Procedures

This study was approved by the Institutional Review Board at the University of Lynchburg before participant recruitment began. Prior to data collection, all participants signed an informed consent document. All participants completed the SCAT3 and ImPACT prior to the season's start and within one week of the end of the season (last game). Participants wore the xPatch for all games and practices during both seasons of data collection. If a participant participated in any part of the day's activity, it was counted as an AE. The xPatch stored the magnitude (linear and rotational accelerations) of all head impacts over 10 g. The lower bound threshold of 10 g was selected because impacts below 10 g are typically due to activities of daily living and not impacts on the head [28]. We used event film to verify each head impact included in the analyses. Cumulative PLA and PRA were calculated by summing the values for each head impact verified for all exposures during data collection. Daily densities for each participant for both PLA and PRA were calculated by summing the impact accelerations for all head impacts sustained by a player for a single day and dividing the cumulative daily accelerations by the sum of the time from the previous impact [29].

$$\sum_{i=1}^{Daily\ impact\ count} \frac{Acceleration_i}{Time\ from\ previous\ impact_i}$$

IV Statistical Analysis

We compared the pre-season and post-season scores (independent variable of time) on the SCAT3 component scores (dependent variables of symptom total, symptom severity, orientation, immediate memory, concentration, delayed recall and modified BESS) and ImPACT subsets (dependent variables of verbal memory, visual-memory, visual motor speed, reaction time, and symptom score) tests. Although the symptom severity score from the SCAT3 and the symptom score from ImPACT are based on similar information, we collected the SCAT3 symptoms verbally and the ImPACT symptoms via computer. Some suggest increased levels of disclosure when symptoms are not collected in person, leading us to include both in analyses [30]. All of the dependent variables associated with the SCAT3 test were count data and therefore, the Wilcoxon Signed-Rank nonparametric test was used for analysis. For the ImPACT variables, visual motor speed and reaction time met the assumption of normality and therefore, a paired t-test was used for pre-season to post-season comparisons.

The remaining variables for the ImPACT test (verbal memory, visual memory, and symptom score) violated the normality assumption, and Wilcoxon Signed-Rank tests were used. All season change calculations were based on pre-season minus post-season; therefore a positive z-score indicated a decrease in score from pre-season to post-season whereas a negative z-score indicated an increase in the variable post-season compared with pre-season. Higher scores denote better performance for orientation, immediate memory, concentration, delayed recall, verbal memory, visual-memory, and visual motor speed. A lower score is preferred for symptom total, symptom severity, modified BESS, reaction time, and symptom total. We used the Adaptive False Discovery Rate to control for a Type I error due to the number of pairwise comparisons [31, 32].

Spearman rank correlation coefficients were used to assess the relationship between ordinal variables (cognitive change scores of pre-season to post-season) and continuous head impact measures (daily density). Magnitude of the correlations was categorized as negligible (r_s=0.0-0.1), weak (r_s=0.10-0.39), moderate (r_s=0.4-0.69), strong (r_s=0.7-.89), and very strong (r_s=0.9-1.0) [33]. For correlational analyses, data were stratified on sex because it has been shown that men and women recover differently from SRCs [2, 5, 6]. All statistical analyses were performed in SPSS (IBM Corporation, Armonk, NY, version 26.0) with an *a priori* criterion of alpha=0.05.

Results

I Cognitive Change Measures

i Women's Sports

There was a statistically significant increase in the orientation score, suggesting improvement, on the SCAT3 post-season compared with pre-season (Z=-2.45, *P*=0.01) for women's soccer players. There were no other significant differences in the SCAT3 and no differences in the ImPACT scores across the course of the soccer season (Table 1). There was a statistically significant increase, showing improvement in the delayed recall score (SCAT3) post-season compared with pre-season (Z=-2.27, *P*=0.02) for women's lacrosse players. There were no other statistically significant differences in clinical measures across the course of the lacrosse season (Table1).

Table 1: Comparison of pre- and post-season [median (range)] SCAT3 and ImPACT scores for women's lacrosse and soccer.

		Women's Lacrosse			Women's Soccer		
		Pre-season	Post-season	*P*	Pre-season	Post-season	*P*
SCAT3	Symptom Total	0 (0-8)	1 (0-13)	0.77	2 (0-7)	1 (0-8)	0.28
	Symptom Severity	0 (0-8)	1 (0-32)	0.54	2.5 (0-12)	1 (0-20)	0.23
	Orientation	5 (5-5)	5 (3-5)	0.18	5 (4-5)	5 (4-5)	0.01
	Immediately Memory	15 (13-15)	15 (13-15)	0.11	15 (13-15)	15 (14-15)	0.23
	Concentration	3 (1-5)	4 (1-5)	0.15	4 (2-5)	3.5 (2-5)	0.70
	Delayed Recall	3 (2-5)	4 (2-5)	0.02	4 (1-5)	4 (1-5)	0.17
	Modified BESS	2 (0-9)	2 (0-10)	0.61	2 (0-8)	2 (0-6)	0.76
ImPACT	Verbal Memory	86 (48-100)	84 (51-99)	0.15	92 (72-100)	93.5 (66-100)	0.97
	Visual Memory	70 (44-96)	72 (38-99)	0.79	80 (49-99)	83 (53-100)	0.55
	Visual Motor Speed*	42.8 ± 6.9	41.4 ± 7.7	0.64	46.9 ± 3.9	47.4 ± 4.3	0.53
	Reaction Time*	0.57 ± 0.07	0.57 ± 0.07	0.62	0.54 ± 0.05	0.53 ± 0.05	0.10
	Symptoms	0 (0-34)	0 (0-37)	0.07	2 (0-15)	0 (0-16)	0.79

*mean ± standard deviation as these are continuous variables.

ii Men's Sports

The SCAT3 evaluation showed two related changes in men's soccer players. Symptom total, which is the total number of clinical symptoms of an SRC, was significantly higher at the post-season when compared to the pre-season (Z=-2.61, *P*=0.01). In addition, the symptom severity score was also statistically higher at the post-season (Z=-2.28, *P*=0.02). There were no other statistically significant differences across the course of the men's soccer season (Table 2). There were no statistically significant differences across the course of the lacrosse season as measured by the SCAT3. In the ImPACT test, verbal memory was significantly higher at the post-season measurement compared to the pre-season (Z=-2.323, *P*=0.02) testing. There were no other statistically significant changes seen in the ImPACT test constructs (Table 2) for men's lacrosse players.

Table 2: Comparison of pre- and post-season [median (range)] SCAT3 and ImPACT scores for men's lacrosse and soccer.

		Men's Lacrosse			Men's Soccer		
		Pre-season	Post-season	*P*	Pre-season	Post-season	*P*
SCAT3	Symptom Total	1 (0-12)	0.50 (0-9)	0.88	1 (0-7)	0 (0-5)	0.01
	Symptom Severity	1.5 (0-16)	0.50 (0-14)	0.56	1 (0-19)	0 (0-8)	0.02
	Orientation	5 (4-5)	5 (4-5)	0.10	5 (4-5)	5 (4-5)	0.32
	Immediately Memory	15 (5-15)	15 (13-15)	0.68	15 (12-15)	15 (13-15)	0.06
	Concentration	4 (2-5)	4 (2-5)	0.92	3 (1-5)	3 (0-5)	0.67
	Delayed Recall	4 (1-5)	4 (1-5)	0.75	4 (1-5)	4 (2-5)	0.77
	Modified BESS	1 (0-5)	2 (0-6)	0.08	3 (0-8)	3 (0-12)	0.84
ImPACT	Verbal Memory	89.5 (65-100)	91 (71-100)	0.02	87 (50-98)	90 (63-100)	0.31
	Visual Memory	84.5 (52-96)	79.5 (47-99)	0.23	81 (43-100)	82 (54-100)	0.78
	Visual Motor Speed*	44.0 ± 5.4	45.1 ± 4.5	0.28	43.3 ± 5.6	45.1 ± 4.9	0.17
	Reaction Time*	0.56 ± 0.05	0.56 ± 0.06	0.50	0.57 ± 0.04	0.55 ± 0.04	0.13
	Symptoms	0.50 (0-18)	0 (0-26)	0.58	0 (0-18)	0 (0-18)	0.05

*mean ± standard deviation as these are continuous variables.

II Head Impact Measures

Descriptive statistics for the head impact biomechanical measures can be seen in (Table 3). In men's sports, the only statistically significant pairwise comparison was between cumulative PRA and SCAT3 concentration change from pre-season to post-season (r_s=0.32, *P*=0.02). As concentration scores decreased, cumulative PRA increased. In women's sports there were multiple statistically significant relationships including change in reaction time with cumulative PLA (r_s=-0.30, *P*=0.03), PLA daily density (r_s=-0.31, *P*=0.04), and PRA daily density (r_s=-0.31, *P*=0.03). The significant inverse relationship postulates that as cumulative PLA, PLA daily density, and PRA daily density increased, reaction time became slower over the course of the season. Additionally, there were statistically significant correlations between ImPACT symptom change with cumulative PLA (r_s=-0.38, *P*=0.008) and cumulative PRA (r_s=-0.37, *P*=0.009)] for women. Again, as cumulative PLA and cumulative PRA increased over the course of the season, so did the symptom score from the ImPACT test.

Table 3: Descriptive statistics for head impact biomechanical measures.

		Mean ± Standard Deviation	95% Confident Interval
Women	Cumulative PLA (*g*)	516.0 ± 605.6	343.9 – 688.1
	PLA Daily Density (*g*/sec)	516.4 ± 1426.9	110.9 – 922.0
	Cumulative PRA (rad/sec^2)	5681000.0 ± 7297271.4	3607138.5 – 7754861.6
	PRA Daily Density (krad/sec)	5143239.02 ±14331920.04	1070152.4 – 9216325.6
Men	Cumulative PLA (*g*)	892.3 ± 1197.2	548.4 – 1236.1
	PLA Daily Density (*g*/sec)	3496.0 ± 17831.7	-1625.89 – 8617.9
	Cumulative PRA (rad/sec^2)	8192853.1 ± 10876376.6	5068792.9 – 11316913.2
	PRA Daily Density (krad/sec)	26547255.8 ± 142339989.3	-14337295.8 – 67432341.3

PLA: cumulative Peak Linear Accelerations; PRA: cumulative Peak Rotational Accelerations.

Discussion

We found improvement in some clinical measures used to detect SRC over the course of 1 season of collegiate men's or women's lacrosse or soccer suggesting a learning effect as has been found previously [25]. However, we found improvement in clinical SRC measures was dependent on head impact biomechanics, especially for women. Women with higher cumulative PLA, cumulative PLA daily density, and PRA daily density had decreased reaction time over the course of the season. Also, for women, as cumulative PLA and cumulative PRA increased, their ImPACT symptom score also increased. For men, concentration scores within the SAC decreased as cumulative PRA increased. Although we found statistically significant correlations, the magnitude of those relationships was weak. Further, it is important to note that the changes we identified after sport participation were subtle, likely because participants were uninjured, and may be linked to head impact biomechanics. Although our findings may not be immediately clinically relevant, over the course of a lifetime, they may be compounded and the long-term cumulative effect of repetitive head impacts remains not fully understood.

Broglio *et al.* evaluated cognitive function in high school football players after 1 season, finding that they did not show a decrease in cognitive performance compared to non-contact sports athletes [7, 34]. Similar to our study, they showed that some measurements actually improved. Other studies with football players have identified similar findings, but our work extends the literature by using head impact biomechanics to contextualize improvements [35-37]. Clinical SRC measures were found not to change after repetitive head impact in a group of football and women's soccer players [11]. Further, no changes in neurocognition as measured by ImPACT were identified in adolescent girls' soccer players following a purposeful heading protocol [38]. Heading frequency was also found not to alter cognitive function in men's professional soccer players [39]. In men's lacrosse players, previous studies have found no decline in neurocognition after 1 season of play as measured by the CTMT and Stroop test, similar to our findings [12]. Finally, a large study of high school and collegiate athletes found no clinically significant changes in symptoms, neurocognitive performance, and balance over 1 season and longitudinally over 4 seasons [14].

However, subconcussive head impacts can alter cognitive ability in soccer players, football players, and hockey players [40, 41]. After 1 season of men's lacrosse participation, Balance Error Scoring System scores and sway velocities increased, suggesting deficits in postural stability [13, 42]. Cumulative rotational velocity has also been linked to decreased visuomotor tracking ability after men's lacrosse participation [43]. Other studies have found structural brain changes following football or women's soccer participation without diagnosed SRC [8, 10, 44-46]. Further, structural alterations have been linked to purposeful heading frequency and have been found in professional soccer players with no prior history of SRC [47, 48]. Other studies have suggested subclinical changes in neurocognitive function in football, ice hockey, and soccer participants who sustained repetitive head impacts [10].

Perhaps the deterioration in brain function that has been shown to occur following repetitive head impacts can only be detected by clinical measures later in life [49]. Our participants were all healthy collegiate athletes who may have sufficient cognitive reserve to sustain repetitive head impacts without deterioration of neurocognition [11, 50, 51]. However, it is important to note that we used diagnostic tests designed to identify concussive injury and we included no data from concussive impacts in the current study. In order to detect acute neurocognitive changes, diagnostic tests that are not primarily used clinically to detect brain function changes associated with SRC may need to be completed. Additional longitudinal studies with various neurocognitive assessments that are more sensitive will need to be conducted to provide additional insight to the acute and long-term effects of repetitive head impacts.

Performance increased from pre-season to post-season under multiple circumstances. We believe the findings suggest a learning effect from taking the assessments a second time, as has been found previously [25]. However, most of our participants had completed a SCAT3 and the ImPACT previously, which would have reduced unfamiliarity and overall, our scores are similar to those reported previously [11, 25, 52]. It is interesting that the biomechanics of head impacts seem to factor into the improvement, especially for women. Sex differences in neurocognitive function and neuroimaging have previously been noted. The number of symptoms and symptom severity have been found to be higher among women, and higher neurocognitive deficits have been noted in women [1, 53-55]. In our study, reaction time was also significantly correlated with increases in various impact measures in women. Reaction time has been previously shown to be sensitive to concussion in athletes [56]. It has also been noted that women hockey players had significantly different DTI measures following a season of ice hockey that was not recorded in their male counterparts [57]. It is possible that the physical changes in the brain noted in DTI measures could be an indicator of differences in force attenuation in the brain between men and women. We believe sex differences in neurocognition is an area rich for exploration in future studies.

Limitations and Future Directions

We acknowledge that we did not have a control group to use as a comparison. Adding measures from non-contact sports such as tennis or golf would have strengthened our design and should be considered in future studies. Our participants all competed at the NCAA Division III level and came from 1 institution. Therefore, our results should not be generalized to other populations. Style of play likely influences repetitive head impact frequency and magnitude. Additionally, there are limitations to the xPatch and while mouthpiece sensor systems are likely more accurate based on laboratory testing, they also have multiple limitations in field research that make their use difficult [26]. Finally, we used ImPACT and the SCAT3 as clinical measures of neurocognition. Other options exist and could produce different results.

Conclusion

This study examined clinical changes and head impact biomechanics during a single season of lacrosse and soccer in a group of non-concussed athletes. Men had a greater number of changes over the course of the season; however, the changes noted did not appear related to head impact biomechanics. Women had several statistically significant correlations between head impacts and deterioration in some constructs, especially symptoms and reaction time. We also noted statistically significant changes over the course of the season, but these were likely attributed to the learning effects of the tests utilized.

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Conflicts of Interest

None.

REFERENCES

1. Zuckerman SL, Kerr ZY, Yengo Kahn A, Wasserman E, Covassin T et al. (2015) Epidemiology of Sports-Related Concussion in NCAA Athletes From 2009-2010 to 2013-2014: Incidence, Recurrence, and Mechanisms. *Am J Sports Med* 43: 2654-2662. [Crossref]
2. Bretzin AC, Covassin T, Fox ME, Petit KM, Savage JL et al. (2018) Sex Differences in the Clinical Incidence of Concussions, Missed School Days, and Time Loss in High School Student-Athletes: Part 1. *Am J Sports Med* 46: 2263-2269. [Crossref]
3. Covassin T, Savage JL, Bretzin AC, Fox ME (2018) Sex differences in sport-related concussion long-term outcomes. *Int J Psychophysiol* 132(Pt A): 9-13. [Crossref]
4. DiStefano LJ, Dann CL, Chang CJ, Putukian M, Pierpoint LA et al. (2018) The First Decade of Web-Based Sports Injury Surveillance: Descriptive Epidemiology of Injuries in US High School Girls' Soccer (2005-2006 Through 2013-2014) and National Collegiate Athletic Association Women's Soccer (2004-2005 Through 2013-2014). *J Athl Train* 53: 880-892. [Crossref]
5. O'Connor KL, Baker MM, Dalton SL, Dompier TP, Broglio SP et al. (2017) Epidemiology of sport-related concussions in high school athletes: National Athletic Treatment, Injury and Outcomes Network (NATION), 2011-2012 through 2013-2014. *J Athl Train* 52: 175-185. [Crossref]
6. Neidecker JM, Gealt DB, Luksch JR, Weaver MD (2017) First-time sports-related concussion recovery: the role of sex, age, and sport. *J Am Osteopath Assoc* 117: 635-642. [Crossref]
7. Broglio SP, Eckner JT, Martini D, Sosnoff JJ, Kutcher JS et al. (2011) Cumulative head impact burden in high school football. *J Neurotrauma* 28: 2069-2078. [Crossref]
8. Slobounov SM, Walter A, Breiter HC, Zhu DC, Bai X et al. (2017) The effect of repetitive subconcussive collisions on brain integrity in collegiate football players over a single football season: A multi-modal neuroimaging study. *Neuroimage Clin* 14: 708-718. [Crossref]
9. Bailes JE, Petraglia AL, Omalu BI, Nauman E, Talavage T (2013) Role of subconcussion in repetitive mild traumatic brain injury. *J Neurosurg* 119: 1235-1245. [Crossref]
10. Talavage TM, Nauman EA, Breedlove EL, Yoruk U, Dye AE et al. (2014) Functionally-detected cognitive impairment in high school football players without clinically-diagnosed concussion. *J Neurotraum* 31: 327-338. [Crossref]
11. Caccese JB, Best C, Lamond LC, Difabio M, Kaminski TW et al. (2019) Effects of Repetitive Head Impacts on a Concussion Assessment Battery. *Med Sci Sports Exerc* 51: 1355-1361. [Crossref]
12. Marchesseault ER, Nguyen D, Spahr L, Beals C, Razak B et al. (2018) Head impacts and cognitive performance in men's lacrosse. *Phys Sportsmed* 46: 324-330. [Crossref]
13. Miyashita TL, Diakogeorgiou E, Marrie K (2017) Correlation of Head Impacts to Change in Balance Error Scoring System Scores in Division I Men's Lacrosse Players. *Sports Health* 9: 318-323. [Crossref]
14. Eckner JT, Wang J, Nelson LD, Bancroft R, Pohorence M et al. (2019) Effect of Routine Sport Participation on Short-Term Clinical Neurological Outcomes: A Comparison of Non-Contact, Contact, and Collision Sport Athletes. *Sports Med* 50: 1027-1038. [Crossref]
15. Cooley CN, Beranek TJ, Warpinski MA, Alexander R, Esquivel AO (2018) A comparison of head injuries in male and female lacrosse participants seen in US emergency departments from 2005 to 2016. *Am J Emerg Med* 37: 199-203. [Crossref]
16. Atkinson L, Kelley C (2019) NFHS Girls Lacrosse Rule Book, editors: Niehoff, Karissa.
17. Sutton M, Chan V, Escobar M, Mollayeva T, Hu Z, Colantonio A (2019) Neck Injury Comorbidity in Concussion-Related Emergency Department Visits: A Population-Based Study of Sex Differences Across the Life Span. *J Womens Health (Larchmt)* 28: 473-482. [Crossref]
18. Chin EY, Nelson LD, Barr WB, McCrory P, McCrea MA (2016) Reliability and Validity of the Sport Concussion Assessment Tool-3 (SCAT3) in High School and Collegiate Athletes. *Am J Sports Med* 44: 2276-2285. [Crossref]
19. McCrea M (2001) Standardized Mental Status Testing on the Sideline After Sport-Related Concussion. *J Athl Train* 36: 274-279. [Crossref]
20. Hunt TN, Ferrara MS, Bornstein RA, Baumgartner TA (2009) The reliability of the modified Balance Error Scoring System. *Clin J Sport Med* 19: 471-475. [Crossref]
21. Allen BJ, Gfeller JD (2011) The Immediate Post-Concussion Assessment and Cognitive Testing battery and traditional neuropsychological measures: a construct and concurrent validity study. *Brain Inj* 25:179-191. [Crossref]
22. Iverson GL, Lovell MR, Collins MW (2005) Validity of ImPACT for measuring processing speed following sports-related concussion. *J Clin Exp Neuropsychol* 27: 683-689. [Crossref]
23. Iverson GL, Lovell MR, Collins MW (2003) Interpreting change on ImPACT following sport concussion. *Clin Neuropsychol* 17: 460-467. [Crossref]
24. Schatz P, Pardini JE, Lovell MR, Collins MW, Podell K (2006) Sensitivity and specificity of the ImPACT Test Battery for concussion in athletes. *Arch Clin Neuropsychol* 21: 91-99. [Crossref]
25. Broglio SP, Katz BP, Zhao S, McCrea M, McAllister T et al. (2018) Test-Retest Reliability and Interpretation of Common Concussion Assessment Tools: Findings from the NCAA-DoD CARE Consortium. *Sports Med* 48: 1255-1268. [Crossref]
26. Wu LC, Nangia V, Bui K, Hammoor B, Kurt M et al. (2016) In Vivo Evaluation of Wearable Head Impact Sensors. *Ann Biomed Eng* 44: 1234-1245. [Crossref]
27. Cummiskey B, Schiffmiller D, Talavage TM, Leverenz L, Meyer JJ et al. (2016) Reliability and accuracy of helmet-mounted and head-mounted devices used to measure head accelerations. *P I Mech Eng P-J Spo* 231: 144-153.
28. Ng TP, Bussone WR, Duma SM (2006) The effect of gender and body size on linear accelerations of the head observed during daily activities. *Biomed Sci Instrum* 42: 25-30. [Crossref]
29. Breedlove KM, Memmini AK, Broglio SP (2019) Evaluation of Concussion Prediction with Head Impact Density by Receiver Operating Characteristic. *Med Sci Sport Exer* 51: 471.
30. Johnston KM, Bloom GA, Ramsay J, Kissick J, Montgomery D et al. (2004) Current concepts in concussion rehabilitation. *Curr Sport Med Rep* 3: 316-323. [Crossref]
31. Keselman HJ, Cribbie R, Holland B (2002) Controlling the rate of Type I error over a large set of statistical tests. *Br J Math Stat Psychol* 55(Pt 1): 27-39. [Crossref]
32. Benjamini Y, Hochberg Y (2000) On the Adaptive Control of the False Discovery Rate in Multiple Testing With Independent Statistics. *J Educ Behav Stat* 25: 60-83.

33. Schober P, Boer C, Schwarte LA (2018) Correlation Coefficients: Appropriate Use and Interpretation. *Anesth Analg* 126: 1763-1768. [Crossref]

34. Broglio SP, Williams R, Rettmann A, Moore B, Eckner JT et al. (2018) No Seasonal Changes in Cognitive Functioning Among High School Football Athletes: Implementation of a Novel Electrophysiological Measure and Standard Clinical Measures. *Clin J Sport Med* 28: 130-138. [Crossref]

35. Gysland SM, Mihalik JP, Register Mihalik JK, Trulock SC, Shields EW et al. (2012) The relationship between subconcussive impacts and concussion history on clinical measures of neurologic function in collegiate football players. *Ann Biomed Eng* 40: 14-22. [Crossref]

36. McAllister TW, Flashman LA, Maerlender A, Greenwald RM, Beckwith JG et al. (2012) Cognitive effects of one season of head impacts in a cohort of collegiate contact sport athletes. *Neurology* 78: 1777-1784. [Crossref]

37. Murray NG, Grimes KE, Shiflett ED, Munkasy BA, D'Amico NR et al. (2018) Repetitive head impacts do not affect postural control following a competitive athletic season. *Int J Psychophysiol* 132: 81-86. [Crossref]

38. Gutierrez GM, Conte C, Lightbourne K (2014) The relationship between impact force, neck strength, and neurocognitive performance in soccer heading in adolescent females. *Pediatr Exerc Sci* 26: 33-40. [Crossref]

39. Rodrigues AC, Lima MDM, De Souza LC, Furtado C, Marques CE et al. (2019) No Evidence of Association Between Soccer Heading and Cognitive Performance in Professional Soccer Players: Cross-Sectional Results. *Front Neurol* 10: 209. [Crossref]

40. Zhang MR, Red SD, Lin AH, Patel SS, Sereno AB (2013) Evidence of cognitive dysfunction after soccer playing with ball heading using a novel tablet-based approach. *PloS One* 8: e57364. [Crossref]

41. McAllister TW, Flashman LA, Maerlender A, Greenwald RM, Beckwith JG et al. (2012) Cognitive effects of one season of head impacts in a cohort of collegiate contact sport athletes. *Neurology* 78: 1777-1784. [Crossref]

42. Miyashita TL, Diakogeorgiou E, Marrie K (2020) The role of subconcussive impacts on sway velocities in Division I men's lacrosse players. *Sports Biomech* 19: 180-188. [Crossref]

43. Brokaw E, Fine M, Kindschi K, Santago I, Lum P et al. (2018) Cross-sectional evaluation of visuomotor tracking performance following subconcussive head impacts. *Technol Health Care* 26: 109-118. [Crossref]

44. Breedlove EL, Robinson M, Talavage TM, Morigaki KE, Yoruk U et al. (2012) Biomechanical correlates of symptomatic and asymptomatic neurophysiological impairment in high school football. *J Biomech* 45: 1265-1272. [Crossref]

45. Bari S, Svaldi DO, Jang I, Shenk TE, Poole VN et al. (2019) Dependence on subconcussive impacts of brain metabolism in collision sport athletes: an MR spectroscopic study. *Brain Imaging Behav* 13: 735-749. [Crossref]

46. Svaldi DO, Joshi C, McCuen EC, Music JP, Hannemann R et al. (2020) Accumulation of high magnitude acceleration events predicts cerebrovascular reactivity changes in female high school soccer athletes. *Brain Imaging Behav* 14: 164-174. [Crossref]

47. Lipton ML, Kim N, Zimmerman ME, Kim M, Stewart WF et al. (2013) Soccer heading is associated with white matter microstructural and cognitive abnormalities. *Radiology* 268: 850-857. [Crossref]

48. Koerte IK, Ertl Wagner B, Reiser M, Zafonte R, Shenton ME (2012) White matter integrity in the brains of professional soccer players without a symptomatic concussion. *JAMA* 308: 1859-1861. [Crossref]

49. Tremblay S, Pascual Leone A, Théoret H (2018) A review of the effects of physical activity and sports concussion on brain function and anatomy. *Int J Psychophysiol* 132: 167-175. [Crossref]

50. Stern Y (2002) What is cognitive reserve? Theory and research application of the reserve concept. *J Int Neuropsychol Soc* 8: 448-460. [Crossref]

51. Stern Y (2009) Cognitive reserve. *Neuropsychologia* 47: 2015-2028. [Crossref]

52. Chin EY, Nelson LD, Barr WB, McCrory P, McCrea MA (2016) Reliability and validity of the Sport Concussion Assessment Tool–3 (SCAT3) in high school and collegiate athletes. *Am J Sports Med* 44: 2276-2285. [Crossref]

53. Covassin T, Elbin RJ, Harris W, Parker T, Kontos A (2012) The role of age and sex in symptoms, neurocognitive performance, and postural stability in athletes after concussion. *Am J Sports Med* 40: 1303-1312. [Crossref]

54. Covassin T, Schatz P, Swanik CB (2007) Sex differences in neuropsychological function and post-concussion symptoms of concussed collegiate athletes. *Neurosurgery* 61: 345-351. [Crossref]

55. Majerske CW, Mihalik JP, Ren D, Collins MW, Reddy CC et al. (2008) Concussion in sports: postconcussive activity levels, symptoms, and neurocognitive performance. *J Athl Train* 43: 265-274. [Crossref]

56. Eckner JT, Kutcher JS, Broglio SP, Richardson JK (2014) Effect of sport-related concussion on clinically measured simple reaction time. *Br J Sports Med* 48: 112-118. [Crossref]

57. Sollmann N, Echlin PS, Schultz V, Viher PV, Lyall AE et al. (2018) Sex differences in white matter alterations following repetitive subconcussive head impacts in collegiate ice hockey players. *NeuroImage Clin* 17: 642-649. [Crossref]