Journal of Biomechanics ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Biomechanics of head impacts associated with diagnosed concussion in female collegiate ice hockey players

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ARTICLE INFO

Article history:
Accepted 2 April 2015

Keywords:
Impact biomechanics
Concussion
Female
Hockey

ABSTRACT

Epidemiological evidence suggests that female athletes may be at a greater risk of concussion than their male counterparts. The purpose of this study was to examine the biomechanics of head impacts associated with diagnosed concussions in a cohort of female collegiate ice hockey players. Instrumented helmets were worn by 58 female ice hockey players from 2 NCAA programs over a three year period. Kinematic measures of single impacts associated with diagnosed concussion and head impact exposure on days with and without diagnosed concussion were evaluated. Nine concussions were diagnosed. Head impact exposure was greater in frequency and magnitude on days of diagnosed concussions than on days without diagnosed concussion for individual athletes. Peak linear accelerations of head impacts associated with diagnosed concussion in this study are substantially lower than those previously reported in male athletes, while peak rotational accelerations are comparable. Further research is warranted to determine the extent to which female athletes' biomechanical tolerance to concussion injuries differs from males.

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1. Introduction

Epidemiological evidence suggests that female athletes may be at a greater risk of concussion than their male counterparts (Dick, 2009). Research conducted in sports where males and females participate at the same level, such as ice hockey, has shown that female athletes sustain concussions at a higher rate (Agel and Harvey, 2010; Dick, 2009). It has been reported that females experience a greater number of symptoms associated with concussions and that these symptoms are often more severe (Broshek et al., 2005; Colvin et al., 2009). Recent studies have also suggested that females may be at a greater risk of post-concussive syndrome, where the acute symptoms associated with concussion injuries become chronic (Preiss-Farzanegan et al., 2009). Several sex-specific characteristics have been proposed as the rationale for these differences, including physiological differences and psychological factors, but the exact reasons remain unclear. While it has been generally accepted that the mechanism of concussion injury is related to head acceleration (McCrory et al., 2009), the exact relationship between the biomechanics of head impacts, sex, and clinical outcome of concussion is unknown.

Recent studies have focused on understanding the biomechanics of head impacts sustained in contact sports by utilizing an accelerometer based head impact monitoring device, the Head Impact Telemetry (HIT) System (Simbex, Lebanon, NH). The HIT System allows researchers to monitor and record head impacts sustained by individual helmeted athletes during play. Utilizing this system, researchers have quantified head impact exposure, a multifactorial term including frequency, magnitude and location on the helmet of head impacts, for individual athletes at different

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http://dx.doi.org/10.1016/j.jbiomech.2015.04.005
0021-9290/© 2015 Published by Elsevier Ltd.

levels of play in football and ice hockey (Broglio et al., 2009; Crisco et al., 2011; Mihalik et al., 2008; Wilcox et al., 2013).

Data from the HIT System has also been used to evaluate the biomechanics of head impacts associated with diagnosed concussions in high school and collegiate football players (Beckwith et al., 2013; Funk et al., 2012; Guskiewicz et al., 2007; Rowson et al., 2012). Beckwith et al. (2013) reported that individual players sustained more head impacts and impacts of greater severity on days of diagnosed concussion than on days without. While these studies have provided valuable insights into the biomechanics of impacts associated with diagnosed concussion in male football players, quantification and analysis of head impacts associated with diagnosed concussion in female athletes are currently lacking.

The purpose of this study was to evaluate the biomechanics of head impacts associated with diagnosed concussions in a study population of female collegiate ice hockey players.

2. Methods

Over a three year period, 58 female ice hockey players from 2 National Collegiate Athletic Association (NCAA) athletic programs (Brown University and Dartmouth College) participated in this observational study after informed consent was obtained with institutional review board approval. Players participated during multiple years; 19, 20, and 19 players participated in one, two, and three seasons respectively. This participant turnover is typical of fluctuations on collegiate athletic teams.

All participants wore instrumented helmets (Easton S9, Van Nuys, CA; Head Impact Telemetry (HIT) System, Simbex, Lebanon, NH) to collect the magnitude of head impacts sustained during practices and games. These helmets measured and recorded biomechanical data from head impacts including linear and rotational acceleration of the center of gravity of the head. The instrumented helmets each consist of six single-axis accelerometers arranged tangentially to the head and mounted elastically within the liners of helmets to maintain contact with the head, thus isolating the accelerometers from shell vibrations (Brainard et al., 2012; Manoogian et al., 2006; Mihalik et al., 2008). System design, processing methods, accuracy, and data reduction techniques have been previously described in detail (Chu et al., 2006; Crisco et al., 2004; Duma et al., 2005; Greenwald et al., 2008; Mihalik et al., 2008). Acceleration data is collected at 1 kHz, time stamped and stored (up to 100 impacts in static memory). Data is then transmitted by radio-frequency telemetry to a computer and entered into a secure database.

For this study, concussions were defined as an alteration in mental status, as reported or observed by the player or medical staff, resulting from a blow to the head. Diagnosis of concussion was made by the team physician or certified athletic trainer (ATC) at each respective institution. For each diagnosed concussion, suspected date, time, and symptom presentation within 72 h of the injury were documented. Anecdotal descriptions of the events surrounding injury were also collected to further aid in corroborating data from the instrumented helmets with diagnosed concussions.

To evaluate the biomechanics of impacts associated with diagnosed concussion, two different approaches were taken: (1) the examination of single impacts linked to injury, and (2) the cumulative analysis of all impacts sustained on days of injury. Single impacts were identified when a concussion event was attributed by the player or observers to a specific identifiable impact. Impact magnitude variables included peak linear acceleration (g), peak rotational acceleration (rad/s^2), and HITsp (Crisco et al., 2004; Greenwald et al., 2008). HITsp is a weighted measure of head impact severity that includes linear and rotational acceleration, impact duration, and impact location (Greenwald et al., 2008). For the cumulative analysis, head impact exposure was computed using a single measure of impact frequency, the total number of impacts per day, for individual players on days with and without diagnosed concussion (Beckwith et al., 2013). Each individual player's distribution of peak linear acceleration (g), peak rotational acceleration (rad/s^2), and HITsp per day was quantified by the 50th and 95th percentile value of all impacts per day. Results are expressed as median values and 25–75% interquartile range of those percentile values.

2.1. Statistical analysis

Head impact frequency and magnitude variables were found to be non-normally distributed (Shapiro–Wilk test, $p < 0.05$). Therefore, to evaluate differences in these measures for days with and without concussion, Wilcoxon sign-ranked tests for pairs were used. Statistical analyses were performed using SigmaPlot 12.0 (Systat Software, Chicago, IL).

3. Results

There were a total of nine diagnosed concussions and approximately half of these injuries (4/9) were associated with an identifiable single impact. The average ($\pm$standard deviation) peak linear acceleration, peak rotational acceleration, and HITsp of these impacts were $43.0 \pm 11.5g$, 4030 ± 1435 rad/s^2, and 25.6 ± 4.8, respectively (Table 1).

Significant differences were observed in the frequency and magnitude of head impacts that players sustained on days with and without diagnosed concussion. Players sustained a greater number of head impacts ($p=0.023$) on days of diagnosed concussion than on days without (Fig. 1). The 50th and 95th percentile values of peak linear acceleration and peak rotational acceleration were significantly higher on days with diagnosed concussion than on days without (Table 2). Ninety-fifth percentile HITsp was also significantly higher on days with diagnosed concussion than on days without.

4. Discussion

The purpose of this study was to examine the biomechanics of head impacts associated with diagnosed concussion in a study population of female collegiate ice hockey players. Data was collected over a three year span from approximately 60 athletes. While 15% of these athletes were diagnosed with a concussion during the course of the study, this yielded only nine concussion cases for analysis. Herein, we report and discuss our findings with full disclosure of the limitations of such a small dataset.

Substantial research has focused on single impacts associated with concussion injury with the objective of identifying a biomechanical threshold for the injury. A study in a large cohort of high school and collegiate football players reported an average peak linear and peak rotational acceleration of $112.1 \pm 35.4g$ and 4253 ± 2287 rad/s^2 for single impacts associated with diagnosed concussion (Beckwith et al., 2013). Other studies in football have reported peak linear accelerations associated with concussions ranging from 60.51 to 168.71g (Broglio et al., 2012; Guskiewicz et al., 2007). In a study of collegiate football players, the average linear acceleration of concussive impacts was $145 \pm 35g$, and a risk analysis resulted in a threshold of 100 g as a cutoff for identifying potential concussions (Funk et al., 2012). Comparable to a study in a larger cohort of athletes, approximately 50% (4/9) of the diagnosed concussions in our study were associated with a single identifiable impact (Duhaime et al., 2012). The average peak linear acceleration of the impacts associated with diagnosed concussions in the current study ($43 \pm 11.5g$,) is substantially lower than any values reported for football players in the literature. If the recommended cutoff for collegiate football players (100 g) was used to monitor this group of female athletes, not one of the impacts that were associated with diagnosed concussions would have reached this threshold. These findings suggest that biomechanical thresholds may need to be sex-specific. Interestingly, the average peak rotational acceleration of these impacts

Table 1
Peak linear acceleration, peak rotational acceleration, and HITsp for single impacts ($n=4$) associated with diagnosed concussions in a cohort of female collegiate ice hockey players.

Peak linear acceleration (g)	Peak rotational acceleration (rad/s^2)	HITsp
53.3	1959	18.8
30.4	4945	27.0
36.1	5045	26.5
52.2	4169	30.1

Please cite this article as: Wilcox, B.J., et al., Biomechanics of head impacts associated with diagnosed concussion in female collegiate ice hockey players. Journal of Biomechanics (2015), http://dx.doi.org/10.1016/j.jbiomech.2015.04.005

(4029.5 ± 1243 rad/s^2) is comparable to those previously reported in male football players.

While studies have shown that both linear and rotational accelerations of the head play a role in concussion, the relative contributions of these kinematic components to this complex injury remain unknown (Guskiewicz and Mihalik, 2011). In this study, peak linear accelerations associated with diagnosed concussion, which has been shown to be the most predictive impact severity metric in football (Beckwith et al., 2013), suggest that females have a lower biomechanical tolerance to concussion injuries than their male counterparts. However, when considering peak rotational acceleration alone, the measures recorded from female and male athletes are remarkably similar which could support a similar tolerance to rotational acceleration. While it is well established that linear and rotational head accelerations are correlated, particularly in helmeted contact sports (Pellman et al., 2003; Rowson et al., 2012, 2009), the exact relationship for individual impacts depends upon several factors including impact location, anticipation of impact and, accordingly, neck strength. Given these factors, it is possible that this relationship differs between males and females.

Similar to previous studies, we found that head impact exposure on days of diagnosed concussion is higher for individual athletes than on days without diagnosed concussion, in both frequency and magnitude (Beckwith et al., 2013). This supports previous assertions that diagnosis of concussion is related to head impact exposure (Beckwith et al., 2013; Crisco and Greenwald, 2011). Several measures of head impact exposure on days of diagnosed concussions for the female collegiate hockey players in the current study, however, were substantially lower than the same variables previously reported for male football players (Beckwith et al., 2013). This further supports the postulation that female athletes may have a differing biomechanical tolerance to concussions than their male counterparts.

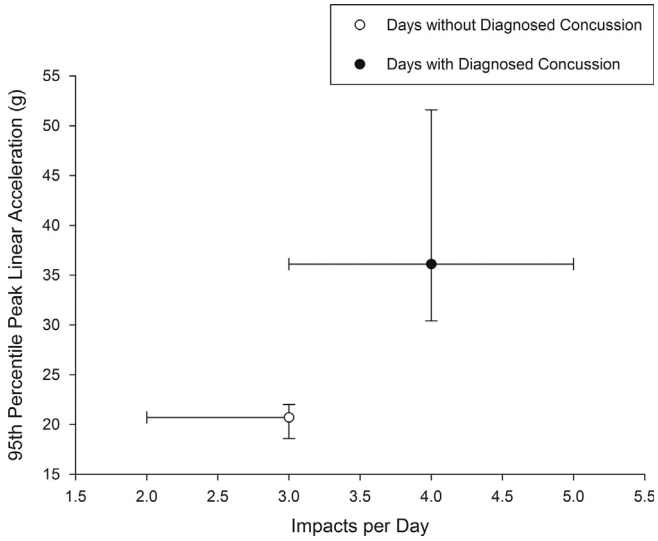


Fig. 1. Median [25–75%] of the 95th percentile peak linear acceleration as a function of the median [25–75%] frequency of impacts per day. Filled markers represent days with diagnosed concussion; unfilled markers represent days without diagnosed concussion.

Several sex-specific characteristics have been proposed to explain differences between males and females in concussion injuries including physiological differences, such as anthropometrics and hormone regulation (Bramlett and Dietrich, 2001; Stein and Hoffman, 2003), and psychological factors, including speculation that females tend to be more honest than males in reporting injuries (Covassin et al., 2012; Dick, 2009). Whether this reflects actual increased tissue damage or greater symptom intensity for a given biomechanical input, increased concern or focus on potential consequences of injury, or some other factor remains speculative.

This study has several limitations. While approximately 15% of the athletes in the study were diagnosed with a concussion, this accounts for a relatively small sample size of concussion cases ($n=9$). Additionally, a limitation in evaluating single impacts associated with diagnosed concussions is the inherent error associated with the use of any measurement device, in this case the HIT System. In appreciation of these limitations, the values reported in this short communication should be interpreted carefully. While several biomechanical measures of head impacts associated with diagnosed concussion in female athletes were substantially lower than data previously reported in male athletes collected with similarly instrumented helmets with presumably similar limitations, further investigation is necessary to draw any conclusions. To address the concerns associated with evaluating a limited dataset of single impacts, we analyzed head impact exposure cumulatively for the days that players were and were not diagnosed with concussion injuries. However, an additional limitation exists in that it is not known whether a cumulative measure over a longer period of time would be more appropriate than limiting the analysis to a single day.

Another important consideration in this study is that diagnosis of concussion was represented as a binary state and did not acknowledge that there exists a spectrum of concussive injuries (Duhaime et al., 2012). The diagnosed concussions presented in this study exhibited a spectrum of signs and symptoms that may represent very different injuries. Moreover, it is possible that the diagnosed concussions in the female ice hockey players were of a lower severity than those previously reported in male athletes.

We reported the biomechanics of head impacts associated with nine diagnosed concussions in a study population of female ice hockey players. Head impact exposure was greater in frequency and magnitude on days of diagnosed concussions than on days without diagnosed concussion for individual athletes. Peak linear accelerations of impacts associated with diagnosed concussion were found to be substantially lower than those previously reported in male athletes, while rotational accelerations were comparable. Further research is warranted to determine the extent

Table 2
Magnitudes, reported as median (25–75% interquartile range), of head impacts sustained on days with diagnosed concussion were more severe than on days without diagnosed concussion.

	Percentile	Days w/diagnosed concussion	Days w/out diagnosed concussion	p-value
Peak linear acceleration(g)	50th	21.9 (17.4–22.8)	15.3 (15.1–15.6)	$*p=0.001$
	95th	36.1 (30.4–51.6)	20.7 (18.6–22.0)	$*p=0.001$
Peak rotational acceleration (rad/s^2)	50th	2046 (1676–2202)	1249 (1169–1397)	$*p=0.047$
	95th	3491 (2411–4169)	1769 (1621–2123)	$*p=0.015$
HITsp	50th	14.7 (13.5–18.4)	13.5 (13.4–13.7)	$p=0.241$
	95th	23.2 (17.9–26.5)	15.4 (14.8–16.2)	$*p=0.012$

Please cite this article as: Wilcox, B.J., et al., Biomechanics of head impacts associated with diagnosed concussion in female collegiate ice hockey players. Journal of Biomechanics (2015), http://dx.doi.org/10.1016/j.jbiomech.2015.04.005

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to which female athletes' biomechanical tolerance to concussion injuries differs from males.

Conflict of interest disclosure

Joseph J. Crisco, Richard M. Greenwald, and Simbex have a financial interest in the instruments (HIT System, Sideline Response System (Riddell, Inc.)) that were used to collect the biomechanical data reported in this study.

Acknowledgments

Research reported in this publication was supported by the National Institute of Child Health and Human Development, the National Institute of Neurological Disorders and Stroke, and the National Institute of General Medical Sciences at the National Institute of Health under award numbers R01HD048638, RO1NS055020, R25GM083270 and R25GM083270-S1 and the National Operating Committee on Standards for Athletic Equipment (NOCSAE). The content is solely the responsibility of the authors and does not necessarily represent the official views of the National Institutes of Health or NOCSAE. We gratefully acknowledge and thank the engineering team at Simbex for all of their technical support. We would like to thank Lindley Brainard and Wendy Chamberlin at Simbex for their role in data collection and clinical coordination. We would also like to thank Russell Fiore, M.Ed., A.T.C, Emily Burmeister M.S., A.T.C, and Brian Daigneault, MS, A.T.C at Brown University; Jeff Frechette, A.T.C., and Tracey Poro, A.T.C.at Dartmouth College Sports Medicine and Mary Hynes, R.N., M.P.H. at Dartmouth Medical School for their support on this project.

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Please cite this article as: Wilcox, B.J., et al., Biomechanics of head impacts associated with diagnosed concussion in female collegiate ice hockey players. Journal of Biomechanics (2015), http://dx.doi.org/10.1016/j.jbiomech.2015.04.005