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Head Impact Biomechanics Differ Between Girls and Boys Youth Ice Hockey Players

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Abstract—The influence of sex on head impact biomechanics is unknown for youth ice hockey. We sought to determine sex differences in head impact severity and frequency in youth ice hockey players. Male ($n = 110$) and female ($n = 25$) players (13–16 years old) were recruited from a local hockey organization. Players wore helmets instrumented with the Head Impact Telemetry System for all competitions and practices throughout the season. Seven team-seasons were captured. Random intercepts general mixed linear models determined whether linear acceleration and rotational acceleration differed by sex. Linear regression models evaluated the relationship between sex and impact frequency. All head impact biomechanics were natural log-transformed as their distributions were right-skewed. Females sustained fewer impacts per player than males (27 fewer impacts per player-season, $p < 0.0001$) even when analysis was limited to games only (21 fewer impacts per player-season, $p < 0.0001$). The linear acceleration was higher among females (1.07 g; 95% CI 1.00, 1.13; $p = 0.04$). There were no other meaningful sex differences in head impact severity. Female players are not permitted to body check, and this likely explains why they sustain fewer head impacts than males. However, as a result, females likely sustain a higher proportion of head impacts through illegal or unintentional head contact, and these impacts may result in more force being delivered to the head.

Keywords—Child, Concussion, Gender, Injury prevention, Kinematics, Mild traumatic brain injury, Pediatrics, Sports.

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INTRODUCTION

Youth ice hockey represents a unique pediatric population sport since it involves body collisions occurring at relatively higher speeds compared to football and soccer. Over 1 million youth athletes play organized ice hockey in North America with growing participation.[13] Concussion rates for male adolescent ice hockey players are 4 per 10,000 athlete exposures, with injury rates more than doubling during competitive play.[14] As many as 10% of male high school ice hockey players are believed to sustain a concussion throughout one regular season of play[9] and concussions are among the leading specific injury diagnoses sustained in male players at the youth level.[8]

Little data about concussion injury incidence exist for female youth ice hockey players. One study suggests that concussions account for 15.1% of all sustained injuries in female youth players, the fourth most prevalent diagnosis behind muscle strain (28.3%), contusion (16.9%), and ligament sprain (16.9%).[5] In adult ice hockey cohorts, females are at similar or higher concussion risk to males.[1,12] The reasons for higher concussion rates among female athletes remain unknown, although speculative reasons include cultural and hormonal factors.[5] Researchers have evaluated head impact biomechanics in adult ice hockey cohorts to better understand sex differences in concussion injury rates. College female ice hockey players sustain concussions at substantially lower linear accelerations than values reported for male athletes, indicating that anatomical and biomechanical differences may also increase susceptibility in females.[22] Additionally, women's ice hockey is a contact sport that does not permit body checking, as opposed to men's ice hockey, which is a collision sport. Collision sports include those where deliberate body-to-body collisions are permitted during regular participation. Contact sports include those where body-to-body contact is expected to occur during regular participation, but deliberate collisions are not permitted. Therefore, these increased concussion rates among women's ice hockey players are surprising due to the limited amount of player-to-player contact permitted within the women's game.

The risk factors previously associated with body checking and their potential contribution to concussion injury rates have yet to be fully explored in both boys and girls ice hockey. Previous research suggests that poor collision anticipation is associated with increased head impact severity.[15] Males, who expect to be body checked, may play with a heightened awareness enabling them to better anticipate and mitigate the head impact forces associated with body collisions. Illegal contact, such as head contact, elbowing, and high sticking infractions, result in significantly greater biomechanical head impact measures than legal body collisions.[16] While there is no specific head injury threshold associated with concussion,[10] head impacts with higher linear and rotational acceleration are believed to place athletes at greater concussion risk.[3] Previous head impact biomechanics studies in college ice hockey players suggested females sustained a lower head impact frequency per playing session and were less likely to sustain head impacts with higher linear and rotational acceleration than their male counterparts.[4,22] However, sex differences in head impact biomechanics have not been studied at the youth level.

Understanding factors contributing to more frequent and severe head impacts are necessary to design and implement appropriate injury prevention strategies. This is critically important at the youth level, where brain maturation is an ongoing process.[2] Therefore, the purpose of this study was to quantify sex differences in head impact frequency and severity sustained by youth ice hockey players. We hypothesized female ice hockey players would experience more pronounced head impact severities (i.e., linear acceleration and rotational acceleration), but not higher impact frequency, than male ice hockey players of a similar age.

MATERIALS AND METHODS

Study Design and Participants

A prospective cohort study was designed to capture head impact biomechanics in youth hockey players. A convenience sample of male and female Bantam-level (13–14 years) and Midget-level (15–16 years) ice hockey players were recruited from local ice hockey associations governing the majority of hockey players in the state. Males were recruited and participated over 5 hockey seasons. During these last two seasons, female cohorts were added to this ongoing study that originally included only male youth ice hockey players. Players participated in at least two practice or game sessions each week over the course of his or her playing seasons, which were equal in length for both sexes. A detailed explanation of the study was provided to all the athletes, coaches, and parents prior to the start of the season. Every parent and player signed parental permission and minor assent forms approved by the university's institutional review board prior to enrollment. Seven team-seasons were captured, with the potential that some players participated in the study for more than one season. While it is possible to do so, none of the female hockey players in our study participated in boys ice hockey.

Instrumentation

Commercially available Reebok RBK 6K and 8K (Reebok-CCM Hockey, Inc.; St-Laurent, Quebec, Canada), CCM Vector 08 (Reebok-CCM Hockey, Inc.; St-Laurent, Quebec, Canada), or Easton Stealth S9 (Easton Sports, Inc.; Van Nuys, CA) helmets were used in this study. All helmets were modified to fit the Head Impact Telemetry (HIT) System technology (Simbex; Lebanon, NH). The liner in each helmet was reconfigured to accept the HIT System components: six single-axis accelerometers, a battery pack, and the telemetry instrumentation (Fig. 1). All modified helmets passed safety standards set by both the American Society for Testing and Materials (1045-99) and Canadian Standards Association (Z262.1-M90). In addition, the Hockey Equipment Certification Council (HECC) approved the modified helmets for use during competition. The HIT System has been described in detail previously.[15,16] Briefly, all head impacts detected by the HIT System are time-stamped, encoded, and locally stored. Data collected through the HIT System are immediately transmitted to a sideline controller equipped with the Sideline Response System (Riddell; Elyria, OH) using a radiofrequency telemetry link. In special circumstances when the real-time data transmission was absent (e.g., signal interruptions, sideline system not set up, etc.), head impacts were locally stored in non-volatile memory built into the monitoring system.

Procedures

Procedures for this study have been previously described.[15,16] Briefly, an athletic trainer measured and

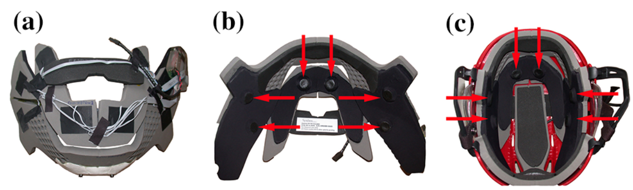

FIGURE 1. The ice hockey helmet liners were removed from the helmet shell (Easton Stealth S9 model depicted). Following this, six single-axis accelerometers were fitted into custom holes cut into the liner. The figure depicts the location of the helmet accelerometers in the protective liner (hard shell removed) in both exterior (a) and interior (b, arrows) views. The location of the six accelerometers (two in front, and two on each side) as viewed from the inside of a fully assembled playing ice hockey helmet (c, arrows).

properly fit players for a helmet and facemask prior to the start of the season. Participants were instructed to keep their heads still while the athletic trainer attempted to move the helmet. This was repeated until proper fit was assured, and fit check procedures were repeatedly administered throughout the study to monitor helmet fit. Participants wore their helmet for all games and practices throughout the competitive season.

Data Reduction

Raw head impact data were exported from the Sideline Response System into Matlab (The Mathworks, Inc.; Natick, MA). Impacts occurring outside of team-sanctioned practices, scrimmages, and games were removed from analyses. Impacts registering a linear acceleration less than 10 g were also excluded from analyses as they cannot be distinguished from voluntary head movements.[6,11] Resultant linear and rotational head accelerations were calculated. Each individual hit was categorized as having mild, moderate, or severe linear acceleration or rotational acceleration based on the respective 75th and 95th percentiles for each head impact biomechanics outcome. A hit was considered to have severe linear acceleration if it was 45 g or above, moderate between 25 g and 45 g, and mild below 25 g. A hit was considered to have severe rotational acceleration if it was 4000 rad/s^2 or above, moderate between 2000 rad/s^2 and 4000 rad/s^2, and mild below 2000 rad/s^2. These cutoff values were based on the 75th percentile (moderate) and 95th percentile (severe) computed from the combined sample (boys and girls) evaluated in our study.

Statistical Analyses

Descriptive statistics of the sample and head impact biomechanics outcomes (resultant linear acceleration and resultant rotational acceleration) were calculated. For each head impact biomechanics measure, separate random intercepts general mixed linear models were run to account for multiple observations (hits) for each player. All head impact biomechanics measures (dependent variable) were natural log-transformed as the distribution of these outcomes was right-skewed. The primary independent variable for each model was sex. All statistical models controlled for level of play (Bantam vs. Midget), player position (forward vs. defense), and event type (practice vs. game) as previous studies have found these variables to significantly affect head impact severity outcomes.[4,17,18,21] Our analysis models also controlled for head impact location.

Random intercepts mixed logistic models were also used to examine the association between sex and hit severity level. Random intercepts mixed proportional odds and multinomial logistic models using the three-level (mild, moderate, and severe) severity categories did not converge. Therefore, random intercepts mixed binary logistic models were used to estimate the association between sex and sustaining an impact in the 95th percentile or greater for each head impact biomechanics measure. The same covariates were included in this model.

Linear regression models were calculated to estimate the association between sex and the natural log of total hits sustained. Linear regression models controlled for level of play and player position. We excluded impacts sustained by goaltenders (260 impacts) and players for whom we did not know the position (11 impacts). All results are presented as the exponentiated betas for greater interpretability. All analyses were performed using SAS 9.3 (SAS Institute, Cary, NC).

RESULTS

Analyses included 110 male players (height: 170.7 $\pm$ 8.4 cm; mass: 64.3 $\pm$ 11.5 kg) from seven team-seasons and 25 female players (height: 161.9 $\pm$ 5.3 cm; mass: 54.5 $\pm$ 11.5 kg) from three team-seasons. Of the male players (mean age: 14.4 $\pm$ 1.0 years), 75 (68.2%) played at the Bantam level and 35 (31.8%) played at the Midget level. Among females (mean age: 14.4 $\pm$ 1.2 years), 3 (12.0%) played at the Bantam level, and 22 (88.0%)

played at the Midget level. There were 82 forwards (68 males; 14 females) and 53 defensemen (42 males; 11 females) in the sample.

Head Impact Frequency

There were 29,288 impacts among males (median: 264 per player per season) and only 599 among females (median: 13 per player per season). These impacts are described in Tables 1 and 2.

Female players consistently sustained significantly fewer impacts than male players (27 fewer impacts per player-season; 95% CI − 40 to − 18; $p < 0.0001$). Only 4% of impacts ($n = 24$) sustained by females occurred during practices and, therefore, we reanalyzed our findings when restricting impacts to those sustained during competitive matches only. Female players continued to show lower impact frequencies than males in competitive events (21 fewer impacts per player-season; 95% CI − 33 to 14; $p < 0.0001$).

Head Impact Severity

Linear acceleration was slightly higher in impacts among females than impacts among males (increase of 1.07 g; 95% CI 1.00 to 1.13; $p = 0.04$), but there was no significant difference in rotational acceleration between males and females in our sample (Table 3). There were no statistically significant differences in the odds of sustaining a severe vs. mild/moderate impact between males and females for any of the head impact biomechanics measures (Table 4). Although this lacked statistical significance, we did observe that girls had 41% lower odds of sustaining a hit with severe rotational acceleration (odds ratio [OR] 0.59; 95% CI 0.33 to 1.05; $p = 0.07$).

DISCUSSION

This study evaluated sex differences in head impact severity and frequency in youth ice hockey players. Females experienced considerably less head impact exposures than males playing a similar sport. Head impact severity was largely equivalent among male and female youth ice hockey players; however, linear acceleration was higher in impacts among females than impacts among males (increase of 1.07 g).

Despite significant rule differences regarding body contact (body checking is legal in men's ice hockey only), previous studies have reported similar or higher concussion rates in female compared to male ice hockey players. Investigating factors influencing head impact biomechanics are a necessary first step to develop and implement specific strategies reducing ice hockey concussion incidence. At the college level, male players had significantly higher head impact severities than females for rotational acceleration,[21] and were 1.3, 1.9, and 3.5 times more likely to sustain impacts greater than 100 g (linear acceleration), 5000 rad/s^2 (rotational acceleration), and 10,000 rad/s^2 (rotational acceleration), respectively.[4] As severity outcomes for player-to-player contact are largely dependent on the

TABLE 1. Descriptive statistics of head impacts.

Characteristic	Female (n = 599)	Male (n = 29288)
Session type		
Practice	24 (4.0%)	6579 (22.5%)
Game/scrimmage	575 (96.0%)	22709 (77.5%)
Hit location		
Front	176 (29.4%)	8926 (30.5%)
Back	230 (38.4%)	7039 (24.0%)
Side	123 (20.5%)	9951 (34.0%)
Top	70 (11.7%)	3372 (11.5%)
Median linear acceleration (IQR)	18.1 g (14.0–25.0)	17.1 g (13.0–24.3)
Median rotational acceleration (IQR)	1501.5 rad/s^2 (1079.2–2211.0)	1352.8 rad/s^2 (913.8–2098.8)
Linear impact severity[a]		
Mild (< 25 g)	448 (74.8%)	22359 (76.3%)
Moderate (25 to < 45 g)	122 (20.4%)	5400 (18.4%)
Severe (≥ 45 g)	29 (4.8%)	1529 (5.2%)
Rotational impact severity[a]		
Mild (< 2000 rad/s^2)	421 (70.3%)	21251 (72.6%)
Moderate (2000 to < 4000 rad/s^2)	149 (24.9%)	6507 (22.2%)
Severe (≥ 4000 rad/s^2)	29 (4.8%)	1530 (5.2%)

All values represent head impact frequency (percentage of impacts in category within sex), unless otherwise specified.
[a]The cutoff values used for mild, moderate, and severe impacts were based on the 75th percentile (moderate) and 95th percentile (severe) computed from the combined sample evaluated in our study.

TABLE 2. Impact frequency per player, by impact severity category.

Impacts	Females (n = 25)	Males (n = 110)
Median total impacts (IQR)	13 (1–23)	264 (186–313)
Median linear acceleration (IQR)		
Mild (< 25 g)	7 (1–16)	199 (148–254)
Moderate (25 to < 45 g)	2 (0–7)	40 (25–59)
Severe (≥ 45 g)	0 (0–2)	11 (6–18)
Median rotational acceleration (IQR)		
Mild (< 2000 rad/s^2)	10 (1–20)	177 (117–242)
Moderate (2000 rad/s^2 to < 4000 rad/s^2)	3 (0–5)	53 (31–76)
Severe (≥ 4000 rad/s^2)	0 (0–1)	10 (6–18)

TABLE 3. Association between sex and head impact biomechanics measures.

	Linear acceleration (g)			Rotational acceleration (rad/s^2)		
	Mean difference	95% CI	p	Mean difference	95% CI	p
Female (vs. male)	1.07	1.00, 1.13	0.04	− 1.05	− 1.17, 1.07	0.42
U14 (vs. U16)	1.05	1.02, 1.09	0.001	− 1.11	− 1.19, − 1.04	0.003
Defense (vs. forward)	− 1.03	− 1.10, 1.03	0.14	− 1.00	− 1.12, 1.11	0.93
Game/scrimmage (vs. practice)	1.04	1.03, 1.06	< 0.0001	1.08	1.06, 1.10	< 0.0001
Location (vs. front)			< 0.0001			< 0.0001
Back	1.08	1.07, 1.10		1.00	− 1.01, 1.02	
Side	− 1.04	− 1.05, − 1.02		1.09	1.07, 1.11	
Top	1.16	1.14, 1.18		− 1.30	− 1.33, − 1.27	

*Mean difference and 95% confidence interval estimates, adjusted for all other variables listed in the table, were derived from exponentiating beta coefficients from models employing our dependent variables of natural logarithm for linear acceleration (i.e., ln(linear)) and rotational acceleration (i.e. ln(rotational).

TABLE 4. Odds ratios (OR) of sustaining an impact in the top 5% of impact severity (linear acceleration ≥ 45 g, rotational acceleration ≥ 4000 rad/s^2).

	Linear acceleration (g)			Rotational acceleration (rad/s^2)		
	OR[a]	95% CI	p	OR[a]	95% CI	p
Female (vs. male)	0.86	0.53, 1.40	0.55	0.59	0.33, 1.05	0.07
U14 (vs. U16)	0.97	0.79, 1.19	0.76	0.54	0.41, 0.71	< 0.0001
Defense (vs. forward)	0.89	0.58, 1.35	0.34	0.96	0.56, 1.65	0.79
Game/scrimmage (vs. practice)	1.01	0.89, 1.15	0.86	1.45	1.26, 1.68	< 0.0001
Location (vs. front)			< 0.0001			< 0.0001
Back	2.49	2.16, 2.86		1.35	1.17, 1.55	
Side	0.86	0.73, 1.00		1.27	1.11, 1.55	
Top	2.73	2.32, 3.22		0.69	0.55, 0.88	

[a]Odds ratios are adjusted for all other variables shown in the table.

mass and acceleration of the players engaged in the collision, heavier athletes and/or those traveling at greater speeds would theoretically create more severe impacts. In our cohort of youth athletes (ages 13–16 years), anthropometric outcomes, specifically body mass, are more similar between sexes (mean mass: 64.3 kg male; 54.5 kg female) than those reported in a collegiate sample (mean mass: 86.0 kg male; 67.2 kg female).[4] This may account, at least in part, for why the head impact severity data reported in this study differs from collegiate studies.

Despite these anthropometric differences, the median and 95th percentile values for linear acceleration and rotational acceleration found in this study were surprisingly similar to values reported in college ice hockey samples. Wilcox et al.[21] reported median linear acceleration (females: 15.0 g; males: 15.7 g) and rotational acceleration (females: 1211 rad/s^2; males: 1630 rad/s^2) in a sample of college ice hockey players. Median values reported in our study are found in Table 2 and are largely comparable with those presented by Wilcox et al. Values for the 95th percentiles were also similar between Wilcox et al.'s college study [college linear: 43.7 g (males), 44.9 g (females); college rotational: 4,764 rad/s^2 (males), 3,709 rad/s^2 (females)] and our youth study [youth linear: 45.6 g (boys), 44.9 g (girls); youth rotational: 3,916 rad/s^2 (boys), 4,058 rad/s^2 (girls)]. While values are similar between youth and college cohorts, the variability (IQR) observed in head impact severity outcomes was much greater in the youth cohort we studied. Increased variability may be due to wide ranges of skill level and playing experience found at youth level.

The head impact frequency sustained throughout a playing season was significantly higher in male youth hockey players, paralleling previous studies at the college level.[4,21] Body checking is illegal at all levels of women's hockey, while it is permitted at and above the Bantam-level for males. Rule differences surrounding body contact likely account for the large discrepancy in impact frequencies we observed between our female and male hockey players. The low impact frequency was especially apparent for females in the practice setting, where only 24 impacts (4% of total impacts collected in females) occurred. These impacts were sustained by only seven of our 25 female participants, with five of these seven players experiencing no greater than 3 measurable practice head impacts. We speculate the higher proportion of impacts sustained by females during competition may point to several possible explanations that would be worth studying within the context of health behavior strategies: (1) females are more aggressive competing against opponents, (2) they are not hindered during competition by fears associated with potentially injuring a teammate in practice, and (3) girls' hockey coaches are not preparing their players adequately in practice by introducing game-like contact scenarios. Male players also sustained more impacts during competitions than practices (77.5% vs. 22.5% of total impacts). In combination, this suggests that there are unique factors surrounding competitions encompassing both the men's and women's game leading to more frequent and severe head impacts.

The relatively higher head impact frequencies sustained during competition suggests female athletes were receiving either illegal player-to-player or unintentional (e.g. falling into ice/boards) head contact during game-play. While these mechanisms were not informed by video, there are a limited number of scenarios that could result in head impacts sustained during on-ice participation. Future studies should explore these factors in more detail. Even in men's hockey, contact directed to the head or "blindside" body checks (those from behind the player when they are unable to anticipate a potential hit) are illegal forms of body collision. Previous work in male athletes has shown illegal head contact results in higher linear acceleration than legal body checking.[16] Blindside hits are especially dangerous as players are unable to anticipate the contact and may result in more severe head impacts.[15] This study and the previous literature[18] have found that hits to the side and back of the head cause significantly higher linear or rotational accelerations, potentially increasing injury risk as players are unable to anticipate the collision or altogether avoid a dangerous situation. The important role coaches and referees play in enhancing player safety within this context cannot be overstated in this population, as they are responsible for teaching and enforcing good sportsmanship and playing rules.

Despite the absence of body checking, female ice hockey players have concussion rates higher than their male counterparts.[1,12] We hypothesized that this was due to females sustaining higher linear and rotational head impact accelerations, but the magnitude of the differences in impact measures that we observed seems clinically unlikely to account for the observed difference in concussion incidence. The influence of sex in care-seeking may account for some of these concussion incidence differences, assuming that men may be potentially less likely to disclose concussion symptoms to health care providers. Coach, parent, and peer messaging about the importance of concussion disclosure may also differ by sex. The effect of cervical muscle strength and activation may be another factor of interest. The literature surrounding cervical muscle characteristics and head impact biomechanics is largely mixed,[7,19,20] but research in ice hockey has been completed in mostly male cohorts. Finally, there may be differences in rule enforcement between males and females. Future studies should evaluate these combined behavioral, environmental, and neuromuscular factors to determine their joint contribution to head impact severity and observed concussion incidence.

Limitations

A number of limiting factors should be noted. This observational investigation was part of a larger study that originally included only male youth ice hockey players; female cohorts were not added until later in the study period. We therefore have a relatively small number of female participants, particularly at the Bantam level, and fewer female team-seasons of data available for comparison. Despite being sufficiently powered to identify several statistically significant findings with our available data, we were not able to analyze categorical severity outcomes as originally planned because of insufficient sample size for model convergence. We were able to successfully adapt our analysis plan to evaluate severe vs. non-severe (mild and moderate) head impact outcomes, but this may have prevented us from discovering sex differences at lower severity levels. Data collection for this study took place over several years. Many factors, including coaching philosophies and playing style, may have changed throughout this study and could influence our results, especially as concussion awareness and media attention became more prevalent in later study years. We removed head impacts occurring outside of sanctioned playing time and below 10 g in efforts to eliminate erroneous data points. However, we were unable to manually review all impacts via video analysis and, therefore, we cannot be certain that every recorded impact was a true head hit.

CONCLUSIONS

Ice hockey is a unique sport due to the potential for full body collisions at speeds higher than those observed in other sports such as football or soccer. Understanding characteristics contributing to more severe head impacts is necessary to design and implement specific prevention strategies targeted at reducing head injury in hockey cohorts. Male and female youth ice hockey players sustain head impacts of roughly the same linear acceleration and rotational acceleration. Although male players sustain significantly more impacts over the course of a season than females, females have a slightly higher average linear acceleration per impact than males. Future studies should continue to evaluate sex factors that may explain differences in concussion rates, with the goal of developing sex-specific preventive strategies specific to these two ice hockey populations.

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