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original research

Head-Impact Mechanisms in Men's and Women's Collegiate Ice Hockey

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Context: Concussion injury rates in men's and women's ice hockey are reported to be among the highest of all collegiate sports. Quantification of the frequency of head impacts and the magnitude of head acceleration as a function of the different impact mechanisms (eg, head contact with the ice) that occur in ice hockey could provide a better understanding of this high injury rate.

Objective: To quantify and compare the per-game frequency and magnitude of head impacts associated with various impact mechanisms in men's and women's collegiate ice hockey players.

Design: Cohort study.

Setting: Collegiate ice hockey rink.

Patients or Other Participants: Twenty-three men and 31 women from 2 National Collegiate Athletic Association Division I ice hockey teams.

Main Outcome Measure(s): We analyzed magnitude and frequency (per game) of head impacts per player among impact mechanisms and between sexes using generalized mixed linear models and generalized estimating equations to account for repeated measures within players.

Intervention(s): Participants wore helmets instrumented with accelerometers to allow us to collect biomechanical measures of head impacts sustained during play. Video footage from 53 games was synchronized with the biomechanical data. Head impacts were classified into 8 categories: contact with another player; the ice, boards or glass, stick, puck, or goal; indirect contact; and contact from celebrating.

Results: For men and women, contact with another player was the most frequent impact mechanism, and contact with the ice generated the greatest-magnitude head accelerations. The men had higher per-game frequencies of head impacts from contact with another player and contact with the boards than did the women ($P < .001$), and these impacts were greater in peak rotational acceleration ($P = .027$).

Conclusions: Identifying the impact mechanisms in collegiate ice hockey that result in frequent and high-magnitude head impacts will provide us with data that may improve our understanding of the high rate of concussion in the sport and inform injury-prevention strategies.

Key Words: impact biomechanics, sport, concussion, sex

Key Points

- The most frequent head-impact mechanism in both men's and women's collegiate ice hockey was contact with another player. Contact with the ice was the mechanism that resulted in head impacts with the greatest magnitude.
- Male collegiate ice hockey players experienced head impacts from contact with another player and contact with the boards more frequently than did female players, and these impacts were generally of greater magnitude.

Ice hockey is a high-intensity, high-speed collision sport in which most injuries are caused by blunt trauma or direct contact with another player or object as opposed to overuse injuries.[1] High rates of injury have been reported in both men's and women's collegiate ice hockey (5.95/1000 and 5.12/1000 athlete-exposures [AEs], respectively), and the most common injury in both populations is concussion.[2] The rate of concussion has been reported to be higher in women's ice hockey (0.82/1000 AEs) than in men's (0.72/1000 AEs), but the reasons for this are not well understood.[2] Concussions are usually attributed to a direct impact to the head but can also be caused by an impact to the body that results in an acceleration of the head.[3] The high rate of injury, including concussions, in ice hockey can be attributed to the unique factors of the game: the playing area is made of solid ice and enveloped by rigid boards, players manipulate pucks that, when shot, can exceed speeds of 80 mph (117 kph), and players travel at speeds of up to 30 mph (44 kph) and purposefully collide with opponents.[4,5] These factors allow for a number of different head-impact mechanisms, or circumstances in which a head impact occurs (head contact with ice, boards, etc), in ice hockey.

Currently, data quantifying the biomechanics of head impacts as a function of the different impact mechanisms that occur in ice hockey are lacking. Previous authors[6,7] have quantified the frequency and magnitude of head impacts in cohorts of male and female hockey players at different levels of play using the Head Impact Telemetry (HIT) System (Simbex, Lebanon, NH). The HIT System measures and records biomechanical data from head impacts, including the linear and rotational acceleration of the head, impact duration, and impact location on the helmet.[5–19] These studies have provided valuable information on individual players' exposure to head impacts but did not identify or examine the relationship with mechanisms of impact. Other researchers[2,4,20–22] have reported injury epidemiology, including diagnosed concussions, by specific injury mechanisms in collegiate ice hockey. Agel et al[20,21] used the National Collegiate Athletic Association (NCAA) Injury Surveillance System to report concussion mechanisms in collegiate men and women. Diagnosed concussions were classified into 1 of 7 mechanisms: contact with another player, contact with the ice surface, contact with the boards or glass, contact with the goal, contact with the stick, contact with the puck, or no apparent contact. Another author[23] classified injury mechanisms in National Hockey League players by reviewing video footage from games in which diagnosed concussions occurred. The most common mechanism that resulted in diagnosed concussions for both studies was player-to-player contact.[20,21,23] Although these assessments provided important information on injury and concussion mechanisms in ice hockey, the collection and analysis of the impact biomechanics that resulted from these mechanisms were beyond the scope of the study designs. Synchronizing video with the biomechanics of head impacts would provide a quantitative approach to evaluating head impact mechanisms and biomechanics.

The aim of our study was to quantify and compare the frequency and magnitude of head impacts associated with various impact mechanisms in men's and women's collegiate ice hockey players. We accomplished this by synchronizing video footage from games with biomechanical data from the HIT System. We hypothesized that the frequency and magnitude of head impacts would differ among the various head-impact mechanisms and that sex would be a significant factor in both frequency and magnitude.

METHODS

A total of 23 men and 31 women from Brown University's ice hockey teams participated in this study. We obtained institutional review board approval from Brown University and Rhode Island Hospital. The female players (age range = 18–24 years, height = 168.9 ± 7.1 cm, weight = 68.0 ± 8.2 kg; 10 defenders and 21 forwards) wore instrumented helmets for 3 seasons (2008–2009, 2009–2010, 2010–2011). A total of 13, 10, and 8 of the female players participated in 1, 2, and 3 seasons, respectively. The male players (age range = 19–25 years, height = 182.6 ± 4.1 cm, weight = 85.2 ± 4.7 kg; 8 defenders and 15 forwards) wore instrumented helmets over the course of 1 season (2009–2010). Data collection for the men's team was limited to a single season because the team accepted a new equipment contract after that season, and the HIT System technology was not compatible with the helmet models specified within the new contract. Goalies were not included in this study.

Home games were professionally video recorded at 30 frames per second using a professional broadcast camera (model DVC-PRO AJ-D810ap; Panasonic Corporation of North America, Newark, NJ). This camera provided 750 horizontal and 450 vertical lines of resolution. The broadcast lens (model Fujinon A18×7.6 mm; Fujifilm USA, Stamford, CT) had a focal length of 7.6–137 mm. The camera followed the puck during play. Video footage was collected at all home games for which the camera equipment and operator were available, resulting in footage for 12 of the 15 men's home games and 41 of the 44 women's home games.

Biomechanical data from head impacts were collected using helmets instrumented with the HIT System. Participants were fitted with S9 Easton helmets (Van Nuys, CA) that had been modified to accept the HIT System. The HIT System instrumentation, data-reduction methods, and accuracy of the HIT algorithm have been described in detail and previously verified.[7–10,14–17,24] Briefly, 6 single-axis accelerometers, arranged tangentially to the head, were elastically mounted within the helmet's foam liner to maintain contact with the head and to decouple shell vibrations.[10,15] Acceleration data associated with unique player identifications were collected at 1 kHz, time stamped, stored in the helmet (up to 100 impacts in static memory), transmitted by radiofrequency telemetry to a computer, and then entered into a secure database. For each impact, magnitude was quantified by peak linear acceleration (g) and peak rotational acceleration (rad/s^2) of the head, as well as HITsp, a weighted measure of head impact severity that includes linear and rotational acceleration, impact duration, and impact location.[15] The biomechanical data were filtered to include only head-impact events that resulted in a peak linear acceleration greater than 20g. This threshold approximates the mean of all head-impact events sustained in contact sports[5,7,12,13,17,18,25] and is well below the reported acceleration levels for diagnosed sport-related concussions.[26–28]

Game video and biomechanical data were time synchronized at the beginning and end of each game period by manually generating an impact event on a spare HIT System unit within the video field of view. Video was reviewed using VLC media player (version 2.0.0; VideoLAN, Paris, France). Identification of the impacts on video was aided by player identification and location of impact on the helmet recorded by the HIT System. Head impacts were classified into mechanism categories modeled after the NCAA Injury Surveillance System's Game Concussion Mechanisms of Injury, previously described by Agel et al[2,20,21] and consisted of contact with another player, contact with the ice surface, contact with the boards or glass, contact with the goal, contact with the stick, contact with the puck, indirect contact, and contact from celebrating. An event was classified as 1 of these mechanisms when there was direct head contact with another player, the ice surface, boards or glass, stick, puck, or goal. An impact event was classified as *indirect contact* when an acceleration event above 20g was recorded but the head did not appear to make contact with any object or player. This usually occurred as a secondary event: for example, when a player was clearly hit in the torso or fell to the ice, but the player's head did not appear to make contact with any other person or object. For impacts such as these, the primary mechanism was not categorized or reported. An eighth category, contact from celebrating, was included due to the observation of relatively frequent head impacts greater than

Table 1. Head Impacts for Each Category of Head Impact Mechanism Across the Entire Study for Each Team, Independent of Players

	Head Impacts, % (No.)	
Mechanism	Men (n = 270)	Women (n = 242)
Contact with another player	50.4 (136)	50 (121)
Contact with ice	7 (19)	11.2 (27)
Contact with boards or glass	31.1 (84)	17.3 (42)
Contact with stick	1.9 (5)	2.9 (7)
Contact with goal	0.4 (1)	0 (0)
Contact with puck	0.4 (1)	0.8 (2)
Indirect contact	4.4 (12)	15.3 (37)
Celebrating	4.4 (12)	2.5 (6)

20*g* that resulted from teammates hitting each other in the head in a congratulatory way after a good play or a goal. Because the videographer followed the puck during play, some head impacts recorded by the HIT System were not captured on video. These impacts were sustained by players outside of the field of view of the camera or were obstructed from view by the angle of the camera or by an object, such as the boards or another player. We did not include these head impacts in the present analysis because the mechanism of contact could not be classified.

Statistical Analysis

We computed the percentages of all head impacts in each mechanism category and between sexes independent of player but did not use these values in hypothesis testing. All hypothesis testing was performed using SAS (version 9.2; SAS Institute Inc, Cary, NC). Alpha was set to .05 for all analyses. A generalized estimating equation for negative binomial data, offset with the natural logarithm of the number of games each player played in, was used to test whether frequency (per game) of head impacts per player differed among impact mechanisms and between sexes (1 count per player per game per mechanism). Generalized linear mixed models for lognormal data were used to test whether the peak linear acceleration, peak rotational acceleration, and HITsp of impacts experienced by players varied as a function of mechanism and sex. Compound symmetry variance-covariance structures were used to model the nature of the within-subjects correlation by game (games have the same variance and there is a single covariance between games). Follow-up pairwise comparisons were adjusted using the Holm test to maintain overall α at .05 for all models. All models were also adjusted for model misspecification using classical sandwich estimation, making inferences robust to errors in distribution and variance-covariance structure selection.

RESULTS

A total of 4497 head impacts, 1965 sustained by men and 2532 sustained by women, were recorded during 53 home games. A total of 616 head impacts had a resultant peak linear acceleration greater than 20*g*. For the 12 men's home games, 270 impacts (81% of the 333 impacts >20*g* recorded) were successfully captured on video and classified (Table 1). For the 41 women's home games, 242 impacts (85.5% of the 283 impacts >20*g* recorded) were successfully captured on video and classified.

Table 2. Head-Impact Frequency per Game By Head-Impact Mechanism (See Results for Statistical Analysis) Between Sexes

Mechanism	Men	Women	*P* Value
Contact with another player	0.464	0.208	<.001[a]
Contact with ice	0.104	0.106	.950
Contact with boards	0.349	0.095	<.001[a]
Indirect contact	0.087	0.100	.539
Celebrating	0.080	0.073	.618

[a] Statistically different between sexes.

Approximately half of these impacts were caused by contact with another player on both the men's and women's teams (50.4% and 50%, respectively). For the men's team, 31.1% of head impacts were caused by contact with the boards or glass, 7% by contact with the ice, and 4.5% by indirect contact and contact from celebrating. For the women's team, 17.3% of head impacts were caused by contact with the boards or glass, 15.3% by indirect contact, and 11.2% by contact with the ice. Contacts with the stick, goal, and puck each accounted for less than 3% of the impacts for both men and women and were not analyzed further.

In men's ice hockey, head impacts for individual players resulting from contact with another player occurred at a frequency of approximately once in every 2 games (0.46 per game; Table 2). The frequency of impacts per game that were caused by contact with another player and contact with the boards (0.349 per game) were both higher than the frequency of impacts from contact with the ice, indirect contact, and celebrating ($P < .001$ for each comparison). In women's ice hockey, the frequency of impacts per game that were caused by contact with another player (0.21 per game) was higher than those that were caused by contact with the boards, indirect contact, and celebrating ($P < .001$ for each comparison).

The means and 95% confidence intervals for peak linear acceleration, rotational acceleration, and HITsp for all impacts analyzed in this study were, respectively, 31.2*g* (28.9*g*, 33.7*g*), 2881.0 rad/s^2 (2580.0, 3217.2), and 18.8 (17.3, 30.4) for men and 28.3*g* (26.6*g*, 30.1*g*), 1766.8 rad/s^2 (1508.0, 2068.8), and 16.74 (15.7, 17.9) for women. Across all mechanisms, peak rotational acceleration and HITsp were both higher in men than in women ($P < .001$, $P = .035$, respectively), whereas the difference in peak linear acceleration was not significant ($P = .054$). In men's ice hockey, peak linear accelerations caused by contact with the ice were greater than those from contact with another player ($P < .001$; Table 3). In women's ice hockey, peak linear acceleration was greater in head impacts caused by contact with the ice than those caused by contact with another player ($P = .029$), contact with the boards or glass ($P < .001$), indirect contact ($P = .043$), or celebrating ($P < .001$). Women also experienced greater peak rotational acceleration in head impacts caused by contact with another player than by contact with the boards ($P = .03$). Head impacts sustained while celebrating in men's and women's hockey were generally lower in linear acceleration, rotational acceleration, and HITsp than in the other mechanisms.

The frequency of head impacts per game resulting from contact with another player and contact with the boards or glass were both higher ($P < .001$) for men than for women.

Table 3. **Resultant Peak Linear Acceleration, Peak Rotational Acceleration, and HITsp of Head Impacts Greater than 20*g* Sustained by Men's and Women's Collegiate Ice Hockey Players for Each Injury Mechanism (Mean [95% Confidence Interval])**

Mechanism	Linear Acceleration (*g*)	Rotational Acceleration (rad/s^2)	HITsp
Men			
Contact with another player	28.0 (26.4, 29.7)	2901.8 (2514.5, 3348.7)	19.2 (17.7, 20.7)
Contact with ice	40.1 (31.8, 50.5)	3454.9 (2590.2, 4608.4)	22.8 (17.9, 29.1)
Contact with boards	32.1 (29.7, 34.7)	3350.4 (2995.9, 3746.8)	21.0 (20.2, 21.8)
Indirect contact	31.5 (26.4, 37.8)	2873.8 (1949.8, 4235.7)	19.7 (15.2, 25.5)
Celebrating	25.9 (23.6, 28.4)	2056.3 (1707.9, 2475.7)	12.9 (11.3, 14.7)
Women			
Contact with another player	27.9 (26.3, 29.6)	2323.0 (2031.6, 2656.9)	17.9 (16.8, 18.9)
Contact with ice	35.2 (30.9, 40.0)	2318.9 (1644.2, 3270.4)	21.2 (17.7, 25.5)
Contact with boards	26.8 (25.8, 27.9)	1859.5 (1587.0, 2178.8)	16.7 (14.5, 19.2)
Indirect contact	29.5 (25.6, 34.0)	1861.3 (1387.1, 2497.6)	19.1 (17.1, 21.4)
Celebrating	23.3 (20.1, 27.0)	923.3 (675.2, 1262.5)	10.9 (8.8, 13.5)

Although contact with another player was the most frequent impact mechanism in both men and women, these impacts were not the greatest in magnitude (Figure). Peak linear acceleration ($P < .001$) and HITsp ($P = .003$) from contact with the boards or glass were both greater for men than for women. Peak rotational acceleration was greater for men than for women in contact with another player ($P = .027$), contact with the boards or glass ($P < .001$), and celebrating ($P < .001$). No other comparisons of impact magnitude between men and women were statistically significant.

DISCUSSION

The purpose of our study was to quantify and compare the frequency and magnitude of head impacts associated with various impact mechanisms in men's and women's collegiate ice hockey. The impact mechanisms of head contact that we identified were contact with another player, the ice surface, boards or glass, stick, goal, or puck; indirect contact, and celebrating. These categories were modeled from previous studies[2,20,21] that used the NCAA Injury Surveillance System data to report the epidemiology of injury mechanisms in men's and women's collegiate ice hockey.

Male players experienced head impacts greater than 20*g* from contact with another player and contact with the boards once every 2 to 3 games, whereas women had less than 1 every 3 to 5 games. Peak rotational acceleration of the impacts from these mechanisms was also greater for men than for women by approximately 25%. We attribute this difference to the fact that checking, or purposeful body contact of an opposing player, is permitted in men's

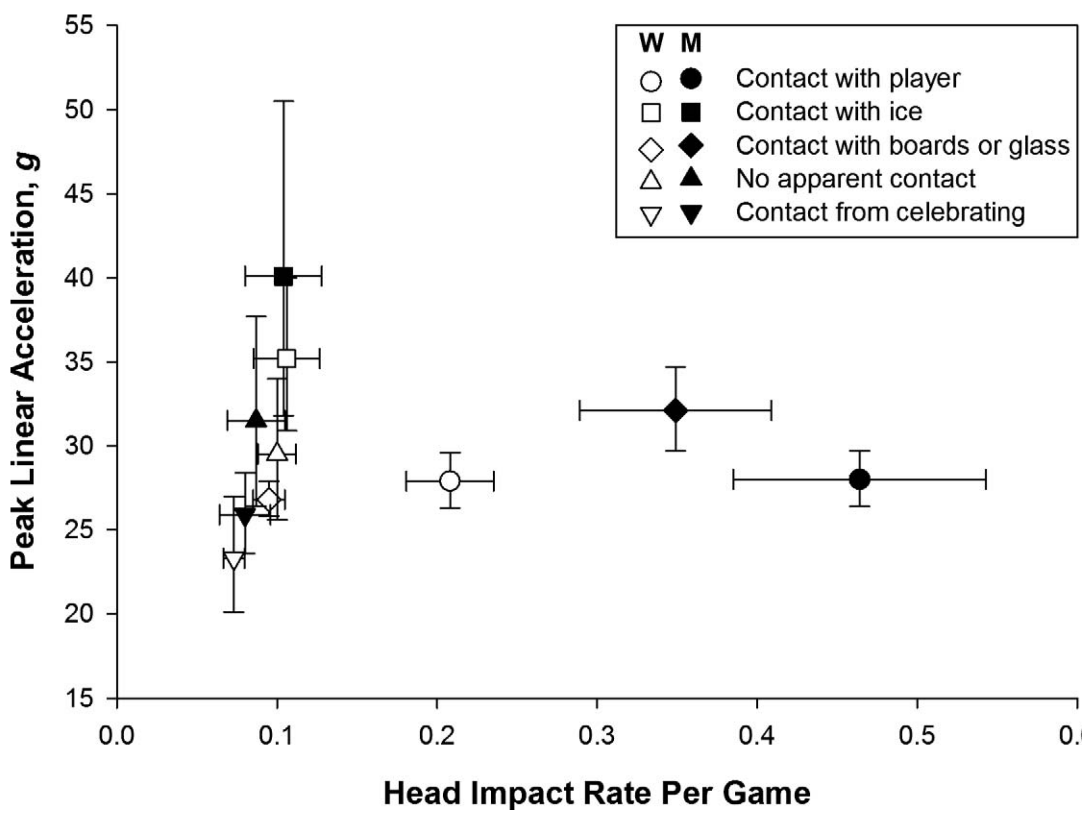

Figure. Peak linear acceleration (*g*) as a function of the frequency of head impacts per game for each head impact mechanism (Means and 95% confidence intervals). Unfilled markers represent women; filled markers represent men.

collegiate ice hockey but illegal in the women's sport. The high rate of contact with another player and with the boards in men's hockey was expected, as checking is an important part of the game and frequently results in secondary impact of the head or body to the boards. In a study of male players at the professional level, the predominant mechanism of concussion was reported to be player-to-player contact.[23] Similarly, player-to-player contact was the most common cause of concussions at the collegiate level, accounting for 72% of diagnosed concussions in males and 41% of those in females during games.[2,20,21] Even though checking is not allowed by the NCAA in women's ice hockey, these data confirm, as previous authors[6] have reported, frequent and high-magnitude player-to-player contact during women's play. It has been speculated that, because many female hockey players are not taught and do not practice checking skills, they may be less prepared to absorb impacts when they experience collisions.[2] Researchers[18] have shown that anticipated head impacts result in less severe head impacts than unanticipated impacts in youth hockey. Inconsistent enforcement of the rules leaves female players more vulnerable to impacts caused by player contact because they may not be expecting the contact.[20] Whereas we did not identify illegal plays or infractions, a review of the penalties along with comparisons of secondary contact after player-to-player contact may provide a better understanding of the role that checking plays in the high concussion rate in men's and women's collegiate ice hockey.

Contact with another player was the mechanism that resulted in the highest rate of per-game head impacts but impacts from contact with the ice had the greatest magnitude (Figure). These impacts had greater mean peak linear acceleration than impacts caused by other mechanisms in both men's and women's ice hockey. This finding is not surprising given the fact that these players can move at speeds upwards of 30 mph (44 kph),[4] are falling onto the ice from a height several inches higher than their own (skates and blades can add inches to players' heights), and are hitting the hard ice surface. Although contact with the ice occurred at a relatively low frequency when compared with other impact mechanisms, this mechanism occurred approximately once every 10 games for individual male and female players. Given that NCAA teams are allowed to play 34 games during a regular season (not including conference postseason tournaments), our results suggest that an average player experiences these high-magnitude head impacts with the ice approximately 3 times per season. No differences were evident between men and women in the frequency and magnitude of impacts that occurred from contact with the ice. Interestingly, previous authors[20,21] reported that contact with the ice resulted in 28.1% of game concussions for female collegiate ice hockey players but only 7% of game concussions for their male counterparts. The incidence of diagnosed concussions has been reported as higher in female hockey players than in males,[2,29] yet the frequency and magnitude data we collected confirm previous reports that females sustain fewer impacts, and these impacts result in lower head accelerations than in males.[6] Several explanations for why females have a higher rate of concussion than males have been proposed, including physiologic and psychological differences, but the exact reasons remain unclear.[29]

Regardless of head-impact mechanism, the mean peak linear accelerations we report were greater than those previously reported by other investigators who have used the HIT System, including youth hockey and collegiate football players. Mihalik et al[7] studied a cohort of youth male hockey players and noted a mean peak linear acceleration of 18.98*g*. Crisco et al[12,13] reported the 50th percentile peak linear acceleration of 20.3*g* to 20.5*g* in collegiate football players. In addition to the factors of age, sex, and sport, these differences can be attributed to the 20-*g* acceleration threshold we selected for analysis. A primary benefit of the HIT System is its ability to capture head-acceleration events that may not be easily discernible in the fast-paced environment of contact sports. To accommodate the practical limitations of video review, we elected to use 20*g* (an approximation of the mean values of head-impact events sustained in contact sports[5,7,12,13,17,18,25]) as the inclusion threshold for biomechanical data. This threshold level isolated head-acceleration events with a high likelihood of producing a clear physical response that could be identified on video (in comparison, an aggressive pillow fight results in approximately 20*g*[30]) while still including events well below acceleration magnitudes associated with diagnosed sport-related concussions.[26–28] Approximately equal proportions of impacts less than 20*g* for both males (86.3% [1695/1965]) and females (90.4% [2290/2532]) were observed. Although the acceleration threshold does not affect the associations between impact mechanism and biomechanical responses we report, future authors should avoid direct comparisons with the mean acceleration values shown in Table 3 without considering this threshold. It is also important to note that accelerations of less than 20*g* are considered relatively low in magnitude for single events[19,25] but the long-term consequences of such repeated events are unknown.

This threshold was just 1 of several recognized limitations of the study. Classification of the impact mechanisms was ultimately subjective. Video is a relatively simple method of observing head-impact mechanisms in hockey, yet it can be challenging because of the fast pace of the game. Approximately 15% to 20% of impacts above 20*g* that were recorded by the HIT System were not captured on video because they occurred outside of the camera's field of view or they were obstructed from view by the angle of the camera or by an object, such as the boards or another player. Also, our study included an unequal number of seasons and games for men and women. Although we only analyzed data from a series of home games as opposed to all AEs (all practices and games) during each season, the incidence of injury has been reported as higher in games than in practices and 77% of concussions occurred in games.[1,2] The HIT System provides additional biomechanical variables that were not included in the analysis, including location of impacts on the helmet and duration of acceleration. These variables were beyond the scope of our analysis, but future analysis of these measures in relation to head impact mechanism is warranted. A final limitation is that no diagnosed concussions occurred during the games included in this study.

In summary, the most frequent head-impact mechanism in both men's and women's collegiate ice hockey was contact with another player, and contact with the ice was the mechanism that resulted in head impacts with the greatest magnitude. Recently, research related to head injuries in sports has primarily focused on addressing 2 main concerns, the high rate of diagnosed and undiagnosed concussions and the potential long-term effects of repetitive head impacts. If one assumes that impacts of greater magnitude have more associated risk for concussion,[26] then the strategies to address these 2 concerns may be different. To reduce the frequency of head impacts, player contact rules should be reconsidered. To reduce high-magnitude head impacts, reevaluating helmet design to protect against contact with the ice may be warranted. Sex was a factor in per-game frequency and magnitude of head impacts associated with several impact mechanisms. Men experienced head impacts from contact with another player and contact with the boards more frequently than did women, and these impacts were generally of greater magnitude. Further study is required to better understand why female athletes are reported to have higher concussion rates than their male counterparts,[2] given that females sustained less-frequent and lower-magnitude head impacts in our study. The identification of impact mechanisms in collegiate ice hockey players that result in frequent and high-magnitude head impacts is an important step in understanding the high rate of concussions in the sport and could inform concussion-prevention strategies.

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