University of Nebraska - Lincoln
DigitalCommons@University of Nebraska - Lincoln

Faculty Publications, Department of Psychology

Psychology, Department of

2012

Gender Differences in Head Impacts Sustained by Collegiate Ice Hockey Players

Lindley L. Brainard
Simbex, Lebanon, NH

Jonathan G. Beckwith
Simbex, Lebanon, NH

Jeffrey J. Chu
1Simbex, Lebanon, NH

Joseph J. Crisco
Brown University, Joseph_Crisco_III@Brown.Edu

Thomas W. McAllister
Dartmouth Medical School, Hanover

See next page for additional authors

Authors
Lindley L. Brainard; Jonathan G. Beckwith; Jeffrey J. Chu; Joseph J. Crisco; Thomas W. McAllister; Ann-Christine Duhaime,; Arthur C. Maerlender; and Richard M. Greenwald

Published in final edited form as:
Med Sci Sports Exerc. 2012 February ; 44(2): 297–304. doi:10.1249/MSS.0b013e31822b0ab4.

Gender Differences in Head Impacts Sustained by Collegiate Ice Hockey Players

Lindley L. Brainard[1], **Jonathan G. Beckwith**[1], **Jeffrey J. Chu**[1], **Joseph J. Crisco**[2], **Thomas W. McAllister**[3], **Ann-Christine Duhaime**[4], **Arthur C. Maerlender**[3], and **Richard M. Greenwald**[1,5]

[1]Simbex, Lebanon, NH, USA

[2]Bioengineering Laboratory, Department of Orthopedics, Alpert Medical School of Brown University and Rhode Island Hospital, Providence, RI, USA

[3]Department of Psychiatry, Dartmouth Medical School, Hanover, NH, USA

[4]Massachusetts General Hospital and Harvard Medical School, Boston, MA, USA

[5]Thayer School of Engineering, Dartmouth College, Hanover, NH, USA

Abstract

Purpose—This study aims to quantify the frequency, magnitude, and location of head impacts sustained by male and female collegiate ice hockey players over two seasons of play.

Methods—Over two seasons, 88 collegiate athletes (51 female, 37 male) on two female and male NCAA varsity ice hockey teams wore instrumented helmets. Each helmet was equipped with 6 single-axis accelerometers and a miniature data acquisition system to capture and record head impacts sustained during play. Data collected from the helmets were post-processed to compute linear and rotational acceleration of the head as well as impact location. The head impact exposure data (frequency, location, and magnitude) were then compared across gender.

Results—Female hockey players experienced a significantly lower ($p < 0.001$) number of impacts per athlete exposure than males (female: 1.7 ± 0.7; male: 2.9 ± 1.2). The frequency of impacts by location was the same between gender ($p > 0.278$) for all locations except the right side of the head, where males received fewer impacts than females ($p = 0.031$). Female hockey players were 1.1 times more likely than males to sustain an impact less than 50 g while males were 1.3 times more likely to sustain an impact greater than 100 g. Similarly, males were 1.9 times more likely to sustain an impact with peak rotational acceleration greater than 5,000 rad/s^2 and 3.5 times more likely to sustain an impact greater than 10,000 rad/s^2.

Conclusions—Although the incidence of concussion has typically been higher for female hockey players than male hockey players, female players sustain fewer impacts and impacts resulting in lower head acceleration than males. Further study is required to better understand the

Corresponding Author: Jonathan G. Beckwith, Simbex, 10 Water Street, Suite 410, Lebanon, New Hampshire, 03766, Phone: 603-448-2367; Fax: 603-448-0380; jbeckwith@simbex.com.

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

Disclosure of Funding: The research for this study is supported by the National Institute for Child Health and Human Development at the National Institutes of Health (Grant R01HD048638) and from the National Operating Committee on Standards for Athletic Equipment (NOCSAE).

NIH-PA Author Manuscript
NIH-PA Author Manuscript

intrinsic and extrinsic risk factors that lead to higher rates of concussion for females that have been previously reported.

Keywords

concussion; brain injury; sports; ice-hockey; gender; head impact

INTRODUCTION

Since the inception of Title IX as part of the Equality in Education Act of 1972, opportunities for women to participate in sports have increased significantly.(42) The National Collegiate Athletic Association (NCAA) reported an 80% increase in participation in women's collegiate sports between 1988 and 2004, while men's participation increased by only 20%.(28) This increase can, in part be attributed to participation in contact sports such as lacrosse, rugby, and ice hockey This expansion of opportunity for females and the resulting increase in potential for contact, has highlighted the need to better understand differences between female and male athletes, especially with respect to injury incidence, severity and mechanism.

The Center for Disease Control and Prevention reports sport- and recreation-related brain injuries are rapidly reaching epidemic levels with an estimated incidence range of 1.6 - 3.8 million in the United States per year.(8, 29) While public awareness of this epidemic has increased, a significant number of these injuries still go undiagnosed.(9, 10, 41) Recent studies have associated depression, Alzheimer's disease and other neurocognitive disorders with exposure to frequent head impacts and multiple head injuries, specifically in boxers and professional football players.(21, 22, 27) Additionally, a link has been observed between head impact exposure (frequency, location, and magnitude of sustained head impacts) and neurocognitive and neurophysiologic impairment of otherwise asymptomatic athletes participating in contact sports.(6, 40) Such associations are especially concerning because the populations most frequently linked to these risks include children and young adults playing high school and collegiate contact sports, emphasizing the need for improved understanding of the mechanisms and outcomes of concussive injuries and making research in this field all the more imperative.(3, 24)

To date there is little conclusive understanding of the biomechanics leading to concussions, and even less knowledge on the role, if any, gender plays in the mechanism of injury and resulting sequelae. The majority of gender specific studies on incidence, epidemiology, and mechanism of sports-related head injury have been conducted among soccer players,(12, 17) with incidence rates reported for additional sports such as lacrosse, basketball, baseball, softball and gymnastics.(13, 19) Recently, the NCAA reported the results of the Injury Surveillance Study (ISS), a 16-year epidemiological survey of injury rates among 17 male and female collegiate level sports. In that study, concussions ranked second among all injuries with respect to frequency per athlete exposure, with women's ice hockey having the second highest rate of concussions of all sports surveyed and the highest rate of concussions among the gender-specific sports surveyed.(1, 28) While there is still significant debate over the specific gender characteristics that might influence the incidence and severity of brain injuries, including both physiological and psychological differences, general trends have shown women to be at greater risk for sustaining concussions during practices and competitions than men.(1, 13, 18, 19, 28)

Several previous studies have demonstrated the effectiveness of utilizing athletic fields as "living laboratories" to explore the relationship between exposure to head impacts and mild traumatic brain injury (mTBI).(8, 20, 31, 39) Contact sports (e.g. American-style football and ice hockey) provide a unique opportunity to collect *in vivo* head impact data since players participating in these activities willingly expose themselves to head contact. The Head Impact Telemetry (HIT) System (Simbex; Lebanon, NH) allows researchers to monitor and record head impacts occurring during play to individual athletes on the field in real time. The system was originally designed for use in American-style football,(16, 20, 33, 39) and the technology has since been transferred to additional sports such as boxing, skiing/snowboarding, and ice hockey.(5, 26)

While football provides an ideal environment for monitoring and analyzing head impacts due to the large number of player exposures during practices and games, it does not allow for comparisons of differences and potential effects of repetitive head impacts by gender. In contrast, ice hockey, played by both men and women using the same equipment and on the same surface, allows for a more direct comparison of head impact biomechanics by gender. Although epidemiological research has concluded that females sustain concussions at higher rates than their male counterparts,(1, 13, 19, 28) it is unclear how the biomechanics related to their head impacts differ; therefore, it is difficult to determine what safety mitigation (e.g. modified protective equipment, rule changes, etc) is required, if any, to protect athletes of different gender. The specific aim of this study was to quantify the frequency, magnitude, and location of head impacts sustained by male and female ice hockey players. We tested the hypotheses that the number of head impacts sustained and the peak linear and rotational head acceleration following impact differ by gender. Moreover, we hypothesize impact location is not dependent on impact location.

PARTICIPANTS AND METHODS

Participants

Collegiate ice hockey players on two female and two male NCAA varsity teams wore instrumented helmets during the 2008–2009 (one male team only) and 2009–2010 seasons to record the impact magnitude and location of all head impacts sustained during organized play. Participation was voluntary with no preference given to any one player over another. Prior to the start of the season, a detailed explanation of the study was presented to team members, and all players except goalies (female, N = 19–23 per team and year; male, N = 24–25 per team and year) were given the opportunity to participate. Helmet instrumentation was not available at the time for goalie-specific helmets. Informed consent documents were approved by each institution’s Institutional Review Board and signed by all participating athletes. After consent, each athlete was fitted for an instrumented helmet according to manufacturer’s specification prior to use on the ice.

Helmet Instrumentation

Two commercially available hockey helmet models (Easton S9, Easton-Bell Sports Inc. and CCM Vector, Reebok-CCM Hockey Inc) were used in the study. Each helmet was fitted with an instrumented helmet unit (IHU; Figure 1). The IHU contained six single-axis linear accelerometers, a single electronics board combining data acquisition (10 bit, 1000 Hz), radiofrequency (RF) telemetry (903–927 MHz) components, and a rechargeable battery capable of powering the IHU for 1–2 weeks. Accelerometers were integrated into compressible foam inserts that protruded outward from the liner towards the head. This design allows the accelerometers to maintain contact with the head throughout the impact event ensuring that head acceleration measurements are not affected by helmet shell vibrations.(30) The measurement accuracy of the IHU has been previously validated against an instrumented anthropomorphic head-form over a range of impact locations and magnitudes with overall peak linear and rotational acceleration errors of 9% and 11%, respectively.(25) The helmets fitted with the IHU were certified by the Hockey Equipment

Certification Council (HECC) in accordance with ASTM mechanical testing standards F-1045.(2, 34)

Data Reduction

IHU recorded 40 ms of acceleration data, 8 ms pre-trigger and 32 ms post-trigger, when any accelerometer exceeded a study defined threshold of 9.6 g. Head accelerations lower than this level are associated primarily with non-contact events such as running and jumping.(35) Recorded data were associated with a time stamp and player identifier, and transmitted wirelessly to a rink-side computer (Figure 1). If communication was unavailable, the IHU had the capability of storing up to 100 events in non-volatile memory that could be retrieved when communication was restored. Recorded data were consolidated into a single relational database with all personal identifiers replaced by randomly generated study identification numbers.

Data collected from the six non-orthogonal accelerometers of the IHU were processed using a novel algorithm for impact location and time-series linear and rotational acceleration of each of the three head center of gravity (CG) axes.(11, 14) Peak linear and rotational accelerations were defined as the maximum resultant linear and rotational accelerations within the 40 ms recording window. Impact location, recorded as azimuth and elevation with respect to the head CG, was categorized into five general location bins (Figure 2): Front (F), Back (B), Left Side (L), Right Side (R), and Top (T). This generalized grouping, described previously,(14, 26, 33) separates location into 90° regions about the circumference of the head with Top impacts including all impacts with elevation greater than 65° with respect to a horizontal plane passing through the estimated CG.

A team session was designated as any practice, scrimmage, or game in which the athletes were exposed to potential head contact. Staff members from each team documented start and end times for each session and identified each player participating in the session. Athlete-exposure (A–E) were defined for each player as any team session in which the player participated regardless of whether a head impact was sustained during that particular session.(28) Data recorded from events occurring outside of defined times for team organized competitive periods were excluded from all analyses.

Additionally, data were reduced following processing to exclude any event with peak linear acceleration less than 10 g (14, 26, 33) in order to eliminate events that were most likely triggered following non-impact events (e.g. forcefully donning/doffing helmet, athlete manually triggering single acceleration channels, etc.). Any impact event in which the acceleration-time history pattern of the six linear accelerometers did not match the expected acceleration signals for rigid body head acceleration, such as when a single accelerometer spikes during vigorous helmet removal, were also excluded.(14) Finally, accelerometer output for all impacts exceeding 125g was visually reviewed to verify acceleration data was free of signal artifacts indicative of potential hardware malfunction (e.g. shorts in accelerometer signal). These methods have been previously verified by comparing measured impacts with video footage.(8, 16, 33)

Data Analysis

All statistical analyses were performed using Matlab (version 7.0, The MathWorks Inc., Natick. MA). Descriptive statistics are provided for all measures of impact frequency, acceleration magnitude, and location. Prior to all comparative analyses, Lilliefors tests were conducted to verify assumptions of normality. Multiple two-sample t-tests were used to test the hypotheses that the number of impacts by season and the number of impacts by athlete exposure differ by gender. The top 1%, 2%, and 5% of all impacts by peak linear and rotational acceleration were compared by gender using a Kruskal-Wallis Nonparametric one-way analysis of variance. To evaluate differences in the distributions of impact locations as a function of gender, chi squared independence tests were performed. Additionally, chi squared tests were conducted on distributions of impact locations for the top 1%, 2%, and 5% by linear acceleration only, to determine if differences in impact location exist by gender for the highest magnitude impacts. A significance level of $\alpha = 0.05$ was set a priori for all statistical tests.

RESULTS

Over two seasons, ninety-five athletes were initially enrolled in the study with seven voluntarily leaving the study following initial team sessions. Any head impact data recorded from these players (< 20 impacts per player) was excluded from analysis. Seven of the thirty-seven male athletes ((age: 21.4 ± 1.4 yr, height: 183.5 ± 4.3 cm, weight: 86.0 ± 5.0 kg) and twenty-one of the fifty-one female athletes (age: 19.9 ± 1.1 yr, height: 168.8 ± 6.3 cm, weight: 67.2 ± 6.7 kg) participated in both years, providing 116 monitored athlete years (44 male, 72 female). Height and weight of the athletes was significantly different ($\alpha = 0.05$, $p < 0.001$) by gender, however the variance was similar to differences observed for this age group in the general population.(32) Distribution of athletes by position group were similar for both males (64% Forwards, 24% Defenseman) and females (65% Forwards, 25% Defenseman).

28,178 head impacts were recorded during all team sessions with 12,897 sustained by females and 15,281 from males. Female athletes participated in fewer team sessions (105.3 ± 17.5) than male athletes (118.0 ± 26.8). The slight difference in number of team sessions can be attributed primarily to length of post-season play, which was based on team performance and not initial scheduling. The number of impacts per season a player received was significantly lower in female athletes, who recorded an average of 179.2 ± 80.5 impacts per season (range 11 to 373), while male athletes sustained an average of 347.3 ± 170.2 impacts per season (range 56 to 785) ($p<0.001$). Female hockey players experienced a significantly lower ($p < 0.001$) number of impacts per athlete exposure (1.7 ± 0.7) than males (2.9 ± 1.2). The range of impacts per athlete exposure was 0.2 to 3.2 for females and 0.7 to 6.3 for males (Figure 3). Both females and males sustained at least one impact in approximately half of all athlete exposures (57.1% - male, 55.6% - female).

Distributions of all impacts by peak linear and peak rotational acceleration magnitudes were skewed towards lower magnitudes (Figure 4). 95% of all impacts were less than 43.7 g and 4,764 rad/s^2 for males, and less than 44.9g and 3,709 rad/s^2 for females (Table 1). Male players experienced significantly higher linear acceleration for the top 1% of all impacts ($p = 0.003$), but not the top 2% ($p = 0.07$) or the top 5% ($p = 0.179$). Impacts sustained by males resulted in higher rotational head accelerations than females for the top 1, 2, and 5% of all impacts ($p < 0.001$).

For all athletes, the highest frequency of impacts by location occurred to the Front (30%) and Back (33%) of the head followed by the Left (14%), Right (14%), and Top (9%). The frequency of impacts by impact location was dependent on gender ($\chi^2(4) = 27.39$, $p < 0.001$) with males experiencing a slightly lower number of both left (13.8% - male, 14.9% female) and right (13.6% - male, 15.4% - female) side of the head impacts (Table 2). When considering only impacts with highest peak linear acceleration, both males and females sustained the majority of impacts to the Back of the head (male: 52%; female: 60%). Distributions of highest magnitude impacts by location differed by gender (Table 2) with females sustaining a higher ratio of top percentile impacts to the Top of the head and males sustaining a disproportionate ratio of top percentile Left and Right side impacts.

DISCUSSION

In light of rapidly expanding participation by female athletes in contact sports, there is an increasing need to understand gender differences that may exist with respect to brain injury. The NCAA has reported that female hockey players have higher rates of concussion when compared to males, but the reasons for this are not clear. (1, 13, 19, 28) Several factors, including rule variations within the sport by gender, the physiology of the athletes, and the competitive level of play may influence the frequency and severity of contact in each of the respective games. By NCAA regulations, body and board checking are not allowable in women’s ice hockey, although there is clearly significant body contact during actual play. (38) Male hockey players are generally larger both in height and weight than female hockey players, and the men’s game appears to be played at a greater speed than the women’s game at the collegiate level; however, to properly understand an athlete’s risk for brain injury, the biomechanics of head impacts sustained must be known. This two year study quantifies and determines the similarities and differences in head impact exposure (frequency, location, and magnitude) for male and female athletes participating in Division I collegiate ice hockey.

We found that male hockey players sustain nearly twice as many impacts per team session (practice and game) over the course of the season. The maximum number of impacts in a season of ice hockey was 785 and 373 for men and women respectively, with an average of 347.3 and 179.2. In comparison, it has been reported that individual collegiate football players have sustained up to 1,444 impacts per season and the median player sustains between 257 – 438 impacts per season.(15) Documenting these differences between male and female hockey players, as well as between hockey and football players, are important because we do not yet know how impact frequency relates to mTBI and the potential for short term or long term changes in brain structure or function that have been linked to the injury. Ongoing analysis of both biomechanical and clinical variables, such as symptomology following injury, may lead to further understanding of the potential deleterious effects of impact frequency, magnitude, and direction.

In this study we examined the frequency of head contact by normalizing the number of head impacts by athlete exposure (1, 28), which was defined as any time a player was present on the ice - regardless of whether he or she received any head impacts for that day. It is important to appreciate that impact frequency by athlete exposure is most useful when evaluating risk of injury due to participation, not necessarily due to head impact. An alternative approach has been presented by Crisco et. al who normalized frequency of head impacts by player session (defined as a team session when at least one head impact is recorded) when reporting similar head impact exposure data for football players.(15) Because there will be practices or games in which a head impact is not recorded, the latter definition is a more appropriate method for exploring the relationships between head impact exposure, including single and repeated head impacts, and injury. Ultimately, this nuance in methodology did not influence analyses of frequency by gender as both males and females sustained impacts in approximately the same percentage of athletic exposures; however, other researchers should be aware of the difference when applying these data to future work.

Two recent studies have reported similar values for mean peak linear and rotational acceleration of head impacts sustained prior to diagnosis of mTBI in football. Beckwith et. al reported mean values of 107 ± 31 g and 7,079 ± 3,408 rad/s^2 from 55 impacts associated with diagnosis of concussion that were recorded with the HIT System.(4) Pellman et. al reported mean values of 98 ± 28 g and 6,432 ± 1,813 rad/s^2 from 25 laboratory reconstructions of NFL impacts.(37) 1.12% of the 12,897 impacts sustained by female hockey players were recorded above 76 g (i.e. the mean linear acceleration prior to diagnosed concussion minus one standard deviation from Beckwith et. al), whereas 1.26%

of the impacts sustained by male hockey players were above this level. In addition, when considering the impacts with the greatest magnitude, male hockey players experienced significantly higher linear (top 1 percentile of all) and rotational acceleration levels (top 1, 2, and 5 percentile of all) than female players. Simply put, female hockey players were 1.1 times more likely than males to sustain an impact less than 50g while males were 1.3 times more likely to sustain an impact greater than 100g. Similarly, males were 1.9 times more likely than females to sustain an impact with peak angular acceleration greater than 5,000 rad/s^2 and 3.5 times more likely to sustain an impact greater than 10,000 rad/s^2.

Distributions of impacts occurring within defined regions around the head were dependent on gender, but the differences in percentage by location were small (0.3 – 1.8% location region difference for all impacts). For both males and females combined, impacts were equally distributed between the Front, Back, and Sides (left and right side combined) with the top of the head receiving less than 9% of all impacts. These data are consistent with those reported by Gwin et al. (Front – 26.5%, Back 33.2%, Side 32.6%, and Top – 7.8%) who employed a similar method to record impact exposure from a cohort of twelve male hockey players distributed across two seasons.(26) The frequency of impacts to the left and right side of the head were found to be lower for males than females; however, considering the previously reported values by Gwin et al., the variability observed may fall within the standard deviation that occurs between teams and seasons. Another key observation is that the highest magnitude impacts occurred most frequently to the back of the head for both males and females. Although the mechanism of contact was not monitored in this study (e.g. head to ice, head to head, etc.), the findings are in agreement with epidemiological studies used to develop initial hockey helmet standards that suggested increased protection was needed for the back of the head due to the prevalence of slips and / or falling backwards and hitting the ice.(36) These data suggest location of head impacts sustained while playing hockey is likely linked to the inherent characteristics of the sport, though slight differences may exist in the ways male and females play it.

Recent studies on male football players have shown that biomechanical variables related to single head impacts (eg. linear acceleration, rotational acceleration, and impact location) are sensitive to diagnosed concussion, but the specificity of these measures to injury is low. (7, 20, 23) Head impact exposure data for hockey players presented in this study appears to be in agreement, as indicated by the frequency of head impacts occurring above previously suggested injury tolerance levels without diagnosis of concussion. One potential explanation is the risk of concussion following exposure to head impact could be modulated by any number of physiologic variables including neck strength, center of rotation and range of motion in the neck, body center of mass (related to rotation that would occur when losing balance), brain morphology, and / or weight and speed of the athlete. Speculatively, another potential risk factor for female hockey players may be that lack of experience and instruction with respect to receiving and giving body checks (due to rules against checking in the female game) leaves them less prepared when contact occurs. This reduced contact could lead to heightened awareness of concussion symptoms, when present, resulting in a higher percentage of diagnosed injuries for females. While there is insufficient occurrence of mTBI within this multi-season ice hockey data set to explore these relationships and draw meaningful conclusions regarding injury thresholds for hockey players, if we rely upon historical concussion rates that show higher occurrence of injury for females, the data presented here suggest additional intrinsic and extrinsic factors specific to gender modulate the relationship between brain injury and head impact exposure. In order to provide the best protection and care to athletes, identifying these factors, correlating the biomechanics of head impact and the occurrence of injury by gender, and developing techniques to better educate athletes about injury should be a research priority.

There are several limitations in this study. Primarily, there were a disproportionate number of male to female participants (44 vs. 72), and the study was limited to two institutions. While it is possible that variability in team and individual playing style may have skewed the data slightly, due to the number of recorded events (n = 28,178) and the large differences observed in both frequency and magnitude (particularly rotational acceleration) it is unlikely that additional data collection would alter these findings. This manuscript also does not quantify the events surrounding the recorded head impacts or correlate impact magnitude with the type of head contact most commonly occurring during play, such as frequency of head impact around the boards and in open ice or severity of head impact as a result of a fall, a check, or a rules infraction. These factors may play an important role in explaining the differences observed in this study, and, if so, could provide a means for preventing potentially injurious head contact.

Although female hockey players report higher incidence rates of concussions when compared to their male counterparts, their impact exposures are less frequent and of lower magnitude, contradicting conventional wisdom that higher impact frequency and / or impact magnitude alone leads to an increased risk for mTBI. It is evident that further exploration of the mechanism of brain injury is needed with an emphasis on understanding the intrinsic and extrinsic risk factors for brain injury that differentiates athletes of different gender.

This study is the first to quantify and compare the frequency and severity of head impacts between male and female hockey players. At a fundamental level, these exposure data indicate that significant differences in head impact exposure exist between athletes of different gender participating in the same sport, and represent a critical first step to understanding the disparities among injury prevalence and outcomes in male and female athletes.

Acknowledgments

The authors acknowledge that publication of the results of the present study do not constitute endorsement by the American College of Sports Medicine.

Funding Sources: The research for this study is supported by the National Institute for Child Health and Human Development at the National Institutes of Health (Grant R01HD048638) and from the National Operating Committee on Standards for Athletic Equipment (NOCSAE).

External Support: Support and assistance in the design and manufacturing of the hockey helmet development came from Easton-Bell Sports, Inc. and Reebok-CCM Hockey, Inc. We appreciate and acknowledge the researchers and institutions from which the data were collected, Jeff Frechette ATC and Tracy Poro ATC, Dartmouth College Sports Medicine, Mary Hynes, R.N., MPH, Dartmouth Medical School, and Bethany Therrien, E. Jacqueline Dwulet, and Emily Burmeister, MS, ATC, Department of Engineering, Brown University.

References

1. Agel J, Dick R, Nelson B, Marshall SW, Dompier TP. Descriptive epidemiology of collegiate women's ice hockey injuries: National Collegiate Athletic Association Injury Surveillance System, 2000–2001 through 2003–2004. J Athl Train. 2007; 42(2):249–54. [PubMed: 17710173]
2. ASTM Standard F1045–07. Standard Performance Specification for Ice Hockey Helmets. ASTM International; West Conshohocken, PA: 2008. p. 150
3. Aubry M, Cantu R, Dvorak J, et al. Summary and agreement statement of the First International Conference on Concussion in Sport, Vienna 2001. Recommendations for the improvement of safety and health of athletes who may suffer concussive injuries. Br J Sports Med. 2002; 36(1):6–10. [PubMed: 11867482]
4. Beckwith, JG.; Chu, JJ.; Crisco, JJ. American Society of Biomechanics. State College, PA: Penn State University; 2009. Severity of Head Impacts Resulting in Mild Traumatic Brain Injury; p. 1144

5. Beckwith JG, Chu JJ, Greenwald RM. Validation of a noninvasive system for measuring head acceleration for use during boxing competition. J Appl Biomech. 2007; 23(3):238–44. [PubMed: 18089922]

6. Beckwith, JG.; Chu, JJ.; McAllister, TW., et al. Eighth World Congress on Brain Injury. Washington, DC: Brain Injury; 2010. Neurocognitive Function and the Severity of Head Impacts Sustained in Athletic Competition; p. 446

7. Broglio SP, Schnebel B, Sosnoff JJ, et al. Biomechanical properties of concussions in high school football. Med Sci Sports Exerc. 2010; 42(11):2064–71. [PubMed: 20351593]

8. Brolinson PG, Manoogian S, McNeely D, Goforth M, Greenwald RM, Duma SM. Analysis of linear head accelerations from collegiate football impacts. Curr Sports Med Rep. 2006; 5(1):23–8. [PubMed: 16483513]

9. Centers for Disease Control & Prevention. Nonfatal traumatic brain injuries from sports and recreation activities--United States, 2001–2005. Morbidity and Mortality Weekly Report. 2007; 56(29):733–7. [PubMed: 17657206]

10. Centers for Disease Control and Prevention (CDC). Report to Congress on Mild Traumatic Brain Injury in the United States: Steps to Prevent a Serious Public Health Problem. Atlanta, GA: National Center for injury Prevention and Control; 2003. p. 1-45.

11. Chu, J.; Beckwith, JG.; Crisco, JJ.; Greenwald, RM. A Novel Algorithm to Measure Linear and Rotational Acceleration Using Single-Axis Accelerometers. Journal of Biomechanics; 5th World Congress of Biomechanics; Munich, Germany. 2006. p. S534

12. Colvin AC, Mullen J, Lovell MR, West RV, Collins MW, Groh M. The role of concussion history and gender in recovery from soccer-related concussion. The American Journal of Sports Medicine. 2009; 37(9):1699–704. [PubMed: 19460813]

13. Covassin T, Swanik CB, Sachs ML. Sex Differences and the Incidence of Concussions Among Collegiate Athletes. J Athl Train. 2003; 38(3):238–44. [PubMed: 14608434]

14. Crisco JJ, Chu JJ, Greenwald RM. An algorithm for estimating acceleration magnitude and impact location using multiple nonorthogonal single-axis accelerometers. J Biomech Eng. 2004; 126(6): 849–54. [PubMed: 15796345]

15. Crisco JJ, Fiore R, Beckwith JG, et al. Frequency and location of head impact exposures in individual collegiate football players. J Athl Train. 2010; 45(6):549–59. [PubMed: 21062178]

16. Duma SM, Manoogian SJ, Bussone WR, et al. Analysis of real-time head accelerations in collegiate football players. Clin J Sport Med. 2005; 15(1):3–8. [PubMed: 15654184]

17. Dvorak J, McCrory P, Kirkendall DT. Head injuries in the female football player: incidence, mechanisms, risk factors and management. Br J Sports Med. 2007; 41(Suppl 1):i44–i6. [PubMed: 17496069]

18. Fuller CW, Junge A, Dvorak J. A six year prospective study of the incidence and causes of head and neck injuries in international football. Br J Sports Med. 2005; 39(Suppl 1):i3–9. [PubMed: 16046353]

19. Gessel LM, Fields SK, Collins CL, Dick RW, Comstock RD. Concussions among United States high school and collegiate athletes. J Athl Train. 2007; 42(4):495–503. [PubMed: 18174937]

20. Greenwald RM, Gwin JT, Chu JJ, Crisco JJ. Head impact severity measures for evaluating mild traumatic brain injury risk exposure. Neurosurgery. 2008; 62(4):789–98. [PubMed: 18496184]

21. Guskiewicz KM, Marshall SW, Bailes J, et al. Association between recurrent concussion and late-life cognitive impairment in retired professional football players. Neurosurgery. 2005; 57(4):719–26. [PubMed: 16239884]

22. Guskiewicz KM, Marshall SW, Bailes J, et al. Recurrent concussion and risk of depression in retired professional football players. Med Sci Sports Exerc. 2007; 39(6):903–9. [PubMed: 17545878]

23. Guskiewicz KM, Mihalik JP. Biomechanics of sport concussion: quest for the elusive injury threshold. Exerc Sport Sci Rev. 2011; 39(1):4–11. [PubMed: 21088602]

24. Guskiewicz KM, Weaver NL, Padua DA, Garrett WEJ. Epidemiology of concussion in collegiate and high school football players. The American Journal of Sports Medicine. 2000; 28(5):643–50. [PubMed: 11032218]

25. Gwin, JT.; Chu, JJ.; Greenwald, RM. Head Impact Telemetry System for Measurement of Head Acceleration in Ice Hockey. Journal of Biomechanics; 5th World Congress of Biomechancis; Munich, Germany. 2006. p. S153
26. Gwin JT, Chu JJ, McAllister TA, Greenwald RM. In situ Measures of Head Impact Acceleration in NCAA Division I Men's Ice Hockey: Implications for ASTM F1045 and Other Ice Hockey Helmet Standards. Journal of ASTM International. 2009; 6(6):1–10.
27. Heilbronner RL, Bush SS, Ravdin LD, et al. Neuropsychological consequences of boxing and recommendations to improve safety: a National Academy of Neuropsychology education paper. Archives of Clinical Neuropsychology. 2009; 24(1):11–9. [PubMed: 19395353]
28. Hootman JM, Dick R, Agel J. Epidemiology of collegiate injuries for 15 sports: summary and recommendations for injury prevention initiatives. J Athl Train. 2007; 42(2):311–9. [PubMed: 17710181]
29. Langlois JA, Rutland-Brown W, Wald MM. The epidemiology and impact of traumatic brain injury: a brief overview. J Head Trauma Rehabil. 2006; 21(5):375–8. [PubMed: 16983222]
30. Manoogian S, McNeely D, Duma S, Brolinson G, Greenwald R. Head acceleration is less than 10 percent of helmet acceleration in football impacts. Biomed Sci Instrum. 2006; 42:383–8. [PubMed: 16817638]
31. McCrea M, Hammeke T, Olsen G, Leo P, Guskiewicz K. Unreported concussion in high school football players: implications for prevention. Clin J Sport Med. 2004; 14(1):13–7. [PubMed: 14712161]
32. McDowell MA, Fryar CD, Hirsch R, Ogden CL. Anthropometric reference data for children and adults: U.S. population, 1999–2002. Adv Data. 2005; (361):1–5. [PubMed: 16018338]
33. Mihalik JP, Guskiewicz KM, Jeffries JA, Greenwald RM, Marshall SW. Characteristics of head impacts sustained by youth ice hockey players. Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology. 2008; 222(1):45–52.
34. National Committee on Standards for Athletic Equipment. Document #081-04m04 (Proposed Status). Jan. 2006 NOCSAE Standard Linear Impactor Test Method and Equipment Used in Evaluating the Performance Characteristics of Protective Headgear and Faceguards; p. 1-6.
35. Ng TP, Bussone WR, Duma SM. The effect of gender and body size on linear accelerations of the head observed during daily activities. Biomed Sci Instrum. 2006; 42:25–30. [PubMed: 16817580]
36. Odelgard, B. The Development of Head, Face and Neck Protectors in Ice Hockey Players. In: Castaldi, CR.; Hoerner, EF., editors. Safety in Ice Hockey, ASTM STP 1050. Philadelphia: American Society for Testing and Materials; 1989. p. 164-83.
37. Pellman EJ, Viano DC, Tucker AM, Casson IR, Waeckerle JF. Concussion in professional football: reconstruction of game impacts and injuries. Neurosurgery. 2003; 53(4):799–814. [PubMed: 14519212]
38. Piotowski, S. 2008–10 NCAA Men's and Women's Ice Hockey Rules and Interpretations. Indianapolis, Indiana: The National Collegiate Athletic Association; 2008. p. 178
39. Schnebel B, Gwin JT, Anderson S, Gatlin R. In vivo study of head impacts in football: a comparison of National Collegiate Athletic Association Division I versus high school impacts. Neurosurgery. 2007; 60(3):490–6. [PubMed: 17327793]
40. Talavage TM, Nauman EA, Breedlove EL, et al. Functionally-Detected Cognitive Impairment in High School Football Players Without Clinically-Diagnosed Concussion. J Neurotrauma. 2010 Epub ahead of print.
41. Thurman DJ, Branche CM, Sniezek JE. The epidemiology of sports-related traumatic brain injuries in the United States: recent developments. The Journal of Head Trauma Rehabilitation. 1998; 13(2):1–8. [PubMed: 9575252]
42. United States Department of Labor [Internet]. Title IX, Education Amendments of 1972. Washington, DC: Office of the Assistant Secretary of Administration and Management; [cited 2011 June 24]. Available from: http://www.dol.gov/oasam/regs/statutes/titleIX.htm

Figure 1.
The Head Impact Telemetry (HIT) System was used to record frequency, location, and severity of head impacts in ice hockey. *Left:* Inside view of an Easton S9 equipped with an instrumented helmet unit (IHU). *Right:* A rink-side antennae connected to a laptop computer actively communicates with IHU to collect and process impact data received via radio transmitter.

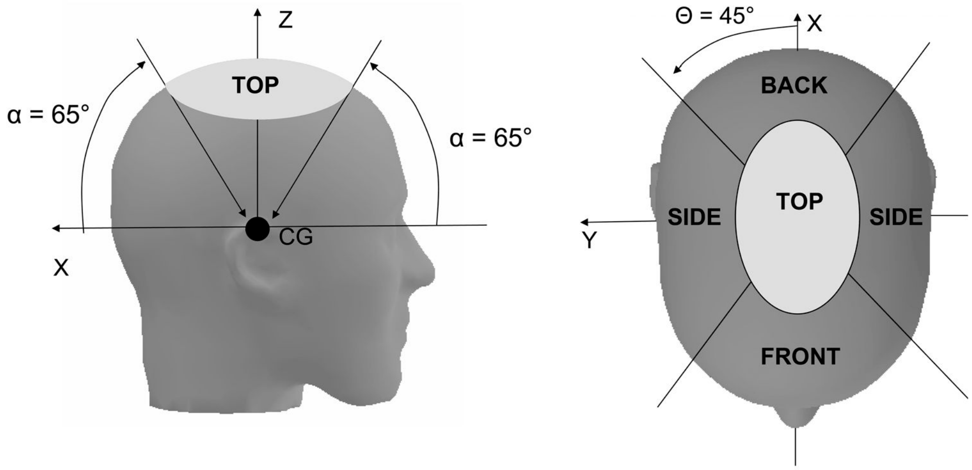

Figure 2.
Impacts were separated into four generalized location groups based on recorded azimuth (θ) and elevation (α). Top impacts include all impacts with elevation 65° or higher. Front, Back, and Side regions were separated into four equally distributed 90° regions as shown with the left and right sides combined into a single Side location. Used by permission, courtesy of Greenwald et al.(20)

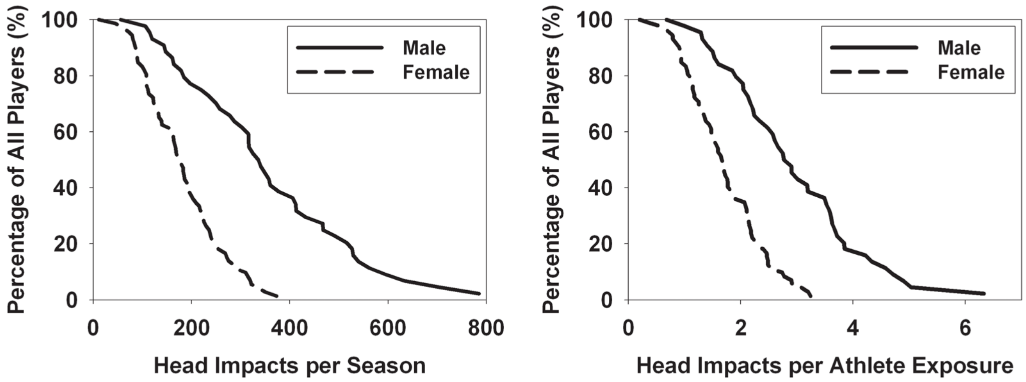

Figure 3.
Male hockey players sustained more head impacts than their female counterparts per season and per Athlete Exposure ($p<0.001$).

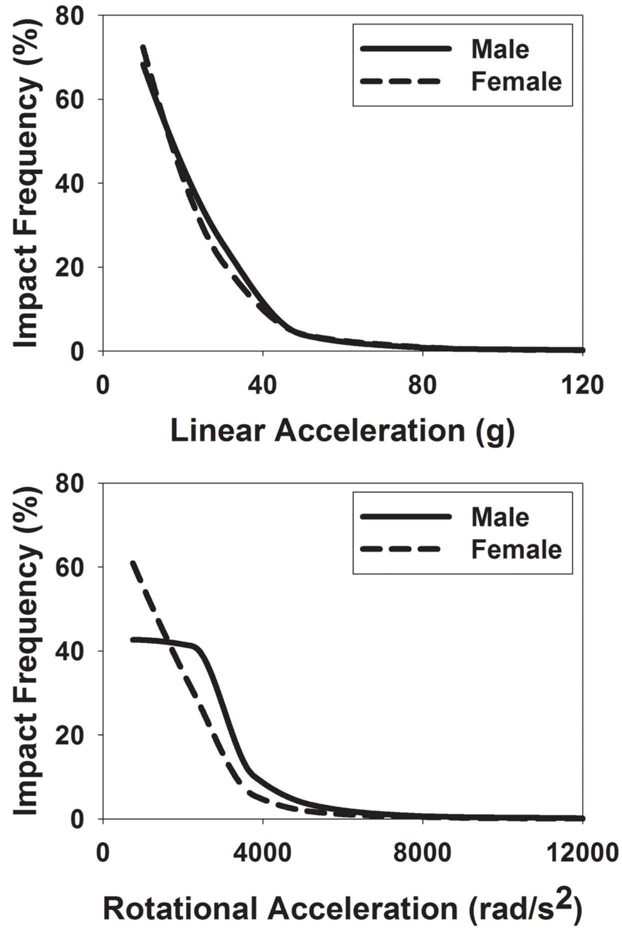

Figure 4.
Distributions of impacts by peak linear and rotational acceleration were non-normally distributed towards low magnitude impacts for both males and females; however, males sustained head impacts with higher peak linear and rotational acceleration more frequently than females.

NIH-PA Author Manuscript
NIH-PA Author Manuscript

Table 1

Male hockey players sustained head impacts with higher peak linear acceleration (Top 1 %, $p = 0.003$) and peak rotational acceleration (Top 1, 2, and 5%, $p < 0.001$) than female hockey players.

	Male Hockey (Total Impacts = 15,281)				Female Hockey (Total Impacts = 12,897)			
	Linear Acc. (g)		Rotational Acc. (rad/s^2)		Linear Acc. (g)		Rotational Acc. (rad/s^2)	
	Mean	Cutoff	Mean	Cutoff	Mean	Cutoff	Mean	Cutoff
Top 1 %	109.4 ± 25.6	≥ 80.4	10,911 ± 2,486	≥ 8,375	103.0 ± 24.5	≥ 79.0	8,335 ± 1,980	≥ 6,596
Top 2 %	90.4 ± 26.6	≥ 63.1	9,083 ± 2,564	≥ 6,462	86.5 ± 24.2	≥ 63.5	7,057 ± 1,919	≥ 5,172
Top 5 %	67.2 ± 25.8	≥ 43.7	6,921 ± 2,429	≥ 4,764	66.4 ± 22.8	≥ 44.9	5,422 ± 1,831	≥ 3,709

Table 2

Chi-square tests for independence indicate distributions of impacts by location are dependent on gender. When evaluating only impacts of the highest magnitude (by peak linear acceleration), both males and females sustained the greatest number of impacts to the back of the head.

	Impact Location					Chi Squared Independent Test	
Peak Linear Acceleration	**Front**	**Back**	**Left**	**Right**	**Top**	**χ^2 (*df*=4)**	**Significance**
Top 1%							
Male	26	79	16	7	25	20.53	< 0.001
Female	4	78	6	6	35		
Top 2%							
Male	66	135	38	18	47	30.24	< 0.001
Female	25	160	14	10	48		
Top 5%							
Male	164	320	110	67	99	46.68	< 0.001
Female	70	361	59	58	93		
All							
Male	4,583	4,970	2,171	2,147	1,410	27.39	< 0.001
Female	3,704	4,047	1,981	2,027	1,138		