Short communication

Impact attenuation of male and female lacrosse helmets using a modal impulse hammer ☆

Kevin G. McIver [a], Goutham N. Sankaran [a], Patrick Lee [a], Sean Bucherl [b], Nicolas Leiva [b], Thomas M. Talavage [a,c], Larry Leverenz [d], Eric A. Nauman [a,b,e,*]

[a] School of Mechanical Engineering, Purdue University, West Lafayette, IN 47907, United States
[b] Weldon School of Biomedical Engineering, Purdue University, West Lafayette, IN 47907, United States
[c] School of Electrical and Computer Engineering, Purdue University, West Lafayette, IN 47907, United States
[d] Department of Health and Kinesiology, Purdue University, West Lafayette, IN 47907, United States
[e] Department of Basic Medical Sciences, Purdue University, West Lafayette, IN 47907, United States

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ABSTRACT

It has been established that substantial negative changes in neurocognitive function can be observed in a large percentage of athletes who participate in contact sports such as soccer or football, motivating a need for improved safety systems. Head accelerations in men's lacrosse are similar to those in football and female lacrosse players experience high rates of concussions, necessitating better head protection in both sports. Previous studies have sought to evaluate the ability of modern football helmets to mitigate impacts both normal and oblique to the surface of the helmet using a system that quantifies both the input load and the resulting accelerations of a Hybrid III headform. This study quantifies the inputs and outputs of the helmet-Hybrid III headform system in order to compare the impact attenuation capability of two male and two female lacrosse helmets. Of those helmets tested, the better performing male helmet was the Schutt Stallion 650 and the better performing female helmet was the Hummingbird excepting device failure at the rear boss impact location, but football helmets still generally outperformed the lacrosse helmets tested here.

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1. Introduction

Lacrosse is one of the fastest growing contact sports in North America (Hinton et al., 2005), and head injury is a significant risk (Marshall et al., 2015). Both laboratory and on-field studies have demonstrated average peak translational accelerations similar to those experienced in helmeted American football players and women's soccer players (Clark and Hoshizaki, 2016; O'Day et al., 2017; Vollavanh et al., 2018). Vollavanh et al. (2018) found that, in men's lacrosse, head acceleration events (HAEs) are primarily caused by head-to-head, head-to-body, and head-to-stick impacts and further studies demonstrated that most (78%) of the HAEs were experienced on the front and sides of the head (O'Day et al., 2017; Vollavanh et al., 2018). Moreover, while the National Collegiate Athletic Association (NCAA) does not consider women's lacrosse a contact sport (Lacrosse, 2010; Smith, 2017), it ranks just behind American football with regard to the incidence rate of concussions and female players have a higher incidence of head, face and eye injuries than men (Marshall et al., 2015). Taken together, these data suggest that head impacts are important sources of injury in both men's and women's lacrosse. In light of recent work demonstrating that substantial neurophysiological changes can occur without symptoms in athletes that play contact sports (Abbas et al., 2015; Poole et al., 2014; Svaldi et al., in press; Talavage et al., 2014), mechanisms for reducing the magnitude of head impacts in lacrosse deserve further investigation.

In 1973, the National Committee on Operating Standards for Athletic Equipment (NOCSAE) created a drop tower-based criterion to certify football helmets which reduced the incidence of fatalities (Breedlove et al., 2018; Newman et al., 2005). Similar standards introduced for lacrosse helmets (NOCSAE, 2018) demonstrated that football helmets far outperformed those used in men's lacrosse, led

to recalls, and called into question the effects of refurbishing (Bowman et al., 2015). In addition, United States Lacrosse requires women's helmets to follow ASTM Safety Standard F3137-15, which specifies that helmet shells must remain flexible to protect unhelmeted players and also uses typical drop systems for testing (ASTM, 2015). While drop tower testing has assisted in the development of helmets that prevent skull fracture, it does not provide sufficient data to quantify impact attenuation of specific helmet types as it reduces the degrees of freedom the headform can move in, allowing little to no angular acceleration, thereby limiting the data available to analyze impact attenuation holistically. Consequently, the overall goal of this study was to evaluate the ability of men's and women's lacrosse helmets to mitigate the effects of head impacts using a common, modal hammer-based protocol that quantifies both the input load and output accelerations and to compare these data to previously collected data obtained for football helmets (Cummiskey et al., 2019).

2. Theory

A dimensional analysis framework was developed previously (Cummiskey et al., 2019) to quantify the impact attenuation of helmets by measuring the input force directed at a hybrid III headform and relating it to the resulting translational and rotational accelerations (Cummiskey et al., 2017). To accomplish this the output dimensionless groups, Π_1 and Π_2 were given by,

$$\Pi_1 = \frac{a_p(t^*)^2}{W_n}, \tag{1}$$

and

$$\Pi_2 = \ddot{\theta}_p(t^*)^2 \tag{2}$$

which relate the peak translational acceleration, a_p, and peak angular acceleration, $\ddot{\theta}_p$, to the width of the neck, w_n, and t^*, the difference between a reference time ($t_r = 100$ ms) and the impact duration. The dimensionless input parameters, π_1, π_2, and, π_3 were given by,

$$\pi_1 = \frac{(t^*) \int F(t)dt}{m_h w_n} \tag{3}$$

$$\pi_2 = \frac{m_T}{m_h} \tag{4}$$

and,

$$\pi_3 = \frac{L_n}{W_n} \tag{5}$$

where $\int F(t)dt$, was the impulse delivered to the head, m_h, was the mass of the head, m_T, was the total combined mass of the head and helmet, and, L_n, was the neck length. Details of the derivation can be found in Cummiskey et al. (2019). Combining this approach with intermediate asymptotics as described by Barenblatt (1996) yields a functional relationship between each output dimensionless group and the corresponding input groups,

$$\Pi_i = A_i \pi_1^{\beta_{1i}} \pi_2^{\beta_{2i}} \pi_3^{\beta_{3i}} \tag{6}$$

3. Methods

3.1. Data collection

The study was designed to test the effectiveness of the two most commonly used helmet models designed for men's lacrosse—the Schutt Stallion 650 (Schutt Sports; Litchfield, IL), and the Cascade CPX-R (Cascade; Liverpool, NY)—and the two most commonly used helmet models designed for women's lacrosse— the Hummingbird (Hummingbird Sports; Holmdel, NJ), and the Cascade LX (Cascade; Liverpool, NY). The men's helmets are similar to each other and differ primarily in padding type and thickness as well as minor geometric features at some locations. The women's helmets both possess flexible shells, an uncommon design element in modern helmets (Newman, 2007). The mass of each size large helmet was measured three times and averaged to minimize error. The Schutt Stallion 650 had a mass of 1.426 kg, the Cascade CPX-R had a mass of 1.109 kg, the Hummingbird had a mass of 0.728 kg, and the Cascade LX was the lightest helmet at 0.609 kg. Each helmet was fitted according to manufacturer recommendations to a 50th percentile Hybrid III head and neck assembly testing rig, secured to a steel baseplate. Subsequently, the helmet was struck repeatedly at seven different locations. Impacts were administered to each helmet and the bare headform using a modally tuned impulse hammer (PCB Piezotronics, Inc.; Depew, NY; see Fig. 1) as described by Cummiskey et al. (2017) to record force during the impact window. To measure the resulting accelerations at the center of mass (CoM), a nine-accelerometer array in a 3-2-2-2 setup was used, as defined by Cummiskey et al. (2019, 2017) and Padgaonkar et al. (1975). Linear accelerations on each axis were measured, and resultant translational and angular accelerations were calculated. A 200 ms time series was collected for each normal and oblique impact with a 70 ms pre-trigger, providing 130 ms of acceleration and impact force measurements, which were collected at 5120 Hz. The 20 impacts at each location were administered manually and equally divided into five distinct impulse ranges from 2 to 4Ns, 5-7Ns, 8-10Ns, 11-13Ns, 14 + Ns.

Each helmet model was tested in triplicate for a total of 420 measurements per protective device to correct for any systematic errors that may result from a defect in a single device. During testing, the Hummingbird helmet suffered from significant damage from impacts to the Rear Boss and Rear Boss Oblique, leading to 10 missing measurements at Rear Boss, and 40 at the Rear Boss Oblique. Further, no data were collected at the Rear test location for this helmet.

3.2. Post-processing

Impact measurement data were collected and processed in a custom MATLAB program that read the data for each test and filtered it using a Butterworth filter with a cutoff frequency of 750 Hz. Standard kinematic equations were used to calculate resultant angular and translation acceleration at the CoM (Cummiskey et al., 2019; Cummiskey et al., 2017; Padgaonkar et al., 1975).

3.3. Statistical analysis

For this analysis (Cummiskey et al., 2019) both π_2 and π_3 were removed from the final statistical model due to their relative invariance within the constraints of the headform model. A modified version of Grubb's method was used to remove outliers, defined as falling three standard deviations or more relative to an initial curve fit. After removal of outliers, a final curve fit was generated, using a log transformation of Eq. (6),

$$\ln(\Pi_i) = \ln(A_i) + \beta_{1i}\ln(\pi_1) \tag{7}$$

Running mean variance tests on each headgear's Π_1 and Π_2 vs. π_1 examined differences in performance between headgear and the bare head using an ANCOVA test with an α level of 0.05. To compare the differences found in the ANCOVA test, a Tukey post-hoc test with a Holm-Sidak p-value correction was utilized (Cummiskey et al., 2019).

The regression coefficients were utilized with the intermediate asymptotic fit model to determine the effect size between the
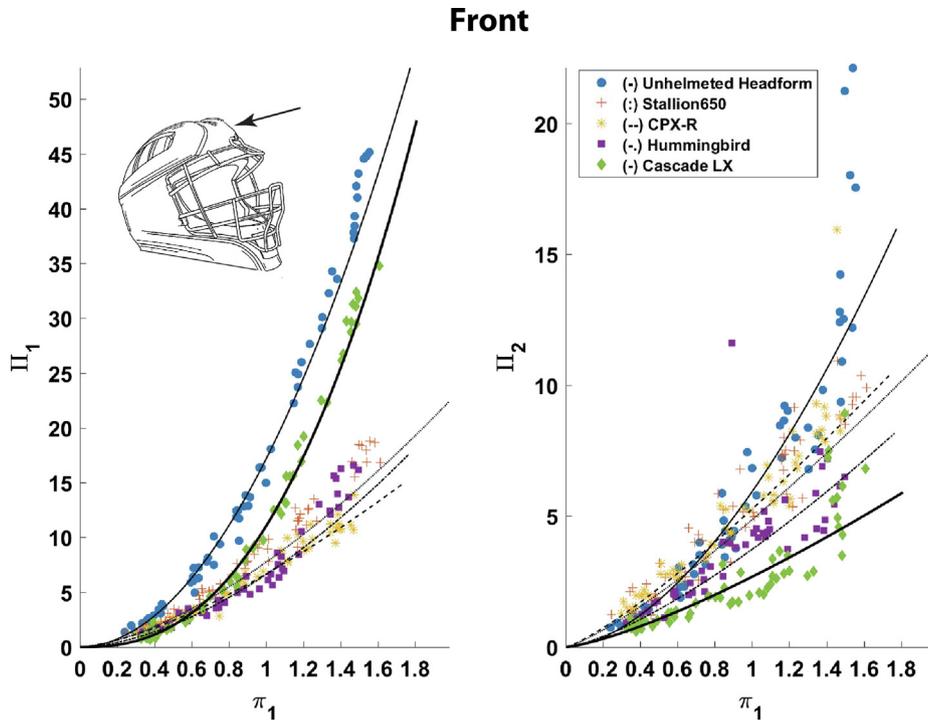
Front

Fig. 1. An impulse hammer in combination with a 3-2-2-2 setup of accelerometers to generate accelerations at the center of mass. At the Front location, the lowest translational accelerations were found in the CPX-R and Hummingbird helmets while the lowest angular accelerations were found in the Cascade LX.

helmets and bare head at 100 evenly spaced values spanning the distance between the minimum and maximum values for π_1 and averaged for each location. This method of analysis was also applied to data obtained for football helmets tested previously (Cummiskey et al., 2019). The effect size calculation provided a measure of the average difference between groups relative to the variability of the overall measurements.

4. Results

Relative to the unhelmeted Hybrid III, each of the helmets significantly reduced the dimensionless translational acceleration at each of the impact locations, with the caveat that we were unable to successfully test the Rear location of the Hummingbird due to product failure (Table 1). There was considerable variability between locations, especially the Front (Fig. 1), Front-Oblique (Fig. 2), and Side (Fig. 3). The Cascade CPX-R exhibited the lowest β_1 values at the first three locations, with the Schutt Stallion 650

demonstrating the lowest values at the last four test locations although there was no significant difference in the β_1 values between the two helmets at the Front-Oblique and Front Boss locations (Table 1).

Relative to the unhelmeted Hybrid III, the male lacrosse helmets consistently produced statistically significant reduction in the β_2 values for the dimensionless angular accelerations for each helmet-location combination (Table 2). Female lacrosse helmets did not consistently produce statistically significant reductions for the dimensionless angular acceleration, with the Hummingbird failing to reduce the angular parameter at the Rear Boss, Rear Boss Oblique or Rear locations, and the Cascade LX failing to reduce the angular parameter significantly at the Front Boss or Rear Boss Oblique locations. The Cascade LX exhibited significantly lower A_2 values than the Hummingbird, and male helmets at the Front. The Hummingbird helmets had significantly lower A_2 values at the Front Oblique, and Front Boss locations than did the Schutt Stallion, Cascade CPX-R or Cascade LX.

Table 1
Parameter values in for A and β in each cell with results from ANCOVA for the dimensionless translational acceleration parameter, Π_1 between types of headgear denoted with letters.

Locations								
		Front	Front-O	Front Boss	Side	Rear Boss	Rear Boss-O	Rear
Hybrid III	A_1	17.54 (bcde)	17.31 (bcde)	17.14 (bcde)	17.87 (bcde)	17.92 (bcde)	19.81 (bcde)	18.85 (bce)
	β_1	1.96 (bcde)	2.06 (bcde)	2.04 (bce)	2.07 (bce)	2.02 (bce)	2.05 (bce)	2.08 (bce)
Schutt Stallion 650	A_1	8.89 (acde)	8.23 (acde)	7.22 (acde)	7.60 (acde)	7.65 (acde)	7.49 (acde)	6.36 (ace)
	β_1	1.55 (acde)	1.53 (ade)	1.46 (ade)	0.88 (acde)	0.94 (acde)	1.06 (acde)	1.14 (ace)
Cascade CPX-R	A_1	7.03 (abe)	6.73 (abde)	6.72 (abde)	8.33 (abde)	8.13 (abde)	8.36 (abde)	6.53 (abe)
	β_1	1.46 (abde)	1.52 (ade)	1.38 (ade)	1.66 (abde)	1.61 (abde)	1.84 (abe)	1.28 (abe)
Hummingbird	A_1	7.09 (abe)	7.58 (abce)	7.64 (abce)	7.10 (abce)	7.21 (abce)	6.47 (abce)	–
	β_1	1.71 (abce)	1.90 (abce)	1.98 (bce)	2.06 (bce)	2.00 (bce)	2.01 (b)	–
Cascade LX	A_1	11.04 (abcd)	12.27 (abcd)	13.31 (abcd)	12.96 (abcd)	13.74 (abcd)	14.95 (abcd)	12.28 (abc)
	β_1	2.48 (abcd)	2.34 (abcd)	2.21 (abcd)	2.63 (abcd)	2.37 (abcd)	2.19 (abc)	2.43 (abc)

*The annotations, a, b, c, d, and e indicate significant difference ($p < 0.05$) between the regression parameters of the unhelmeted Hybrid III, Schutt Stallion 650, Cascade CPX-R, Hummingbird and Cascade LX respectively to the helmet denoted by the Row label.
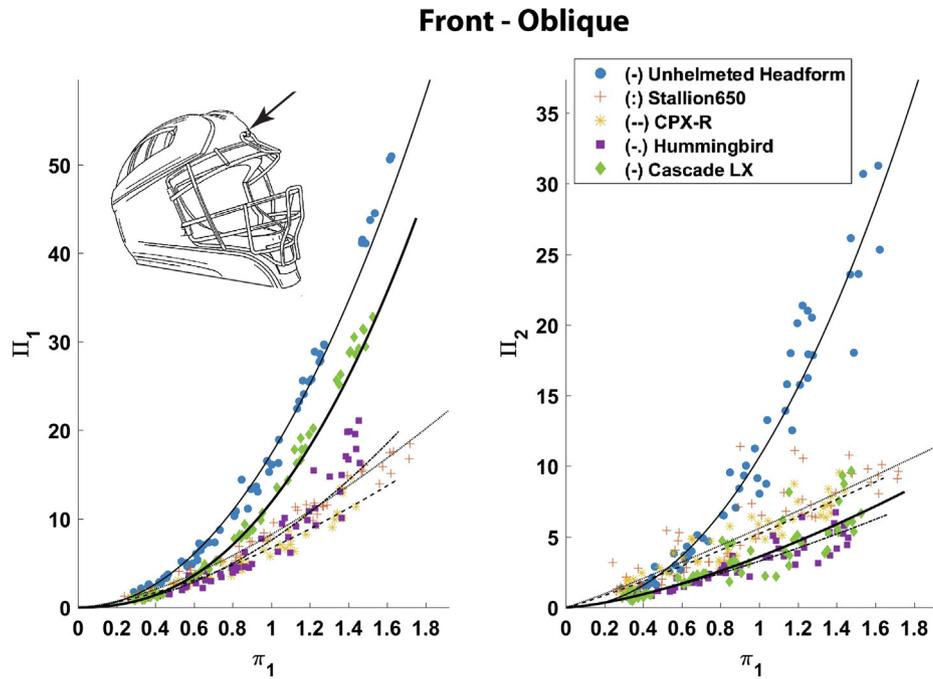
Front - Oblique

Fig. 2. An impulse hammer in combination with a 3-2-2-2 setup of accelerometers to generate accelerations at the center of mass. At the Front-Oblique location, the worst performance was found in the Cascade LX but it and the Hummingbird exhibited the best angular accelerations.
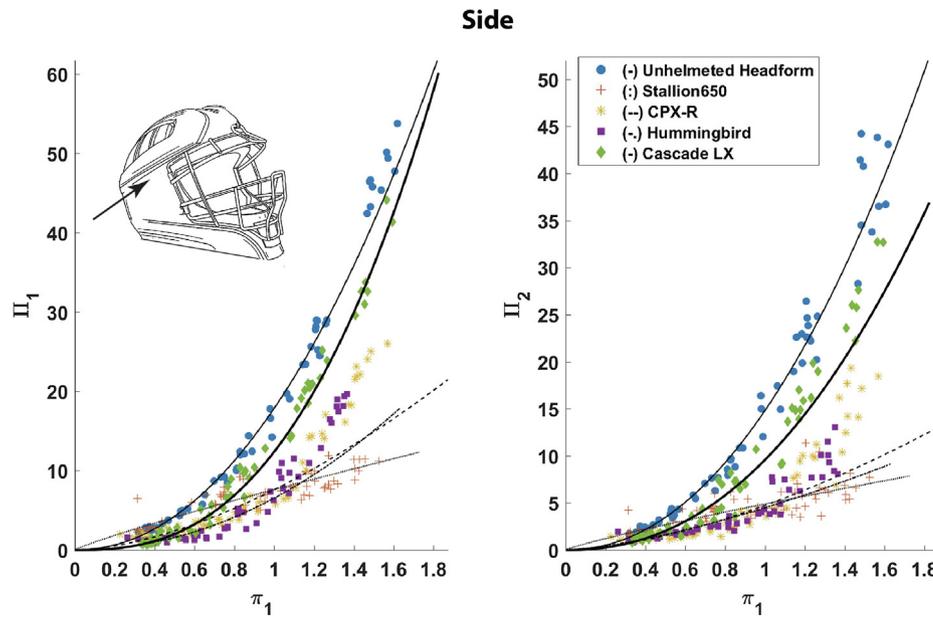
Side

Fig. 3. An impulse hammer in combination with a 3-2-2-2 setup of accelerometers to generate accelerations at the center of mass. At the Side location, the lowest translational and angular accelerations were found in the Stallion 650 and the Hummingbird helmets.

When comparing the effect size between helmets and the bare head, the Schutt Stallion provided the most substantial reduction from the bare headform at four of the seven locations (Table 3). The Hummingbird exhibited the most substantial effect size at the Rear Boss-Oblique location.

The effect size values for the dimensionless angular acceleration were significantly more variable between helmets (Table 3). More than half of the values (18/28) were greater than unity, with the Cascade LX demonstrating the most substantial effect size at the Front location, the Hummingbird demonstrating the most substantial effect size at the Front Oblique and Front Boss locations, and

the Schutt Stallion 650 providing the most substantial effect size at the rest of the locations.

Comparison of these data to those collected previously for football helmets (Cummiskey et al., 2019) demonstrates that football helmets consistently reduce the translational accelerations substantially better than the lacrosse helmets tested here (Fig. 4). The differences are most pronounced for values of, $\pi_1 > 1$. Football helmets also demonstrated generally better effect sizes at each location (Table 4). The notable exceptions include the rear boss and rear oblique. None of the helmets had an effect size greater than one for rear impacts.

Table 2

Parameter values in for A and β in each cell with results from ANCOVA for the dimensionless angular acceleration parameter, Π_2 between types of headgear denoted with letters.

Locations								
		Front	Front-O	Front Boss	Side	Rear Boss	Rear Boss-O	Rear
Hybrid III	A_2	6.05 (bcde)	10.65 (bcde)	10.16 (bcde)	14.82 (bcde)	10.69 (bcde)	7.43 (bcde)	4.22 (bc)
	β_2	1.73 (bcde)	2.09 (bcde)	1.77 (bcd)	2.10 (bcde)	2.00 (bce)	1.99 (bc)	1.56 (bce)
Schutt Stallion 650	A_2	5.43 (acde)	5.60 (acde)	5.41 (acde)	4.89 (ace)	3.47 (acde)	2.69 (acde)	3.05 (ae)
	β_2	1.25 (a)	1.09 (ade)	1.45 (ae)	0.87 (acde)	1.06 (acde)	0.78 (acde)	0.99 (ae)
Cascade CPX-R	A_2	5.51 (abde)	5.23 (abde)	4.17 (abde)	5.19 (abde)	5.07 (abde)	5.50 (abde)	3.11 (ae)
	β_2	1.23 (ad)	1.13 (ade)	1.32 (ae)	1.62 (abe)	1.47 (abde)	1.72 (abe)	0.96 (ae)
Hummingbird	A_2	3.94 (abce)	3.27 (abce)	3.33 (abce)	4.75 (ace)	5.93 (abce)	4.54 (abce)	–
	β_2	1.38 (ac)	1.37 (abc)	1.43 (ae)	1.45 (abe)	1.91 (bce)	1.76 (be)	–
Cascade LX	A_2	2.68 (abcd)	3.66 (abcd)	7.33 (abcd)	9.95 (abcd)	7.22 (abcd)	7.04 (abcd)	4.11 (bc)
	β_2	1.33 (a)	1.47 (abc)	1.91 (bcd)	2.24 (abcd)	2.31 (abcd)	2.13 (bcd)	1.72 (abc)

*The annotations, a, b, c, d, and e indicate significant difference (p < 0.05) between the regression parameters of the unhelmeted Hybrid III, Schutt Stallion 650, Cascade CPX-R, Hummingbird and Cascade LX respectively to the helmet denoted by the Row label.

Table 3

Effect Sizes for the Π_1 and Π_2 parameters when comparing each device to the unhelmeted headform performance. At each location, the largest effect size greater than one is highlighted.

|	Schutt Stallion 650	Cascade CPX-R	Hummingbird	Cascade LX
	Π_1	Π_1	Π_1	Π_1
Forehead	6.14	6.69	5.74	3.55
Forehead Oblique	7.77	6.22	4.29	3.34
Front Boss	6.75	6.14	4.04	2.43
Side	5.00	3.16	3.10	1.83
Rear Boss	4.91	3.94	3.80	1.92
RB-Obl	5.78	5.11	6.27	2.26
Rear	5.57	5.64	–	3.07
	Π_2	Π_2	Π_2	Π_2
Forehead	0.60	0.47	0.94	1.73
Forehead Oblique	3.00	2.85	4.11	3.62
Front Boss	1.50	2.09	2.68	0.89
Side	4.18	3.09	3.16	1.87
Rear Boss	3.14	1.86	1.86	1.24
RB-Obl	2.13	0.73	0.91	0.10
Rear	0.90	0.75	–	0.10
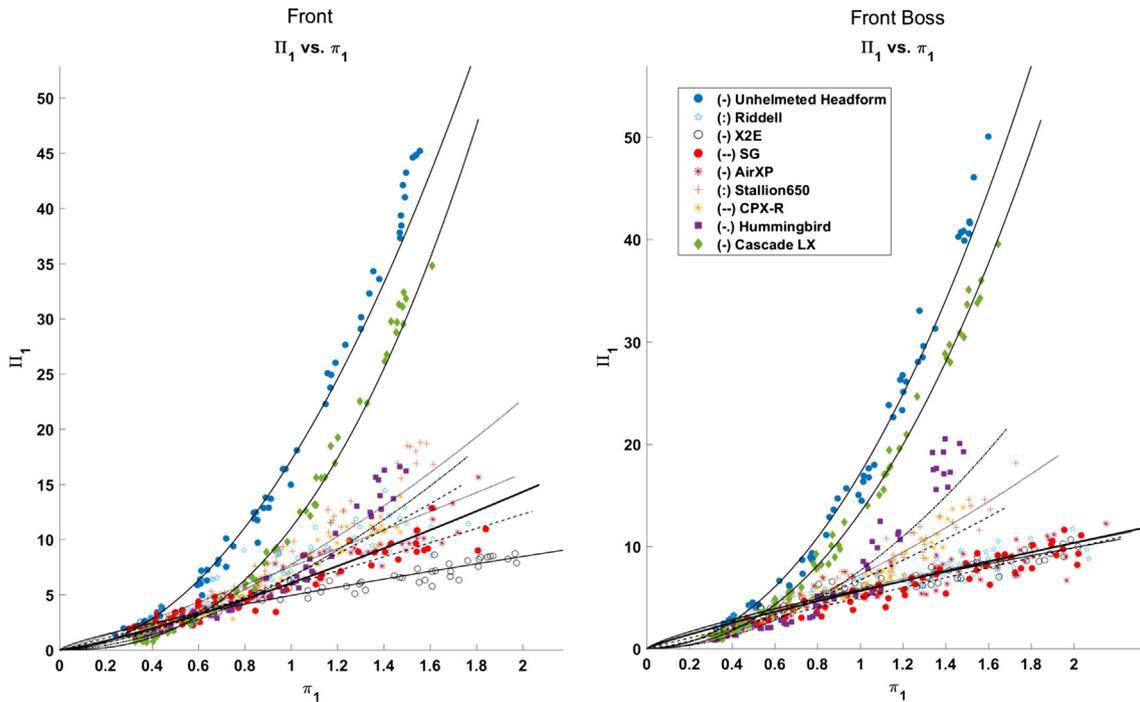
Fig. 4. Football helmets generally demonstrate lower values of Π_1 for normal impacts to the front of the helmet and the front boss than do male and female lacrosse helmets, particularly at values of the dimensionless impulse above one. The unhelmeted Hybrid III headform (blue circles) exhibits the highest dimensionless acceleration at both locations. Included for comparison are the Revolution Speed (Riddell; Rosemont, IL), X2E (Xenith; Detroit, MI), SG (SG Helmets; Brownsburg, IN), and AiR XP PRO (Schutt; Litchfield, IL) all previously reported by Cummiskey et al. (2019). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 4
Effect Sizes for the Π_1 and Π_2 parameters when comparing each previously tested device to the bare head data. At each location, the largest effect size greater than one is highlighted.

	Riddell Speed Π_1	Xenith X2E Π_1	Simpson SG Π_1	Schutt Air XP Pro Π_1
Forehead	5.65	9.91	7.73	7.42
Forehead Oblique	10.18	10.99	8.67	10.32
Front Boss	8.23	9.13	8.75	7.2
Side	6.63	5.88	5	4.24
Rear Boss	5.31	5.27	4.41	4.71
RB-Obl	6.3	7.94	6.69	3.9
Rear	5.89	5.43	4.96	5.34
	Π_2	Π_2	Π_2	Π_2
Forehead	1.44	2.16	1.34	2.02
Forehead Oblique	4.69	5.59	4.56	4.87
Front Boss	2.74	3.06	2.81	2.78
Side	4.42	4.11	2.9	2.8
Rear Boss	2.34	1.9	1.34	1.41
RB-Obl	1.44	2.09	1.33	0.68
Rear	0.29	0.6	0.53	0.8

5. Discussion

The goal of this study was to provide a transfer function as previously proscribed by Cummiskey et al. (2019) to assess the performance of male and female lacrosse helmets at mitigating head impacts by quantifying the impulse delivered to the headform-helmet system and the resultant translational and angular accelerations (Cummiskey et al., 2019). This study was motivated by the finding that, while American football is considered to be more inherently dangerous than lacrosse and women's soccer, the HAEs are similar across these sports (O'Day et al., 2017; Vollavanh et al., 2018). These data suggest that it should be possible to develop safety equipment that dramatically reduces HAEs in men's and women's lacrosse.

The ability of lacrosse helmets to attenuate the impacts delivered varied by helmet type and location. There was a clear effect of the mass added by the helmet, type of padding, and in the case of the Hummingbird helmet, damage accumulation. For translational acceleration, the male lacrosse helmets consistently (7 of 7 locations) provided the best performance. The results were more varied for angular accelerations, but the Schutt performed best at 4 of the 7 locations again.

Compared to a previous study utilizing the same testing setup (Cummiskey et al., 2019), effect size values for the lacrosse helmets relative to the bare head demonstrated substantial differences in performance, with the smallest effect size for the front impact location being 5.65 for the 2013 Riddell Speed, and the largest being 9.91 for the Xenith X2E, and both helmets outperformed the best lacrosse helmet (Table 4). It is interesting to note that the effect size compared to the bare head of football helmets, and male and female lacrosse helmets decreased on the side and rear impact locations.

The Cascade CPXR and the Schutt Stallion helmet possess design features that allow them to attenuate translational acceleration more effectively than the other lacrosse helmet designs. This may be due to the mass of the helmets being higher than the female lacrosse helmets. It may also be accounted for due to the hard outer shells flexing during impact. To complete the assessment of design features that can be used to mitigate impacts, additional helmet models should be evaluated to separate the effects of padding type, helmet shell design, and mass through the inclusion of the, π_2 variable.

The effect size data indicated that the Cascade LX and Hummingbird possess design features that allow them to attenuate significant amounts of angular acceleration despite their performance being less desirable with respect to translational acceleration. The Cascade LX has a flexible polymer outer shell that may contribute to the better attenuation clearly visible at the first two locations, however this design seems to fair less well at other tested locations. The Hummingbird performed better with respect to translational acceleration than the Cascade LX and beat all of the tested helmets at attenuating angular acceleration at the Front Oblique and Front Boss location. The Hummingbird may have suffered plastic deformation through the testing process, as the button that holds two pieces of the helmet together failed prior to the end of testing for all three of the tested devices.

Previous research focused on the use of the NOCSAE drop test as the primary mode of testing. It was used to demonstrate that football helmets dramatically outperform lacrosse helmets in the laboratory (Breedlove et al., 2016) however no previous research has compared male and female lacrosse helmets. Women's lacrosse players often do not wear helmets at all, which may contribute to the higher incidence of head and facial injuries observed in the sport (Marshall et al., 2015). Given that head accelerations are similar in helmeted football players, women's soccer, and helmeted men's lacrosse, (Bailes et al., 2013; Breedlove et al., 2012; Broglio et al., 2012; Broglio et al., 2013; McCuen et al., 2015; O'Day et al., 2017; Vollavanh et al., 2018), and that head injuries occur at a high rate in women's lacrosse, considerable design improvements should be incorporated into all lacrosse helmets. In addition, a rule change requiring athletes to wear helmets in women's lacrosse may be desirable.

Declaration Competing Interest

The authors do not have any conflicts of interest to report.

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