1. TITLE PAGE

Impact Mitigation Properties and Material Characterization of Women's Lacrosse Headgear

Running Title: Impact Mitigation of Women's Lacrosse Headgear

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2. ABSTRACT AND KEY TERMS

Abstract

The purpose of this study was to examine the impact attenuation properties of women's lacrosse headgear and to characterize mechanical properties of the materials of which they are composed. Impacts using a linear impactor (2.2 m/s, 2.9 m/s, and 5.0 m/s) and a projectile shooter (13.4 m/s and 27.0 m/s) were applied to a Hybrid III 50th male head-neck assembly at six impact locations to replicate realistic women's lacrosse head impacts. Individual materials that make up the headgear were tested in compression at two quasi-static strain rates, 0.01/s and1/s, and 100/s using uniaxial test machines. For the linear impactor tests, results showed a significant decrease in peak linear and rotational acceleration (PLA and PRA), peak rotational velocity (PRV), head injury criteria and brain injury criteria in the helmeted impacts ($p<0.022$). During the ball impacts PRV and PRA were significantly lower for both helmeted conditions compared with no helmet ($p<0.01$). Material characterization tests indicated a range of rate effects in these materials ranging from weak to pronounced, and these effects correspondingly influenced the strain energy density graphs. The connection of the materials' rate effects to the performance of the headgear is described in general and in relation to the impact tests.

Key Terms

women's lacrosse, head impacts, soft headgear, helmets, sport-related concussion

Abbreviations

SRC	Sport related concussion
TPU	Thermoplastic polyurethane
PLA	Peak linear acceleration
PRA	Peak rotational acceleration
PRV	Peak rotational velocity
HIC	Head injury criteria
BrIC	Brain injury criteria
NOCSAE	National Operating Committee on Standards for Athletic Equipment
ASTM	American Society for Testing and Materials

3. INTRODUCTION

Sport related concussion (SRC) rates are high in the US, with roughly 300,000 occurring annually [19]. Concussion rates and mechanisms vary by sport and have been reported in several epidemiological studies [10, 13, 19, 22, 27, 32]. Men's lacrosse is a collision sport and so athletes are required to wear helmets and protective gear while women's lacrosse is not, and athletes are only required to wear protective eye goggles. Optional head protection is available for female lacrosse athletes. Since the headgear is optional, it must have a soft outer shell, which is different than the hard outer shell of most sports helmets [20]. Even though rules do not allow any intentional contacts, unintentional impacts occur and can result in concussion [5, 7, 17]. Lincoln et al. found that the rates of head and face injuries were significantly higher in women's lacrosse when compared to men's lacrosse and that over four years of competition, 40% of high school female lacrosse players sustained a concussion [17].

The ability of a helmet to reduce the severity of an impact is in part dependent on its materials. Consequently, material consideration is an important part of the design and can affect its performance. Head protection used for sports applications commonly incorporate polymer foams (i.e. thermoplastic polyurethane (TPU), polypropylene, polyethylene, etc.) that are viscoelastic, allowing them to store and dissipate energy as they deform and to recover to their original shape for fairly high loads, dependent on the particular material. These characteristics allow them to sustain a high number of impacts without diminished performance and to transfer lower contact force to the head than the initial force of the impact. Like most polymers, the mechanical properties of these foams are strain rate dependent. Strain rate dependence results in higher contact stress and lower strain at higher rate impacts, so it is important that foams used in sports head protection equipment be designed based on characterization data over a range of strain rates. Current helmet safety standards created by ASTM and the National Committee on Standards for Athletic Equipment (NOCSAE) only consider linear acceleration-based impact metrics (peak linear acceleration and HIC).

Because women's lacrosse headgear is newer, few laboratory studies have tested their abilities to attenuate impacts for all impact types that players are likely to experience during competition. One study, conducted in 2014, examined some of the first commercially available soft headgear and compared it to a men's lacrosse helmet and an unhelmeted condition. [26] They found that head impact metrics at higher velocity ball impacts were not reduced by the soft headgear. [26] A more recent study compared the ability of two newer commercially available women's lacrosse headgear to reduce peak linear and peak rotational acceleration (PLA and PRA) and found that there was a significant difference between the two but attributed that to motion of the headgear during impact and did not compare it to an unhelmeted impact. [2] In addition to the laboratory testing, one recent study examining headgear effectiveness on field has demonstrated that there was a decrease in PLA and PRA in one season where the athletes wore the headgear compared with the previous season where they had not.[4]

The purpose of this study was to investigate how well commercially available head protection for women's lacrosse mitigated both linear and rotational head impact metrics during lower and higher velocities. In this study, a variety of impact locations, and severities were used, using both a lacrosse ball and linear impactor. We included rotational velocity kinematic concussion metrics because of their higher correlation to brain strains than other kinematic concussion metrics [3]. Materials from the headgear were also tested in compression at various strain rates to determine their stress-strain behaviors at multiple strain rates, as well as strain energy density.

4. MATERIALS AND METHODS

Impact Testing

We examined two different commercially available lacrosse women's headgear – Cascade LX (2021) and the Hummingbird v2 (2021). A Hybrid III 50th percentile male head-neck assembly was instrumented with tri-axial piezo-resistive accelerometers (Diversified Technical Systems, Inc., Seal Beach, CA) and tri-axial ARS PRO-8K angular rate sensors (Diversified Technical Systems, Inc., Seal Beach, CA) located at the center of gravity of the head and secured to a linear bearing table. A linear impactor (Cadex, St-Jean-sur-Richelieu, Quebec, Canada) was used to administer impacts to the instrumented headform with and without the headgear. Linear acceleration and angular rate data were collected at 20 kHz. The headform was impacted at six different impact locations: front, side, rear, front boss, rear boss center of gravity (RBCG), rear boss non-centric (RBNC) at 2.2 m/s, 2.9 m/s and 5.0 m/s (+/-2%). (Fig 1) The 2.9 m/s impact speed was tested because it replicates lower severity impacts that frequently occur in women's lacrosse and was used in a previous impact study on women's lacrosse headgear [2]. The 5.0 m/s was chosen because it corresponds to the high-speed running of a female in competitive sports [16, 21] and was used in a previous study to determine the ability of men's lacrosse helmets to mitigate women's lacrosse replicated impacts [6]. Both impact speeds were tested at all six impact locations for three trials each on the bare headform and on the headform with each of the two helmets. Two samples of each brand were tested. The impactor head made initial contact with the headform or headgear roughly 2 inches from where it bottoms out. This allowed for repeatability across trials and ensured that each impact was equivalent for all impact locations and all headgear conditions.

Projectile Testing

Ball impact testing utilized the same methodology as the linear impactor testing but with a different impact mechanism. The projectile shooting arm of the Cadex linear impactor was used to shoot NOCSAE certified lacrosse balls at an unhelmeted headform, and at a new sample of each headgear three times. Lacrosse ball impact speeds of 13.4 m/s and 27.0 m/s were chosen because they correspond to women's lacrosse passing and shooting speeds, respectively [18]. Also, 27.0 m/s is the impact speed used for the ball impact absorption test in the ASTM F3137-15 standard specification for women's lacrosse headgear [1]. Ball impact speed was measured using a velocity time gate and the impact speeds were considered within tolerance if they were within +/- 3% of the desired impact speed. A high-speed camera (Apple, Cupertino, CA) was used to record all ball impacts at 120 frames per second to visually confirm that the lacrosse ball successfully impacted the desired impact location. If it was determined that the lacrosse ball did not accurately hit the desired location, the trial was redone.

Data Processing

All impact data were filtered and processed using DIAdem (NI, Austin, TX) Crash Analysis Toolkit built-in data filters. Linear acceleration data was filtered using the SAE J211 channel frequency class (CFC) 1000 filter. The CFC 60 filter was used to filter rotational velocity data [9]. Once filtered, rotational velocity data was used to calculate rotational acceleration in DIAdem.

Peak resultant linear acceleration (PLA), peak resultant rotational acceleration (PRA), peak resultant rotational velocity (PRV), head injury criterion (HIC_{15}, also denoted as "HIC", where the time interval is limited to a maximum of 15 ms), and brain injury criterion (BrIC) were calculated using the DIAdem Crash Analysis Toolkit.

$$HIC_{15} = max\left\{(t - t_0)\left[\left(\frac{1}{t - t_0}\right)\int_{t_0}^{t} |a(t)|dt\right]^{2.5}\right\},$$

where t-t_0 is the 15 ms time interval that maximizes HIC_{15} and a is acceleration of the center of mass of the head.[31]

$$BrIC = \sqrt{\left(\frac{\omega_x}{\omega_{xcr}}\right)^2 + \left(\frac{\omega_y}{\omega_{ycr}}\right)^2 + \left(\frac{\omega_z}{\omega_{zcr}}\right)^2}\ ,$$

where ω_i are the maximum components of angular velocity and ω_{icr} are directionally dependent critical values.[30]

Statistical Analysis

Descriptive statistics were reported for the various impact locations. However, because of the small sample size, differences in impact kinematics between unhelmeted and protective headgear impacts were compared by examining all locations together for each speed, and then for all speeds at each location. Data were tested for normality on a 95% confidence interval ($\alpha = 0.05$) using a Chi-square goodness of fit test in MATLAB (MATLAB R2020a; MathWorks, Natick, MA), and it was found that the data were not normally distributed. Therefore, Mann-Whitney U tests were used to compare the mean between two sets of data. Statistical significance of the Mann-Whitney U tests was determined on a 95% confidence interval ($\alpha = 0.05$), with a separate test being done for each concussion metric as the dependent variable for every comparison. All Mann-Whitney U tests were conducted in MATLAB.

Material Testing

Compressive material testing was conducted on the different materials within each headgear. These samples were taken from new headgear that had not undergone previous impact testing. Materials were named by headgear location (inner or outer) and color. For the Cascade headgear, this included inner black, inner gray, outer gray, outer white, and yellow materials (Figure 2a). For the Hummingbird headgear, this included inner black, inner charcoal, and outer white materials (Figure 2b).

Test specimens of each material were cut out using a custom guillotine and drilling method to extract samples from a new headgear that were approximately 6.3 mm in diameter (Table 1). Some materials were limited in thickness, in particular the outer materials on the Cascade headgear (Table 1). Three samples of each material were compressed up to 75% strain at two quasi-static strain rates, 0.01/s and1/s, and one high strain rate of about 100/s. The high strain rate value was selected, as it was 100 times the quasi-static rate of 1/s. Quasi-static rate tests were performed using a uniaxial test machine system (Model 100-Q-225, TestResources Inc., Shakopee, MN). Displacement and force were recorded by the test machine at a rate of 25 Hz for the 0.01/s strain rate tests and 1 kHz for the 1/s strain rate tests.

Table 1. Average diameter and thickness of material samples.

Headgear	Material	Diameter (mm)	Thickness (mm)
Cascade	Inner Black	6.20 ± 0.27	3.41 ± 0.15
	Inner Gray	6.01 ± 0.22	3.40 ± 0.17
	Outer Gray	6.65 ± 0.14	2.74 ± 0.15
	Outer White	6.43 ± 0.06	2.37 ± 0.06
	Yellow	6.47 ± 0.20	3.45 ± 0.25
Hummingbird	Inner Black	6.32 ± 0.23	3.63 ± 0.36
	Inner Charcoal	6.19 ± 0.11	4.96 ± 0.20
	Outer White	6.13 ± 0.14	4.37 ± 0.49
All Samples Combined	-	6.32 ± 0.26	3.47 ± 0.85

For high-rate testing, only the outer materials of the Cascade (outer gray and outer white) and Hummingbird (outer white) headgear were tested. High-rate tests were conducted on a custom made impact system previously described in detail [15]. Briefly, the machine uses an air driven projectile to load disk-shaped material specimens at moderate rate in compression. The apparatus uses direct measurements of force and material response, rather than indirect measurements as in a Hopkinson system. Data was acquired at 25kHz using an OROS model OR-35 four channel analyzer and data acquisition system with OROS NVGate software. The data collected were time, acceleration of the specimen’s deformation (PCB Piezotronics Inc., Model 350B23), fixture acceleration (PCB Piezotronics Inc., Model 353A03), and compressive force applied to the specimen during the process (PCB Piezotronics Inc., Model 200C20). The specimen's deformation was determined by first integrating the fixture and specimen accelerations twice, then subtracting the resulting fixture displacement from the specimen displacement.

All data analysis was performed in MATLAB using custom scripts. Stress-strain curves were created for each test using the data acquired from testing. First, displacement data was used to calculate linear engineering strain:

$$\varepsilon = d/L_0$$

where, ε is engineering strain, d is the change in specimen's thickness and L_0 is original thickness of specimen.

Uniform axial normal stress was computed using:

$$\sigma = F/A_0$$

where, σ is engineering stress, F is force applied to the specimen, A_0 is original cross-sectional area of specimen.

All stress-strain data was filtered using a low-pass filter. Three different low-pass filters were created based on the sampling rate from each strain rate's test. The order of each filter, determined through trial and error, was set so that the derivative of each stress-strain curve was as smooth as possible while not sacrificing the shape of the stress-strain curve.

Strain energy per unit volume, or strain energy density was calculated from stress-strain data using:

$$e = \int_0^{\varepsilon} \sigma(\varepsilon) d\varepsilon \,,$$

where *e* is strain energy per unit volume, σ is engineering stress and ε is engineering strain. Tangent modulus (slope of the stress-strain curve) of each material at each strain rate was calculated in MATLAB using the forward difference method.

5. RESULTS

Impact Results

Impact testing results for the Hybrid III headform with no headgear, with the Cascade headgear, and with the Hummingbird headgear are shown in Tables 2 and 3 for linear impactor testing and Tables 4 and 5 for ball impact testing. For all three impact velocities, when data across all impact locations were grouped together, PLA, PRV, PRA, HIC and BrIC were significantly lower in the impacts with headgear compared to the headform with no headgear ($p<0.022$) (Table 2). There were no significant differences between the two headgears at 5.0 m/s for any of the concussion metrics. However, measured values were significantly lower for the Hummingbird headgear at 2.9 m/s for PLA ($p=0.005$), PRA ($p=0.017$), and HIC ($p=0.009$). Data were grouped by impact location, with each impact location group including data from all three impact speeds. (Table 3) For this comparison, both the Cascade and the Hummingbird headgears had significantly lower concussion metric values than the unhelmeted condition in 23/30 of the comparisons. The headgears significantly reduced all linear metrics at each impact location except HIC for the RBCG location. There were no concussion metrics at any of the impact locations that had a statistically significant difference between the Cascade dataset and the Hummingbird dataset.

Table 2: Linear impactor headgear comparison Mann-Whitney U test results with data grouped by impact speed. Bold p-values indicate statistical significance ($p < 0.05$).

Metric	Impact Speed (m/s)	Cascade Mean	Humming-bird Mean	No Headgear Mean	Cascade/ No Headgear p-value	Hummingbird/ No Headgear p-value	Cascade / Hummingbird p-value
PLA g	2.2	23.4	20.1	72.2	**<0.001**	**<0.001**	0.091
	2.9	41.3	32.0	107.9	**<0.001**	**<0.001**	**0.005**
	5	105.3	103.6	195.1	**<0.001**	**<0.001**	0.812
PRV rad/s	2.2	12.5	10.9	15.5	**<0.001**	**<0.001**	0.038
	2.9	16.8	15.3	20.2	**<0.001**	**<0.001**	0.150
	5	27.3	27.0	32.6	**<0.001**	**<0.001**	0.558
PRA rad/s^2	2.2	1404.0	1006.4	3335.1	**<0.001**	**<0.001**	**0.001**
	2.9	2098.4	1675.3	4540.0	**<0.001**	**<0.001**	**0.017**
	5	4551.9	4005.6	7577.4	**<0.001**	**<0.001**	0.438
HIC	2.2	10.2	6.0	66.9	**<0.001**	**<0.001**	**<0.001**
	2.9	30.5	18.7	164.9	**<0.001**	**<0.001**	**0.009**
	5	226.9	191.6	486.7	**0.005**	**<0.001**	0.200
BrIC	2.2	0.23	0.19	0.29	**0.002**	**<0.001**	0.071
	2.9	0.30	0.27	0.38	**0.009**	**<0.001**	0.233
	5	0.50	0.48	0.61	**0.022**	**<0.001**	0.333

Table 3: Linear impactor headgear comparison Mann-Whitney U test results with data grouped by impact location. Bold p-values indicate statistical significance ($p < 0.05$). Units for PLA – g; PRV – rad/s; PRA – rad/s^2.

Impact Location	Metric	Cascade Mean	Humming-bird Mean	No Headgear Mean	Cascade / No Headgear p-value	Humming-bird / No Headgear p-value	Cascade / Humming-bird p-value
Front	PLA	67.4	50.6	128.8	**0.050**	**0.001**	0.258
	PRV	23.8	18.9	22.6	0.258	0.258	0.258
	PRA	2137.1	1325.3	3349.3	**0.050**	**<0.001**	0.258
	HIC	140.2	60.6	264.9	**0.050**	**0.008**	0.094
	BrIC	0.42	0.34	0.40	0.253	0.245	0.246
Front Boss	PLA	61.9	58.5	136.3	**0.014**	**0.040**	0.796
	PRV	20.5	21.7	23.0	0.258	0.436	0.730
	PRA	3047.7	1876.7	6232.4	**0.004**	**<0.001**	0.050
	HIC	104.4	110.8	347.4	**0.050**	**0.050**	0.666
	BrIC	0.43	0.40	0.47	0.249	0.246	0.591
Rear	PLA	47.0	56.8	119.5	**<0.001**	**0.019**	0.730
	PRV	13.8	12.4	20.7	**0.011**	**0.011**	0.258
	PRA	1609.7	1380.0	3856.4	**<0.001**	**<0.001**	0.340
	HIC	21.3	59.7	174.4	**<0.001**	**0.019**	0.730
	BrIC	0.24	0.22	0.35	**0.010**	**0.019**	0.248
RBCG	PLA	68.0	64.4	119.7	**0.050**	**0.050**	0.489
	PRV	20.3	18.0	22.3	0.258	0.258	0.258
	PRA	3309.2	3319.4	5520.9	**0.050**	**0.050**	0.931
	HIC	130.5	106.4	112.1	0.258	0.258	0.297
	BrIC	0.38	0.34	0.44	0.248	0.057	0.247
RBNC	PLA	46.2	39.1	113.9	**0.024**	**0.004**	0.489
	PRV	17.9	18.2	25.6	**0.050**	**0.050**	0.796
	PRA	2997.7	2627.6	6298.1	**0.008**	**0.024**	0.489
	HIC	59.9	43.0	260.1	**0.050**	**0.006**	0.258
	BrIC	0.32	0.32	0.54	**0.045**	**0.045**	0.699
Side	PLA	49.6	42.0	132.1	**0.006**	**0.004**	0.387
	PRV	17.0	17.2	22.2	**0.050**	**0.050**	0.863
	PRA	3007.2	2845.6	5647.7	**0.031**	**0.014**	0.340
	HIC	79.0	52.2	278.0	**0.050**	**0.006**	0.258
	BrIC	0.27	0.28	0.36	**0.047**	**0.047**	0.348

For ball impacts at 13.4 m/s (Table 4), PLA, PRV, PRA, HIC, and BrIC were all significantly lower for the Hummingbird headgear compared with no headgear ($p<0.04$). PRV, HIC, and BrIC were significantly lower for the Cascade headgear compared with no headgear ($p<0.013$). At 27.0 m/s (Table 4), PRV and PRA were significantly lower for both helmeted conditions compared with no headgear ($p<0.01$). When examining specific locations of the ball impacts, only the Cascade headgear significantly reduced PLA and HIC during rear impacts. (Table 5)

Table 4: Ball impact headgear comparison Mann-Whitney U test results with data grouped by impact speed. Bold p-values indicate statistical significance ($p < 0.05$).

Metric	Impact Speed (m/s)	Cascade Mean	Humming - bird Mean	No Headgear Mean	Cascade / No Headgear p-value	Humming - bird / No Headgear p-value	Cascade / Humming - bird p-value
PLA g	13.4	40.4	34.8	48.3	0.069	**0.018**	0.117
	27.0	94.6	94.6	93.5	0.624	0.646	0.692
PRV rad/s	13.4	4.3	4.5	5.7	**0.013**	**0.011**	0.402
	27.0	8.5	8.8	10.8	**0.010**	**0.006**	0.537
PRA rad/s^2	13.4	1062.7	973.2	1314.8	0.052	**0.017**	0.304
	27.0	2134.8	2101.8	2911.5	**0.006**	**0.005**	0.788
HIC	13.4	9.9	5.7	20.5	**0.001**	**0.001**	0.056
	27.0	42.9	55.5	63.8	0.261	0.669	0.496
BrIC	13.4	0.08	0.08	0.11	**0.012**	**0.040**	0.898
	27.0	0.16	0.16	0.20	0.062	0.063	0.544

Table 5: Ball impact headgear comparison Mann-Whitney U test results with data grouped by impact location. Bold p-values indicate statistical significance ($p < 0.05$). Units for PLA – g; PRV – rad/s; PRA – rad/s^2.

Impact Location	Metric	Cascade Mean	Hummingbird Mean	No Headgear Mean	Cascade - No Headgear p-value	Hummingbird - No Headgear p-value	Cascade - Humming bird p-value
Front	PLA	43.3	31.9	52.5	0.180	0.180	0.310
	PRV	4.4	4.3	5.5	0.180	0.180	0.485
	PRA	622.0	709.3	988.0	0.180	0.180	0.699
	HIC	11.4	6.5	25.7	0.180	0.180	0.180
	BrIC	0.08	0.08	0.10	0.165	0.169	1.000
Front Boss	PLA	75.3	64.7	60.8	0.485	1.000	0.180
	PRV	6.7	7.4	9.7	0.180	0.180	0.240
	PRA	1578.0	1557.3	2623.9	0.180	0.180	0.818
	HIC	25.2	20.5	29.9	0.180	0.180	0.240
	BrIC	0.14	0.16	0.19	0.188	0.154	0.262
Rear	PLA	65.4	69.0	88.3	**0.026**	0.093	1.000
	PRV	4.7	5.0	6.4	0.180	0.180	0.394
	PRA	1165.9	968.8	2071.4	0.310	0.065	0.180
	HIC	51.6	60.3	116.0	**0.041**	0.132	1.000
	BrIC	0.09	0.10	0.12	0.167	0.251	0.407
RBCG	PLA	86.8	99.6	88.5	0.818	0.310	0.589
	PRV	6.8	7.7	8.9	0.180	0.180	0.180

	PRA	1864.9	1913.7	2268.7	0.180	0.310	0.818
	HIC	27.8	53.4	48.6	0.180	0.589	0.589
	BrIC	0.14	0.14	0.17	0.162	0.180	1.000
RBNC	PLA	66.0	68.4	65.3	1.000	1.000	0.699
	PRV	7.3	7.9	10.8	0.180	0.180	0.180
	PRA	1947.0	2012.7	2714.5	0.180	0.180	0.310
	HIC	20.1	18.7	15.9	1.000	0.699	0.394
	BrIC	0.13	0.14	0.21	0.165	0.154	0.331
Side	PLA	68.2	54.6	69.9	0.937	0.310	0.240
	PRV	8.6	7.5	8.1	0.310	0.180	0.180
	PRA	2414.8	2063.5	2012.6	0.180	0.485	0.180
	HIC	22.1	24.3	16.8	0.937	0.937	0.818
	BrIC	0.14	0.12	0.13	0.600	0.245	0.229

Material Characterization

Because the impact tests end at different maximum strains, all stress-strain plots shown in Figure 3 were truncated at the smallest maximum strain across the tests. Accordingly, only the available data up to the strain truncation point of each plot was used in the creation of the averaged strain energy density plots (Figure 4).

The Cascade Inner Black, Inner Gray, and Yellow (Table 6) materials all exhibited a substantial increase in tangent modulus from 0.01/s testing to 1/s testing, especially in the linear region. For the Cascade outer materials (Table 6), the strain rate stiffening effect was not as prominent between 0.01/s and 1/s testing, but this effect was larger in the densification region. Comparing to 100/s strain rate testing, these outer materials exhibited substantial strain rate stiffening, and this was greatest in the linear region. The Hummingbird Inner Charcoal material (Table 7) also had strain rate stiffening, with the stiffening having a greater effect in the linear region. The Hummingbird Inner Black and Outer White (Table 7) materials showed little to no strain rate stiffening between 0.01/s strain rate and 1/s strain rate testing. However, the Outer White material did substantially stiffen at 100/s.

Strain rate hardening was also observed in all the materials, especially in the plateau region (portion of stress-strain curve with almost zero slope), as shown in Figure 3 and Tables 6 and 7. In Table 6, for example, at the strain of 0.25 of the Cascade Outer White material, stress increases from 5.05 MPa at 0.01/s strain rate to 6.54 MP at 1/s, resulting 29% difference. Moreover, the stress difference between 0.01/s and 100/s is 271%. Figure 3(d) shows this rate hardening at the strain of 0.25. The rate hardening can also be seen in the strain energy density curves, Figure 4(d).

Table 6 Cascade material stress and tangent modulus at regions of interest (or at a denoted strain value if a given region of interest was not present). Percent "Diff (%)" refers to the change in stress or tangent modulus value from 0.01/s strain rate to 1/s strain rate, 100/s was only tested on outer materials.

		Stress (MPa)			Tangent Modulus (MPa)		
Material	**Strain**	**0.01/s Rate**	**1/s Rate**	**Diff (%)**	**0.01/s Rate**	**1/s Rate**	**Diff (%)**
Inner Black	Linear Region	0.008	0.026	225	0.188	0.795	324
	Plateau Region	0.043	0.079	86	0.135	0.124	-8
	Densification Region	0.118	0.14	19	0.444	0.351	-21
Inner Gray	Linear Region	0.016	0.044	169	0.476	1.227	158
	Plateau Region	0.084	0.215	157	0.176	0.13	-26
	Densification Region	0.172	0.324	89	0.585	0.752	28
Outer Gray	Linear Region	0.261	0.416	59	7.229	9.047	25
	0.30	5.723	8.893	55	28.344	39.233	38
	Densification Region	10.804	16.277	51	30.598	45.213	48
Outer White	Linear Region	0.451	0.427	-5	7.205	7.188	0
	0.25	5.053	6.543	29	27.499	37.614	37
	Densification Region	10.17	13.394	32	31.512	40.907	30
Yellow	Linear Region	0.004	0.028	675	0.133	0.777	483
	Plateau Region	0.045	0.149	234	0.089	0.19	114
	Densification Region	0.088	0.289	228	0.368	1.234	236
Material	**Strain**	**100/s**	**% Diff (0.01/s to 100/s)**	**% Diff (1/s to 100/s)**	**100/s**	**% Diff (0.01/s to 100/s)**	**% Diff (1/s to 100/s)**
Outer Gray	Linear Region	2.96	1035	612	78.98	993%	773
	0.30	26.91	370	203	138.14	387%	252

	Densification Region	63.63	489	291	299.99	880%	563
Outer White	Linear Region	2.98	561	599	75.35	946%	948
	0.25	18.75	271	187	98.44	258%	162
	Densification Region	47.38	366	254	255.42	711%	524

Table 7: Hummingbird material stress and tangent modulus at regions of interest. Percent diff refers to the change in stress or tangent modulus value from 0.01/s strain rate to 1/s strain rate, 100/s was only tested on the outer material.

		Stress (MPa)			**Tangent Modulus (MPa)**		
Material	**Strain**	**0.01/s Rate**	**1/s Rate**	**Diff (%)**	**0.01/s Rate**	**1/s Rate**	**Diff (%)**
Inner Charcoal	Linear Region	0.061	0.202	229	1.358	4.891	260
	Plateau Region	0.155	0.388	151	0.319	0.502	57
	Densification Region	0.376	0.729	94	1.621	2.613	61
Inner Black	Linear Region	1.3E-03	1.6E-03	23	9.4E-03	1.2E-02	28
	Plateau Region	2.58E-03	2.81E-03	9	~0	~0	-
	Densification Region	4.37E-03	4.95E-03	13	1.46E-02	1.59E-02	9
Outer White	Linear Region	0.063	0.036	-42	1.551	1.087	-30
	Plateau Region	0.239	0.286	20	0.548	0.614	12
	Densification Region	0.773	0.821	6	4.322	3.998	-8
Material	**Strain**	**100/s**	**% Diff (0.01/s to 100/s)**	**% Diff (1/s to 100/s)**	**100/s**	**% Diff (0.01/s to 100/s)**	**% Diff (1/s to 100/s)**
Outer White	Linear Region	0.1	59	175	1.425	-8	31
	Plateau Region	0.315	32	10	1.023	87	67
	Densification Region	16.553	2041	1916	273.57	6229	6743

6. DISCUSSION

The purpose of this study was to gain insight on the impact mitigation properties of women's lacrosse headgear. To do so, impacts of low and high severity that occur in the sport were tested and rotational velocity-based metrics were included in analysis of the impacts. We compared the severity of head impact metrics at different impact locations. For linear impactor and ball impacts at each impact location, all five concussion metrics increased as impact speed increased. This is consistent with other studies that have tested multiple linear impactor speeds and/or multiple ball impact speeds relating to women's lacrosse [12, 20, 28].

The Cascade and the Hummingbird headgear significantly reduced all concussion metrics compared to no headgear condition at all linear impactor speeds when data from all of the locations was combined. The Hummingbird headgear also had significantly lower PRA, PLA, and HIC values than the Cascade headgear in some conditions. Bowman et al. also measured PLA and PRA at 2.9 m/s at front, front boss, side and RBNC using a pendulum and NOCSAE headform.[2] It is challenging to compare values because of the differences in instrumentation and test set up. The magnitude of PLA and PRA were much higher for both headgear in the Bowman et al. study compared with ours, however, they also found that the Hummingbird headgear was able to reduce both PLA and PRA at 2.9 m/s more than the Cascade headgear.

Both headgear were able to significantly reduce all 5 concussion metrics compared to the no headgear condition for 5.0 m/s linear impactor impacts. At this impact speed, there were no concussion metrics that were significantly different in value between the Cascade and the Hummingbird headgear. This study was the first to examine the impact mitigation of the women's lacrosse headgear at 5.0 m/s linear impactor conditions. However, Clark and Hoshizaki (2016) studied this impact speed on a headform with no head protection and one with a men's lacrosse helmet to determine the potential effectiveness of head protection use in women's lacrosse [6]. They found that the men's lacrosse helmet was able to significantly reduce PLA of the headform at both a front and side impact location, but that it was not able to significantly reduce PRA at either of the impact locations. One possible reason that the women's lacrosse headgear we tested were able to reduce PRA while the men's lacrosse helmet in the previous study did not, is the difference in composition and design of the headgear/helmet. The men's helmet was made with a hard outer shell, and it is possible that was the primary material used to mitigate the effect of impact forces and prevent penetration, whereas the women's headgear must rely on other materials. Another possible explanation is a difference in test set up. Both studies used a Hybrid III headform, however, in the Clark study, it was fixed to a table, as opposed to our study that used a linear bearing table that allowed some motion after the impact. Values for PLA and PRA for the non-helmeted headform were much smaller for the Clark and Hoshizaki study compared with ours. One study that examined the effectiveness of the headgear on the field found a large reduction in the highest magnitude impacts when wearing the headgear vs no headgear. When examining all impacts over the two-year period, the vast majority (83%) occurred without headgear. [4] This is consistent with our findings.

Linear impactor concussion metric values for each helmeted condition were relatively consistent across all impact locations for translational kinematic concussion metrics (PLA and HIC), although these values were somewhat lower for rear and RBNC impacts. Conversely, there was a greater variety for rotational kinematic concussion metrics (PRA, PRV, and BrIC) across impact locations. The location of an impact and the angle of the impact source relative to the impact location can greatly influence the resulting rotation of the head, which explains why rotational metrics saw more variation across different impact locations than translational metrics did. Impacts that occurred with the impactor or the ball at a trajectory that did not go through the center of gravity of the head (front boss and RBNC), or with the head rotated so that one of its main axes was not parallel to the trajectory of the impactor or the ball (RBCG), resulted in the greatest rotational acceleration. These impact locations likely exhibited the highest rotational metric values because their orientation in reference to the impact source allowed for the most multi-axial rotation.

Ball impact concussion metrics followed similar trends as described above for rotational metrics. However, the translational metrics for ball impacts appeared to vary more across impact locations for both impact speeds than they did for linear impactor impacts because these impacts are highly localized and only occur for a short time duration, and therefore, the tilt of the head at a given impact location has a greater effect on the translational metric values. The front and front boss impact locations both have a 15˚ forward tilt which may allow the neck component to resist translation more effectively than it does in the other impact locations. This is likely why these impact locations had lower ball impact translation values and the rear and RBCG locations had greater translational ball impact metrics values.

In this study, we also examined the individual materials that made up the headgear. Of the materials that were tested, most exhibited the initial linear region, plateau, and densification regions that are characteristic of polymer cellular foams. The exceptions to this were the two outer materials of the Cascade headgear. At quasi-static strain rates (0.01/s and 1/s), these materials had a linear region spanning from around 0.1 strain until the truncation strain value. For high-rate impacts, these materials exhibited a linear or even slightly exponential stress-strain curve shape from zero strain until the end of the test. This is likely because the Cascade Outer Gray and Outer White materials may not be cellular foams. [11] Although no microscopy was performed in this study to examine the microstructure of the materials used in these headgear, it did not appear that the Cascade outer materials were constructed as cellular foams.

All tested materials strain-rate hardened and stiffened to some extent. The magnitude of the rate effects was usually greatest in the linear region of the stress-strain curve, except for the Hummingbird Outer White material. This finding that the greatest rate effects occur in the initial linear region of the stress-strain curve is consistent with previous studies that have tested polymer foams at various strain rates [23, 24, 29, 33, 34]. This phenomenon is a result of what is occurring within the foam during the initial linear region of the stress-strain curve. When foams first start to deform, their cell walls begin to bend, causing the initial spike in stress [25]. The key to low levels of stress in this stage of deformation is for the cell walls and molecules of the foam to easily slide past each other [8]. As strain rate increases, the cell walls and molecules of the foam do not slide past each other as easily while the foam deforms, causing an increase in the stress required for a given strain. During the plateau region of the stress-strain curve, the cell structures within the foam continuously collapse [25]. This stage occurs after most cell wall bending has occurred, which is why the stress required to further compress the foam remains relatively constant. Since this is the case, an increase in strain rate does not have nearly as much of an effect on the tangent modulus (stiffening) in the plateau region of the curve. This is evident in most of the materials tested but is especially clear in Cascade Inner Black and Inner Gray materials and the Hummingbird Inner Charcoal and Inner Black materials.

Strain rate effects are a general characteristic of typical polymer materials used in sports head protection and have both negative and positive effects. Rate effects increase the contact stress at a given strain, which can be a negative effect. However, the attendant decrease in strain brought about by rate effects, has a positive effect later in the impact by reducing overall deformation, which can prevent the material from collapsing which would cause a more direct impact to the head. These effects become more evident when analyzing the strain energy density curves[14] (sometimes called energy dissipation diagrams) of the materials used in the women's lacrosse headgear (Figure 4). Each curve relates the stress in the material to the accumulated energy per unit volume "absorbed" by the material as it deforms and indicates the potential of the material to absorb impact energy at low stress. The curves computed for this study are expressed in terms of up to 3 strain rates. The materials in the headgear follow different stress-strain curves and consequently exhibit different strain energy characteristics at different strain rates (impact severity). The importance of knowing these characteristics when designing safety materials can be seen by Figure 4(d) which shows that when the Cascade Outer White material absorbs 2 MJ/m^3, imparted quasi-statically (0.01/s), it does so at a stress of about 10 MPa. However, if the same energy is imparted at a rate more indicative of an impact (100/s), 18 MPa of stress develops in the material. In the case of a head impact, this stress is either passed on to another material or area in the helmet/headgear or is transmitted as contact stress to the head. Therefore, this rate hardening could be partially responsible for the higher concussion metrics observed in higher velocity impacts (5.0 m/s) compared to lower velocity (2.9 m/s). For the 2.9 m/s impacts, the PLA of the Cascade headgear is only 38% of the PLA of the no-headgear case. However, the ratio increases to 54% at the 5.0 m/s impacts, indicating the decrease of headgear performance, partially due to the rate hardening of the headgear materials. In addition to the negative effect of the rate hardening, the positive effect mentioned above can also be observed in Figures 3(d) and 4(d). When the material absorbs the strain energy density of 2 MJ/m^3, the developed strains, corresponding to the stresses of 10 MPa at 0.01/s and 18 MPa at 100/s are 0.42 and 0.24, respectively. The decrease in strain at the severe impact of 100/s plays a role in preventing the collapse of headgear materials.

Although the interaction of the materials and their ability to dissipate energy as a system was not examined, the apparent strain rate effects of the materials may have helped contribute to the ability of the headgear to mitigate impacts of various severities during the whole headgear impact testing portion of this study. A previous study found a correlation between larger energy required to deform the material and larger reductions in head accelerations during ball impacts.[26]

There were several limitations in this study including the small sample size of both the whole headgear testing and the material testing. In addition, only the outer headgear materials were tested at the highest strain rate (~100/s) since they are the materials that are initially contacted and so most likely to experience high-rate loading. However, measurement of the full range of rate dependent properties of all the protective materials in a safety system, such as a helmet/headgear, would be necessary for a finite element driven design of the system.

The overall goal of this study was to examine the ability of commercially available women's lacrosse headgear to reduce various concussion metrics and characterize the mechanical behavior of the constituent materials at multiple strain rates. Impact testing results showed that both the Cascade and the Hummingbird headgear were able to significantly reduce the PLA, HIC, PRA, PRV, and BrIC in all linear impactor impact speeds, but the reductions were more subtle for the rotational velocity-based metrics (PRV and BrIC) than they were for the other metrics. For ball impacts, both headgear were able to significantly reduce PRV and PRA (and BrIC for the Cascade), but not PLA or HIC (and BrIC for the Hummingbird). In general, these reductions of concussion metrics for the ball impacts were not as large as they were for the linear impactor impacts. Material testing results depicted that the material of both headgear experienced strain rate effects, which is characteristic of polymers used in sports head protection. Although rate effects are important to the ability of headgear to effectively mitigate impacts and optimize player safety across a variety of impact severities, they also have negative effects that must be considered in the design of headgear.

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FIGURES

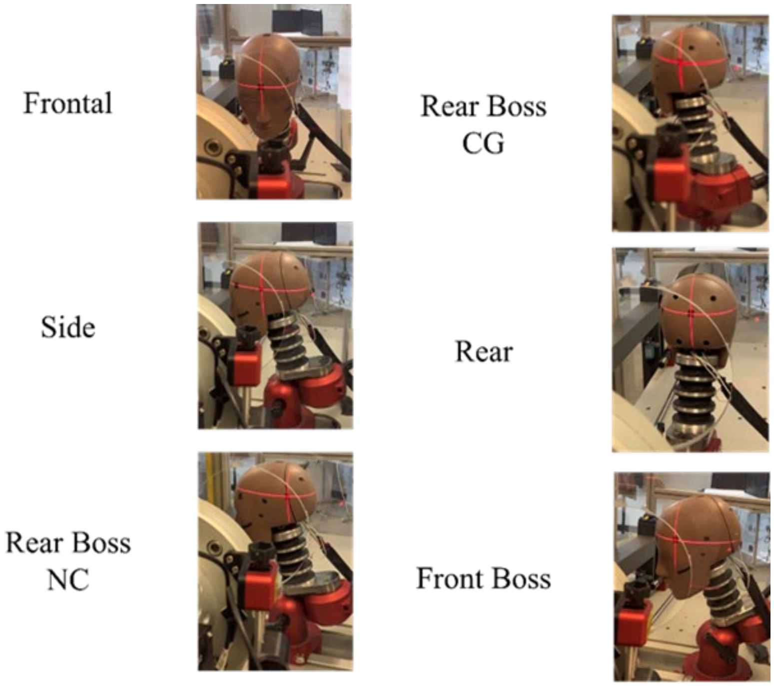

Figure 1. Impact Locations

(a) (b)

Figure 2: Tested materials of the (a) Cascade LX headgear (2021) and the (b) Hummingbird v2 headgear (2021)

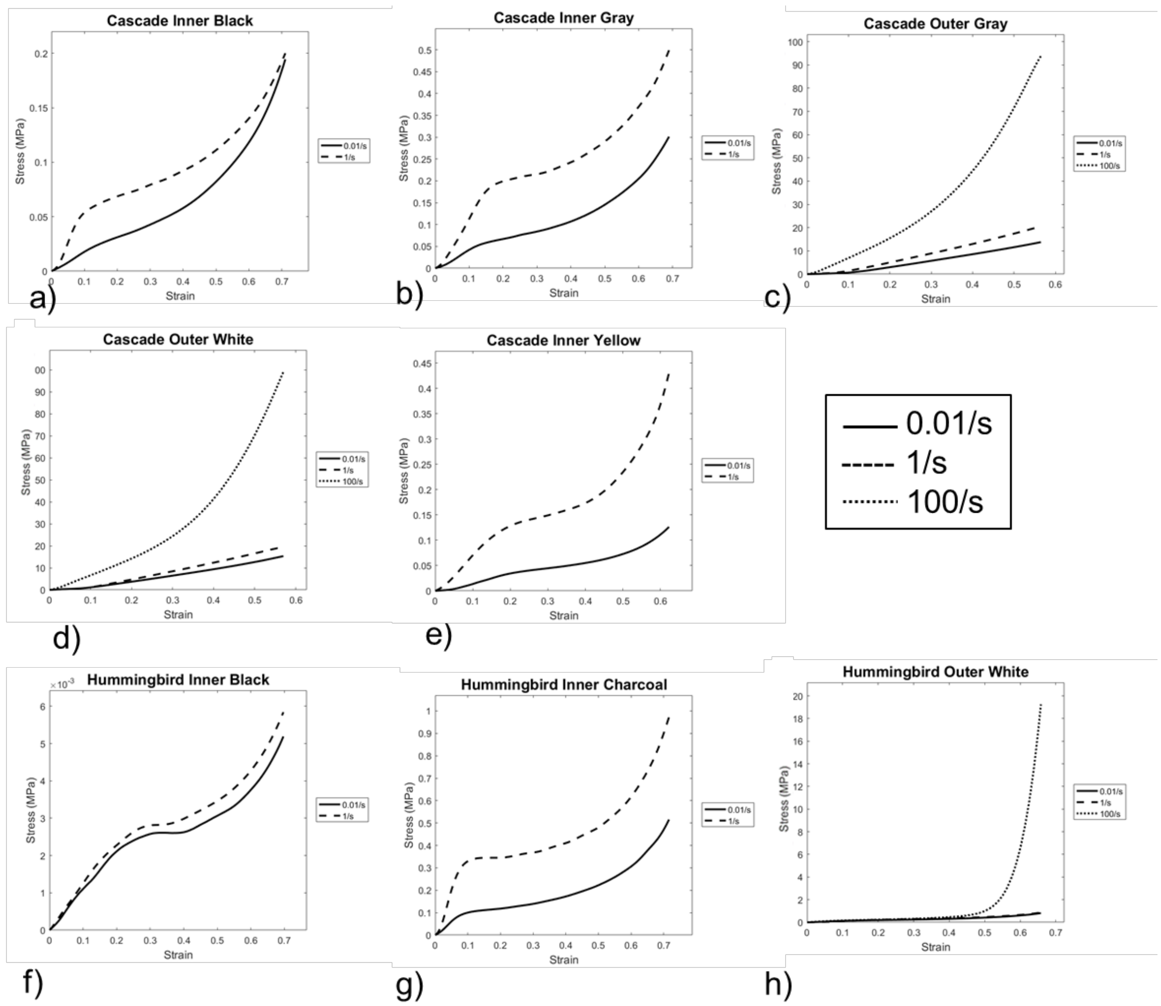

Figure 3: Average stress-strain curves for the Cascade (a) Inner Black, (b) Inner Gray, (c) Outer Gray, (d) Outer White, and (e) Yellow materials and the Hummingbird (f) Inner Charcoal, (g) Inner Black, and (h) Outer White materials. Note, only the outer materials were tested at 100/s strain rate.

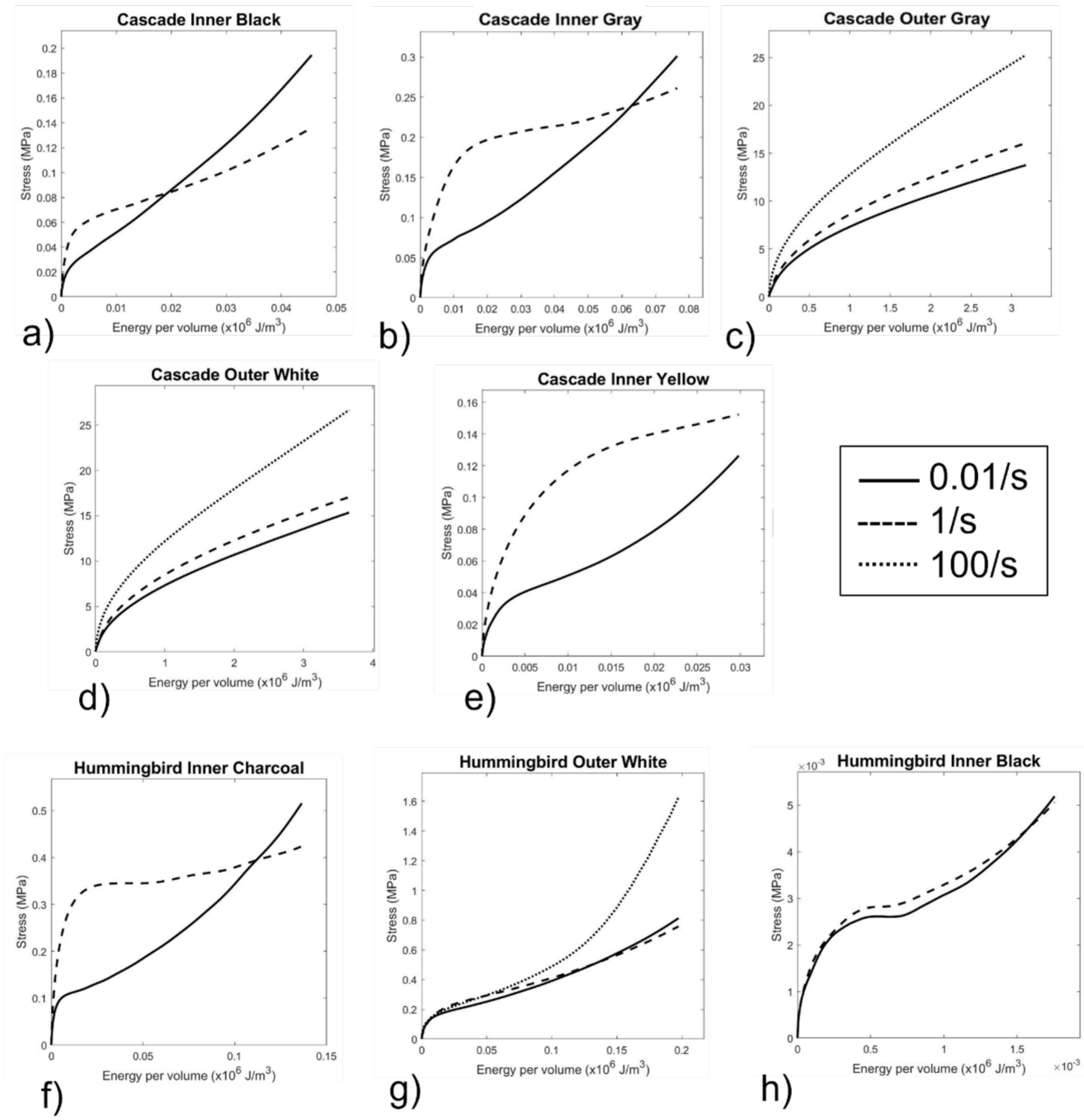

Figure 4: Strain energy density curves for the Cascade (a) Inner Black, (b) Inner Gray, (c) Outer Gray, (d) Outer White, and (e) Yellow materials and the Hummingbird (f) Inner Charcoal, (g) Inner Black, and (h) Outer White materials.