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Original Article

Impact Attenuation Capabilities of Football and Lacrosse Helmets

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ABSTRACT

Although the National Operating Committee on Standards for Athletic Equipment (NOCSAE) standards are similar for football and lacrosse helmets, it remains unknown how helmets for each sport compare on drop tests. Due to the increased concern over head injury in sport and the rapid growth in lacrosse participation, it is useful to compare the performance of various football and lacrosse helmets. Therefore, the goal of this study was to document the impact attenuation properties of football and lacrosse helmets and to identify the relative performance between helmets for the two sports. Six models of football and six models of lacrosse helmets were tested using a drop tower at three prescribed velocities and six locations on the helmets. A repeated measures ANOVA was conducted to determine the effect of sport on Gadd Severity Index (GSI) scores and linear accelerations. The interaction between location and sport was significant at the low ($F_{2.64,89.71}=7.68$, $P<.001$, $\eta^2=.025$), medium ($F_{2.85,96.85}=16.78$, $P<.001$, $\eta^2=.085$), and high ($F_{2.96,100.69}=16.67$, $P<.001$, $\eta^2=.093$) velocities for GSI scores. When comparing peak acceleration results, we found a significant interaction between location and sport for the medium ($F_{3.40,115.616}=5.57$, $P=.001$, $\omega^2=.031$) and high ($F_{3.46,117.50}=6.42$, $P<.001$, $\omega^2=.047$) velocities. Features of football helmet design provide superior protection compared to lacrosse helmets. Further investigation of helmet design features across sports will yield insight into how design features influence helmet performance during laboratory testing.

INTRODUCTION

The National Operating Committee on Standards for Athletic Equipment (NOCSAE) maintains standards to certify the safety of athletic helmets. Helmets that meet certain impact attenuation thresholds are awarded the NOCSAE seal of approval (NOCSAE, 2013a, b). These thresholds were originally developed in 1973 with the aim of preventing life-threatening head injuries, such as subdural hematomas and skull fractures, with considerable success (Bachynski and Goldberg, 2014; Levy et al., 2004). It should be noted, however, that the standard does not specifically address concussions or, of more recent interest, subconcussive impacts. Since the drafting of the original standard, NOCSAE has also written standards for helmets and athletic equipment used in other sports, such as lacrosse (NOCSAE, 2011, 2012).

These standards employ similar testing methods and criteria despite the fact that the equipment and style of play are distinct between football and lacrosse. Both are required to have Gadd Severity Index (GSI) scores under 300 during low velocity drops and under 1200 during medium and high velocity drops (NOCSAE, 2012, 2013a). GSI is generally a good indicator of severe neurotrauma risk (Goldsmith and Monson, 2005), and these thresholds were set to ensure that the helmets would reliably prevent injuries such as skull fracture. In other words, these thresholds are not, nor should they be, sport specific nor are they meant to evaluate protection against a concussion. Additionally, helmets are required not to break, crack, or suffer any structural damage that results in un-restorable alterations to helmet fit during testing (NOCSAE, 2012, 2013a). Currently the National Collegiate Athletic Association (NCAA) and the National Federation of High School Sports (NFHSS) require that helmets used in competition

meet the NOCSAE standard (Hillman, 2005); therefore, manufacturers frequently cite performance on the standard test as evidence of the capabilities of their helmets (Levy et al., 2004). Despite the importance of helmets to overall athlete health during participation in contact sports and the national requirements that helmets be certified, there is little published data characterizing the performance of athletic helmets and the effects of design changes.

Bishop et al (1984) performed an important set of experiments on football helmets that evaluated the relative abilities of suspension, padded-suspension, and padded helmets to mitigate impacts according to a modified NOCSAE test protocol. They found that the padded helmets achieved the best results, but the results were difficult to generalize because the helmets had all been in use for 6-8 years and they only examined a single drop height and a single location on each helmet. More recently, others compared the response of a NOCSAE headform on a Hybrid III neckform when struck by a swinging, helmeted NOCSAE headform (Bartsch et al., 2012). They examined five impact locations using three different impact speeds and found that leather helmets performed as well or better than modern helmets in terms of reducing linear, and angular accelerations. In lacrosse, the 1996-1997 season saw a substantial shift in design as manufacturers dramatically changed helmet designs to adopt a lighter and more streamlined look (Caswell and Deivert, 2002) that improved vision and cervical mobility (Dick et al., 2007). This contemporary aesthetic attenuated impacts better than the previous designs only at the right rear boss drop position, and GSI scores still increased sharply upon repetitive impacts for both designs (Caswell and Deivert, 2002).

In view of the existing research on helmet performance and concussion prevention, the following axioms were adopted for this research. First, all athletic helmets should be able to fulfill the GSI thresholds laid out by NOCSAE, as the thresholds for severe neurotrauma are not sport specific. Second, helmets should maximize the degree to which they mitigate impacts while maintaining their functionality for sport-specific applications. It has been suggested that impact mitigation is related to a reduced risk of concussion (Rowson and Duma, 2011); therefore, it is important to better understand the impact response of helmets used in contact sports. Many factors influence the risk of concussion, and differences in gameplay influence the relative importance of those risk factors. While current biomechanical metrics may not capture all aspects of concussion risk, they are nevertheless valuable in evaluating the biomechanics of head impacts. Many helmet evaluation studies focus on drawing the best conclusions possible from the available metrics (Hutchinson, 2014; Post et al., 2013; Rowson and Duma, 2011; Scher et al., 2008). Accordingly, this paper aims to report typical values for many commonly worn helmets with regards to their performance on a NOCSAE-style drop test with respect to the metrics of GSI and peak linear acceleration. These metrics are relevant to football, lacrosse, or any other contact sport simply due to their descriptive, though certainly not comprehensive, nature. Such basic knowledge is essential to further investigations of helmet performance.

Finally, it is observed that the sport-specific design trends in athletic helmets reflect a combination of historic/aesthetic design inertia and true sport-specific requirement differences (Newman, 2015). However, helmets may be viewed more

generally as devices which mitigate the effect of head impacts on neural health. While some design requirements differ between sports, this fundamental function is universal, and the effectiveness or ineffectiveness of technologies in one lineage of sports helmets is potentially relevant to other helmet types. Such an approach is valuable to engineers and biomechanicians as they evaluate trends in helmet performance and new technologies. It is also relevant to clinicians who are frequently faced with evaluating the claims of constantly changing helmet technology in sport.

Therefore, this paper compares the performance of football and lacrosse helmets with respect to GSI and peak linear acceleration during drop tests. While differences in impact performance between helmets of various sports has long been assumed, this paper investigates these discrepancies and begins to explore why variations exist. Such a cross-sport analysis has not been reported to our knowledge, and similar studies could be conducted to compare with other helmeted contact sports, such as hockey. Through this cross-sport comparison approach, it is hoped that effective design features will be identified and incorporated across sports where possible.

METHODS

Helmets

A total of 36 football and lacrosse helmets of various brands and models were tested (Table 1). All the helmets used for this study were size large or one size fits most for some lacrosse models. In addition, all helmets were new and never used for athletic activity. A power analysis was conducted using a previously published study with similar data (Bowman et al., 2015) which demonstrated three helmets per group were

adequate to detect differences in impact attenuation (α value of 0.05 and $1-\beta=0.80$).

Table 1. Helmets included in the study. All helmets were new and never used in athletic activity.

Sport	Brand	Model	Number
Football	Riddell (Rosemont, Illinois)	Revolution	3
		Speed	3
	Schutt (Litchfield, Illinois)	Ion 4	3
		X1	3
	Xenith (Lowell, Massachusetts)	X2E	3
		Epic	3
Lacrosse	Cascade (Liverpool, New York)	Pro7	3
		CPX	3
		CPX-R	3
		R	3
	Warrior (Warren, Michigan)	Trojan	3
		Venom	3

Instruments

A drop tower was constructed based on NOCSAE standards and used for all drop tests (NOCSAE, 2012) (Figure 1). The tower featured an anvil with a ½-inch polymer pad against which a headform (18.415 cm circumference) fitted with a helmet was impacted. The headform was attached to a carriage that runs along guide wires. The headform is repositionable for six standard impact orientations (Figure 2). A triaxial accelerometer (PCB Piezotronics, Inc. Depew, NY) placed at the headform center of mass measured impact events. An analog filter (Cadex; Quebec, Canada) meeting the 80-channel, class 1000 filter with 1000 Hz corner frequency as required by NOCSAE (NOCSAE, 2013b) preprocessed acceleration signals and also operated a time gate,

which measured impact velocity just prior to impact. Filtered acceleration and velocity data were sampled at 10 kHz by a National Instruments (Austin, TX) data acquisition board, which was controlled by a LabVIEW program (National Instruments). A custom Matlab (Mathworks, Newton, MA) program conducted data post-processing.

Data Collection Procedures

We appropriately fit all helmets to a medium (circumference 18.415 cm) headform and dropped them at the NOCSAE prescribed velocities of 3.46 (low), 4.89 (medium), and 5.47 (high) m/s with 75 seconds +/- 15 seconds between drops.(NOCSAE, 2011, 2012, 2013a, b)

We dropped the helmets in the six orientations prescribed by NOCSAE (NOCSAE, 2012, 2013a, b): Front, Right Front Boss, Top, Right Rear Boss, Rear, and Side. In order to facilitate comparisons between the two sport helmets, we tested all helmets at ambient temperature (range 70.7-71.6°F) on all six locations at the three prescribed speeds. Although we tried to follow the NOCSAE guidelines as much as possible, these tests were not intended to be NOCSAE certification tests, and we did not conduct any high temperature testing, randomized drops, nor the football recommended drop velocity of 4.23 m/s.

We took several safeguards to assure measurement accuracy. First, we calibrated the triaxial accelerometer using a PCB 394C06 uniaxial calibrator for each of the three axes (PCB Piezotronics, Inc. Depew, NY). We completed system checks, measuring velocity, peak acceleration, and GSI of the unhelmeted headform at the beginning, after any change to the headform orientation, after we tested a maximum of four helmets, and at the end of testing. For a system check to pass, the velocity, peak

acceleration, and GSI of the tests before or after a testing segment could differ by no more than 7%. This was done to ensure that the configuration of the testing apparatus had not significantly changed across the drops. A failed system check resulted in discarding of that testing segment between the two tests and recollection of the data.

There was no procedural accounting for any possible location ordering effect because the authors believed that all of the impacts sustained by the helmets during testing were within the expected range of athletic helmets and thus drop order should not affect the outcomes of this study. Velocity ordering was consistent among all samples. Velocity increased from lowest to highest with a fixed time interval between each impact, which is consistent with the NOCSAE standard and was put in place to mitigate differences in viscoelastic recovery

Similar to the NOCSAE standard, a helmet failed if any GSI exceeded 1200, if the low velocity (3.46 m/s) GSI exceeded 300, or if any permanent structural changes, such as cracking or breaking of the suspension system, were observed (NOCSAE, 2012, 2013a, b).

Statistical Analysis

We used a repeated measure ANOVA to determine the effect of helmet sport on GSI scores at each of the 3 prescribed velocities using IBM SPSS Statistics (version 21; IBM Corporation, Armonk, NY). We used drop location as the repeated variable and set the alpha level to .05 *a priori*. When we discovered significant interactions, we used a 1-way ANOVA to determine where significant differences occurred, paired samples t-tests to determine GSI score differences between sports for a given location, and

calculated descriptive statistics including means and 95% confidence intervals (CIs) using SPSS. In addition, we also examined the effect of helmet sport on peak accelerations of the headform at all 3 velocities using the same statistical approach.

RESULTS

We collected data from 36 individual helmets at 3 velocities across 6 impact locations for a total of 648 impacts. Nine lacrosse helmets failed to meet the NOCSAE standard (failure could result from a GSI exceeding 1200 for any velocity drop, a GSI exceeding 300 for the lowest velocity, or damage such as a crack in the helmet construction). Six helmets exceeded the 1200 GSI threshold, one helmet sustained permanent structural damage, and two helmets exceeded the 1200 GSI threshold and suffered structural damage (this was responsibly disclosed to NOCSAE prior to publication (Breedlove et al., 2013)). No football helmets failed to meet the standard.

GSI

A repeated measures ANOVA indicated that the interaction between location and sport was significant at the low ($F_{2.64,89.71}=7.68$, $P<.001$, $\omega^2=.025$), medium ($F_{2.85,96.85}=16.78$, $P<.001$, $\omega^2=.085$), and high ($F_{2.96,100.69}=16.67$, $P<.001$, $\omega^2=.093$) velocities (see Figure 3). Mauchly's test of sphericity was significant at each velocity, indicating that data were heteroskedastic for different impact locations leading us to use the Greenhouse-Geisser correction when interpreting results.

We used a one-way ANOVA to follow-up the significant interactions by comparing the GSI scores of the football and lacrosse helmets across the 6 locations

228 (see Figure 3). We found that the football helmets outperformed the lacrosse helmets
229 at every comparison except at the right rear boss position during the high velocity
230 testing ($P<.003$).

231 Pairwise comparison of GSI scores within each sport and at each velocity
232 indicated significant differences between locations (Table 2). In short, the front and top
233 locations had particularly high GSI scores for the lacrosse helmets.

234

235 **Table 2.** P-values for comparisons of the GSI scores among the different locations during low, medium, and high velocity
 236 testing with football and lacrosse helmets.

Comparison	Football			Lacrosse		
	Low Velocity	Medium Velocity	High Velocity	Low Velocity	Medium Velocity	High Velocity
Front – Front Right Boss	.004	.058	.012	.004	<.001	<.001 ²³⁹
Front – Side	.710	.207	.012	<.001	<.001	<.001 ²⁴⁰
Front – Right Rear Boss	.191	.286	.363	<.001	<.001	<.001 ²⁴¹
Front – Rear	.873	.422	.044	.293	.001	<.001 ²⁴²
Front – Top	.264	.018	.607	<.001	.004	.847 ²⁴³
Right Front Boss – Side	.288	.758	.298	.966	.880	.977 ²⁴⁴
Right Front Boss – Right Rear Boss	.963	.907	.377	.006	<.001	<.001 ²⁴⁵
Right Front Boss – Rear	.266	.720	.499	.336	.568	.095 ²⁴⁶
Right Front Boss – Top	.011	<.001	.003	<.001	<.001	<.001 ²⁴⁷
Side – Right Rear Boss	.003	.595	.049	.003	.065	.014 ²⁴⁸
Side – Rear	.531	.265	.574	.422	.849	.471 ²⁴⁹
Side – Top	.004	<.001	<.001	<.001	<.001	<.001 ²⁵⁰
Right Rear Boss – Rear	.006	.764	.159	.005	.014	.004 ²⁵¹
Right Rear Boss – Top	<.001	<.001	.075	<.001	<.001	<.001 ²⁵²
Rear - Top	.030	<.001	.003	<.001	<.001	<.001 ²⁵³

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Peak Accelerations

We also found significant interactions between location and sport at the medium ($F_{3.40,115.616}=5.57$, $P=.001$, $\omega^2=.031$) and high ($F_{3.46,117.50}=6.42$, $P<.001$, $\omega^2=.047$) velocities (see Figure 4) for peak accelerations. Main effects for sport ($F_{1,34}=140.88$, $P<.001$, $\omega^2=.518$) and location ($F_{2.75,93.41}=4.49$, $P=.007$, $\omega^2=.030$) were also significant during the low velocity drops. Similar to the GSI analyses, Mauchly's test of sphericity was significant at each velocity, leading us to use the Greenhouse-Geisser correction when interpreting results.

We used a one-way ANOVA to follow-up the significant interactions by comparing the peak acceleration scores of the football and lacrosse helmets across the 6 locations (see Figure 4). We found that the football helmets produced lower peak accelerations than the lacrosse helmets at every comparison except at the right rear boss position during the medium ($P<.003$) and high velocity testing ($P<.001$). In addition, we found significant differences in peak accelerations between drop locations within each sport during 5 of the 15 pairwise comparisons at the low velocity ($P<.01$), 9 of 15 at the medium velocity ($P<.015$), and 8 of 15 comparisons at the high velocity ($P<.049$).

DISCUSSION

Lacrosse is currently one of the fastest growing sports in North America (Hinton et al., 2005) with a net gain of 174 programs at the collegiate level between 1988 and

2014 as compared to 67 new football programs (NCAA, 2013). High participation rates-- 32,500 athletes playing intercollegiate football and lacrosse and over 1.1 million at the high school level--warrant an in-depth investigation in helmet design and efficacy. The goal of this study was to evaluate helmets currently in use for both sports in order to determine the relative impact mitigation that each style of helmet provides. We found a dramatic difference in the GSI values and peak accelerations of lacrosse and football helmets tested according to a protocol based on the NOCSAE standard as of 2014. In addition to the lacrosse helmets exhibiting significantly higher values of GSI and peak linear acceleration at all but one of the combinations of test location and impact velocity, half the lacrosse helmets tested failed to meet the NOCSAE criterion. These findings were responsibly disclosed to NOCSAE in November 2013—prior to submission of the manuscript and prior to the 2014 recall of some affected models (Breedlove et al., 2013). Independent testing confirmed the failing performance by the lacrosse helmets when they were subjected to the full range of tests (STX).

Previous research on head impacts in football indicate that, overall, football players sustain more head impacts than lacrosse players (Duma et al., 2005; Higgins and Bowman, 2015; Koehling et al., 2015; Martini et al., 2013; O'Day et al., 2015; Vollavanh et al., 2015). However, the accelerations of the head impacts that do occur in both sports are comparable to the linear accelerations obtained in the low and medium velocity drop tests (Duma et al., 2005; Martini et al., 2013; Vollavanh et al., 2015). Since this study was not meant to evaluate the effectiveness in helmet attenuation over time, we believed it was useful to compare across testing. However, the clinical implications of reduced GSI scores under the NOCSAE threshold of 1200 GSI remain

unknown. It has been found that the average linear accelerations in NCAA division I and division III lacrosse players were near 30 g for both practices and games (Higgins and Bowman, 2015) while average linear accelerations were approximately 28 g for high school (Breedlove et al., 2012) and 22.25 g for collegiate (Mihalik et al., 2007) football players. These relatively low accelerations result in GSI values nowhere near 1200, yet are still associated with subconcussive neurophysiological changes and an increased risk of concussion (Breedlove et al., 2012).

Based on the connections between drop testing results and possible concussive risk (Rowson and Duma, 2011) as well as the evidence that head impact magnitude, but not frequency, is similar between football and lacrosse (Duma et al., 2005; Higgins and Bowman, 2015; Koehling et al., 2015; Martini et al., 2013; O'Day et al., 2015; Vollavanh et al., 2015), there is justification to expect that football and lacrosse helmets need to attenuate impact forces similarly. Consequently, we believe lacrosse helmet modifications to reduce GSI scores are warranted. While a systematic study has not been conducted to identify football helmet design features that improve impact attenuation, there appear to be aspects of football helmet design that could be integrated into lacrosse helmets to improve their performance. Notable differences in design that may account for the performance disparity include pad material and thickness as well as shell material and stiffness (Bower et al., In press; Bowman et al., 2015; Martin et al., 1994).

We believe it is noteworthy that the front and top drop locations had particularly high GSI scores for the lacrosse helmets. Previous work identified a correspondence between front and top impacts and subconcussive changes in neurophysiology

(Breedlove et al., 2012; Talavage et al., 2014), and additional research identified a correlation between concussion severity and strains in the frontal regions of the brain (Ommaya and Hirsch, 1971). Additionally, the majority of concussions were caused by front or top impacts to the helmet in one study of collegiate football (Guskiewicz et al., 2007), and hits to the facemask caused the second most concussions next to the side in a high school lacrosse study (Lincoln et al., 2013). Thus, the front and top locations of the helmet should be manufactured to mitigate impact forces in an effort to reduce clinical sequelae. In addition, perhaps behavioral modification of athletes can help reduce the number and magnitude of impacts to these locations.

Athletic helmets and the associated NOCSAE drop tests were designed to prevent life threatening injuries such as skull fracture, subdural hematomas, and others (Gadd, 1966). All football and lacrosse helmets must meet the NOCSAE standards which hold the same GSI threshold for football and lacrosse helmets (NOCSAE, 2013b). Therefore it was disturbing that we found some lacrosse helmets failed to meet the NOCSAE standard for protective lacrosse helmets (NOCSAE, 2012).

Limitations and Future Directions

It is important to note some limitations to the current study. While we attempted to choose a wide range of helmets currently available, our sample was not comprehensive. As helmet manufacturers continue to strive to make better products, new helmet models should also be studied. Further, we only performed the drop testing protocol on 3 helmets from each brand or style. However, NOCSAE standards require statistical process control of certified helmets; therefore, we believe the variability

among helmets within a particular brand should be minimal. The NOCSAE has also released new standards for testing helmets with a lateral impactor to better reflect the forces that have been shown to cause injury in football players (NOCSAE, 2006). It would be interesting to see how football and lacrosse helmet lateral impactor test results would compare.

CONCLUSIONS

While football helmets generally exhibited GSI values well below the NOCSAE threshold of 1200, lacrosse helmets were consistently close to the threshold and in 8 cases exceeded the threshold, in violation of NOCSAE standards. Features of football helmet design provide superior protection compared to lacrosse helmets. Such a cross-sport analysis is novel, and further investigation of helmet design features across sports will yield insight into how design features influence helmet performance during laboratory testing. NOCSAE testing results are not generally published in the literature; however, this research indicates that all helmets that receive NOCSAE certification are not equal in their ability to attenuate head impacts. Open publication of testing results provides valuable information to decision makers who select helmets for the protection of athletes.

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Sport	Brand	Model	Number
Football	Riddell (Rosemont, Illinois)	Revolution	3
		Speed	3
	Schutt (Litchfield, Illinois)	Ion 4	3
		X1	3
	Xenith (Lowell, Massachusetts)	X2E	3
		Epic	3
Lacrosse	Cascade (Liverpool, New York)	Pro7	3
		CPX	3
		CPX-R	3
		R	3
		Trojan	3
		Venom	3

Table 1. Helmets included in the study. All helmets were new and never used in athletic activity.

Comparison	Football			Lacrosse		
	Low Velocity	Medium Velocity	High Velocity	Low Velocity	Medium Velocity	High Velocity
Front – Front Right Boss	.004	.058	.012	.004	<.001	<.001
Front – Side	.710	.207	.012	<.001	<.001	<.001
Front – Right Rear Boss	.191	.286	.363	<.001	<.001	<.001
Front – Rear	.873	.422	.044	.293	.001	<.001
Front – Top	.264	.018	.607	<.001	.004	.847
Right Front Boss – Side	.288	.758	.298	.966	.880	.977
Right Front Boss – Right Rear Boss	.963	.907	.377	.006	<.001	<.001
Right Front Boss – Rear	.266	.720	.499	.336	.568	.095
Right Front Boss – Top	.011	<.001	.003	<.001	<.001	<.001
Side – Right Rear Boss	.003	.595	.049	.003	.065	.014
Side – Rear	.531	.265	.574	.422	.849	.471
Side – Top	.004	<.001	<.001	<.001	<.001	<.001
Right Rear Boss – Rear	.006	.764	.159	.005	.014	.004
Right Rear Boss – Top	<.001	<.001	.075	<.001	<.001	<.001
Rear - Top	.030	<.001	.003	<.001	<.001	<.001

Table 2. P-values for comparisons of the GSI scores among the different locations during low, medium, and high velocity testing with football and lacrosse helmets.

Figure 1. The impact rig consists of a NOCSAE certified head form (1) with the test helmet (2) fitted and secured according to standard protocols. The head form and helmet are attached to the drop carriage frame (3) which slides smoothly over two 1/8" steel cables (7). A motor (8) moves the drop carriage up to the correct height so that it can achieve the pre-set impact velocity following the drop. The head form/helmet strikes a 1/2" MEP test pad secured to an anvil (5) and an anvil base plate (6) for stability.

Figure 2. Front and rear views of typical football and lacrosse helmets adapted from US Patent publications 20120291183, 20080163410, 20120297525, and 20130180034. Each helmet was tested in six locations, (1) front, (2) front boss, (3) side, (4) rear boss, (5) rear, and (6) top as indicated.

Figure 3. GSI scores of football and lacrosse helmets at the 6 drop locations for low, medium, and high velocity drops. * indicates $p < 0.05$.

Figure 4. Peak accelerations of football and lacrosse helmets at the 6 drop locations for low, medium, and high velocity drops. * indicates $p < 0.05$.