Biomechanical performance of leather and modern football helmets

Technical note

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With the increased national concern about concussions in football, recent research has focused on evaluating the impact performance of modern football helmets. Specifically, this technical note offers a biomechanical analysis of classic leather helmets compared with modern helmets. Furthermore, modern helmets were examined to illustrate the performance differences between the better- and worse-performing ones. A total of 1224 drop tests were performed from a range of drop heights and impact locations on 11 different helmet types (10 modern and 1 leather helmet model). The resulting head acceleration was used to assess the risk of concussion for each drop test. The results of this analysis demonstrate that modern helmets are significantly and substantially superior to leather helmets in all impact scenarios, and that notable differences exist among modern helmets.

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KEY WORDS • concussion • helmet • football • head acceleration •
Summation of Tests for the Analysis of Risk (STAR) evaluation system • injury risk

SPORTS-RELATED concussions are a growing public health concern. It is estimated that as many as 3.8 million of these injuries occur in the US annually.⁹ Furthermore, recent research has raised the possibility of links between repetitive concussions and neurodegenerative processes in some athletes.^{6,13,14} These factors, combined with the overwhelming popularity of professional sports in the US, have thrust the issue of sports-related concussions into the national spotlight.

With these concerns in mind, recent research has focused on evaluating and comparing helmet impact performance. In 2003, Pellman et al.¹⁵ reconstructed concussive impacts in the NFL from game film by using crash test dummies. Through analysis of these data, they later went on to develop test protocols in which a linear impactor was used to address helmet performance in reducing concussion risk in football. They concluded that superior impact performance was associated with helmets that had thicker padding and fuller coverage.¹⁶ Using similar test

protocols, researchers investigated how helmet performance had improved between 1970 and 2010.^{22,23} These studies also concluded that the additional size and padding of the best modern helmets provide superior impact performance to that of older helmets,²² but also found that not all modern helmets provided improved impact performance over helmets from the 1990s.²³

In 2012, Bartsch et al.¹ conducted a study in which the impact responses of modern football helmets were compared with those of vintage leather football helmets. The authors concluded that modern helmets did not always provide impact performance that was superior to leather football helmets, suggesting that modern helmets are overly optimized toward high-severity impacts. In response, the NOCSAE Scientific Advisory Committee published a letter to the editor criticizing the validity of the study.² The purpose of this technical note is to provide data that clarify the limitations of the study by Bartsch et al. by offering biomechanical analysis based on helmet testing methodologies that compare relative helmet performance.¹⁷

This article contains some figures that are displayed in color online but in black-and-white in the print edition.

Abbreviations used in this paper: NFL = National Football League; NOCSAE = National Operating Committee on Standards for Athletic Equipment; STAR = Summation of Tests for the Analysis of Risk.

Methods

Drop Tests

Modern and leather football helmet evaluations were performed using previously established methods, which consist of a series of 20 drop tests (4 impact locations $\times$ 5 drop heights) that represent a football player's head impact exposure.¹⁷ Each configuration was tested using a NOCSAE-style drop test system that has been shown to generate head form impact responses similar to the head impact response measured directly in football players wearing instrumented helmets.^{11,12,17} Figure 1 displays the NOCSAE head form oriented in the 4 impact locations tested (front, side, rear, and top). The 5 drop heights tested were 12, 24, 36, 48, and 60 in. For each drop test, linear acceleration of the head form was recorded using a triaxial accelerometer.

Leather Football Helmet Testing

Two vintage Hutch H-18 leather football helmets were tested (Fig. 2). These leather helmets are the same model as one of the leather helmets tested by Bartsch et al.¹ in 2012. There were 12 drop tests performed on each leather helmet, for a total of 24 tests. Drop tests were conducted for each impact location for drop heights of 12, 24, and 36 in. Drop tests were not performed for the 48- and 60-in drop heights because the accelerations associated with the 36-in drop tests were approaching values known to potentially damage the NOCSAE head form.

Modern Helmet Analysis

A total of 10 modern football helmets have been tested previously, and the results are publicly available as part of the 2011 Virginia Tech Helmet Ratings (Table 1) (<http://www.sbes.vt.edu/pdf/STARRankings2011.pdf>).¹⁷ A total of 1200 drop tests were performed on the 10 modern helmets (3 of each model, 2 trials, 20 drops each), and STAR¹⁷ values for each helmet model were determined and then statistically compared between models. Helmets were rated by the number of stars and grouped based on statistical significance ($p < 0.05$). For the purposes of comparing leather helmets to modern helmets, the 10 helmets previously tested were split into 2 groups:

helmets that were rated with 4 or 5 stars, and helmets that were rated with ≤ 3 stars. The average peak acceleration for each drop test configuration was determined for each modern helmet group. Average peak accelerations for each group (leather helmet; 5- or 4-star modern helmet; and ≤ 3 -star modern helmet) were statistically compared by drop height using the Student t-test and a significance level of $p < 0.05$.

Results

For the leather helmets, the peak resultant linear accelerations ranged from 76g to 153g for the 12-in drop height, and from 245g to 297g for the 36-in drop height (Table 2). Drop tests were not performed at drop heights > 36 in due to the risk of damaging the NOCSAE head form.

The leather helmet group had a substantially greater average peak acceleration associated with each drop height compared with modern helmets (Fig. 3). At the 12-in drop height, modern helmets provided a 59%–63% reduction in peak head acceleration when compared with leather helmets. At the 36-in drop height, modern helmets provided a 67%–73% reduction in peak head acceleration when compared with leather helmets. The leather helmets were not tested at the 48-in and 60-in drop heights. The reduction in peak head acceleration offered by the 5- or 4-star modern helmet group compared with the ≤ 3 -star modern helmet group increased with increasing drop height: 11% reduction at the 12-in drop height, 18% reduction at the 36-in drop height, and 22% reduction at the 60-in drop height. All comparisons were statistically significant ($p < 0.001$).

Discussion

In this analysis, the comparative performance of football helmets was evaluated using drop tests on a near-rigid impact surface. We tested the leather and modern helmets at similar severities to those used by Bartsch et al.,¹ as is shown by the fact that the modern helmets produced average peak accelerations ranging from 36g to 87g for the drop heights from which the leather helmets were

FIG. 1. Depictions of 4 impact locations being evaluated in the STAR evaluation system (front [A], side [B], rear [C], and top [D]). The NOCSAE head form locks into each configuration on an adjustable mount, ensuring precise adjustment of impact location for each test.

Fig. 2. Photograph of the Hutch H-18 leather football helmets (circa 1930s) that were tested using the protocol established by the STAR evaluation system.

tested. In every impact configuration, leather helmets resulted in significantly and substantially higher head accelerations than modern helmets. The acceleration values resulting from the leather helmet tests were within the range of acceleration values known to be associated with concussions for all impact configurations.¹⁷ Using previously developed tools to estimate risk of concussion from linear acceleration, modern helmets reduced the risk of concussion by 45% for the 24-in drop height ($p < 0.0001$) and by 96% for the 36-in drop height ($p < 0.0001$). This analysis shows that all modern helmets are substantially superior to the leather helmet in every impact configuration tested.

In contrast, Bartsch et al.¹ reported that head injury risks while wearing vintage leather helmets were comparable to or better than injury risks while wearing modern helmets for near- and subconcussive head impacts. The authors suggested that this was a result of modern helmets being overly optimized toward high-severity impacts. To evaluate helmets, they impacted a stationary, helmeted, NOCSAE head form with a swinging NOCSAE head form fitted with a Riddell VSR4 helmet. They equipped the stationary head form with 11 different modern helmets and 2 different leather helmets, performed the tests, and com-

TABLE 1: Star ratings for the 10 modern football helmets tested*

Helmet Model	Star Rating
Riddell Revolution Speed	5
Schutt ION 4D	4
Schutt DNA Pro+	4
Xenith X1	4
Riddell Revolution	4
Riddell Revolution IQ	4
Schutt Air XP	3
Schutt Air Advantage	2
Riddell VSR4	1
Adams A2000 Pro Elite	0

* Star rating groups are differentiated by statistical significance ($p < 0.05$). See <http://www.sbes.vt.edu/pdf/STARRankings2011.pdf> for details.

TABLE 2: Peak resultant linear acceleration for each drop test conducted on the 2 leather football helmets*

Impact Location	Drop Height	Peak Acceleration (g)	
		1st Helmet	2nd Helmet
front	12 in	99	102
front	24 in	181	179
front	36 in	245	248
side	12 in	82	86
side	24 in	177	191
side	36 in	252	278
rear	12 in	98	90
rear	24 in	210	177
rear	36 in	296	259
top	12 in	153	76
top	24 in	224	172
top	36 in	297	250

* Both helmets were model Hutch H-18.

pared the results. This testing methodology should not be used to evaluate comparative helmet impact performance because the impactor, a swinging NOCSAE head form, adds compliance to the system due to the Riddell VSR4 helmet that has been placed on the head form. When the leather helmets were impacted, the padding in the VSR4 helmet compressed and modulated the impact energy transfer, because the VSR4 padding is much more compliant than the leather helmet. This resulted in a head form response for the leather helmets that was not representative of the ability of leather helmets to reduce head acceleration, but rather the ability of the impactor to modulate energy transfer to the struck head form. In addition, the impact speed for those tests was very low. A more appropriate conclusion in the study of Bartsch et al. would be that leather helmets performed similarly to modern helmets when struck by a Riddell VSR4 helmet at lower impact severities.

Furthermore, a compliant impactor can mask the differences between modern helmets, because the impactor offers additional padding that makes the overall system more compliant and may prevent a bottoming-out effect in the helmet intended to be evaluated. Bartsch et al.¹ only tested low energies that would not fully compress the VSR4 padding. If higher energies were tested, more notable differences would probably have been found between the modern helmet types.

In other studies, Viano and colleagues^{22,23} investigated how helmet performance has improved between 1970 and 2010, and reported that not all modern helmets provided improved impact performance over helmets from the 1990s. To evaluate helmets, they used a linear impactor to strike a stationary, helmeted, Hybrid III head. The impactor face featured 35-mm vinyl nitrile foam covered by a hard plastic cap to simulate the shell and liner worn by a helmeted striking player. This impactor was originally designed to model helmet-to-helmet impacts in the NFL, and is capable of modeling these impacts.^{15,16} However, the padded impactor face adds compliance and has the potential to mask differences between helmets. The

FIG. 3. Bar graph showing that the leather helmets had a substantially greater peak acceleration associated with each drop height compared with modern helmets. Each bar represents the averaged peak acceleration for each drop height. The difference between 5- or 4-star and $\leq$ 3-star modern helmets increased with increased drop height. All comparisons were statistically significant ($p < 0.001$). Asterisks denote that drop tests were not performed at drop heights > 36 in for the leather helmets due to the risk of damaging the NOCSAE head form. Peak accelerations for these tests would have resulted in greater accelerations than the 36-in drop height tests.

effect of the padded impactor was less prominent in Viano and Halstead²² than in Bartsch et al.,¹ because Viano and Halstead tested at much higher impact energies and the helmets they tested had substantially more padding than the leather helmets tested by Bartsch et al.

It should be noted that only linear acceleration was used to estimate the risk of concussion in this analysis. Injury risk curves such as the one used in this study relate mechanical stimuli to injury probability, and are commonly used to evaluate product safety.^{3–5} Although linear acceleration highly correlates to concussive events, other biomechanical parameters have also been linked to injury.^{7,8,10,24} Most notably, rotational acceleration has been associated with injury, but rotational acceleration is highly correlated to linear acceleration for impacts in football.¹⁹ Therefore, a helmet that lowers linear acceleration will also lower rotational acceleration for the vast majority of helmet impacts.

Conclusions

The results of this analysis demonstrate that modern helmets are significantly superior to leather helmets in all impact scenarios, and that notable differences exist among modern helmets. Comparative engineering analyses provide safety equipment manufacturers with design guidelines for improvements in their equipment; however, in the context of the findings one must consider the mechanical systems used to evaluate the equipment.^{19–21} Football helmet performance has improved over time,

and as we learn more about how to assess helmet safety, further advances in safety are anticipated.

Disclosure

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Author contributions to the study and manuscript preparation include the following. Conception and design: Rowson, Duma. Acquisition of data: Rowson, Daniel. Analysis and interpretation of data: all authors. Drafting the article: Rowson. Critically revising the article: Rowson, Duma. Reviewed submitted version of manuscript: Daniel. Statistical analysis: Rowson. Administrative/technical/material support: Duma. Study supervision: Duma.

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