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Concussions in Sports

Laboratory Evaluation of Shell Add-On Products for American Football Helmets for Professional Linemen

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Abstract—The Guardian Cap NXT (GC NXT) and the ProTech Helmet Cap (ProTech) are commercially available aftermarket products designed to augment the energy attenuation characteristics of American football helmets. The ability of these helmet shell add-on products to mitigate the severity of impacts typically experienced by professional offensive and defensive linemen was evaluated for seven helmet models using two test series. In linear impactor tests, the GC NXT reduced head impact severity as measured by the head acceleration response metric (HARM) by 9% relative to the helmets only, while the ProTech reduced HARM by 5%. While both products significantly improved the performance of the football helmets tested overall, effects varied by impact condition and helmet model with the add-ons worsening helmet performance in some conditions. The GC NXT had a strong effect size (Cohen's $d = 0.8$) whereas the ProTech had a medium effect (Cohen's $d = 0.5$). A second study investigated add-on performance for helmet-to-helmet impacts with eccentric impact vectors and resulted in a mixture of increased and decreased HARM when either add-on was placed on one or both helmets. Estimated risk for serious neck injury with add-ons and without differed by less than 4% for these eccentric impacts.

Keywords—Biomechanics, Concussion, American football, Head injury.

INTRODUCTION

First developed in the 1890s, football helmets have evolved significantly over time in their design and performance.[22] Early football helmets were made of leather and provided only minimal padding. By the 1950s, helmet shells were plastic and incorporated a faceguard. The first safety standards for football helmets were established by the National Operating Committee on Standards for Athletic Equipment (NOCSAE) in 1973. By 1979, fatal head injuries in junior and high school football were down 51%; skull fractures were down 65%; and concussions were down 35%.[24] In the 2000s, helmet designs began to focus on providing protection not only from serious head injuries such as skull fractures, but also from concussions.[8] Subsequent research has shown that helmets designed in the 2000s and 2010s performed better than earlier helmet designs in terms of both laboratory testing[30] and on-field concussion rates.[27]

Since the 1980s, most football helmet designs have utilized the same basic architecture: a hard polycarbonate outer shell with energy-absorbing interior padding, a faceguard, and a chin strap.[22] Helmet size and weight increased substantially from the 1970s to the 1990s,[30] suggesting a strategy of increasing interior padding thickness to improve performance. Since the 1990s, the average size and weight of football helmets has been relatively unchanged,[14,30] suggesting that performance improvements over the past two decades can be attributed largely to efforts optimizing the energy absorbing capabilities of the interior padding within the established shell geometry.

Recently, in effort to continue to improve performance, several aftermarket products designed as energy-absorbing add-ons to football helmets have gained popularity at the youth and collegiate levels of play. These helmet add-ons include exterior coverings

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that attach to the helmet shell, such as the Guardian Cap NXT (Guardian Sports, Peachtree Corners, GA, USA) and ProTech (Defend Your Head, Chester Springs, PA, USA) helmet covers. The principle behind both designs is that adding soft padding to the outside of the hard helmet shell effectively increases the thickness of the padding system (interior + exterior), resulting in more thickness over which to absorb the applied force and thereby to lower head accelerations. While increased thickness of the helmet and add-on should theoretically reduce average decelerations, the add-on devices are often required to work with multiple helmets and may not be optimized for use in the same way that the helmet shell and liner were designed. Breedlove *et al*. conducted NOCSAE drop testing on three different helmet models with and without a Guardian Cap and reported that the Guardian Cap failed to significantly improve the helmets' ability to mitigate impact forces at most locations.[5] However, other unpublished testing[1,10] has suggested that the Guardian Cap may be effective at reducing head accelerations in football impacts. As the question of add-on performance remains uncertain, with new add-ons and new helmets entering the marketplace, the utility of these devices in reducing head impact severity has not been fully evaluated.

The purpose of the current study was to assess the ability of two contemporary helmet add-on products to mitigate impact severity in helmet-to-helmet collisions that are typically experienced by American professional football linemen, who typically experience more frequent helmet impacts per game.[9] In the first battery of tests, a padded impactor struck a helmeted Hybrid III dummy head that was mounted via the Hybrid III neck to a sliding track.[26] This test apparatus was chosen for two reasons. First, unlike NOCSAE drop testing, it allowed the head to rotate, which is important because rotational motions of the head are thought to be an important mechanism of concussion.[16] Second, because we have previously conducted similar testing on a wide variety of helmets, we were able to quantify the effect of the helmet add-ons in terms of the overall variability in performance observed among currently popular football helmets.[3] In the second battery of tests, experiments were conducted with two helmeted headforms to investigate interactions in eccentric helmet-to-helmet impacts. These tests were used to investigate the potential for the soft add-on coverings to deform in a way that could potentially grab the helmet in an impact whereas the bare helmet shells might otherwise slide and glance off each other. Cadaver drop testing has confirmed that when the head hits a padded surface, indentation of the padded surface can restrict head motion tangential to the surface thus increasing the risk of cervical spine injury compared to an equivalent impact with a rigid surface.[25] Concern over potential for these add-ons to increase the risk of neck injury coupled with uncertainty regarding how these products affect helmet certification and warranty have been the principal reasons for their delayed usage at different levels of play.

MATERIALS AND METHODS

A two-part laboratory study was designed to simulate helmet-to-helmet impacts with and without helmet shell add-ons for impact conditions characteristic of those experienced by professional American football players. Given the high exposure of offensive and defensive linemen to helmet impacts and concussions, specific focus was placed on replicating the on-field conditions for these positions.[9,20]

For the first test series, an adjustable target table and pneumatic ram (Biokinetics and Associates Ltd., Ottawa, Canada) were used to impact American football helmets using published test methods (Fig. 1) intended to represent impacts sustained by NFL players during games from 2015 to 2019.[3,4] A 50th percentile male Hybrid III dummy head and neck assembly were attached to the sliding target table and instrumented with an upper neck load cell (N6ALB11A, MG Sensor, Rheinmuenster, Germany) and a head sensor array consisting of a 6DX Pro and six collinear accelerometers (6DX-Pro-2000-18000, Diversified Technical Systems, Seal Beach, CA; Endevco 7264B-2000, Meggitt, Irvine, CA). The ram was outfitted with a six axis load cell (N6ACC11A, MG Sensor, Rheinmuenster, Germany) and end cap comprised of a vinyl nitrile (VN600, DerTex, Inc., Saco, Maine) compliant element with a spherical nylon face.[4]

Impact locations and velocities associated with concussion-causing helmet impacts for offensive and defensive linemen were characterized using a combination of video review[20,21] and Next Generation Stats (NGS, Zebra Technologies, Lincolnshire, IL) player position data (Fig. 2). Additional review of video footage from 16 NFL games was performed to catalog helmet impact exposures for linemen. Impact locations from concussive and exposure impacts were classified into nine areas using the definitions established by Lessley *et al*.[21] For most impacts identified by video review, player position data collected through radio frequency identification (RFID) tracking within the NFL NGS system was used to calculate the resultant impact velocity in the horizontal plane using the same process described by Bailey *et al*.[3] Six test conditions consisting of the full combination of two speeds (4 and 7.4 m s^{-1} to approximate average impact speeds of

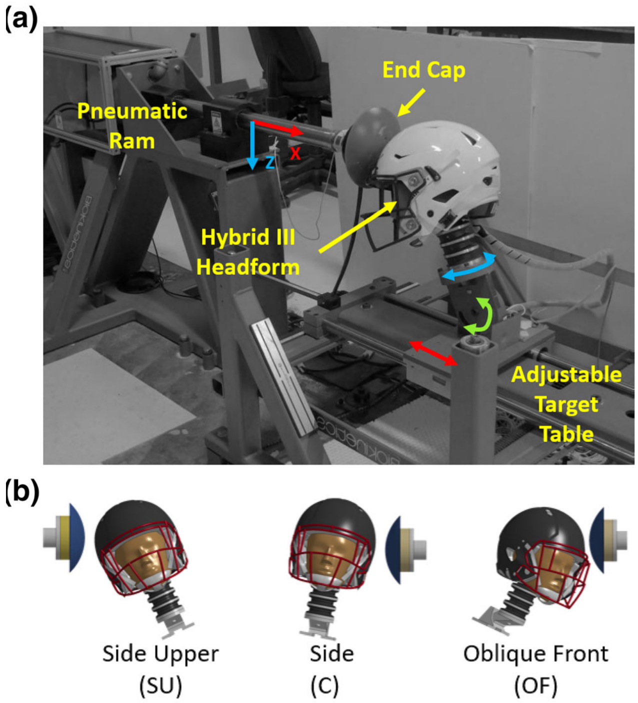

FIGURE 1. (a) Pneumatic ram and adjustable target table test fixture used for testing impact performance of helmet add-ons. (b) Impact locations for pneumatic ram test conditions.

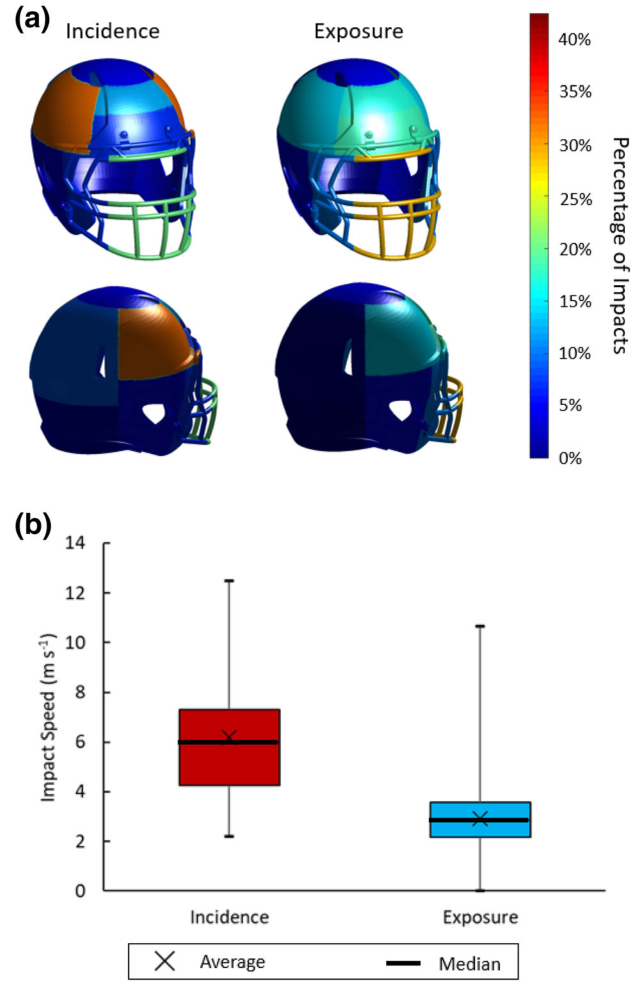

FIGURE 2. (a) Impact locations and (b) impact speeds for offensive and defensive linemen. This data include game concussions for linemen (incidence) for the 2015–2019 NFL seasons and exposure impacts analyzed through a video review of all helmet-to-helmet and helmet-to-body impacts in 16 NFL games.[3,21] Boxes indicate the interquartile range and whiskers indicate the maximum and minimum values for each data set. Note that impact speeds do not account for the vertical component of speed since NGS data is limited to horizontal position tracking.

exposure and concussive impacts, respectively, for linemen), and three common helmet shell impact locations (side, oblique front, and side upper) were derived from these data sets (Fig. 1b). For determining the test condition speeds, approximately 1 m s^{-1} was added to the NGS impact speeds to account for the missing vertical component of velocity since NGS data is limited to two-dimensional position tracking.[3] Note that the specific impact locations were based on a pre-existing test methodology[3] and were not adjusted to specifically engage areas of padding on the add-ons.

The test matrix for the pneumatic ram tests included six common helmets from three manufacturers that encompassed a variety of designs of shells and liners for energy attenuation (Table 1). Models were selected based on frequency of usage by NFL linemen. A review of commercial add-on products identified helmet shell add-on models from Guardian Innovations (Guardian Cap NXT) and Defend Your Head (ProTech Helmet Cap) as products that can be easily attached to and removed from the helmet without adhesive (Fig. 3a). The Defend Your Head ProTech Helmet Cap (ProTech) is customized for individual helmet sizes and shell styles and was only tested on the three Riddell models and the Schutt Vengeance Z10 LTD due to availability of designs (Fig. 3b). Guardian Cap NXT (GC NXT), a new Guardian Cap model modified for use in the NFL impact environment, can be adjusted to fit different helmet models and sizes and was tested with each of the six helmet models. Each helmet and add-on combination was subjected to two impacts at each speed and location combination. The same add-on and helmet were used for repeated impacts.

A second test series was conducted with a subset of helmet models to investigate interactions in eccentric helmet-to-helmet impacts when add-on devices were attached to one or both helmets. Two helmets, the Riddell SpeedFlex Precision and Schutt Vengeance Z10 LTD, were selected based on their compatibility with both add-on products and the desire to include

TABLE 1. Helmet and add-on product sizes and masses.

Helmet model (model number)	Size	Mass (g)
Riddell Speed Classic Icon (R41198)	Large	1753
Riddell SpeedFlex Precision (R41156)	Custom	2164
Riddell SpeedFlex Precision Diamond (R41106)	Custom	2200
Schutt Vengeance Z10 LTD (204200)	Large	1543
Schutt F7 UR1 (208300)*	Small/medium	2145
VICIS Zero1 (2018)*	B	2140
Add-on products	**Size**	**Mass (g)**
Guardian Cap NXT	One size	369 (4)
Defend your head ProTech helmet cap		
ProTech for Riddell Speed Classic	Large	564 (1)
ProTech for Riddell Flex	Large	603 (3)
ProTech for Schutt Vengeance	Small/medium	540 (4)

Note that helmet masses include eye and oral protection style faceguard mass and averages and standard deviations are provided for the add-ons.
*These helmets were only tested with Guardian Cap NXT since no ProTech models were compatible.

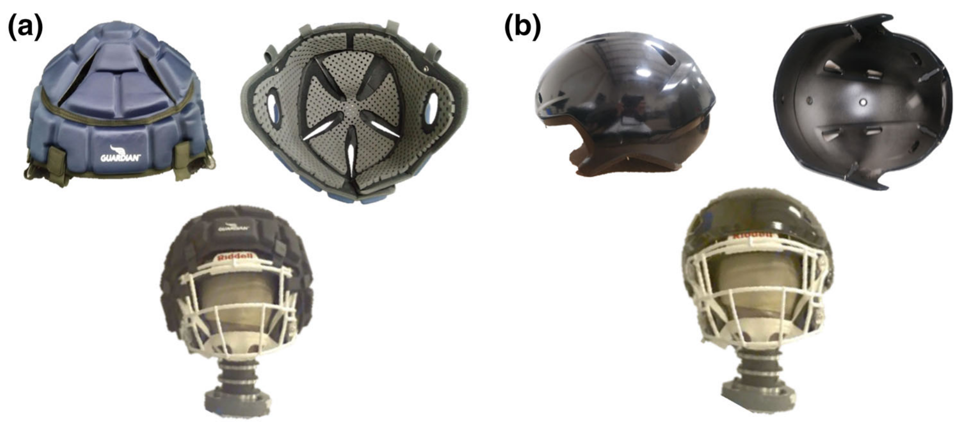

FIGURE 3. (a) Guardian Cap NXT and (b) ProTech helmet shell add-ons tested in this study. Both add-ons are pictured on a Riddell SpeedFlex Precision helmet.

helmets with different padding styles and fitting schemes (i.e. custom fit vs. generic fit). For this study, a Hybrid III 50th male head was rigidly mounted to an electric belt-driven sled[13] (henceforth *ram*), and propelled into a Hybrid III head, neck, and torso mounted to an adjustable stand (henceforth *dummy*) (Fig. 4). In total, the ram mass including the Hybrid III headform was 61.7 kg. The total mass of the dummy head-neck-torso assembly and adjustable stand was 29.1 kg. Both the ram and dummy contained a 6DX Pro (DTS, Seal Beach, CA, USA) located at the head's center of gravity (CG) and an upper neck load cell. High speed video footage of each test was collected at 2 kHz (Photron AX50, Photron USA, Inc., San Diego, CA, USA).

Two test conditions were studied. For both, the neck attached to the ram was rotated 65° upward from vertical so that the front of the helmet and head assembly attached to the ram was propelled into the dummy at 4 m s^{-1}. The dummy was initially centered facing the ram, then tilted forward 15° (α rotation). The dummy was then twisted about its base (β rotation) either 35° or 45°, depending on the test condition. The dummy positions were selected to minimize faceguard interaction between the ram and dummy helmets. The front-oblique test condition (Fig. 4b) was intended to represent a centric impact (head CG path eccentricity = 65 mm) and the rear eccentric test condition (Fig. 4c) was intended as a more eccentric impact (head CG path eccentricity = 101 mm). Both impacts were more eccentric than the three pneumatic ram impacts from the first test series, for which the head CG path eccentricity ranged from 1 to 12 mm. The position of the dummy head CG relative to the

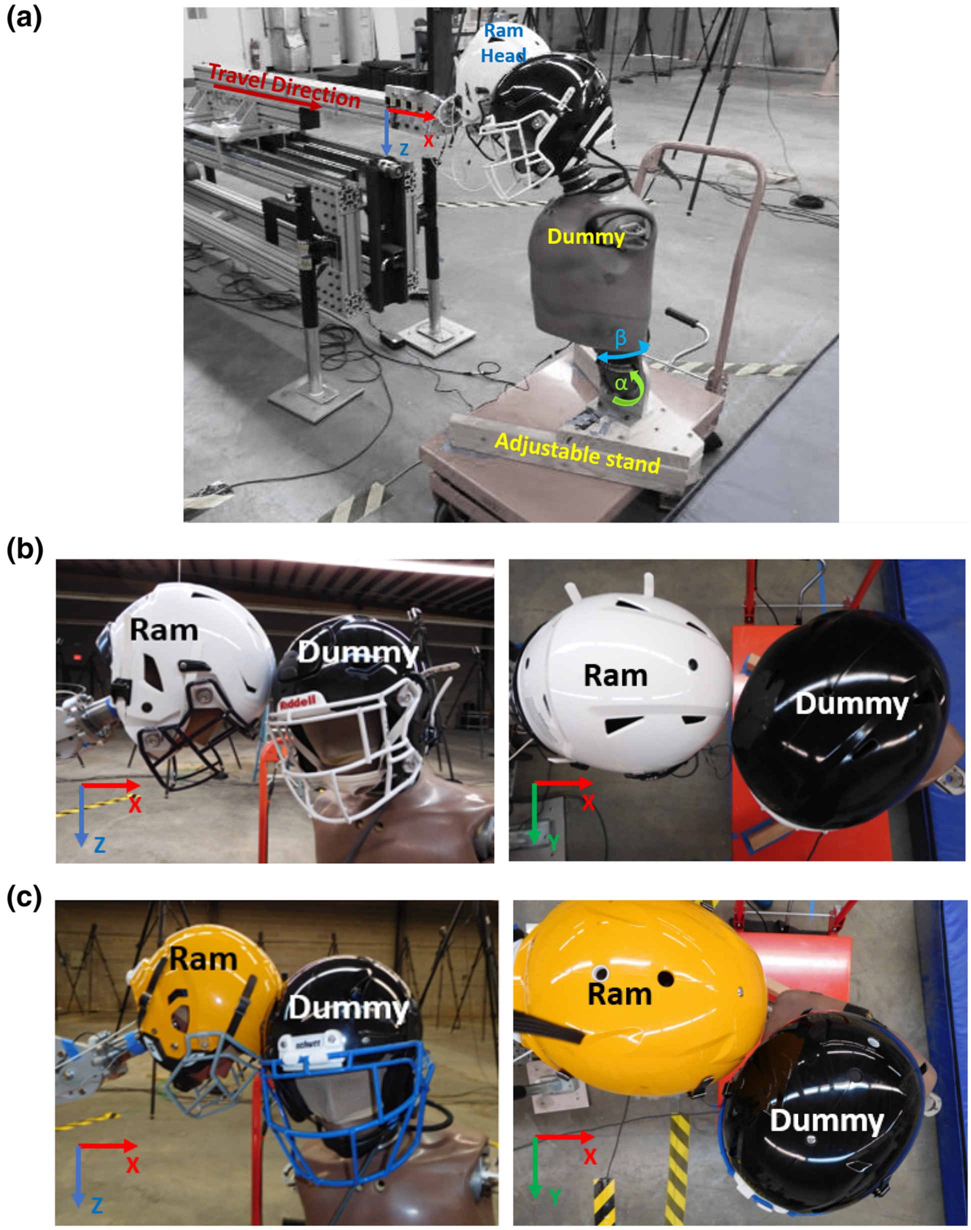

FIGURE 4. (a) Electric belt-driven sled with rigidly-mounted Hybrid III head (ram) and Hybrid III head-neck-torso assembly (dummy) mounted to an adjustable stand. 9b) Side and overhead views of the centric front to front-oblique test condition. c Side and overhead views of the eccentric front to rear side test condition.

TABLE 2. Dummy position information for helmet-to-helmet testing.

	Torso base rotation+		Dummy head CG position relative to ram CG*	
	α (°)	β (°)	Y (mm)	Z (mm)
Front oblique	15	45	46	46
Rear eccentric	15	35	101	− 2

+Rotations are relative to the local torso coordinate system.
*Positions are in the global lab coordinate system.

head CG attached to the ram was measured using a Romer Absolute Arm-6Axis (Exact Metrology, Cincinnati, OH, USA) and recorded for each of the two conditions (Table 2). Laser levels were used to the ensure repeatable positioning of the dummy for repeated tests. Three tests were performed for each condition consisting of two helmet models and two impact locations, with each add-on placed on one, both, or neither of the two helmets (Table 3).

Data Analysis

Accelerometer and angular rate sensor data were sampled at 10 kHz and filtered to channel frequency class (CFC) 180 before calculating angular accelerations.[28] Six degree of freedom head kinematics were transformed to the head CG before calculating head injury criterion (HIC), diffuse axonal multi-axis general evaluation (DAMAGE), and head acceleration response metric (HARM).[3,15,29] Peak neck forces and moments were tabulated and used to calculate the N_{ij} neck injury criteria[12] after filtering to CFC 1000 and CFC 600, respectively, and transforming moments to the location of the occipital condyle joint. Published injury risk functions for N_{ij} were used to estimate the risk of serious neck injury associated with each test [Abbreviated Injury Scale (AIS) score of 3 or greater].[2,12]

The percentage reduction in HARM relative to the helmet with no add-on was calculated for each add-on and helmet combination. Analysis of Variance (ANOVA) was used to determine the effect of the add-ons to a significance level of 0.05:

$$\%\,Reduction = \frac{X_{baseline} - X_{addon}}{X_{baseline}}, \quad (1)$$

where X is the parameter being analyzed, and the baseline condition consists of the result for the helmet tested without the add-on.

As an overall assessment of the performance of helmet-add-on combinations, an Aggregate Score was calculated by weighting and summing the HARM associated with each test condition (2):

$$Aggregate\ Score = \sum_{i=1}^{6} \frac{W_i}{(HARM_{avg})_i} (HARM)_i, \quad (2)$$

where W_i is the test condition weight (Table 4), $HARM_{avg}$ is the HARM averaged for all bare helmets tested, and i is the test condition index. Two sets of weights were used: one based on the frequency of impacts to NFL linemen at each test condition (exposure weight), and one based on the frequency of concussion-causing impacts at each test condition (incidence weight) (Table 4).

Head acceleration data from the helmet-to-helmet study were filtered to CFC 180, while neck forces and moments were filtered to CFC 1000 and CFC 600, respectively. Rotational accelerations were calculated by differentiating angular rates and re-filtering to CFC 180. HARM calculated for the dummy head at each test condition including a helmet add-on was compared to the HARM from the dummy head for the baseline condition of two bare helmets impacting each other.

For the pneumatic ram study, the effect of wearing the add-on on HARM reduction was quantified using Cohen's *d*, which normalizes the mean effect size by the standard deviation, similar to a *Z*-score. In this case, Cohen's *d* was calculated as the difference in the average Aggregate Score between the add-on and the bare helmet tests divided by the standard deviation in the Aggregate Scores pooled over all helmet models:

$$Cohen's\, d = \frac{\overline{AS}_{add-on} - \overline{AS}_{bare}}{SE_{pooled}} \quad (3)$$

The Cohen's *d* statistic was calculated for both helmet add-on models using both exposure weighting and concussion weighting of the test results.[7] In accordance with the proposal of Cohen, we describe *d* values of 0.2, 0.5, and 0.8 as having small, medium, and large effect sizes, respectively.[7]

RESULTS

In most of the pneumatic ram test conditions, the ProTech and GC NXT reduced HARM relative to the bare helmet condition. The performance of the add-on devices varied with helmet model, impact location, and impact velocity. In 30 of 36 test conditions for the GC NXT and 19 of 24 test conditions for the ProTech, the dummy head kinematic measures decreased with the addition of a helmet add-on (Fig. 5). Peak translational and rotational acceleration reductions ranged from − 8.8 to 9.6 g and − 900 to 990 rad s^{-2}, respectively, for different helmet and test condition combinations. Across all test conditions, HARM reductions with the addition of the GC NXT or ProTech ranged from − 10 to 23 and − 11 to 16%, respectively. On average, the GC NXT reduced HARM by 9%, while the ProTech reduced HARM by 5%, which was a statistically significant difference ($p = 0.005$). Statistically significant reductions in HARM were observed for the GC NXT ($p < 0.001$) and ProTech ($p = 0.002$) when assessing the effect across all test conditions and helmet models using analysis of variance (ANOVA).

TABLE 3. Combination of helmet model and add-on combinations used for each of the two impact location conditions for the helmet-to-helmet testing.

Helmet model*	Ram add-on	Dummy add-on
Riddell SpeedFlex Precision	None	None
		Guardian Cap NXT
		ProTech Cap
	Guardian Cap NXT	None
		Guardian Cap NXT
	ProTech Cap	None
		ProTech Cap
Schutt Vengeance Z10 LTD	None	None
		Guardian Cap NXT
		ProTech Cap
	Guardian Cap NXT	Guardian Cap NXT
	ProTech Cap	ProTech Cap

*The same helmet model was used for the dummy and ram in each test condition.

TABLE 4. Test condition weights (W_i) and HARM averages for bare helmet tests used to calculate aggregate performance score for helmet add-ons.

Impact speed	Impact location	Exposure weight (%)	Incidence weight (%)	$HARM_{avg}$
4.0 m s^{-1}	Side (C)	24	11	2.532
	Oblique front (OF)	41	10	2.248
	Side upper (SU)	9	4	2.091
7.4 m s^{-1}	Side (C)	8	34	5.934
	Oblique front (OF)	14	29	5.229
	Side upper (SU)	3	12	4.965

Weights were based upon the frequency of impacts observed from video review analysis.

Since the effect of the add-ons was mixed in terms of increasing or decreasing severity metrics, two Aggregate Scores were calculated to estimate the overall effect of the add-ons for individual helmet models. The finding that both helmet add-ons reduced head kinematic measures was robust and remained after weighting the test results by either impact exposure or concussion incidence. Helmets outfitted with these add-ons exhibited statistically significant improvements for both incidence (GC NXT and ProTech $p < 0.001$) and exposure-weighted Aggregate Score (GC NXT $p < 0.001$; ProTech $p = 0.007$). When averaging across the four models tested with both add-ons, the GC NXT reduced the Aggregate Scores by 7.7 and 12%, for injury and exposure weighting, respectively. The corresponding Cohen's d values were 0.71 and 0.86, respectively, indicating that the GC NXT had a large effect on improving HARM scores. The ProTech reduced Aggregate Scores by 4.8 and 5.3% with Cohen's d values of 0.46 and 0.49 for injury and exposure weighting, respectively, indicating a medium effect on the performance of the helmets tested (Fig. 5).

The helmet add-ons had a minimal effect on the risk of serious neck injury (AIS3+). Estimated reductions in the risk of AIS3+ neck injury using the N_{ij} criteria were less than 2% in all linear impactor test conditions (Fig. 6). The maximum absolute risk of AIS3+ neck injury in any test was 12%, though the use of N_{ij} was intended as a metric of relative risk of injury since the existing injury risk function may not be relevant to the larger, more athletic population of NFL linemen.

In the helmet-to-helmet testing, both add-on models reduced HARM for the centric front oblique test conditions (Fig. 7a). For the rear eccentric condition, adding the GC NXT to one or both helmets reduced HARM. However, adding the ProTech to the dummy helmet increased HARM slightly ($< 4\%$), and adding the ProTech to both the ram and dummy helmets reduced HARM by less than 3% (Fig. 7b). This result was consistent across both helmet models tested.

DISCUSSION

Two models of football helmet add-on products, GC NXT and ProTech, were evaluated in a laboratory setting to assess their ability to limit both rotational and translational measures of head motion relative to helmets alone in impacts representing typical concussive and non-concussive blows experienced by NFL linemen. Helmet add-ons improved performance in both 4 and 7.4 m s^{-1} impacts, but the relative

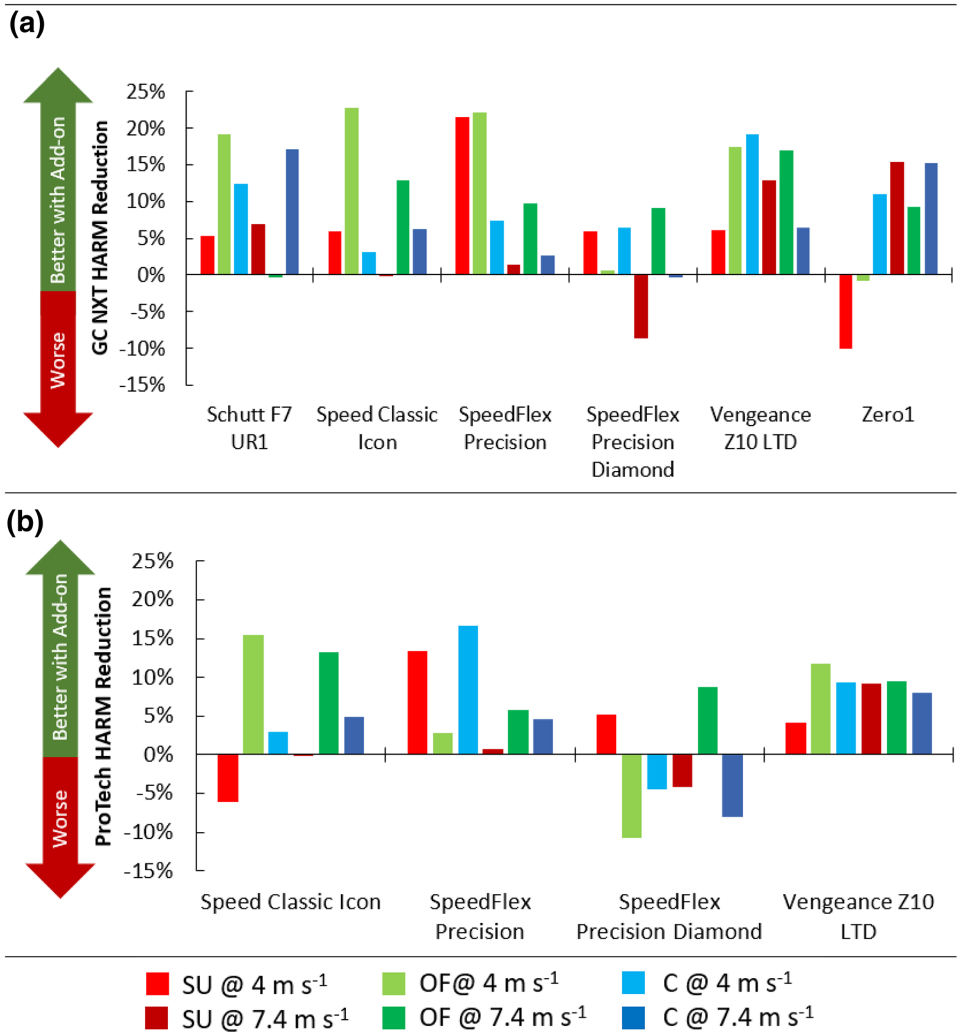

FIGURE 5. Percentage reduction in HARM resulting from the presence of (a) the GC NXT and (b) ProTech. Positive results indicate the helmet performed better with the add-on than without.

improvement was greater in the 4 m s^{-1} impacts that were meant to represent non-concussive impacts to which NFL linemen are commonly exposed. The GC NXT improved the overall impact performance of all six helmet models on which it was tested, while the ProTech improved the overall impact performance in three out of the four helmet models on which it was tested. In all helmet models tested with both add-on products, the GC NXT improved performance more than the ProTech, with the effect size of the GC NXT close to 90% of the standard deviation in the performance of helmets tested when estimating exposure-weighted performance. Effect size for the ProTech was slightly less than 50% of the standard deviation in helmet performance estimated by both Aggregate Scores.

Helmets with better baseline performance as evaluated by HARM tended to be less affected by the presence of the add-ons. The performance of the Riddell SpeedFlex Precision Diamond, which was the best-performing helmet model in this study in the bare helmet condition, was only slightly improved by the GC NXT and was actually worsened by the ProTech (Table 5). Inspection of high-speed video led to the hypothesis that the ProTech may have restricted the flexion of the SpeedFlex Precision Diamond's cantilever shell, changing the way the helmet manages energy. While the authors would have expected this same effect to occur for the other SpeedFlex shell helmets, the stiffness of the underlying padding and how it is affixed to the shell likely contributed to this difference.

The greatest improvements in helmet performance were observed in the Schutt Vengeance Z10 LTD and Riddell Speed Classic Icon, which based on the HARM scores performed the worst of the helmets

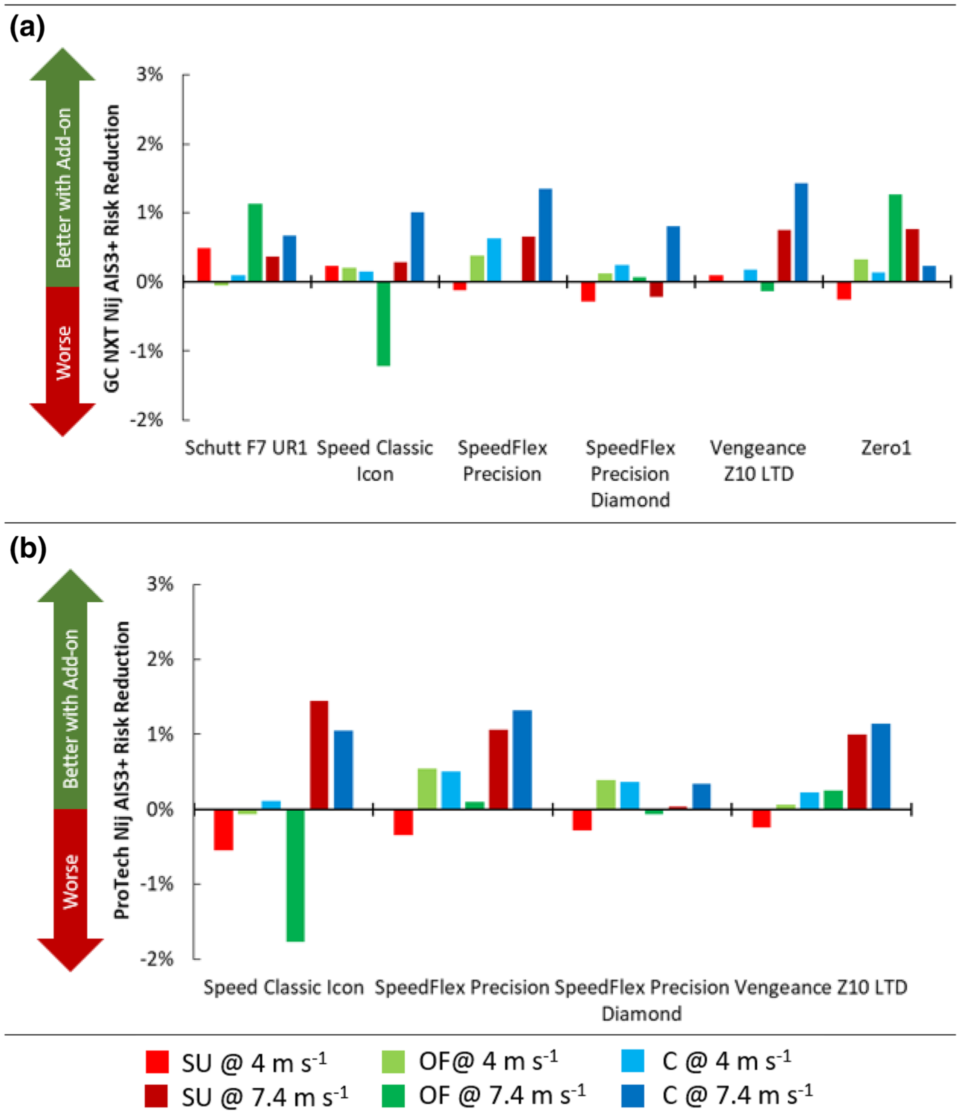

FIGURE 6. Summary of pneumatic ram test results for estimated reduction in risk of an AIS3+ neck injury using N_{ij} resulting from the use of (a) the GC NXT and (b) ProTech. Positive results indicate the risk of injury was lower with the add-on than without.

tested in this bare helmet condition of this study. This trend suggests that the ability of add-on products to improve head protection may be limited in better performing helmet models, which are more optimized for this particular loading environment. Interestingly, the add-ons also improved the performance of the VICIS Zero1, which has a flexible outer shell by design. Additional investigation is necessary to understand the interaction between these add-ons and flexible shelled helmets.

Dummy-to-dummy testing demonstrated that the presence of the ProTech on the helmeted dummy headform resulted in an increase in HARM for the more eccentric impact. Further analysis of the high-speed video footage from the impactor testing indicated that the increased standoff associated with use of the add-ons yielded a change in the point of contact and an increase in the contact area between the ram and dummy helmets. When the ProTech was present on the dummy helmet, the ram helmet contacted the ProTech earlier and stayed in contact longer (resulting in more momentum transfer) than when the dummy helmet did not have a ProTech. When ProTechs were donned on both helmets, the same phenomenon occurred, except that the reduction in peak acceleration compensated for the additional momentum transfer by lowering the HIC and thus lowering the HARM. When no add-ons were present, the helmet shells slid past one another, generating a lower peak acceleration over a shorter duration. The GC NXT also changed

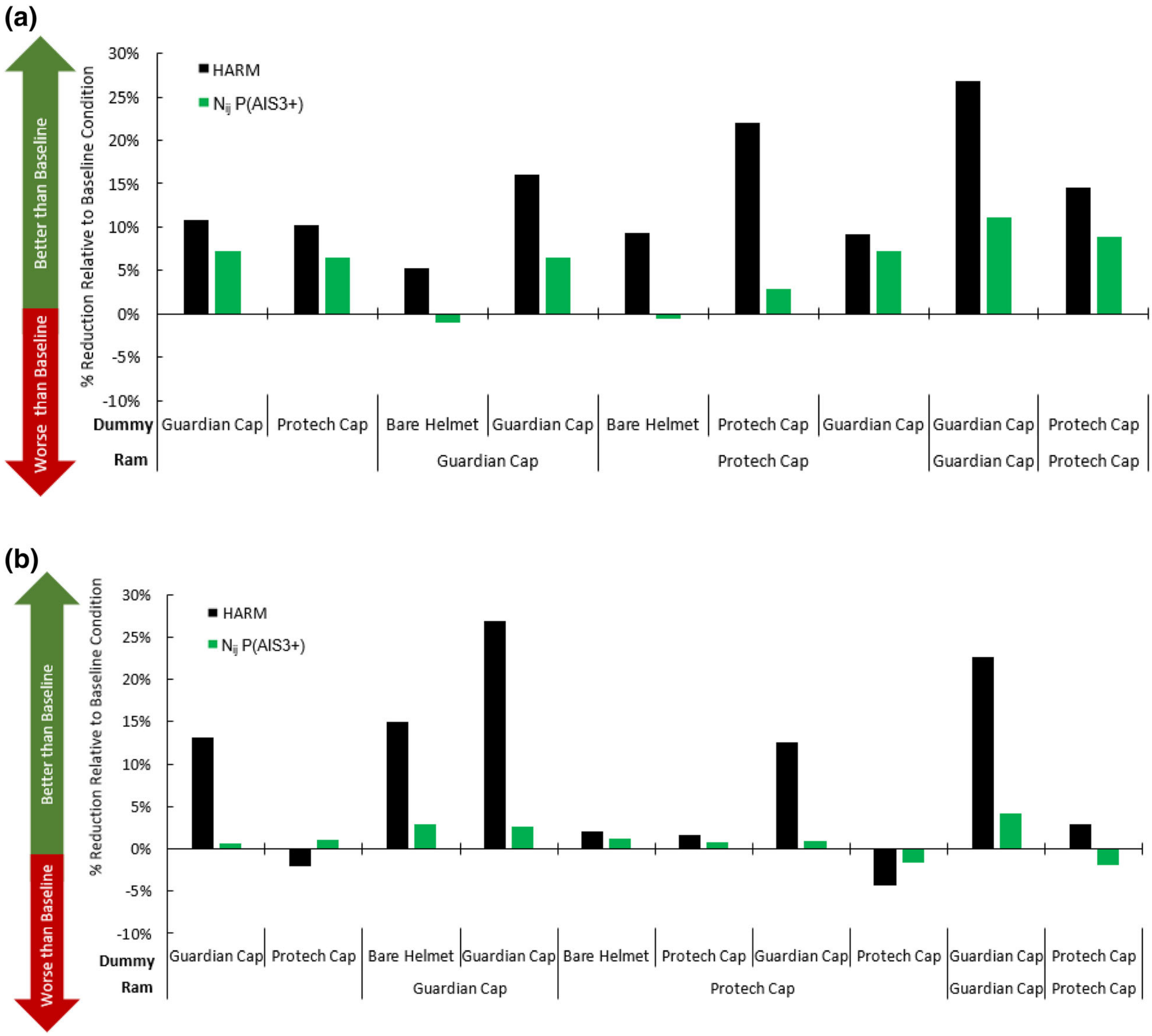

FIGURE 7. Percentage reduction in HARM and probability of an AIS3+ neck injury calculated for the dummy in the helmet-to-helmet (a) front oblique centric and (b) rear eccentric conditions. Results are presented relative to the baseline condition of both the dummy and the ram with bare helmets.

the contact point and area, but allowed for more relative rotation of the helmet and cap. This permitted the helmets to slip past one another in a manner similar the bare helmets. For this test series the relative position of the dummies at time of impact was kept constant, though an alternative approach could have been to keep the eccentricity of the impact constant by changing the position of the dummies. The approach taken was justified by the desire to understand the effect of these add-ons in an on-field environment in which the positioning of the players upon impact would not likely be affected by the presence of the add-ons. A challenge for helmet add-on products is that while adding a thickness of padding to the helmet increases the distance over which to decelerate an impact, it can also potentially increase the offset for tangential loads. This presents a tradeoff between reducing acceleration and minimizing the effect on the degree of eccentricity of the impact.

A concern associated with helmet shell add-on products has been that they may increase neck loads due to the additional mass added to the helmet. The GC NXT increased the mass of the helmets tested by 17–24%, while the mass increased due to the ProTech ranged from 27 to 35%. Additionally, other phenomena such as the add-ons pocketing or grabbing could

TABLE 5. Aggregate scores for helmet-add-on combinations and percentage reduction in Aggregate Score relative to the baseline condition (i.e. the helmet model tested without an add-on).

Helmet model	Cap type	Aggregate Score		Reduction in Aggregate Score	
		Incidence	Exposure	Incidence (%)	Exposure (%)
Riddell Speed Classic Icon	Bare helmet	0.735	0.674	Baseline	
	Guardian Cap NXT	0.679	0.583	7.6	13.5
	ProTech Cap	0.696	0.625	5.2	7.3
Riddell SpeedFlex Precision	Bare helmet	0.601	0.570	Baseline	
	Guardian Cap NXT	0.547	0.474	8.9	16.9
	ProTech Cap	0.570	0.530	5.2	7.2
Riddell SpeedFlex Precision Diamond	Bare helmet	0.537	0.481	Baseline	
	Guardian Cap NXT	0.533	0.467	0.9	3.0
	ProTech Cap	0.538	0.494	− 0.2	− 2.5
Schutt Vengeance Z10 LTD	Bare helmet	0.715	0.632	Baseline	
	Guardian Cap NXT	0.619	0.541	13.4	14.4
	ProTech Cap	0.651	0.574	8.9	9.3
VICIS Zero1	Bare helmet	0.572	0.471	Baseline	
	Guardian Cap NXT	0.517	0.462	9.5	1.9
Schutt F7 UR1	Bare helmet	0.609	0.554	Baseline	
	Guardian Cap NXT	0.563	0.489	7.6	11.8
Average, all helmets	Guardian Cap NXT			8.0	10.3
Average, common helmets*	Guardian Cap NXT			7.7	12.0
	ProTech Cap			4.8	5.3

*Common helmets average includes only helmet models tested with both GC NXT and ProTech.

increase contact times and potentially increase neck loads.[6,17,18] The helmet-to-helmet portion of this study was designed as a pilot study for investigating these issues. While neck forces and moments increased in some conditions due to the presence of these add-on products, the overall effect was to reduce neck loads very slightly. In cases for which neck loads were increased with the add-on products, the differences were small compared to bare helmet tests ($< 2\%$). Further, neck load magnitudes in general were small relative to N_{ij}-estimated injury risk, with less than a 7% probability of serious neck injury in all helmet-to-helmet tests and less than 12% in the pneumatic ram tests.[12] It should also be noted that the physical fitness, age, mass, and anthropometry of the NFL population differs from the general population so the injury probability based on the general population is likely an overestimate.[19,23,11] Future work should investigate the effects of these add-ons under more severe impacts that may be representative of conditions associated with neck injury rather than concussion.

The following limitations should be considered when interpreting the results of this study. First, the add-ons were evaluated using a laboratory study with a finite number of test conditions that may not fully encompass the diversity of impacts professional American football players experience on the field. Temperature-dependence, durability, and the effect of other environmental factors which may be encountered from on-field use of the add-on products were not considered in this study. Next, the degree of improvement in helmet performance conferred by these add-ons differed with helmet model and results may be different with other helmet models. Add-on performance may also vary based on the size of the helmet. This study focused on the performance of these add-on products in impacts typical of helmet-to-helmet impacts sustained by offensive and defensive linemen during NFL games and did not consider the effects of add-on performance on helmet-to-body or helmet-to-ground impacts that comprise 59 and 64% of concussions experienced by offensive and defensive linemen, respectively.[20] Finally, these results were based on testing intended to represent impacts for NFL lineman and thus, the conclusions may not extend to other positions or levels of play due to differences in player size and mass and the types or severity of the impacts commonly experienced.

Results of this laboratory testing with a limited number of helmet models and impact conditions suggest that using the GC NXT may reduce the head impact severity exposure for linemen. While the ProTech resulted in reductions of impact severity for most helmet models and impact scenarios, the mixed results in the helmet-to-helmet impacts suggest further evaluation may be necessary to provide an assessment of the overall benefit of the ProTech. Future studies should investigate the effect of these add-ons through additional laboratory tests with a specific focus on impacts with a greater degree of eccentricity as well as through on-field studies comparing player behavior, injury, or impact severity data collected from sensors.

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REFERENCES

[1]Andrecovich, C. Guardian Cap Testing. Unpublished Report. Report 11101. 1 December 2011. Sport Injury and Ballistic Biomechanics Group, Bioengineering Center, Wayne State University, Detroit, Michigan.

[2]Association for the Advancement of Automatic Medicine. The Abbreviated Injury Scale, 1990 Revision. Association for the Advancement of Automatic Medicine, 2001.

[3]Bailey, A. M., E. J. Sanchez, G. Park, L. F. Gabler, J. R. Funk, J. R. Crandall, M. Wonnacott, C. Withnall, B. S. Myers, and K. B. Arbogast. Development and evaluation of a test method for assessing the performance of American football helmets. *Ann. Biomed. Eng.* 48(11):2566–2579, 2020.

[4]Biomechanics Consulting and Research, LLC. Helmet Test Protocol. Biomechanics Consulting and Research, LLC, 2019. www.biocorellc.com/resources. Accessed 15 March 2021.

[5]Breedlove, K. M., E. Breedlove, E. Nauman, T. G. Bowman, and M. R. Lininger. The ability of an aftermarket helmet add-on device to reduce impact-force accelerations during drop tests. *J. Athl. Train.* 52(9):802–808, 2017.

[6]Bunketorp, A., L. Lindstroem, L. Peterson, and R. Oertengren. Heavy protective helmets and neck injuries—a theoretical and electromyographic study. In: Proceedings of the International Research Council on the Biomechanics of Injury Conference, 13:29–138, 1985.

[7]Cohen, J. Statistical Power Analysis for the Behavioral Sciences. Hillsdale, NJ: Erlbaum, 1988.

[8]Collins, M., M. R. Lovell, G. L. Iverson, T. Ide, and J. Maroon. Examining concussion rates and return to play in high school football players wearing newer helmet technology: a three-year prospective cohort study. *Neurosurgery*. 58(2):275–286, 2006.

[9]Crisco, J. J., B. J. Wilcox, J. G. Beckwith, J. J. Chu, A.-C. Duhaime, S. Rowson, S. M. Duma, A. C. Maerlender, T. W. McAllister, and R. M. Greenwald. Head impact exposure in collegiate football players. *J. Biomech.* 44(15):2673–2678, 2011.

[10]Cuccurullo, N. Effectiveness of a football over helmet padding system in reducing peak acceleration of the head and severity index. PhD Dissertation, State University of New York College at Cortland, 2014.

[11]de la Motte, S. J., T. C. Gribbin, P. Lisman, K. Murphy, and P. A. Deuster. Systematic review of the association between physical fitness and musculoskeletal injury risk: part 2—muscular endurance and muscular strength. *J. Strength Cond. Res.* 31(11):3218–3234, 2017.

[12]Eppinger, R., E. Sun, F. Bandak, M. Haffner, N. Khaewpong, M. Maltese, S. Kuppa, T. Nguyen, E. Takhounts, and R. Tannous. Development of improved injury criteria for the assessment of advanced automotive restraint systems: II. National Highway Traffic Safety Administration, pp. 1–70, 1999.

[13]Funk, J. R., R. Jadischke, A. Bailey, J. Crandall, J. McCarthy, K. Arbogast, and B. Myers. Laboratory reconstructions of concussive helmet-to-helmet impacts in the National Football League. *Ann. Biomed. Eng.* 48(11):2652–2666, 2020.

[14]Funk, J. R., R. E. Quesada, A. M. Miles, and J. R. Crandall. Inertial properties of football helmets. *J. Biomech. Eng.* 140(6):064501, 2018.

[15]Gabler, L. F., J. R. Crandall, and M. B. Panzer. Assessment of kinematic brain injury metrics for predicting strain responses in diverse automotive impact conditions. *Ann. Biomed. Eng.* 44(12):3705–3718, 2016.

[16]Holbourn, A. H. S. Mechanics of head injuries. *Lancet*. 242(6267):438–441, 1943.

[17]Houston, R. L., and J. Sears. Effect of protective helmet mass on head/neck dynamics. *J. Biomech. Eng.* 10:318–323, 1981.

[18]Jadischke, R., D. C. Viano, J. McCarthy, and A. I. King. The effects of helmet weight on Hybrid III head and neck responses by comparing unhelmeted and helmeted impacts. *J. Biomech. Eng.* 138(10):1–10, 2016.

[19]Jones, B. H., K. G. Hauret, S. K. Dye, V. D. Hauschild, S. P. Rossi, M. D. Richardson, and K. E. Friedl. Impact of physical fitness and body composition on injury risk among active young adults: a study of Army trainees. *J. Sci. Med. Sport*. 20:S17–S22, 2017.

[20]Lessley, D. J., R. W. Kent, J. M. Cormier, C. P. Sherwood, J. R. Funk, J. R. Crandall, B. S. Myers, and K. B. Arbogast. Position-specific circumstances of concussion in the NFL: toward the development of position-specific helmets. *Ann. Biomed. Eng.* 48(11):2542–2554, 2020.

[21]Lessley, D. J., R. W. Kent, J. R. Funk, C. P. Sherwood, J. M. Cormier, J. R. Crandall, K. B. Arbogast, and B. S. Myers. Video analysis of reported concussion events in the National Football League during the 2015–2016 and 2016–2017 seasons. *Am. J. Sports Med.* 46(14):3502–3510, 2018.

[22]Levy, M. L., B. M. Ozgur, C. Berry, H. E. Aryan, and M. L. J. Apuzzo. Analysis and evolution of head injury in football. *Neurosurgery*. 55(3):649–655, 2004.

[23]Malone, S., M. Roe, D. A. Doran, T. J. Gabbett, and K. Collins. High chronic training loads and exposure to bouts of maximal velocity running reduce injury risk in elite Gaelic football. *J. Sci. Med. Sport*. 20(3):250–254, 2017.

[24]Mertz, H. J., P. Prasad, and G. Nusholtz. Head injury risk assessment for forehead impacts. SAE Transactions Paper 960099, pp. 26–46, 1996.

[25]Nightingale, R. W., W. J. Richardson, and B. S. Myers. The effects of padded surfaces on the risk for cervical spine injury. *Spine*. 22(20):2380–2387, 1997.

[26] Pellman, E. J., D. C. Viano, C. Withnall, N. Shewchenko, C. A. Bir, and P. D. Halstead. Concussion in professional football: helmet testing to assess impact performance—part 11. *Neurosurgery*. 58(1):78–96, 2006.
[27] Rowson, S., S. M. Duma, R. M. Greenwald, J. G. Beckwith, J. J. Chu, K. M. Guskiewicz, J. P. Mihalik, J. J. Crisco, B. J. Wilcox, and T. W. McAllister. Can helmet design reduce the risk of concussion in football? *J. Neurosurg*. 120(4):919–922, 2014.
[28] Society of Automotive Engineers. Instrumentation for impact test—part 1: electronic instrumentation. Warrendale, PA, SAE International J211/1201403, 2014.
[29] Versace, J. A. Review of the severity index. In: Proceedings of the 15th Stapp Car Crash Conference, SAE Paper No. 710881, pp. 771–796, 1971.
[30] Viano, D. C., and D. Halstead. Change in size and impact performance of football helmets from the 1970s to 2010. *Ann. Biomed. Eng*. 40(1):175–184, 2012.