Impact Performance of Modern Football Helmets

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Abstract—Linear impact tests were conducted on 17 modern football helmets. The helmets were placed on the Hybrid III head with the neck attached to a sliding table. The head was instrumented with an array of 3-2-2-2 accelerometers to determine translational acceleration, rotational acceleration, and HIC. Twenty-three (23) different impacts were conducted on four identical helmets of each model at eight sites on the shell and facemask, four speeds (5.5, 7.4, 9.3, and 11.2 m/s) and two temperatures (22.2 and 37.8 °C). There were 1,850 tests in total; 276 established the 1990s helmet performance (baseline) and 1,564 were on the 17 different helmet models. Differences from the 1990s baseline were evaluated using the Student t test ($p < 0.05$ as significant). Four of the helmets had significantly lower HICs and head accelerations than the 1990s baseline with average reductions of 14.6–21.9% in HIC, 7.3–14.0% in translational acceleration, and 8.4–15.9% in rotational acceleration. Four other helmets showed some improvements. Eight were not statistically different from the 1990s baseline and one had significantly poorer performance. Of the 17 helmet models, four provided a significant reduction in head responses compared to 1990s helmets.

Keywords—Protective headgear, Recreation and sport, Concussion, Helmets, Sport equipment.

INTRODUCTION

The purpose of this study was to conduct a comprehensive evaluation of 2010 helmets in linear impacts to the Hybrid III head. The test conditions were derived from studies of NFL game impacts, some causing concussion. For example, video from 182 NFL game collisions was analyzed and 31 impacts were reconstructed in laboratory tests with helmeted Hybrid III dummies.[11,12] That data provided helmet impact conditions for 25 on-field collisions involving concussion. The analysis also provided an average and standard deviation in the impact velocity associated with concussion of NFL players. Other analyses of the NFL video determined impacts to the facemask.[2] Eight impact sites were selected on the facemask and helmet shell.[2,13,21] The linear impact tests reported here are complementary to the drop-weight testing used to certify football helmets to NOCSAE standards.[6–8] The tests also compliment a recent evaluation of football helmets.[15]

During the 2008–2009 NFL season, 81% of players wore Riddell helmets with more than half using the VSR4 helmet first introduced in the 1990s (Riddell unpublished data). Only 25% of players were using the newer Riddell Revolution, Schutt DNA and other "modern" helmets. Even though the VSR4 received an upgrade in the padding with vinyl nitrile foam in 2000, there is a lack of objective, independent data on its change in performance compared to the 1990s design. The data reported here is intended to provide information on the performance of "modern" helmets in attenuating the forces of impacts to the helmet. Twenty-three separate tests were conducted, involving a linear impact at eight sites on the facemask and shell with four different impact velocities and two helmet temperatures. The testing is comprehensive and provides data on the translational and rotational accelerations of the head. The data establishes a benchmark for performance of helmets available in 2010 as well as what was used in the 1990s.

MATERIALS AND METHODS

Linear impact tests were conducted by two independent laboratories with experience in sport safety research and in evaluating football helmets. The testing

involved 17 models of "modern" football helmets from five manufacturers, who voluntarily supplied helmets for the evaluation. The scope of the testing was intentionally broad to cover a range of conditions in which concussion may occur in the NFL and to include lower severity impacts to ensure evaluation of impacts in normal practice and play. An additional series of tests was conducted on three models of 1990s helmets to establish a "baseline" performance of helmets from that era. Four of the twelve 1990s helmets were new and unused from that era; they were VSR4 helmets from Riddell archives. The others came from a local high school and were in good condition. The helmet performance data provided by these tests is intended to be an unbiased and fair evaluation of the performance of helmets used in football.

Test Conditions and Velocities

Figure 1 shows the eight impact locations on the front, side, and rear of the helmet. The sites were chosen based on video analysis of 182 NFL game impacts of helmet-to-helmet, helmet-to-ground, helmet-to-shoulder pad type collisions and the laboratory reconstruction of 31 impacts.[11,12] The linear impact tests included four impacts on the helmet shell at sites F, C, D, and R. There were two impacts on the facemask at A and A′ and two on the facemask interface with the shell at B and UT.[2,12,21] Using a reconstruction of NFL game concussions, these sites and the test conditions were chosen to cover the type of impact conditions associated with severe impacts and concussion in NFL players[2,11–13,21] and lower speed impacts associated with normal practice and play.[3,14,15]

Each helmet was placed on the Hybrid III head using the standard NOCSAE position in accordance with manufacturer's supplied fitting instructions.[6–8] The Hybrid III dummy head and neck were used because of their specification in US Government standards for automotive crash testing, their known repeatability and humanlike impact responses, and their use in previous helmet impact research on helmet impacts in professional football players.[11–13,19–21] For final adjustment, the brow of the helmet was aligned with the middle positioning indicator on the NOCSAE nose gauge guide and in accordance with supplied fitting instructions. Manufacturers were asked to supply helmets with chinstraps pre-adjusted to fit the Hybrid III, but not all complied. Where necessary, chinstraps were adjusted for a snug fit with the chinstraps buckled.

Table 1 lists the impact sites, velocities and temperatures for the helmet testing. Twenty-three (23) separate impacts were conducted with four impact velocities of 5.5, 7.4, 9.3, and 11.2 m/s (12.3, 16.6, 20.8, and 25.1 mph). Testing at the average impact velocity of 9.3 m/s (20.8 mph) was emphasized and the design and layout of the impactor, sliding table, and installation of the Hybrid III head, neck, and helmet followed methods previously described.[11–13,19–21] Studies from automotive safety have shown that testing at the average condition for an injury balances the design for the more and less severe impacts and also balances the design for those with the strongest and weakest tolerances.[4] Ten impacts were conducted using the average condition for concussion of 9.3 m/s (20.8 mph), including all shell and facemask impacts except the A′ condition. Only two of the facemask impact conditions found by Craig[2] were used in this testing. They were A and A′. The A″ condition is similar to the centered NOCSAE facemask impact. The A″ condition was not tested. The 9.3 m/s severity of impact was also used
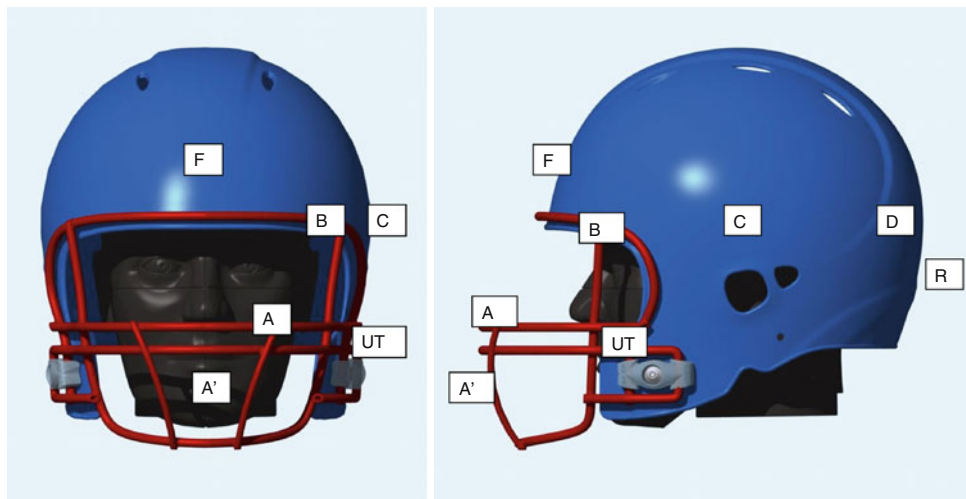
FIGURE 1. Locations for linear impacts to the shell (F, C, D, and R) and facemask (A, A′, B, and UT) of football helmets (based on game video analysis of concussion impacts in the NFL[6,9,11,12,16,18,20]).

TABLE 1.   Test matrix with 23 different impact sites, speeds and temperatures.

Impact site	Impact velocity, m/s (mph)				n
	5.5 (12.2)	7.4 (16.6)	9.3 (20.8)	11.2 (25.1)	
Temperature					
22.2 °C (72°F)					
Shell					
F	X	X	X	X	4
C	X	X	X	X	4
D		X	X		2
R		X	X		2
Facemask					
A	X	X	X		3
A′		X			1
B		X	X		2
UT		X	X		2
37.8 °C (100°F)					
Shell					
F			X		1
C			X		1
A			X		1
Total	3	8	10	2	23

after the helmet was warmed to 37.8 °C (100°F). Two shell impacts were conducted at the highest impact severity of 11.2 m/s (25.1 mph). This condition was associated with NFL players out 7+ days with concussion and represents the condition for the most seriously injured players.[10]

Figure 2 shows the four impact velocities in this study and the nominal delta Vs overlaid on the 25 reconstructed impacts causing concussion in NFL players. Eight impacts were conducted at the threshold condition for concussion at 7.4 m/s (16.6 mph). This condition represents the transition severity for concussion in the NFL.[11–13] Three impacts were conducted at 5.5 m/s (12.1 mph). This severity is below recorded concussions in the NFL[11] and is associated with normal practice and play. The 5.5 m/s (12.1 mph) impacts are below the severity of any known concussion in NFL players. HITS analysis of college and high school play has recorded head impact accelerations of 20–40 g during normal practice and play, which falls within the range of the lowest severity impacts in this test series.[3,14] These tests were added to ensure an assessment of helmet performance in conditions of normal play through the most severe impacts in the NFL.

For the 37.8 °C (100°F) test condition, helmets were conditioned for 4–24 h in a convection oven. The helmet was impacted not less than 2 min and not more than 3 min after removal from the oven. The helmet was then returned to the conditioning oven if further elevated temperature tests were to be conducted on it. The rationale for selecting the 37.8 °C (100°F) test condition was based on field and laboratory studies
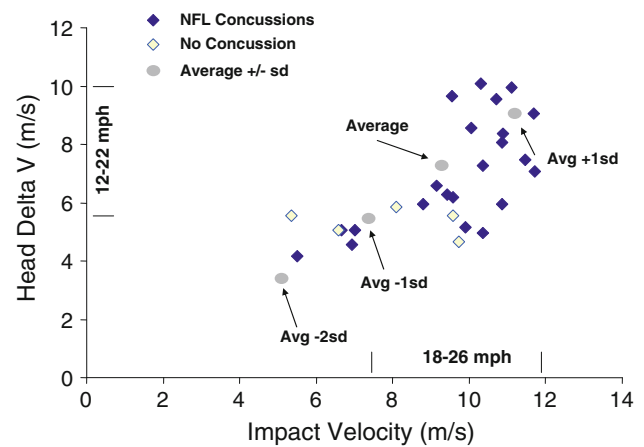
FIGURE 2.   Impact velocity and delta *V* for 23 reconstructed game impacts of NFL player concussions and 5 severe impacts without injury. The linear impact conditions that were used for the evaluation of the force attenuation of helmets are superimposed on the reconstructed game impacts.[6,9]

that demonstrated maximum on field helmet temperatures to be not more than 40.6 °C (105°F) based on Southern Impact Research Center (SIRC) unpublished data. Most data points indicate that helmets attain temperatures of 37.8 °C (100°F) in warm climates. Data were available from actual on field game conditions involving collegiate players in Arizona and New Hampshire, as well as laboratory studies tracking temperature change both in heated environments and with varying workloads on athletes.

Linear Impactor

The linear impactor was designed to simulate the striking head of a football player and photos of the equipment have been previously published.[11,13,21] An air accumulator was charged to the set pressure and was released by a solenoid-activated dump valve onto an air piston. The air piston rapidly accelerated a sliding ram to the desired speed, at which point the ram disengaged from the air piston and was constrained by linear bearings into impact with the helmeted Hybrid III head. The thrust piston was stopped before the sliding ram made head contact, so only the sliding ram was involved in the impact. The velocity of impact was determined by the set pressure in the accumulator.

At the end of the sliding ram was a 152 mm diameter flat aluminum backing plate. Attached to the plate was a 35 mm layer of vinyl nitrile foam covered by a hard plastic cap simulating the shell and liner of a helmeted, striking player. The cap was machined of Nylon and had a domed spherical surface with a 127 ± 5 mm radius. It weighed 0.238 kg. A sample of 14 foam pads weighed 0.0622 ± 0.0019 kg. The cap, foam pad, and backing plate were connected using

hook and loop fastening strips so that the foam could be easily interchanged.

The mechanical properties of the impactor face were based on Der-Tex VN600 foam. The published specifications were greater in range for critical impact measures than the test laboratories were comfortable with. Der-Tex was approached and asked to supply sheets that were as identical as possible for use. A lot of VN600 foam was produced and screened for density, durometer, thickness, and 25% compression defection (CD) by the manufacturer. Mechanical testing determined the pressure causing 25% CD of a 6.5 cm^2 (1 sq″) cylindrical sample of foam using a loading rate of 2.54 cm/min (1″/min). The thickness and density were also determined. Twenty, two-pad sets were selected for a total of 40 pads that were mechanically similar. SIRC determined that the average density of the pads was 97.7 kg/m^3 (6.09 lb/ft^3), the average pressure for 25% CD was 94 kPa (13.6 psi), and the average thickness was 35 mm (1.38″).

The mass of the impactor was 14 kg (31 lb).[11] The impactor mass simulated that of the striking player in a game impact. The struck player is typically hit from the front or side of the helmet with little support provided by the torso.[11,12] There was typically more mass of the striking player involved in the impact because they lined up their head, neck and torso in the collision.[19,20] During the impact, more momentum was transferred to the struck player because of the greater effective mass of the striking player. The biomechanical data from game reconstructions showed that the head acceleration and change in velocity of the striking player were lower than that of the struck player.[19,20] The linear impact provides a momentum exchange to the struck helmet. The change in velocity of the struck helmets is about 60% of the impact velocity so the energy transfer to the struck head is much lower than based on the impact velocity. The linear impacts are different from the NOCSAE drop tests, where all of the impact energy is transferred to the struck helmet. The alignment of the head–neck and orientation of the impact was setup to provide maximum energy transfer to the head.

Helmets Evaluated and Procedures Followed

A meeting was held with the football helmet manufacturers on August 17, 2009 announcing the test program. The manufacturers were asked to voluntarily supply helmets for testing that they intended to make available to the NFL for the 2010 season. Eleven helmets were supplied in the initial round of testing from September to November of 2009. Six additional helmets were tested during the second round from January to February of 2010. Four helmets of each

model were supplied with replacement chinstraps and faceguards. Half of the helmets and parts were sent to Biokinetics and Associates Ltd. in Ottawa and the other half to SIRC in Tennessee. The testing was done at the two independent laboratories following the identical protocol.

Each helmet was assigned an impactor face cap. Each laboratory received 20 pads and randomly assigned a pad to a particular helmet. All testing on that helmet model was performed with that pad. The test matrix was established so there would be a consistent "cool-down" time between impacts to the same pad so its properties were restored. Bare head testing with the end caps used in the testing showed the padding lots provided repeatable head responses ($<3\%$ coefficient of variation in 5 m/s impacts to the head with all of the pads used in the study). After each test, issues related to helmet retention (i.e., chinstrap unlatching, the cup sliding off the chin, loss of the helmet from the head) were noted and the helmet and components were inspected for damage to the chinstrap, facemask, shell, and padding. Twenty different issue types were identified in all of the testing and each issue was coded by number after a test. For this study, the total number of issues for each helmet was considered as important as each of the head responses.

Instrumentation, Filtering, and Data Analysis

The helmeted Hybrid III head was instrumented to measure translational and rotational acceleration, and calculate Severity Index (SI) and Head Injury Criterion (HIC).[11,16,19] Head translational and rotational acceleration were measured using the established sign convention in standard J1733.[17] The positive x-axis is forward, the positive y-axis is through the right ear, and the positive z-axis is down the neck.

The Hybrid III head was machined to provide mounting locations for nine accelerometers in a 3-2-2-2 configuration (from www.radenton.com, reference drawing B-3623). The accelerometers were piezo-resistive and capable of withstanding 2000 g (Endevco models 7264A, B-2000). All data were collected at 10 kHz following the requirements of standard J211-11.[8] The data channels were filtered with CFC 1000 anti-aliasing hardware. For the calculation of rotational acceleration, the data from the nine accelerometers were digitally post-processed to CFC 180[5] for analysis by the method of Padgoankar et al.[9] The reported linear and rotational accelerations involve CFC 180 filtering.

Both laboratories agreed on a testing protocol prior to the start of helmet evaluations. The protocol described a common order in which the helmets were tested. Testing was conducted on all of the shell impact

sites first, followed by all of the facemask impacts. The 5.5 m/s tests were first, followed by the 7.4, 9.3, and 11.2 m/s impacts. All tests for all sites at a particular impact speed were completed before continuing with the next impact speed. The shell impact site test order was: F, C, D, and R. The facemask site order was UT, B, A, and A′. For each site and speed combination, the helmet model sequence remained the same.

The protocol for facemask and chinstrap replacement was agreed upon between the laboratories. For the shell impacts, the facemask was replaced after all tests were completed at a particular impact speed. For the facemask impacts, the facemask was replaced after every A and A′ impact. An exception was that the facemask from the 5.5 m/s impacts was reused for the 7.4 m/s impacts for both the shell and facemask impacts because there was no damage. The precise sequence of testing and changing of components was followed. The chinstrap was replaced whenever the facemask was replaced, or when significant damage was observed.

The Hybrid III vinyl skin has friction against the lining of some football helmets. This makes donning the helmets difficult and causes unrealistic head–helmet interactions. Nylon stockings were tightly fit on the head to reduce friction and provide a reasonable simulation of the skin-to-helmet interface. Two layers of nylon stockings were stretched over the dummy head prior to installation of the helmet. This allowed relative motion between the helmet and head. The stockings remained tightly fit to the head skin. The internal neck cable was tightened to the standard torque of 1.13 Nm (10 in-lbs) prior to testing. A six-axis upper neck load cell (model 1716A, R.A. Denton Inc., www.radenton.com) was installed for the testing only at Biokinetics. That data are not reported in this article.

A twin beam velocity trap was used to trigger the data acquisition system and to provide a measurement of the impact velocity. The velocity trap was positioned so the impactor broke the second beam just before contact with the helmet. High speed video was recorded at 1000 fps for one test of each helmet model, site, and speed combination at each laboratory.

1990s Baseline Helmets

An important aspect of the work was to establish baseline responses for helmets of the 1990s. This was done to determine the level of helmet performance in the 1990s and to establish a benchmark for comparison with the modern helmets of 2010. Twelve helmets were obtained of three different types of 1990s helmets. Riddell provided four old style VSR4 helmets with the original padding as used in the 1990s. These were new and unused helmets. SIRC obtained four old style

VSR4 helmets and Pro Air II's made by Schutt from a local high school that was in good condition. These helmets were subjected to the identical protocol as the 17 modern helmets. The VSR4 helmet has a dual density liner and was used in the NFL game reconstructions.[11–13,19–21]

Weights and Dimensions

The helmet shell plus padding, facemask, and chinstrap were weighed and summed to give the overall weight of each helmet. In addition, a series of standardized measurements were taken of the height, width, and length of the helmet shell and complete helmet with faceguard. These dimensions were taken with the helmet on the Hybrid III head and included distances from the head center of gravity (cg). The Hybrid III headform was positioned so the Frankfort plane was horizontal. The helmet was positioned on the headform using the same techniques as for the impact testing. A plumb gauge was used to transfer the measurement points down to the work surface. This provided measurements of the helmets in a plane parallel to the Frankfort plane.

Statistical Analyses

The average, standard deviation (sd), and 95% confidence interval for responses were determined for each test condition and helmet. The significance of differences from the 1990s baseline was determined using the Student t test assuming unequal variance and a two-sided distribution using a $p < 0.05$ as significant. A t test was also performed using the normalized average response using the baseline condition for normalization. The normalized response was compared to one for the determination of statistical differences for the 23 test conditions for each helmet.[1] This approach was favored over others because it assumed the average response was the best available estimate of the helmet's performance for that condition. It also treated each helmet alone in comparison to the baseline.

The significance of differences in the number of issues during testing was addressed in two ways.[1] Issues included chinstrap unlatching, component tearing or breakage, and loss of helmet retention. Each individual issue was recorded. The total number of issues in the tests was compared to that of the baseline helmets, where zero was no issue in a test, 1 was one issue in a test, 2 was two issues in a test, and so on. The average number of issues in all tests of a helmet was compared to the average for the baseline helmets using the Student t test assuming unequal variance, two-sided distribution and $p < 0.05$ as significant. Second, the 95% confidence interval was determined for the proportion of tests with

an issue, where: $p = n/N$, n was number tests with an issue and N was the total number of tests on the helmet. The 95% confidence interval is $p = p \pm 1.96 \sqrt{(p(1-p)/N)}$. Non-overlapping confidence intervals indicated a significant difference in the proportion of tests with an issue compared to the baseline.

RESULTS

Weights and Dimensions

Table 2 shows the weight of the helmet components and size of the helmet shell and shell plus facemask for the 17 helmets and three 1990s baseline models. The average weight for the 1990s baseline was 1.87 ± 0.04 kg (4.11 ± 0.08 lb), where the shell and padding weighed 1.26 ± 0.01 kg (2.77 ± 0.02 lb) and the facemask 0.52 ± 0.01 kg (1.15 ± 0.02 lb). The average weight for the 17 helmets was 1.95 ± 0.20 kg (4.30 ± 0.44 lb), which was 4.7% greater than the 1990s baseline. The helmets ranged in weight from 1.50 to 2.27 kg (3.29–5.00 lb). The greatest increase in weight was for the chinstraps at 41.4%, but this

involved only an increase from 0.05 to 0.08 kg (0.12–0.17 lb). There was an 8.3% increase in the facemask weight and only a 1.7% increase in shell weight.

Measurements were made of the helmet size while positioned on the Hybrid III head following NOCSAE and the manufacturer's recommended procedures. The 1990s baseline helmets were 32.4 ± 0.5 cm ($12.76'' \pm 0.20''$) in length, 24.2 ± 0.2 cm ($9.54'' \pm 0.06''$) in width, and 28.1 ± 0.3 cm ($11.05'' \pm 0.13''$) in height. The average of the 17 helmets was only slightly larger than the 1990s baseline. They were 34.2 ± 1.3 cm ($13.46'' \pm 0.51''$ in length, 25.8 ± 0.9 cm ($10.14'' \pm 0.37''$) in width, and 28.9 ± 1.5 cm ($11.37'' \pm 0.61''$) in height. On average, the 2010 helmets were 5.5% longer, 6.3% wider, and 2.9% taller. The largest helmets were the DNA 2022 and the Adams 3000. The smallest were the Adams A4 and A2000.

1990s Baseline Responses

Figure 3 shows the average and ±1sd in HIC, peak translational acceleration and peak rotational acceleration for the 14 shell impacts at four sites (F, C, D, and
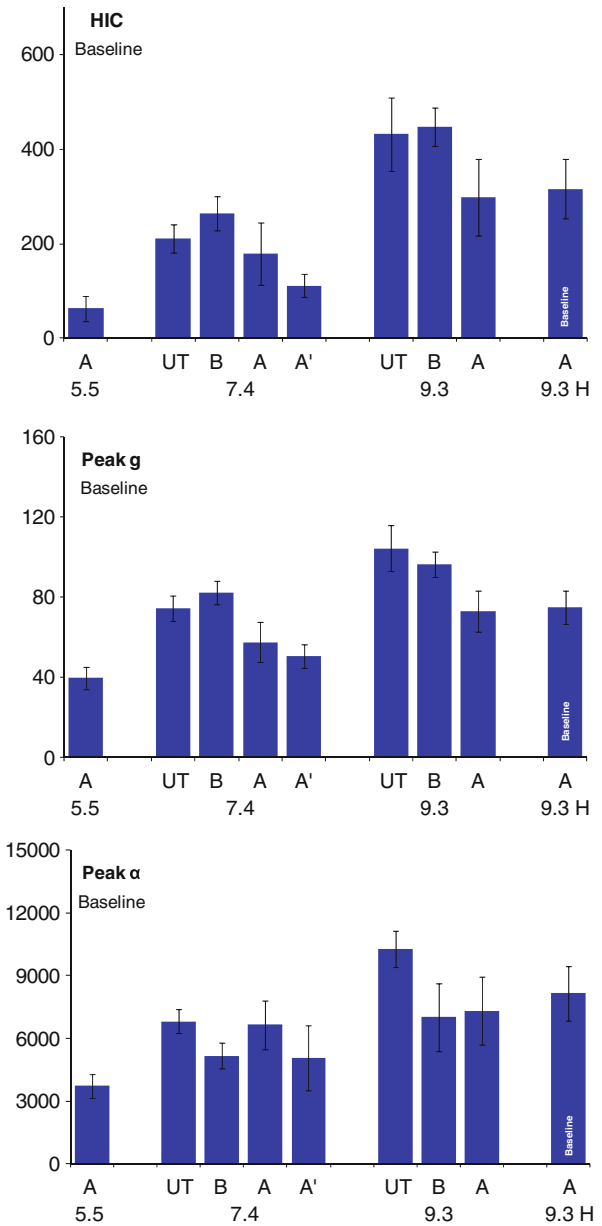
TABLE 2. Weights of the shell plus padding, facemask and chinstrap, and dimensions of the shell and shell plus facemask for each helmet tested compared to the 1990s baseline helmets.

Helmets	Weight (kg)				Shell (cm)			Shell + facemask (cm)		
	Shell + pads	Facemask	Chinstrap	Total	Length	Width	Height	Length	Width	Height
Xenith X1	1.29	0.54	0.14	1.98	29.8	25.0	26.8	34.5	26.1	28.1
Adams A4	0.86	0.54	0.06	1.50	28.3	23.4	24.7	32.1	24.3	26.4
VSR4	1.25	0.52	0.05	1.84	27.8	23.8	25.0	32.9	24.4	27.9
Revolution	1.26	0.58	0.06	1.93	28.9	25.2	26.6	35.3	25.3	28.5
DNA Pro	1.36	0.60	0.08	2.06	30.3	25.2	25.7	35.5	26.4	28.6
Schutt Ion	1.40	0.59	0.08	2.08	30.8	27.2	26.2	34.0	25.8	29.3
Revolution Speed	1.29	0.58	0.06	1.99	29.9	25.0	25.9	34.4	25.2	29.1
Gladiator	1.71	0.32	0.13	2.19	30.9	26.0	27.6	33.1	26.2	31.3
Revolution IQ	1.32	0.57	0.06	2.00	29.0	25.2	26.3	34.1	25.3	29.1
Adams A2000	0.92	0.54	0.10	1.59	28.6	23.3	24.6	31.9	24.3	26.6
Air XP	1.21	0.53	0.08	1.85	29.1	24.3	26.5	32.9	25.8	28.0
Air XP 7891	1.40	0.58	0.08	2.09	30.3	25.6	27.5	36.1	27.2	27.9
Air XP 7890	1.20	0.50	0.08	1.82	29.0	24.1	26.1	33.9	25.8	28.2
Speed Classic	1.24	0.60	0.06	1.94	29.6	25.1	25.5	35.1	26.0	28.7
DNA 2022	1.55	0.63	0.08	2.27	31.7	26.2	27.5	36.2	27.6	30.6
Adams A3000	1.07	0.81	0.06	1.93	30.1	24.3	27.2	34.1	25.7	32.2
ION 4D 2030	1.41	0.62	0.08	2.16	31.0	27.3	25.8	35.0	26.6	30.5
Avg 2010s	**1.28**	**0.57**	**0.08**	**1.95**	**29.7**	**25.1**	**26.2**	**34.2**	**25.8**	**28.9**
sd	0.20	0.09	0.02	0.20	1.1	1.2	0.9	1.3	0.9	1.5
95%CI	0.10	0.04	0.01	0.09	0.5	0.6	0.4	0.6	0.4	0.7
VSR4 Retro HS	1.26	0.52	0.05	1.85	27.7	23.9	24.9	32.7	24.2	28.3
Pro Air II	1.27	0.54	0.08	1.91	28.2	23.7	25.9	31.8	24.4	27.7
VSR4 Retro	1.25	0.52	0.05	1.84	27.8	23.7	25.2	32.7	24.1	28.2
Avg 1990 baseline	**1.26**	**0.52**	**0.06**	**1.87**	**27.9**	**23.8**	**25.3**	**32.4**	**24.2**	**28.1**
sd	0.01	0.01	0.02	0.04	0.3	0.1	0.5	0.5	0.2	0.3
95%CI	0.01	0.01	0.02	0.04	0.3	0.1	0.6	0.6	0.2	0.4
% diff 2010 vs. baseline	**1.7%**	**8.3%**	**41.4%**	**4.7%**	**6.5%**	**5.5%**	**3.4%**	**5.5%**	**6.3%**	**2.9%**
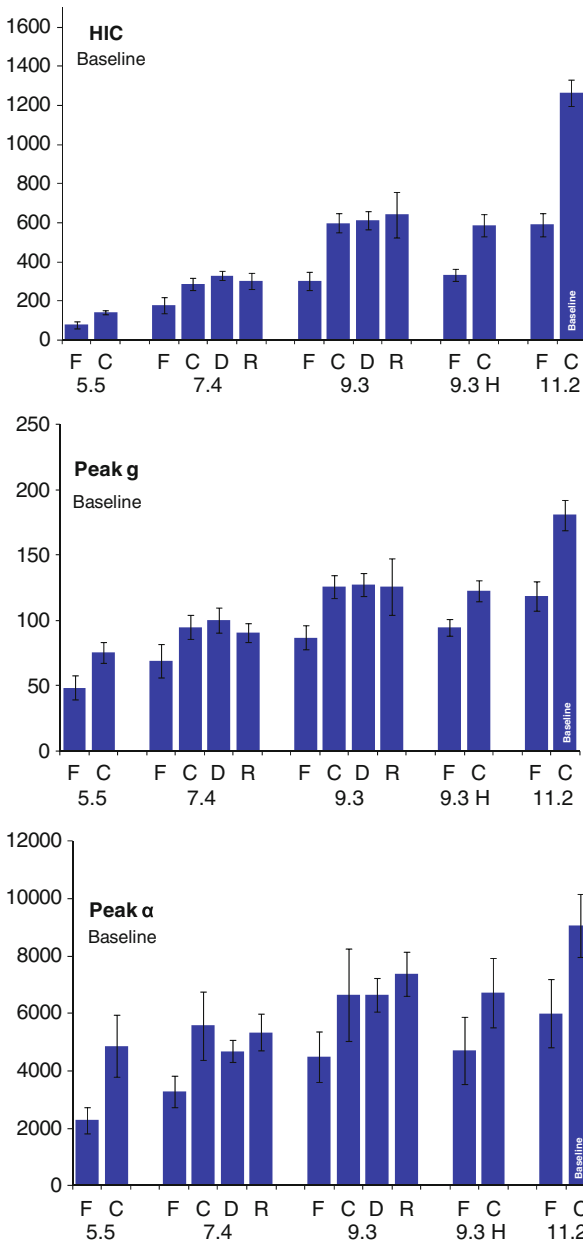
FIGURE 3. Average and ±1sd in 14 shell impacts for HIC, peak head acceleration (*g*), and peak rotational acceleration (*α*) for the 1990s baseline helmets at impact velocities of 5.5–11.2 m/s.

FIGURE 4. Average and ±1sd in 9 facemask impacts for HIC, peak head acceleration (*g*), and peak rotational acceleration (*α*) for the 1990s baseline helmets at impact velocities of 5.5–9.3 m/s.

R) on the 1990s baseline helmets. The test site and speed are listed at the top and the "H" refers to the high temperature testing. The majority of the responses were in the range of 300–800 HIC, 60–150 g, and 4,000–9,000 r/s². For HIC, there was a step increase in value with increasing impact velocity for the four sites on the helmet; however, the front (F) site had the lowest HICs of the four sites. For peak translational and rotational acceleration, the frontal response was again lower than the side and rear responses. Figure 4 shows the average and ±1sd in HIC, peak translational acceleration, and

peak rotational acceleration for the 9 impacts on the facemask (A, A′) and attachment to the shell (B, UT) for the 1990s baseline helmets. Loading on the attachment of the facemask to the shell had higher responses for the 7.4 and 9.3 m/s test conditions than directly on the facemask. Tests were not conducted at 11.3 m/s.

Helmet Response Compared to the 1990s Baseline

Figure 5 shows the percent difference in HIC for each of the helmets tested in the 23 different impacts

Percent Difference in HIC from 1990s Helmets
(+ improvement, - poorer performance, green-significant improvement, red-significantly poorer)

#	Helmet	A 5.5	F 7.4	A' 5.5	C 9.3	F 7.4	A 9.3H	UT 5.5	B 7.4	C 7.4	A 7.4	R 7.4	F 11.2	A 9.3	D 9.3	F 7.4	UT 9.3H	B 7.4	C 9.3	F 9.3	C 9.3	D 9.3H	R 11.2	C 9.3	Average diff (%)	Median diff (%)	+/- 10%	+/- signficant	Total # (22)	# tests (18)	Helmet off (1)
2	A4 (Adams)	-25	-30	-117	-18	-34	-5	-24	-5	-17	-20	21	-35	-16	-4	-34	-16	-20	-18	-33	-13	-12	25	-23	-21	-18	-16	-11	34	27	0
10	A2000 (Adams)	7	13	-78	-9	19	21	-7	5	-5	-7	19	1	-4	-1	19	-1	7	3	-4	6	-11	20	14	0	1	4	3	57	53	1
16	A3000 (Adams)	-69	-15	-59	2	2	-30	2	30	1	-19	24	-8	-28	15	2	3	-9	11	1	16	11	33	21	-3	2	2	3	65	51	0
8	PSE Gladiator (Adams)	-2	11	9	13	6	5	10	15	13	-5	32	-32	-2	22	6	17	-10	7	-29	15	21	37	15	6	10	8	2	134	63	38
3	VSR 4 (Riddell)	13	17	22	13	16	-1	-7	-11	10	19	21	6	19	6	7	8	0	0	9	11	6	24	7	9	9	9	4	13	12	0
4	Revolution (Riddell)	48	23	-2	23	16	48	17	22	22	51	5	5	49	44	3	28	5	10	3	26	29	8	22	22	22	15	13	29	24	0
7	Revo Speed (Riddell)	25	-7	-18	26	3	26	28	10	33	-1	5	-2	2	31	20	24	-8	20	12	31	36	5	32	15	20	13	10	16	16	0
9	Revo IQ (Riddell)	37	22	7	21	17	49	16	29	26	46	6	4	47	41	3	25	1	9	1	26	34	14	14	22	21	16	11	27	21	0
14	Speed Classic (Riddell)	6	-17	-40	14	-5	-8	24	8	8	-10	2	-23	-10	34	-1	32	-16	4	-6	12	39	6	18	3	4	2	6	15	14	0
5	DNA PRO (Schutt)	8	18	1	1	33	25	2	10	8	29	15	31	32	16	19	10	6	16	32	20	14	23	28	17	16	16	10	19	18	0
6	ION 4D (Schutt)	10	-9	8	-5	15	10	-1	1	11	20	9	3	10	15	-22	6	-4	16	-6	19	7	16	23	7	9	8	4	23	19	0
11	Air XP (Schutt)	13	12	-84	1	13	31	2	-9	-5	12	18	5	7	15	12	9	-17	-9	1	-4	7	8	-4	1	7	6	3	12	11	0
12	Air XP 7891 (Schutt)	22	-20	-24	-3	-20	42	3	16	10	17	12	-28	30	19	16	7	3	16	5	18	14	9	18	8	12	9	6	61	41	0
13	Air XP 7890 (Schutt)	29	-5	-37	-1	0	28	8	-6	-12	7	9	-10	13	14	18	13	-29	-8	-1	-5	8	3	-11	1	0	2	1	22	20	0
15	DNA 2022 (Schutt)	0	-49	-19	13	-41	25	17	2	7	6	16	-63	13	23	-4	16	9	17	-24	21	17	25	30	2	13	7	7	53	38	0
17	ION 4D 2030 (Schutt)	21	18	-32	-23	22	27	3	-4	-7	18	9	0	12	16	31	10	-10	8	20	12	11	12	17	8	12	12	5	31	22	0
1	Xenith X1	5	-6	-51	-3	-9	29	1	19	7	7	8	-8	5	18	-26	4	2	3	-22	10	13	10	-6	0	4	2	-1	44	32	1
	Baseline Responses HIC	63	78	111	143	179	179	212	265	289	298	303	305	316	331	336	432	447	586	590	600	612	642	1,266							
	sd	27	20	24	10	42	66	30	37	30	81	39	46	63	24	31	79	41	58	60	48	47	114	66							
	95%CI	16	12	14	6	24	37	17	21	17	46	22	26	36	13	18	45	23	33	34	27	27	65	37							

Column groupings: columns 24–27 are **Differences** (Average diff %, Median diff %, +/- 10%, +/- signficant); columns 28–30 are **Issues** (Total # (22), # tests (18), Helmet off (1)).

FIGURE 5. Percent difference in HIC from baseline for the 17 helmets tested.

compared to the 1990s baseline. A positive difference represents a lower HIC than the 1990s baseline. Cells of data shown in green represent statistically significant improvements (lower responses) on average from the 1990s baseline at the $p < 5.0\%$ level, and those in red are significantly poorer responses. The data are organized by impact site with increasing impact velocity. The helmets were organized by manufacturer and the helmet number (#) is listed along with the specific helmet model. The average HIC average, ± 1sd and 95% confidence interval for the 1990s baseline helmets are shown at the bottom for each test condition.

Also shown in Fig. 5 are four overall measures of the differences for each helmet from the 1990s baseline. They are the overall average difference for the 23 means, the median difference for the 23 conditions, the number of conditions where the average response was more than $\pm 10\%$ different from the 1990s baseline, and the number of differences that were statistically significant at the $p < 0.05$ level. The number of $\pm 10\%$ and significantly different responses was the sum of the number of positive and negative conditions meeting the criterion.

Figure 5 summarizes the number of issues related to chinstrap unlatching, component tearing or breakage and loss of helmet retention for the 17 helmets. The heading shows the average number of issues for the 1990s baseline helmets. There were 22 per four 1990s helmets tested in the 23 conditions (22 issues in 92 tests). Since some of the tests involved multiple issues, there were only 16 tests for the 1990s baseline helmets with an issue (16 tests with issues in 92 impacts). In some cases, the helmet dislodged from the head representing a loss of retention due to chinstrap unlatching or the chinstrap sliding off the chin. On average, there was only one test with the 1990s baseline where the helmet dislodged and came off the head (1 test out of 92). The proportion of issues for each helmet was statistically compared to that of the 1990s baseline helmets. Issue numbers with red background are significantly greater than the 1990s baseline at $p < 0.05$.

The proportion of issues for each helmet was statistically compared to that of the 1990s baseline helmets. Issue numbers with red background are significantly greater than the 1990s baseline at $p < 0.05$. The proportion of issues and 95% confidence interval for the baseline helmets was $19.9 \pm 4.7\%$ (55 in 276 tests). For example, the proportion of issues for helmet #1 was $34.8 \pm 9.7\%$ (32 in 92 tests). Since the confidence intervals do not overlap, helmet #1 has a significantly greater number of issues than the 1990s baseline. The total number of issues in the baseline tests was 68 (range up to 3) in 276 tests. Again for example, helmet #1 had 44 issues (range up to 5) in 92 tests. The average number of issues in tests with helmet #1 was significantly greater than for the baseline (0.478 vs. 0.246, $t = 2.53$, $p < 0.05$).

For the 17 helmets, the average difference from the 1990s baseline varied from improvements in HIC with up to 22% (lower) values to poorer performance with up to -21% (higher) HICs. The median difference varied from a 22% improvement to a -18% (poorer) performance. Five helmets had more than 10 impact conditions where the average HIC was more than $\pm 10\%$ improved over the 1990s baseline. These five helmets also had 10 or more conditions where the difference was statistically significant from the 1990s baseline at $p < 0.05$. One helmet had 11 conditions where the average response was significantly poorer than the baseline at $p < 0.05$.

Six of the helmets had a significantly greater number of issues and one had a significantly higher number of tests with the helmet coming off the head. The chinstrap on helmet #8 consistently unlatched in the tests. The design had the straps fixed to the shell and a central latching at the chin cup. Once the chin cup unlatched, the helmet came off the head.

Figure 6 shows the difference in peak head acceleration for the 17 helmets from the 1990s baseline following the same presentation scheme as in Fig. 5. Again, a number of the helmets showed significant improvements in head accelerations (lower responses) compared to the 1990s baseline. The median improvements were up to 13% with two helmets having 12 conditions out of the 23 with statistically significant improvements in average response. Figure 7 shows the difference in peak rotational acceleration for the 17 helmets from the 1990s baseline. Interestingly, a number of helmets showed significant improvements compared to the baseline with median improvements up to 21% and as many as 14 test conditions with statistically significant improvements in rotational acceleration.

Grouping of Helmet Performance

Table 3 summarizes the statistical analysis of the normalized average responses compared to one for the 1990s baseline. The 23 normalized responses were evaluated using the t test where the t value and p value are given. The level of $p < 0.05$ was used to determine significance, such that no significant difference (NS) means that the 23 different tests were not statistically different from the 1990s baseline helmets. The t statistic is summarized for HIC, peak translational acceleration, and peak rotational acceleration. The last column lists the average number of issues and identifies those helmets with a significantly (S) greater number of issues than the 1990s baseline at the $p < 0.05$ level. The

FIGURE 6. Percent difference in peak acceleration from baseline for the 17 helmets tested.

Percent Difference in Peak Rotational Acceleration from 1990s Helmets
(+ improvement, - poorer performance, green-significant improvement, red-significantly poorer)

	#	Helmet	F 5.5	F 7.4	A 5.5	F 9.3	D 7.4	F 9.3H	C 5.5	A' 7.4	B 7.4	R 7.4	C 7.4	F 11.2	D 9.3	C 9.3	A 7.4	UT 7.4	C 9.3H	B 9.3	A 9.3	R 9.3	A 9.3H	C 11.2	UT 9.3	Average diff (%)	Median diff (%)	+/- 10%	+/- signficant	Total # (22)	# tests (18)	Helmet off (1)
Adams	2	A4	-34	-12	4	10	1	-37	1	-6	-35	14	-9	-30	-1	-18	15	-24	-22	-57	12	4	19	-22	-17	-11	-9	-7	-3	34	27	0
Adams	10	A2000	-19	-10	4	-5	-1	-18	2	6	0	33	3	-36	5	3	35	-8	13	-9	6	16	30	18	-9	3	3	3	2	57	53	1
Adams	16	A3000	-37	-29	12	-32	17	-26	21	39	14	20	14	-12	14	12	30	24	8	16	14	25	15	14	28	9	14	12	10	65	51	0
Adams	8	PSE Gladiator	-14	-38	15	-33	11	-38	34	-44	17	17	25	-63	12	16	33	22	13	9	5	-2	12	6	17	1	12	7	6	134	63	38
Riddell	3	VSR 4	13	6	-23	-10	10	10	17	-16	9	12	28	-16	14	22	-20	-1	12	5	-14	20	-9	11	4	4	9	4	3	13	12	0
Riddell	4	Revolution	4	-26	10	-11	20	3	32	16	16	12	18	-20	21	17	17	7	9	7	20	17	23	17	17	11	16	11	7	29	24	0
Riddell	7	Revo Speed	14	-3	2	-11	13	-19	34	30	2	29	27	-30	-2	20	9	13	12	-6	6	26	20	3	17	9	12	9	6	16	16	0
Riddell	9	Revo IQ	3	-20	-2	-15	8	10	25	2	11	22	14	-11	10	16	18	12	7	3	15	21	24	1	19	8	10	8	8	27	21	0
Riddell	14	Speed Classic	14	20	-3	7	2	2	33	39	-6	11	26	-8	5	24	1	4	18	7	-9	23	27	12	12	11	11	12	10	15	14	0
	5	DNA PRO	11	7	-1	0	16	24	24	27	19	26	28	-5	23	22	29	23	15	-8	16	26	20	10	15	16	19	18	10	19	18	0
	6	ION 4D	0	4	-10	22	18	-23	37	18	13	26	25	16	12	21	5	35	28	1	12	36	29	21	28	16	18	16	10	23	19	0
Schutt	11	Air XP	-8	-13	-19	-17	10	9	15	30	-36	27	19	-8	9	-12	10	6	3	-45	-7	15	7	-16	-1	-1	3	0	3	12	11	0
Schutt	12	Air XP 7891	-12	3	32	24	15	27	34	20	5	23	27	19	8	19	31	22	20	10	15	31	37	17	19	19	20	18	14	61	41	0
Schutt	13	Air XP 7890	6	1	-1	-2	14	6	0	33	-42	14	2	5	19	5	19	3	-1	-24	1	9	24	-11	4	4	4	3	3	22	20	0
Schutt	15	DNA 2022	2	5	4	-12	12	25	39	38	0	25	40	24	4	16	28	30	20	-2	21	29	28	6	27	18	21	14	13	53	38	0
Schutt	17	ION 4D 2030	-40	-44	-15	-5	17	-8	29	36	4	37	27	-7	14	11	6	22	-1	13	-2	33	15	-1	26	7	11	9	6	31	22	0
	1	Xenith X1	-21	-17	5	1	-6	-31	15	31	7	6	6	-6	-17	-10	22	25	-14	6	9	-11	21	-8	21	1	5	-1	3	44	32	1

Baseline Responses

	peak r/s^2	2,289	3,289	3,720	4,492	4,685	4,710	4,861	5,070	5,171	5,351	5,576	5,998	6,634	6,650	6,653	6,819	6,731	7,010	7,326	7,384	8,157	9,056	10,277
	sd	460	541	591	861	388	1,162	1,081	1,570	608	638	1,183	1,185	584	1,620	1,156	571	1,213	1,620	1,608	771	1,314	1,107	851
	95%CI	260	306	334	487	220	657	612	888	344	361	669	671	330	917	654	323	686	917	910	436	744	626	482

FIGURE 7. Percent difference in peak rotational acceleration from baseline for the 17 helmets tested.

TABLE 3. Significance of differences in helmet performance compared to the 1990s baseline and grouping of helmets in terms of head responses and issues in the helmet impacts.

Helmet model	HIC					Peak acceleration (g)					Peak rot. accel. (r/s^2)					Issues # (22)	Sign. worse
	Avg (%)	# ± sign.	t stat	p value	Sign.	Avg (%)	# ± sign.	t stat	p value	Sign.	Avg (%)	# ± sign.	t stat	p value	Sign.		
DNA PRO	17.3	10	7.99	0.000		14.0	12	10.25	0.000		15.9	10	6.94	0.000		19	
Revolution	21.9	13	6.32	0.000		10.8	12	5.31	0.000		10.6	7	3.72	0.001		29	
Revo IQ	21.6	11	6.75	0.000		10.4	11	5.48	0.000		8.4	8	3.34	0.003		27	
Revo Speed	14.6	10	4.48	0.000		7.3	8	3.50	0.002		8.9	6	2.64	0.015		16	
VSR4	9.3	4	4.93	0.000		8.2	7	7.10	0.000	NS	3.6	3	1.19	0.245	NS	13	
ION 4D	6.6	4	2.95	0.007		4.4	9	1.80	0.086	NS	16.4	10	5.24	0.000		23	
ION 4D 2030	8.3	5	2.61	0.016		3.9	4	2.02	0.056	NS	7.3	6	1.61	0.121	NS	31	
Speed Classic	3.1	6	0.80	0.435	NS	2.3	6	0.84	0.410	NS	11.3	10	4.12	0.000		15	
DNA 2022	2.4	7	0.46	0.651	NS	1.0	8	0.28	0.785	NS	17.8	13	5.85	0.000		53	S
Air XP 7891	8.0	6	2.22	0.037		2.3	5	1.80	0.086	NS	19.4	14	8.23	0.000		61	S
Air XP 7890	1.1	1	0.33	0.744	NS	2.4	5	1.31	0.203	NS	3.7	3	1.16	0.260	NS	22	
Gladiator	6.0	2	1.62	0.118	NS	2.2	5	0.72	0.482	NS	1.4	6	0.26	0.796	NS	134	S
A2000	0.1	3	0.02	0.984	NS	0.0	7	1.59	0.126	NS	2.5	2	0.73	0.476	NS	57	S
A3000	-3.2	3	-0.61	0.551	NS	1.8	6	0.52	0.612	NS	8.7	10	1.99	0.059	NS	65	S
Air XP	1.4	3	0.31	0.757	NS	1.5	3	0.68	0.503	NS	-0.9	3	-0.24	0.814	NS	12	
X1	0.4	-1	0.10	0.920	NS	0.5	1	0.27	0.788	NS	1.4	3	0.43	0.674	NS	44	S
A4	-20.5	-11	-3.78	0.001		-12.5	-13	-3.79	0.001		-10.6	-3	-2.56	0.018		34	

table also lists the average difference for the 23 impact tests compared to the 1990s baseline.

The t statistics for the three responses and issues compared to the 1990s baseline allowed the helmets to be organized into four separate groups. The first group (best performing) had all three responses significantly improved compared to the baseline for the 23 test conditions and a statistically similar number of issues as the 1990s baseline helmets. The best performing helmets were the Schutt DNA PRO and the Riddell Revolution, IQ, and Revolution Speed. These helmets were significantly better in attenuating head responses in the impacts. This group was also significantly better than the other 13 helmets tested.

The second group (good performing) involved helmets with at least one response significantly better than the 1990s baseline and a statistically similar number of issues. There were four helmets in this group, two from Schutt (ION 4D and ION 4D 2030) and two from Riddell (VSR4 and Speed Classic). Overall, these helmets were better than the baseline in at least one response but less than the first group.

The third group (poor performing) had either no biomechanical response significantly different for the 23 conditions from the 1990s baseline or had a significantly greater number of issues. In some cases these helmets had significant improvements in many conditions but the improvements were associated with unlatching or component damage. Six of the helmets in the third group showed no significant difference from the 1990s baseline for the 23 test conditions. Four of these had a significantly higher number of issues. There was one helmet in a fourth group (bad performing). All three biomechanical responses were significantly worse than the 1990s baseline and had a negative average difference for the three responses. It was significantly worse than the 1990s baseline and the other three groups.

DISCUSSION

The announcement of the helmet testing with the linear impactor did not offer enough time for the helmet manufactures to make changes in products that were tested. The specifics of the 23 different test conditions were not known by the helmet manufacturers, except for the general understanding of the impact sites and severities for concussion in NFL players.[2,11–13,19–21] The testing reported here did not allow time for refinement or optimization of the football helmets tested. The testing provides a broad array of information and insight on the control of head accelerations in football helmet impacts. However, the full implications of the testing will not be realized for

several years as further improvements in helmet safety are made. Four 2010 helmets performed best when compared to the 1990s baseline helmets.

The four helmets had significantly improved performance compared to the 1990s baseline helmets. The Schutt DNA PRO (#5) and the Riddell Revolution (#4), IQ (#9), and Revolution Speed (#7) had statistically lower biomechanical responses and better force attenuation than the 1990s baseline helmets. Their overall performance was the best for the 23 impacts on the Hybrid III head associated with concussion in NFL players. These helmets included energy absorbing padding of the shell and construction that offered an incremental improvement in safety to protect the head of football players.

The best performing helmets weighed 2.00 kg (4.4 lb) on average. This was only 6.8% greater than the 1.86 kg (4.1 lb) average for the 1990s baseline helmets. These helmets were 7.5% longer than the baseline (34.8 vs. 32.5 cm), 5.4% wider (25.7 vs. 24.1 cm), and only 2.7% higher (28.7 vs. 27.9 cm). These rather modest changes in weight and size indicate that significant improvements in protection can be made without drastically modifying the overall size and weight of the helmet. The sophistication is in the padding system and other components.

Four other helmets provided improved performance on some biomechanical measures compared to the 1990s baseline, but not consistently across all responses. The Riddell VSR4 (#3) and Revolution Speed Classic (#14) and the Schutt ION 4D (#6) and ION 4D 2030 (#17) were better performers than the 1990s baseline helmets. The better performing helmets were 7.4% heavier than the 1990s baseline. These helmets were 5.7% longer than the baseline (34.3 vs. 32.5 cm), 6.1% wider (25.7 vs. 24.1 cm), and 3.7% higher (29.2 vs. 27.9 cm). Again, these are modest differences from the 1990s baseline helmets.

The laboratory testing shows that some 2010 football helmets do not provide consistently improved performance over what was available in the 1990s. Six helmets had a significantly greater number of issues with chinstrap unlatching, component damage or loss of helmet retention. The helmet and its latching system are an integral part of the safety system. The loss of a helmet or unlatching in a play increases the risk of injury to a player.

LIMITATIONS

This study evaluated the protective capacity of helmets planned for use by NFL players. The impact conditions approximate head impacts from studies on NFL player concussions.[2,10–13,19–21] The impact sites

and speeds are based on the observations and analysis of NFL game video and laboratory reconstruction of 31 impacts. There may be other concussion inducing events that occur on the field that are not investigated in this testing program. However, it is presumed that helmet performance levels that are improved would not adversely affect other modalities of injury given the modest changes in mass and size. Further, there has been no effort to determine how typical the NFL collision severities are for other levels of football play, although lower and higher impact velocities were used than the average collision associated with concussion in the NFL.[11–13] Many of the tests were at the average velocity for concussion in the NFL. Fewer tests were conducted at lower speeds, which may be more typical of impacts during lower levels of practice and play, such as amateur play. The helmet rankings described in this work may not apply to amateur play, although one cannot assume that they do not. A follow-on study more thoroughly looks at lower velocities of helmet impact.

Many configurations of helmet and faceguard combinations are possible. No effort was made to understand how the various configurations may affect outcomes in this testing. It is anticipated that basic helmet energy attenuation levels would remain constant to a large degree for a given helmet model. Finally, care should be taken to note that a reported change in performance from baseline is not to be construed as a known change in injury risk. For example, a helmet model with responses 20% better than the 1990s baseline does not mean the risk of injury is 20% less. It may be less or more; however, improved force attenuation means lower head accelerations, which are associated with lower risks for injury. This study involved laboratory tests using a linear impactor and instrumented Hybrid III dummy. There are issues of some player impacts and injuries that it may not address.

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